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

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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 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.



Figure 1. Traffic operation at the u-turn locations

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 model with 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 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 rateP(h > t): probability that the headway is larger than t t_c : critical headway t_f : follow-up headwayn: 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 (χ^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.

For K=1, P(h>t)=
$$e^{-v_c t}$$

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

For K =1,
$$c_{pu} = v_c \frac{e^{-v_c t_c}}{1 - e^{-v_c t_f}}$$
 (4)
For K =2, $c_{pu} = v_c \frac{e^{-2v_c t_c}}{1 - e^{-2v_c t_f}} \left[1 + 2v_c t_c + 2v_c t_f \frac{e^{-2v_c t_f}}{1 - e^{-2v_c t_f}} \right]$
For K =3, $c_{pu} = v_c \frac{e^{-3v_c t_c}}{1 - e^{-3v_c t_f}} \left[1 + 3v_c t_c + \frac{(3v_c t_c)^2}{2} + 3v_c t_f \frac{e^{-3v_c t_f} (1 + 3v_c t_c)}{1 - e^{-3v_c t_f}} + \frac{(3v_c t_f)^2}{2} \frac{e^{-3v_c t_f} (1 + e^{-3v_c t_f})}{(1 - e^{-3v_c t_f})^2} \right]$

where,

 c_{pu} : u-turn potential capacity (veh/s) v_c : conflicting traffic flow rate (veh/s) t_c : critical headway (s) t_f : 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.

$$L = \sum_{i=1}^{n} \ln[F(y_i) - F(x_i)]$$
(5)

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(): cumulative distribution function of the normal distribution

$$t_{c} = e^{\mu + 0.5\sigma^{2}}$$

$$s^{2} = t_{c}^{2} (e^{\sigma^{2}} - 1)$$
(6)

where,

t_c	: mean critical headway
s^2	: variance of the critical headway
μ	: mean of the distribution of the logarithms of the individual driver's critical
	headways
σ^2	· variance of the distribution of the logarithms of the individual driver's

 σ^{\prime} : 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_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.

$$c_f = \frac{3600}{t_s + t_{mv}} \tag{7}$$

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 =
$$\frac{1}{n} \sum_{i=1}^{n} \left| \frac{c_{u}^{i} - c_{f}^{i}}{c_{f}^{i}} \right|$$
 (8)

where,

n	: number of intervals
$c^{i}_{\ u}$: estimated u-turn capacity at time interval <i>i</i> (vph)
c_f^i	: field u-turn capacity at time interval <i>i</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.



Figure 2. Study site location and road configuration

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

Inter	val Time	Traffic		Flow Rate		Conflict	U-turn	U-turn	U-turn	Conflict
		Cour	nt	(1 hr.)		Head-	Service Move-u		Field	Headway
		(5 mi	n.)			way	Time	Time	Capacity	Distribution
		v_c	v_u	V_c	v_u	h_c	t_s	t_{mv}	c_{f}	
	1 11:00-11:05	82	25	984	300	2.5	5.7	2.7	429	Neg.Expo
	2 11:05-11:10	72	18	864	216	2.5	9.5	2.1	310	Neg.Expo
	3 11:10-11:15	86	23	1032	276	2.4	8.0	2.7	336	Neg.Expo
	4 11:15-11:20	90	15	1080	180	2.8	9.4	2.4	305	Erlang-2
	5 11:20-11:25	77	20	924	240	2.9	11.8	2.1	259	Erlang-2
	6 11:25-11:30	77	22	924	264	2.7	10.9	2.5	269	Neg.Expo
	7 11:30-11:35	94	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	12 11:55-12:00	84	16	1008	192	2.4	6.2	3.5	371	Neg.Expo
1	13 12:00-12:05	86	24	1032	288	2.5	6.7	2.6	387	Neg.Expo
	14 12:05-12:10	90	19	1080	228	2.5	10.7	2.6	271	Neg.Expo
	15 12:10-12:15	90	13	1080	156	2.3	7.7	2.6	350	Erlang-2
	16 12:15-12:20	92	18	1104	216	2.5	8.5	2.7	321	Erlang-2
	17 12:20-12:25	85	24	1020	288	2.5	7.0	2.8	367	Neg.Expo
	18 12:25-12:30	78	17	936	204	2.2	5.3	2.8	444	Neg.Expo
	19 12:30-12:35	86	24	1032	288	2.7	8.7	3.0	308	Erlang-2
	20 12:35-12:40	91	24	1092	288	2.2	5.9	2.6	424	Neg.Expo
	21 12:40-12:45	94	23	1128	276	2.2	8.0	2.8	333	Neg.Expo
	22 12:45-12:50	90	12	1080	144	2.2	8.2	2.1	350	Erlang-2
	23 12:50-12:55	89	22	1068	264	2.3	7.5	2.8	350	Erlang-2
	24 12:55-13:00	104	16	1248	192	2.2	10.4	2.8	273	Neg.Expo
	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	Not Fit*
	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	36 11:55-12:00	90	26	1080	312	2.1	6.4	2.9	387	Erlang-2
2	37 12:00-12:05	96	15	1152	180	2.1	12.3	2.4	245	Neg.Expo
	38 12:05-12:10	105	21	1260	252	2.2	7.8	2.6	346	Neg.Expo
	39 12:10-12:15	116	23	1392	276	2.0	9.6	2.8	290	Neg.Expo
	40 12:15-12:20	113	14	1356	168	2.0	13.2	2.8	225	Neg.Expo
	41 12:20-12:25	94	19	1128	228	2.1	7.3	2.4	371	Neg.Expo
	42 12:25-12:30	124	15	1488	180	1.9	13.8	2.3	224	Erlang-2
	43 12:30-12:35	95	34	1140	408	2.2	6.0	2.5	424	Neg.Expo
	44 12:35-12:40	102	22	1224	264	2.1	6.7	2.6	387	Erlang-2
	45 12:40-12:45	106	18	1272	216	2.1	10.4	2.5	279	Erlang-2
	46 12:45-12:50	109	22	1308	264	2.1	10.6	2.5	275	Erlang-2
	47 12:50-12:55	93	26	1116	312	2.2	6.7	2.4	396	Neg.Expo
	48 12:55-13:00	103	28	1236	336	2.1	7.2	2.4	375	Neg.Expo

Table 1. Data collected from video in each interval and its headway distribution

* The headway distribution was not fitted with the test Erlang distributions at the significance level of 0.05.

Table 2. Oup acceptance parameters: entreal neadway and tonow-up neadway									
Day	y Distributio	n Parameter	Critical I	Headway	Follow-up Headway				
_	μ	σ^2	t_c	s^2	t_f	s^2			
1	1.57	0.21	4.9	1.05	3.0	0.89			
2	1.53	0.16	4.7	0.74	2.7	0.71			

Table 2. Gap acceptance parameters: critical headway and follow-up headway

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 $v_c = 984$ vph, $v_u = 300$ vph, $t_c = 4.9$ s, $t_f = 3.0$ s, $h_c = 2.5$ s, and conflicting headway followed negative exponential distribution (Erlang distribution with K = 1). The calculation could be conducted as below.

$$c_{pu} = \left(\frac{984}{3600}\right) \frac{e^{-(984/3600)(4.9)}}{1 - e^{-(984/3600)(3.0)}} = 0.128 \text{ veh/s} \times 3600 \text{ s/hr} = 461 \text{ vph}$$
$$c_{pc} = \frac{3600}{2.5} = 1440 \text{ vph}$$
$$\frac{v_u}{c_{pu}} = \frac{300}{461} = 0.65 < \frac{v_c}{c_{pc}} = \frac{984}{1440} = 0.68$$

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 Δc_u and Δc_c to equalize v/c.

$$h_{i} = \frac{3600 - 461 \times 3.0}{984} = 2.3 \text{ s}$$

$$\frac{\Delta c_{u}}{\Delta c_{c}} = \frac{-16}{21} = -\frac{h_{i}}{t_{f}} = -\frac{2.3}{3.0}$$

$$\frac{v_{u}}{c_{u}} = \frac{300}{461 - 16} = 0.67 = \frac{v_{c}}{c_{c}} = \frac{984}{1440 + 21} = 0.67$$

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

$$\left|\frac{c_u^1 - c_f^1}{c_f^1}\right| = \left|\frac{445 - 429}{429}\right| = 0.04 \text{ or } 4\%$$

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.

Interval		Flow	Rate	U-turn	Estimated		Inter	val	Flow Rate		U-turn	Estimated	
		(vpl	(vph) Potential		Capacity				(vph)		Potential	Capacity	
		Capacity							Capacity				
		v_u	v_c	(vph) c_{pu}	Cu	C_c			Vu	v_c	(vph) c_{pu}	C_u	C _c
	1	300	984	461	445	1461		25	288	888	451	511	1576
	2	216	864	519	398	1594		26	216	1332	N/A*	N/A*	N/A*
	3	276	1032	439	411	1538		27	300	972	528	495	1605
	4	180	1080	294	227	1365		28	180	1224	271	255	1733
	5	240	924	374	334	1286		29	324	984	327	438	1331
	6	264	924	489	410	1436		30	204	1476	180	238	1725
	7	204	1128	272	254	1406		31	324	1020	504	484	1524
	8	204	1140	267	278	1552		32	264	1176	432	382	1702
	9	204	1032	317	322	1630		33	216	1212	276	301	1686
	10	240	1068	300	329	1465	Day 2	34	252	1284	388	335	1709
	11	300	1092	288	410	1491		35	228	1176	223	279	1441
Day	12	192	1008	450	319	1676		36	312	1080	339	458	1585
1	13	288	1032	439	412	1477		37	180	1152	443	297	1902
	14	228	1080	418	330	1562		38	252	1260	398	342	1711
	15	156	1080	294	236	1634		39	276	1392	349	355	1791
	16	216	1104	283	282	1441		40	168	1356	362	243	1965
	17	288	1020	444	417	1477		41	228	1128	453	368	1823
	18	204	936	483	385	1765		42	180	1488	176	222	1836
	19	288	1032	317	359	1285		43	408	1140	448	542	1515
	20	288	1092	413	427	1618		44	264	1224	271	350	1623
	21	276	1128	399	400	1635		45	216	1272	251	284	1675
	22	144	1080	294	229	1714		46	264	1308	237	325	1609
	23	264	1068	300	367	1485		47	312	1116	458	458	1637
	24	192	1248	353	270	1758		48	336	1236	407	450	1657

Table 3. Estimated capacity by balancing v/c

* 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

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

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



Figure 6. Capacity curve for Erlang-2 headway distribution

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.

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