Capacity of U-turn Junction at Midblock Median Opening on Urban Arterial Based on Balancing Volume-to-capacity Ratio

Thakonlaphat JENJIWATTANAKUL a, Kazushi SANO b, Hiroaki NISHIUCHI c

Abstract: U-turn at midblock median opening is frequently provided in developing countries to facilitate the local access. Movement capacity of such u-turn is of interest for deciding the necessary traffic management. HCM 2010 contains the methodology for u-turn capacity estimation, which is based on gap acceptance theory and assumption of major traffic headway distribution. This research evaluated the gap acceptance capacity model and proposed an adjustment method by v/c balancing. Data collection at a u-turn site was conducted for validation. The results showed that the gap acceptance capacity overestimated the field capacity in case of negative exponential headway distribution and underestimated in case of Erlang-2 headway distribution. The difference in driver behavior when responding to different conflicting headway could explain the situation. The proposed adjustment could provide the estimated capacity closer to the measured field capacity. The method also incorporated the interactions between the u-turn and through traffic streams.

Keywords: Capacity, Conflicting Traffic, Gap Acceptance, U-turn, Traffic Interaction

1. INTRODUCTION

There are a lot of midblock u-turn facilities on urban arterials in the developing countries’ cities. These midblock u-turn junctions interrupt the through traffic movement. After arriving the midblock median opening, the u-turn vehicles wait for the large enough gap and make u-turn maneuver. There are interactions between through traffic and u-turn traffic streams. When the through traffic volume increases, it lessen the chances for the u-turn traffic to move. The reduction of traffic volume in one stream could increase the movement capacity in the other stream. The u-turn vehicles affect the through traffic movement in the opposite direction when they move. Those u-turn vehicles also affect the through traffic movement in the same direction when they stop and create queue. Knowing the capacity of all traffic streams at such u-turn junctions leads to the better traffic operation management as well as facilitates the quality/level of service assessments.

The traffic operation at some u-turn locations on urban arterials in Bangkok, Thailand, is illustrated in Figure 1. It can be noticed that the through and u-turn traffic streams are not ideally operated in a major-minor traffic manner. The u-turn vehicles often do not wait for the large enough acceptable gap of the through traffic. They gradually move onto the conflicting lane to show the intention to go. The through vehicles sometimes do not allow for u-turn, by increasing speed or changing lane or honking car horn or opening headlight. Eventually, the through traffic stops and allows the u-turn traffic to move.
The recent Highway Capacity Manual (HCM 2010) includes the major-street u-turn movements in the methodology for two-way stop-controlled (TWSC) intersections (TRB, 2010). The gap-acceptance theory defines the method for capacity estimation. Three basic elements are gap availability, gap usefulness, and relative priority of subjected movements. The potential capacity equation assumes random arrival process of vehicles on the major street. The model also assumes consistent and homogeneous driving behavior. Liu et al. (2007; 2008a; 2008b; 2009) have conducted a series of research relating to capacity of u-turn at median opening. They estimated the parameters (critical headway and follow-up headway) of u-turn movements from the field data. They validated the capacity estimation from the field capacity. The model provides reasonable estimated capacity for u-turn movement at median openings. The HCM 2010 utilizes the values of these parameters of u-turn movement for the capacity analysis in the US. Nevertheless, the critical headway and the follow-up headway need local calibration due to differences in driving style (Vasconcelos et al., 2012). Those parameters also vary according to physical geometry characteristics of the junction (Weinert, 2000).

The model capacity can differ from field capacity. Kyte et al. (2003) listed the three main causes of difference, including headway distribution of major stream, usage of gaps of minor stream, and driver behavior. The arrival of conflicting vehicles on urban arterial sometimes does not follow the random process. In other words, the headways are not negatively exponential distributed. This affects the availability of gaps for the u-turn vehicles. This research considered the headway distribution. The conflicting traffic headway
distribution had been checked before conducting capacity estimation. Unlike crossroads, the u-turn drivers can easily recognize the gap of conflicting traffic because of the better line-of-sight. The critical headway of u-turn movement is smaller than those of other movements on minor streets. The response of the u-turn vehicles to the gap may not be consistent. Sometimes the driver does not accept the first large enough gap. Sometimes the driver accepts the relatively small gap, which is not safe. The individual driver behavior affects the decision on the facing gap. For the gap acceptance at unsignalized intersections, Pollatschek et al. (2002) concluded that the longer waiting time, the smaller accepted gap. Jenjiwattanakul and Sano (2011) conducted a study on the u-turn gap acceptance behavior and got the same conclusion.

Brilon and Miltner (2005) proposed an innovation method, i.e. conflict technique, for capacity estimation of the TWSC intersections. The method incorporates pedestrians and bicyclists according to their priority rankings. The situation of limited priority and priority reversal can also be reasonably represented by this technique. The conflict technique provides the realistic estimated capacity and agrees with the results from the gap acceptance method.

The existing capacity model in HCM 2010 may not be applicable for the u-turn movements at midblock median openings on urban arterials. In addition, the conflicting through traffic stream is not always priority. It sometimes has to stop or decelerate to allow the forcing u-turn traffic movement. The traffic characteristics do not follow the concept of priority-controlled TWSC intersections. The capacity of the conflicting through traffic is also of interest. This research proposed a method to find capacity of u-turn as well as conflicting traffic movements at midblock u-turn junctions on urban arterials. The proposed method comprised two steps of calculation. Firstly, the potential u-turn capacity was estimated based on the gap acceptance theory, according to the known headway distributions. Secondly, the estimated u-turn capacity was adjusted, based on balancing of volume-to-capacity ratio (v/c) of both traffic streams. The results included the capacity of both u-turn traffic and conflicting traffic.

The objectives of this research can be listed as follows:

- evaluate the u-turn capacity estimation based on gap acceptance theory;
- study the effect of conflicting headway distribution on u-turn capacity estimation by gap acceptance theory;
- propose the new methodology to estimate u-turn and conflicting capacity based on v/c balancing; and
- investigate the characteristics of estimated capacity by the new method.

2. METHODOLOGY

2.1 U-turn Potential Capacity

The potential capacity equations were derived by the gap acceptance concept. When a u-turn vehicle faces a gap of conflicting traffic, the driver would recognize gap size and compare with his/her critical gap \( t_c \). The driver does not make a u-turn if the gap size is less than the critical gap. The driver makes a u-turn when the gap size equals to the critical gap or more. For the queued u-turn movement, the followed u-turn vehicles require the lesser critical gap, which is called follow-up headway \( t_f \). So, if the gap size is between \( t_c \) and \( t_c+t_f \), only one vehicle can make u-turn. If the gap size is between \( t_c+t_f \) and \( t_c+2t_f \), two vehicles can make u-turn. If the gap size is between \( t_c+2t_f \) and \( t_c+3t_f \), three vehicles can make u-turn and so on. The potential capacity is the summation of the total u-turn vehicles, according to the above
explanation, as shown in Equation 1. To estimate the potential capacity, the gap size
distribution, the critical gap, and the follow-up headway must be known. Since the gap data
requires too much effort of data collection, the headway is used instead.

\[ c_{pu} = \sum_{n=1}^{\infty} \left\{ v_c \times \left[ P(h > t_c + (n-1)t_f) - P(h > t_c + nt_f) \right] \times n \right\} \]  

(1)

where,
\- \( c_{pu} \): u-turn potential capacity
\- \( v_c \): conflicting traffic flow rate
\- \( P(h > t) \): probability that the headway is larger than \( t \)
\- \( t_c \): critical headway
\- \( t_f \): follow-up headway
\- \( n \): number of u-turn vehicles in the same headway; \( n = 1, 2, 3, ... \)

When one knows the headway distribution of the conflicting traffic stream, one can
determine the probability that the headway is larger than a specific value. The second term in
Equation 1 represents the probability that the headway is between \( t_c + (n-1)t_f \) and \( t_c + nt_f \), which
allows \( n \) vehicles to make u-turn. When the vehicles arrive in random, the headway
distribution is the negative exponential distribution. When the traffic volume is high, the
movement of one vehicle affects or is affected by other vehicles. The vehicle arrival is not
random anymore. The Erlang distribution can explain the traffic condition in the intermediate
state, which lies between the random and constant headway states (May, 1990). The Erlang
distribution can also represent the headway of traffic on multi-lane highway, where the
headway on each lane is negatively exponential distributed. The headway probability density
function of Erlang distribution is shown in Equation 2 (Salter and Hounsell, 1996).

\[ f(t) = \frac{(qK)^K}{(K-1)!} t^{K-1} e^{-qKt} \]  

(2)

where,
\- \( q \): traffic flow rate
\- \( K \): shape factor; \( K = 1, 2, 3 \)

When the shape factor (K) equals to 1, it is the negative exponential distribution, which
represents the random arrival process. Therefore, the Erlang distribution can cover a wide
range of traffic conditions, by varying its shape factor. For this research, we considered the
shape factor of 1, 2, and 3 because the traffic flow rate on an urban arterial is not extremely
high. The distribution of the headway data was determined by the Chi-square (\( \chi^2 \))
goodness-of-fit method.

The probability that the headway is larger than \( t \), for each value of shape factor, is
shown in Equation 3. The potential capacity equations are shown in Equation 4.

\[ \text{For } K=1, \quad P(h > t) = e^{-v_c t} \]  
\[ \text{For } K=2, \quad P(h > t) = e^{-2v_c t} (1 + 2v_c t) \]  
\[ \text{For } K=3, \quad P(h > t) = e^{-3v_c t} \left[ 1 + 3v_c t + \frac{(3v_c t)^2}{2} \right] \]  

(3)
where,  

\[ c_{pu} : \text{u-turn potential capacity (veh/s)} \]
\[ v_c : \text{conflicting traffic flow rate (veh/s)} \]
\[ t_c : \text{critical headway (s)} \]
\[ t_f : \text{follow-up headway (s)} \]

The critical headway was determined by the maximum likelihood method (Tian et al., 1999). It assumes that a driver’s critical headway is between his largest rejected headway and his accepted headway. The method also assumes a log-normal distribution for the critical headways. The log-likelihood of a sample of \( n \) drivers having an accepted headway and a largest rejected headway of \((a_i, r_i)\) is given in Equation 5. After maximizing the log-likelihood function, the mean critical headway and its variance can be calculated from the mean and variance of the distribution of the logarithms of the individual driver’s critical headways, as shown in Equation 6. On the other hand, the follow-up headway was determined directly from the field data, according to the definition provided in HCM 2010.

\[
L = \sum_{i=1}^{n} \ln[F(y_i) - F(x_i)]
\]  

where,
\[ L \] : logarithm of the likelihood function
\[ y_i \] : logarithm of the accepted headway of the \( i \)th driver = \( \ln(a_i) \)
\[ x_i \] : logarithm of the largest rejected headway of the \( i \)th driver = \( \ln(r_i) \)
\[ F(\cdot) \] : cumulative distribution function of the normal distribution

\[
t_c = e^{b \cdot 0.5 \sigma^2}
\]
\[
\sigma^2 = t_c^2 (e^{\sigma^2} - 1)
\]

where,
\[ t_c \] : mean critical headway
\[ \sigma^2 \] : variance of the critical headway
\[ \mu \] : mean of the distribution of the logarithms of the individual driver’s critical headways
\[ \sigma^2 \] : variance of the distribution of the logarithms of the individual driver’s critical headways

2.2 Capacity Adjustment

The traffic condition on an urban arterial tends to reach an equilibrium situation. Considering interactions of both traffic streams, the traffic intensity of u-turn traffic seems to equal to the
traffic intensity of conflicting traffic. The volume-to-capacity ratio \(v/c\) was used as the measurement of traffic intensity in this research. By balancing the v/c, one could estimate the capacity for both u-turn and conflicting traffic directly.

The capacity estimation could be described in steps as follows:

Step 1: collect the traffic volume data of conflicting traffic \(v_c\) and u-turn traffic \(v_u\).

Step 2: calculate the u-turn potential capacity \(c_{pu}\) by Equation 4, as described in section 2.1.

Step 3: calculate the conflicting potential capacity \(c_{pc}\) by inversing the headway; \(c_{pc} = 3600/h_c\), where \(h_c\) is the mean rejected headway of the conflicting traffic.

Step 4: adjust the potential capacities by increasing the capacity of one stream (u-turn or conflict) and decreasing the capacity of the other stream (conflict or u-turn) so that the v/c of both traffic streams are equal; \(v_c/c_c = v_u/c_u\), where \(c_c\) and \(c_u\) are the resulting capacities of conflicting and u-turn traffic, respectively.

The adjustment followed the fact that the seconds consumed by one traffic stream were replaced by the other traffic stream. For instance, when the v/c of u-turn traffic was higher than the v/c of conflicting traffic, we had to increase the capacity of u-turn traffic and decrease the capacity of conflicting traffic. The amount of conflicting capacity reduction was converted into time consumed by such reduction, and that time would be used by u-turn movement to increase u-turn capacity. The follow-up headway \(t_f\) of u-turn movement, representing the continuous u-turn, was used for converting time to amount of vehicle movement. For the conflicting traffic, the imaginary headway \(h_i\), calculated from u-turn potential capacity, was used instead of measured headway \(h_c\). The relationship was derived based on the fact that the total seconds consumed in an hour must be equal 3600, i.e. \(v_c\times h_i + c_{pu}\times t_f = 3600\). So, the imaginary headway could be calculated as \(h_i = (3600 - c_{pu}\times t_f)/v_c\).

2.3 Validation

The estimated u-turn capacity was validated by the field capacity. The field capacity estimation followed the method as described in NCHRP (1996). In this research, the data analysis was based on 5-minute intervals. Since the u-turn traffic during the intervals was undersaturated, the field capacity was estimated by Equation 7 (Kyte et al., 1991). The service time \(t_s\) and move-up time \(t_{mv}\) could be measured from the field observation.

\[
c_f = \frac{3600}{t_s + t_{mv}}
\]

where,

- \(c_f\): u-turn field capacity (vph)
- \(t_s\): average service delay, i.e. waiting time at the stop line (s)
- \(t_{mv}\): average move-up time from the second position to the stop line (s)

The capacity estimation was evaluated by the value of mean absolute percentage error (MAPE) as shown in Equation 8. The low MAPE indicated that the estimated capacity could well predict the field capacity.

\[
MAPE = \frac{1}{n} \sum_{i=1}^{n} \left| \frac{c_i - c'_i}{c'_i} \right|
\]
where,
\[ n \] : number of intervals
\[ c^i_u \] : estimated u-turn capacity at time interval \( i \) (vph)
\[ c^i_f \] : field u-turn capacity at time interval \( i \) (vph)

3. CALCULATION OF CAPACITY

3.1 Data Collection

To illustrate the application of the proposed method, the traffic data were collected at a u-turn midblock median opening on Phetkasem Road, a six-lane urban arterial in western Bangkok, Thailand. Figure 2 illustrates the site location and road configuration. The road, at the u-turn junction, has three through lanes in each direction with an exclusive u-turn lane on both directions. Most u-turn vehicles encroach to the middle lane in order to complete the u-turn maneuver. Since the traffic condition at the site is busy during the peak periods, the data collection is difficult during those periods. In addition, the policeman controls the u-turn movement when the traffic is congested. The data collection was conducted during off-peak period (11:00-13:00 hrs) on two days. A digital camera was set up on the pedestrian bridge to record the traffic movements. The recorded video files were reviewed in the laboratory to extract the required data for further analysis.

Since the data was analyzed in 5-minute intervals, a total of 48 intervals were considered. The data acquisition was based on the timestamp of all movement events. The required data were determined by the calculation from the recorded time. The traffic volume came from the vehicle count in each interval. The headway was the time difference of the passing of two consecutive vehicles on all conflicting lanes. The waiting time was the
difference between the departure time and the arrival time. The u-turn service time was the average of u-turn waiting time in each interval, i.e. total waiting time of u-turn vehicle divided by total u-turn vehicles. On the other hand, the u-turn move-up time was averaging from all non-stop u-turn vehicles. Table 1 summarizes the required data for each interval, including u-turn traffic volume ($v_u$), conflicting traffic volume ($v_c$), and conflicting traffic headway ($h_c$). The field capacity was also indirectly collected for validation. The u-turn field capacity in the undersaturated traffic condition was calculated from the average service time and average move-up time, as described in Equation 7. The service time ($t_s$), move-up time ($t_{mv}$), and u-turn field capacity are also shown in the Table 1.

### 3.2 Gap Acceptance Parameters

The critical headway and the follow-up headway were determined for the whole 2-hours period on each day. To estimate the critical headway by maximum likelihood method, a pair of largest rejected headway and accepted headway for each u-turning vehicle is required. The largest rejected headway of a specific vehicle must be smaller than its accepted headway. The maximization of the log-likelihood function could be determined by the Microsoft Excel’s Solver. The mean critical headway and its variance could be calculated from the mean and variance of the distribution, according to Equation 6. On the other hand, the follow-up headway was averaged from all continuous u-turn events.

Table 2 presents the calculated distribution parameters from maximum likelihood method and the values and variances of critical headway and follow-up headway for each day. Although the data was collected from the same site, the critical headway and the follow-up headway on both days were not the same. In general, the traffic flow is different from day to day. Both gap acceptance parameters on the first day were larger than those on the second day. This implied the quicker u-turn movement on the second day of data collection. It could be verified by the larger u-turn volume on the second day even though the conflicting volume was larger. Normally, when the conflicting volume is larger, the u-turn volume is expected to be smaller according to the gap acceptance theory; less chance to find the acceptable gap. However, the u-turn volume on the second day was not smaller than that on the first day. This is consistent with the finding that the values of gap acceptance parameters were lower on the second day. The differences in driver behaviors might be caused by different driver population and different traffic condition on both days.

### 3.3 Conflicting Headway Distribution

The type of conflicting headway distribution affects the u-turn capacity estimation as shown in Equation 4. Since the analysis period was set at 5-minute interval, the arrival headways of conflicting vehicles were collected for each 5-minute interval. In reality, the traffic arrival pattern changed from time to time. Checking the headway distribution in each interval could help improve the accuracy of capacity estimation.

The u-turn maneuver requires road space. The u-turn movement conflicts with the through movement on more than one lane. This study considered the conflicting through vehicles on median and middle lanes because most u-turn vehicles utilize those two lanes for their movements. The superimposed headways of the vehicles on median and middle lanes, as the u-turn vehicle faces, were considered as the conflicting headways. The parallel conflicting vehicles, coming at the same instance, were counted as one conflicting vehicle.

The headway distribution was determined by the Chi-square goodness-of-fit test with the significance level of 0.05. The test distributions included Erlang-1 ($K=1$; negative
| Time        | Traffic Flow Rate Conflict U-turn U-turn U-turn Conflict |
|-------------|----------------------|------------------|------------------|------------------|------------------|------------------|------------------|
| Interval    | Time                | Count (5 min.)   | Rate (1 hr.)     | Headway Service | Move-up Time     | Capacity Distribution |
|             |                     | v_c             | v_a             | h_c             | t_s             | t_mv             |
| 1           | 11:00-11:05         | 103             | 25              | 984             | 300             | 2.5              | 5.7              | 2.7             | 429 Neg.Expo     |
| 2           | 11:05-11:10         | 109             | 12             | 864             | 216             | 2.5              | 9.5              | 2.1             | 310 Neg.Expo     |
| 3           | 11:10-11:15         | 130             | 26             | 1032            | 276             | 2.4              | 8.0              | 2.7             | 336 Neg.Expo     |
| 4           | 11:15-11:20         | 124             | 15             | 1080            | 180             | 2.8              | 9.4              | 2.4             | 305 Erlang-2     |
| 5           | 11:20-11:25         | 94              | 17             | 924             | 240             | 2.9              | 11.8             | 2.1             | 259 Erlang-2     |
| 6           | 11:25-11:30         | 96              | 17             | 924             | 264             | 2.7              | 10.9             | 2.5             | 269 Neg.Expo     |
| 7           | 11:30-11:35         | 95              | 17             | 1128            | 204             | 2.6              | 9.6              | 2.5             | 298 Erlang-2     |
| 8           | 11:35-11:40         | 95              | 17             | 1140            | 204             | 2.3              | 10.6             | 2.5             | 275 Erlang-2     |
| 9           | 11:40-11:45         | 86              | 17             | 1032            | 204             | 2.2              | 9.6              | 2.2             | 305 Erlang-2     |
| 10          | 11:45-11:50         | 89              | 20             | 1068            | 240             | 2.4              | 9.4              | 2.3             | 308 Erlang-2     |
| 11          | 11:50-11:55         | 91              | 25             | 1092            | 300             | 2.2              | 7.6              | 2.7             | 350 Erlang-2     |

| Day 1      | 11:55-12:00         | 84              | 16             | 1008            | 192             | 2.4              | 6.2              | 3.5             | 371 Neg.Expo     |

| Time        | Traffic Flow Rate Conflict U-turn U-turn U-turn Conflict |
|-------------|----------------------|------------------|------------------|------------------|------------------|------------------|------------------|
| Interval    | Time                | Count (5 min.)   | Rate (1 hr.)     | Headway Service | Move-up Time     | Capacity Distribution |
|             |                     | v_c             | v_a             | h_c             | t_s             | t_mv             |
| 25          | 11:00-11:05         | 74              | 24             | 888             | 288             | 2.2              | 4.6              | 2.8             | 486 Erlang-2     |
| 26          | 11:05-11:10         | 111             | 18             | 1332            | 216             | 2.0              | 9.7              | 2.4             | 298 Neg.Expo     |
| 27          | 11:10-11:15         | 81              | 25             | 972             | 300             | 2.3              | 6.6              | 2.4             | 400 Neg.Expo     |
| 28          | 11:15-11:20         | 102             | 15             | 1224            | 180             | 2.1              | 10.4             | 2.6             | 277 Erlang-2     |
| 29          | 11:20-11:25         | 82              | 27             | 984             | 324             | 2.5              | 9.0              | 2.7             | 308 Erlang-3     |
| 30          | 11:25-11:30         | 123             | 17             | 1476            | 204             | 2.0              | 11.5             | 2.9             | 250 Erlang-2     |
| 31          | 11:30-11:35         | 85              | 27             | 1020            | 324             | 2.4              | 8.9              | 2.6             | 313 Neg.Expo     |
| 32          | 11:35-11:40         | 98              | 22             | 1176            | 264             | 2.2              | 8.4              | 2.8             | 321 Neg.Expo     |
| 33          | 11:40-11:45         | 101             | 18             | 1212            | 216             | 2.1              | 4.8              | 2.8             | 474 Erlang-2     |
| 34          | 11:45-11:50         | 107             | 21             | 1284            | 252             | 2.2              | 13.6             | 2.3             | 226 Neg.Expo     |
| 35          | 11:50-11:55         | 98              | 19             | 1176            | 228             | 2.4              | 13.0             | 2.6             | 231 Erlang-3     |

| Day 2      | 11:55-12:00         | 90              | 26             | 1080            | 312             | 2.1              | 6.4              | 2.9             | 387 Erlang-2     |

* The headway distribution was not fitted with the test Erlang distributions at the significance level of 0.05.
Table 2. Gap acceptance parameters: critical headway and follow-up headway

<table>
<thead>
<tr>
<th>Day</th>
<th>Distribution</th>
<th>Critical Headway</th>
<th>Follow-up Headway</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Parameter</td>
<td>( \mu )</td>
<td>( \sigma^2 )</td>
</tr>
<tr>
<td>1</td>
<td></td>
<td>1.57</td>
<td>0.21</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>1.53</td>
<td>0.16</td>
</tr>
</tbody>
</table>

exponential), Erlang-2 (K=2), and Erlang-3 (K=3). The resulting fitted distribution for each interval is also shown in the Table 1. Of the total 48 intervals, 24 followed the Erlang-1, 21 followed the Erlang-2, 2 followed the Erlang-3, and the remaining 1 interval could not be fitted with the test distributions.

3.4 Capacity Estimation Example

This section illustrates an example of capacity estimation from the collected data. From the data in Table 1 and 2, the input data for interval 1 were \( v_c = 984 \text{ vph} \), \( v_u = 300 \text{ vph} \), \( t_c = 4.9 \text{ s} \), \( t_f = 3.0 \text{ s} \), \( h_c = 2.5 \text{ s} \), and conflicting headway followed negative exponential distribution (Erlang distribution with K = 1). The calculation could be conducted as below.

\[
c_{pu} = \left( \frac{984}{3600} \right) e^{-\left(\frac{984}{3600}\right)(4.9)} = 0.128 \text{ veh/s} \times 3600 \text{ s/hr} = 461 \text{ vph}
\]

\[
c_{pc} = \frac{3600}{2.5} = 1440 \text{ vph}
\]

\[
\frac{v_u}{c_{pu}} = \frac{300}{461} = 0.65 < \frac{v_c}{c_{pc}} = \frac{984}{1440} = 0.68
\]

To balance \( v/c \), decreased \( c_{pu} \) to \( c_u \) and increased \( c_{pc} \) to \( c_c \). The rate of adjustment followed the ratio of \( h_i \) and \( t_f \): \( \Delta c_u/\Delta c_c = -h_i/t_f \). Then solved to find the value of \( \Delta c_u \) and \( \Delta c_c \) to equalize \( v/c \).

\[
h_i = \frac{3600 - 461 \times 3.0}{984} = 2.3 \text{ s}
\]

\[
\frac{\Delta c_u}{\Delta c_c} = \frac{-16}{21} = \frac{-h_i}{t_f} = \frac{-2.3}{3.0}
\]

\[
\frac{v_u}{c_u} = \frac{300}{461-16} = 0.67 \quad \frac{v_c}{c_c} = \frac{984}{1440+21} = 0.67
\]

So, \( c_u = 445 \text{ vph} \) and \( c_c = 1461 \text{ vph} \). In addition, to determine the u-turn field capacity, the input data for interval 1 were \( t_s = 5.7 \text{ s} \) and \( t_{mv} = 2.7 \text{ s} \).

\[
c_f = \frac{3600}{5.7 + 2.7} = 429 \text{ vph}
\]

The absolute percentage error of estimation in interval 1 could be calculated as:

\[
\left| \frac{c_u - c_f}{c_f} \right| = \left| \frac{445 - 429}{429} \right| = 0.04 \quad \text{or} \quad 4\%
\]
4. RESULTS AND DISCUSSION

4.1 Capacity Estimation Results

Based on the collected data and methodology above, the u-turn potential capacity and adjusted capacity by balancing v/c are shown in Table 3. The calculation process also gave the capacity of the conflicting traffic. The following sections discuss the characteristics of the result, the validation of the proposed method, and the developed capacity curves for practical application.

Table 3. Estimated capacity by balancing v/c

<table>
<thead>
<tr>
<th>Day</th>
<th>Interval</th>
<th>Flow Rate (vph)</th>
<th>U-turn Potential Capacity (vph)</th>
<th>Estimated Capacity</th>
<th>Flow Rate (vph)</th>
<th>U-turn Potential Capacity (vph)</th>
<th>Estimated Capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>300</td>
<td>984</td>
<td>461</td>
<td>445</td>
<td>1461</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>216</td>
<td>864</td>
<td>519</td>
<td>398</td>
<td>1594</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>276</td>
<td>1032</td>
<td>439</td>
<td>411</td>
<td>1538</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>180</td>
<td>1080</td>
<td>294</td>
<td>227</td>
<td>1365</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>5</td>
<td>240</td>
<td>924</td>
<td>489</td>
<td>410</td>
<td>1436</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>6</td>
<td>264</td>
<td>924</td>
<td>489</td>
<td>410</td>
<td>1436</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>7</td>
<td>204</td>
<td>1128</td>
<td>272</td>
<td>254</td>
<td>1406</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>8</td>
<td>204</td>
<td>1140</td>
<td>267</td>
<td>278</td>
<td>1552</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>9</td>
<td>204</td>
<td>1032</td>
<td>317</td>
<td>322</td>
<td>1630</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>10</td>
<td>240</td>
<td>1068</td>
<td>300</td>
<td>329</td>
<td>1465</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>11</td>
<td>300</td>
<td>1092</td>
<td>288</td>
<td>410</td>
<td>1491</td>
<td></td>
</tr>
</tbody>
</table>

Day 12 13 14 15 16 17 18 19 20 21 22 23
|                   | 192            | 1008                            | 450               | 319            | 1676                           |                   |
|                   | 288            | 1032                            | 439               | 412            | 1477                           |                   |
|                   | 228            | 1080                            | 418               | 330            | 1562                           |                   |
|                   | 156            | 1080                            | 294               | 236            | 1634                           |                   |
|                   | 216            | 1104                            | 283               | 282            | 1441                           |                   |
|                   | 288            | 1020                            | 444               | 417            | 1477                           |                   |
|                   | 204            | 936                             | 483               | 385            | 1765                           |                   |
|                   | 288            | 1032                            | 317               | 359            | 1285                           |                   |
|                   | 288            | 1092                            | 413               | 427            | 1618                           |                   |
|                   | 276            | 1128                            | 399               | 400            | 1635                           |                   |
|                   | 144            | 1080                            | 294               | 229            | 1714                           |                   |
|                   | 264            | 1068                            | 300               | 367            | 1485                           |                   |

Day 2 3 4 5 6 7 8 9 10 11 12 13
|                   | 36             | 1210                           | 339               | 458            | 1585                           |                   |
|                   | 37             | 1380                           | 443               | 297            | 1902                           |                   |
|                   | 38             | 1126                            | 398               | 342            | 1711                           |                   |
|                   | 39             | 1392                            | 349               | 355            | 1791                           |                   |
|                   | 40             | 1356                            | 362               | 243            | 1965                           |                   |
|                   | 41             | 1128                            | 453               | 368            | 1823                           |                   |
|                   | 42             | 1488                            | 176               | 222            | 1836                           |                   |
|                   | 43             | 1140                            | 448               | 542            | 1515                           |                   |
|                   | 44             | 1224                            | 271               | 350            | 1623                           |                   |
|                   | 45             | 1272                            | 251               | 284            | 1675                           |                   |
|                   | 46             | 1308                            | 237               | 325            | 1609                           |                   |
|                   | 47             | 1116                            | 458               | 458            | 1637                           |                   |
|                   | 48             | 1236                            | 407               | 450            | 1657                           |                   |

* The capacity information was not available since the headway distribution was unknown.

4.2 Effect of Headway Distribution on U-turn Potential Capacity

The u-turn potential capacity, calculated based on gap acceptance theory, was firstly compared with field capacity. As the u-turn traffic movement from field observation was not saturated, the calculation of field capacity followed the concept of service time in an hour. The summation of average service time and move-up time is regarded as the average time that a minor stream vehicle is served by a traffic lane (see Equation 7). This is to evaluate the performance of the gap acceptance model in estimating the u-turn field capacity, before the adjustment by the proposed method. The comparison is shown in Figure 3. The results showed that the headway distribution of conflicting traffic affected the estimation as follows:
• when the headway followed negative exponential (Erlang-1) distribution, the gap acceptance model overestimated the field capacity;
• when the headway followed Erlang-2 distribution, the gap acceptance model underestimated the field capacity;
• when the headway followed Erlang-3 distribution, the number of samples were too few to conclude anything; however, based on the two available data points, the gap acceptance model predicted well.

![Figure 3. Headway distribution and u-turn potential capacity](image)

The above results showed clear sign about the effect of different conflicting headway distribution, except for the Erlang-3 distribution. The only two data points followed the Erlang-3 distribution. They were taken out from the further analysis. The u-turn capacity estimation by the gap acceptance model needed some adjustments. The capacity estimation when headway distribution followed negative exponential needed to decrease. The capacity estimation when headway distribution followed Erlang-2 needed to increase.

According to the past research (Kyte et al., 1991; Pollatschek et al., 2002), when the drivers wait longer, they tend to accept smaller gaps. In other words, the behavior of drivers affects their decision. This behavior could explain the above results. When the headways follow negative exponential distribution (random arrival process), there are more chances or higher probability to have large gaps for u-turn. The drivers feel relax and may not take the first large enough gap for u-turn maneuver. Instead, they are willing to wait for next large gaps. Therefore, the measured field capacity values are less than the theoretical estimation values. On the other hand, when the headways follow Erlang-2 distribution, there are less chances or lower probability to have large gaps for u-turn. The drivers feel difficult to make u-turn. They do not want to miss the first available large gap. They may behave more aggressive to take the smaller headway than their critical headway. So, the measured field capacity values are more than the theoretical estimation values. Nevertheless, the gap acceptance model assumes the consistent and homogenous driver behavior.

### 4.3 Validation of Proposed Methodology

The validation of the proposed method is shown in Figure 4. This figure compares the field
capacity with the estimated capacity by the gap acceptance model and the proposed methodology. The results showed that the proposed method, based on balancing v/c, yielded the better result than the gap acceptance model in term of lower MAPE value. The proposed method could improve the u-turn capacity estimation.

The previous research about u-turn capacity on six-lane streets by Liu et al. (2009) also refers to the MAPE when validating the capacity model. In their study, the model yields the MAPE of 17.8%. The MAPE is higher than their previous study on four-lane highway, which yields the MAPE of 11.3% (Liu et al., 2008a), but still acceptable considering that the capacity data were collected based on 5-minute interval. They explained that the MAPE is expected to decrease if the larger time intervals are used. Normally, the data analysis in a larger aggregate time period could decrease the data dispersion. They concluded that the model can be applied for the u-turn capacity estimation on six-lane streets.

![Figure 4. Comparison of u-turn potential capacity and adjusted capacity](image)

The traffic operation in urban area tends to reach the equilibrium. The drivers on one stream may care about the other conflicting streams. According to the observation at the u-turn junction, when the u-turn traffic has more queue or waited for longer time, the u-turn traffic tends to be more aggressive to make u-turn. At the same time, the conflicting through traffic tends to be willing to stop and allow the u-turn traffic to go. In theory, the through traffic should get priority over the u-turn traffic all the time. However, the major traffic does not always get priority in urban environment. Therefore, the concept of balancing two traffic streams could be valid at u-turn junctions on urban arterials. In this research, the traffic intensity in term of v/c was used to represent the traffic condition in each traffic stream. The v/c balancing of the two traffic streams could provide the better results, comparing to the traditional gap acceptance models.

**4.4 Characteristics of U-turn Capacity by Balancing v/c**

To investigate the characteristics of the new method, two sets of trial capacity estimations were conducted. These trial estimations could illustrate the effects of different traffic volumes and different headway distribution on the calculated capacity values. This is to get overview properties in the real application. The calculation assumed some inputs and varied the traffic volume of both traffic streams as follows:
- constant critical headway \((t_c)\) of 5.0 seconds
- constant follow-up headway \((t_f)\) of 3.0 seconds
- constant conflicting traffic headway \((h_c)\) of 2.5 seconds
- u-turn traffic volume from 100 to 500 vph, with 100 vph increment
- conflicting traffic volume from 800 to 1600 vph, with 200 vph increment
- conflicting headway distribution of negative exponential and Erlang-2

The capacity curves developed from the trial estimation for negative exponential and Erlang-2 conflicting headway distribution are shown in Figure 5 and 6, respectively. The effects of traffic volume and conflicting headway distribution on the estimated capacity based on v/c balancing are listed as below.

- Estimated capacity depended on traffic volume of both streams, representing their interactions. The different value of traffic volume in one traffic stream affected the capacities of both traffic streams. The higher u-turn traffic volume resulted in the higher u-turn capacity and the lower conflicting capacity. The higher conflicting traffic volume brought about the lower u-turn capacity, but the lower conflicting capacity. The influential level of conflicting traffic volume on conflicting capacity decreased when the u-turn traffic volume increased.

- Type of conflicting headway distribution did not affect the shape of the curves. Based on the estimated values, the capacities of Erlang-2 distribution was lower than those of negative exponential distribution (around 10%). The difference was higher when the conflicting volume is higher. For some traffic planning tasks which require a rough estimation, one could assume the negative exponential distribution to simplify the calculation, with a possibility of about 10% overestimated. It could be concluded that, for capacity determination, the Erlang-2 headway distribution was not much different from the general assumption of random arrival process or negative exponential headway distribution.

![Figure 5. Capacity curve for negative exponential headway distribution](image)
The u-turn capacity estimation by balancing v/c is different from the gap acceptance model in nature. For gap acceptance model, the conflicting volume affects the u-turn capacity but the u-turn volume does not. The model is developed based on the theoretical approach with ideal condition assumptions. In the real world, the traffic operation may not follow the premise conditions. The driver behaviors and the interaction between traffic streams could change the traffic condition. The proposed method in this paper took into account the traffic interaction in the capacity estimation process. The observed real situation on urban arterials derived the assumption of v/c balancing.

5. CONCLUSIONS

Since there are a lot of u-turn facilities at the midblock median openings on urban arterials, the reliable capacity analysis method is crucial for traffic planning and management. This research illustrated the application of the methodology described in the HCM 2010 for u-turn capacity estimation in developing countries, where the nature of driving would be different from the United State. The HCM 2010 applies the gap acceptance theory and assumes the negative exponential conflicting headway distribution. This research covered more types of headway distributions for a more accurate estimation. The result showed that the gap acceptance models seemed not so reliable and needed adjustment. The gap acceptance capacity might overestimate or underestimate the field capacity, depending on the types of conflicting headway distribution. The adjustment by inputting the local driving manner characteristics could improve the capacity estimation. The concept of balancing v/c was applied to determine the u-turn traffic capacity as well as the conflicting traffic capacity. The proposed method adjusted the potential capacity and resulted in the estimated balanced capacity.

The findings from this research could lead to the following conclusions:
• Traffic operation in real world did not perfectly follow the gap acceptance model. Driver behavior and traffic interaction could affect the traffic operation.
• Capacity estimation by gap acceptance model might systematically overestimate or underestimate the field capacity.
• Balancing volume-to-capacity ratio could illustrate the traffic operation on urban streets.
• Interaction between traffic streams affected field capacity.
• The Erlang-2 headway distribution did not yield much different estimated capacity, comparing to the popular negative exponential distribution.

This is a good example that practitioners should consider the local calibration when doing the transport/traffic planning and analysis based on the authorized manuals or handbooks from other countries. This study provided an improved estimation method for the capacity of u-turn and conflicting traffic streams on urban arterials. The traffic capacity is the basic useful information, guiding the engineers and planners to develop the appropriate traffic design and management strategies.

One of the limitations of this research was the amount of data collection. The results relied only on the data collected at a specific site. More data collection on other sites could confirm the results from this study. Since the conflicting capacity is a by-product from the calculation process, the validation from field observation is recommended for future study. Further studies could also focus on the expansion of this adjustment method to other locations and/or other traffic facilities such as all-way stop-controlled (AWSC) intersection, where the traffic interactions are normally observed.

REFERENCES


