BUS LANE CAPACITY – A REVISED APPROACH

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Abstract: In Taipei, a bus lane network is implemented to improve the efficiency of bus operation. The capacity of bus lane is becoming a very important issue. The bus fleet size in Taipei is large enough to create a bus platoon on the bus lane. The bus stop berths cannot be used efficiently. It affects the bus lane capacity. The bus lane capacity model in the Highway Capacity Manual already takes the berth number and the signal timing into account, but the effect of bus stopping berth choice and the randomness of service time are still not being involved. Therefore, in this paper, a revised capacity model is developed based on conditional probability structure using a time-space diagram for estimating the difference of ideal theoretical capacity and the capacity under consideration of effective berths and unused service time and green time. Finally, a simplified new formula of bus lane capacity is presented.

1. INTRODUCTION

A bus lane network has been installed to improve the traffic situation in Taipei. It becomes the most important transportation issue in Taipei. Although it is generally accepted that the bus lane can enhance the performance of bus operation, there are many issues to be investigated with respect to planning and designing the lane better. One of these issues is the design of bus stop and analyzing the sufficiency of berths, which influences the capacity of a bus lane.

The Highway Capacity Manual (Transportation Research Board, 1994) proposes a formula to estimate the bus lane capacity. It is based on a single berth stop and taking the influence of signal into account. For a multi-berth stop, the capacity of bus lane is then adjusted using equivalent effective number of berths. However, the model cannot reflect the variability of bus dwell time. A revised equation is reformulated by Levinson using the effective number of berths generated by TRAF-NETSIM simulation results (Levinson, 1998).

There are still several problems existing in the estimation formula of bus lane capacity proposed in the past. Therefore, this paper presents a new capacity formula. In the formula, the time-space diagram concept is used to estimate the total stop time for calculating the ideal capacity of a bus lane. Furthermore, a conditional probability function is generated to take berth choice into account. A comparison of the new formula developed in this paper with the other formulas is conducted to show the advantage of the new formula.

2. LITERATURE REVIEW

The bus lane capacity is a subject scarcely dealt with in the literature. In general, there are three different approaches in traffic flow study. One is simulation approach; another is experiment approach, and the other is mathematical approach. Among all approaches, mathematical model is the commonest treatment in this subject. Therefore, this chapter will outline some popular models in following section.

2.1 Development of HCM Bus Capacity Formulas

For estimating the capacity of Exclusive Bus Lane, a general formula is proposed in the 1994 Highway Capacity Manual. It is given a formula to estimate the capacity of a single berth that takes into account the signal close to the bus stop. Furthermore, it introduces a factor representing an equivalent number of berths to calculate the capacity of bus lane.

In the formulas, several factors have been considered for estimating the capacity of bus lane. It indicates how the number of buses that pass a given stop. The formula in 1994 HCM is:

$$C_v = (g/C)\frac{3600R}{tc + D(g/C)}f(x) \tag{1}$$

Where

C_V : Capacity (bus/h)

R : reductive factor (It represents the effect of variation of dwell time)

tc : average clearance time between buses in seconds

D : average dwell time of a bus at the stop (s)

g/C : effective green time per cycle

$f(x)$: The number of effective berths at the stop

Table 1. The Number of Effective Berths at the Bus Stop

Number of Berths	1	2	3	4	5
Ratio: Effective Berths to Single Berth	1.00	1.75	2.25	2.45	2.50

2.2 Development of Revised HCM Bus Capacity Formulas

The basic bus lane capacity equation was reformulated by Levinson (1998) to provide a more precise consideration of bus dwell time variability. The resulted equations for uninterrupted and interrupted flow conditions were :

Unsignalized :
$$C_v = \frac{3600}{tc + (D + Z_a S_D)} f(x) \quad (2)$$

Signalized :
$$C_v = \frac{(g/C)3600}{tc + (g/C)D + Z_a S_D} f(x) \quad (3)$$

Where Z_a : one-tail normal variation corresponding to probability that queue will not form behind bus stops. (L.O.S. E : P=0.25, Z_a =0.675)

S_D : standard deviation of dwell time (s)

For Effective Berths, iterative runs of TRAF-NETSIM were performed for given block spacing, dwell time, signal timing, and number of bus berths. The simulation results are shown in table 2. The simulation results are slightly higher than the value of HCM.

Table 2. The Number of Effective Berths at the Bus Stop

Number of Berths	1	2	3	4	5
Ratio: Effective Berths to Single Berth	1.00	1.85	2.45	2.65	2.70

2.3 Discussion

Although the revised formula provides a more precise treatment of bus dwell time variability and the estimation of effective berth number, but the general concept is still similar to the method of HCM. Furthermore, for comparing with the formulas developed in the study, the g/C ratio will affect the standard deviation of dwell time, so the Levinson's formula can be further as follow:

$$C_v = \frac{(g/C)3600}{tc + (g/C)[D + Z_a S_D]} f(x) \tag{4}$$

According to previous mention, these two formulas provide a simple method to estimate the capacity of bus lane, but several problems exist in these two models:

1. They cannot estimate the capacity of bus lane, under more than five berths. In Taipei, in view of the huge bus fleet size, a stop normally has more than five berths.

2. Bus stopping position influenced by passenger alighting and boarding location will affect bus lane capacity. The existing formulas without considering this feature cannot precisely estimate the number of effective berths.

3. Because the capacity of bus lane depends on the several random variables that correspond to the dwell time in each berth. The total stop time until the first vehicle leaves is a very important variable for calculating the bus lane capacity. However, HCM model cannot estimate this variable.

4. The existing formulas cannot reflect the impacts of different signal cycle length under the same g/C ratio on capacity value.

3. MODELLING THE CAPACITY OF EXCLUSIVE BUS LANE

In order to estimate bus lane capacity precisely, this study develops a new capacity formula based on time-space diagram concept and by involving conditional probability function. The former is to estimate the total stop time until the first vehicle departures for calculating the ideal capacity of bus lane. The latter is developed to reflect that the bus lane capacity is affected by bus stopping position, so the expected value will be the number of effective berths. Consequently, a new capacity equation is formulated by combining these two models. Figure 1 shows the development procedure of bus lane capacity model, and there are some assumptions existing in this model:

1. The dwell time and stopping position of each vehicle are random variables.

2. The reaction time and move time of each vehicle are the same.

3. Signal phase is fixed.

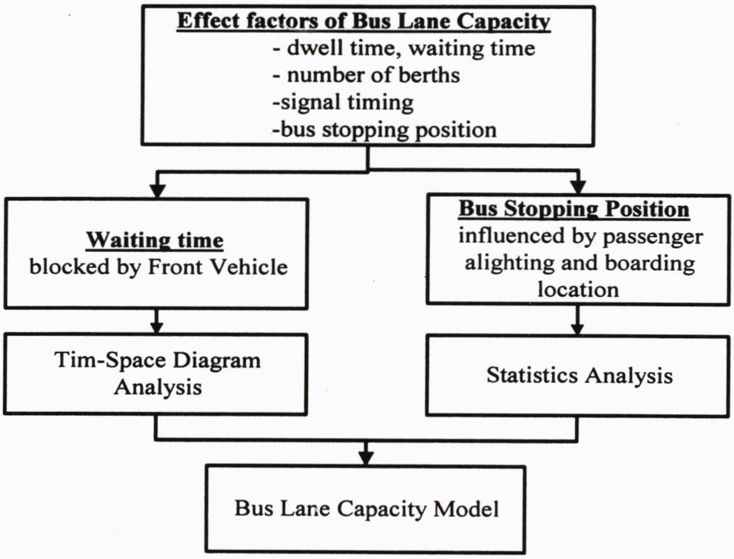

Figure 1. Development procedure of bus lane capacity formula

3.1 「Time-Space Diagram」 Approach

In order to describe the headway characteristic of bus lane operation, this study applies the time-space diagram analysis to estimate the ideal bus lane capacity.

1. Estimation under single berth

Before the operation of bus lane with multiple berths is explained, a single berth bus stop will be considered first. Figure 2 shows the approaching process of bus stop with single berth. There are three random variables existing in the trajectory, which are the reaction time (R) of driver; move time (M) and dwell time (S). Therefore, the headway between vehicle 0 and vehicle 1 will be the sum of these three random variables. The bus lane capacity is the inverse of expected value of headway. It is showed in equation (5) :

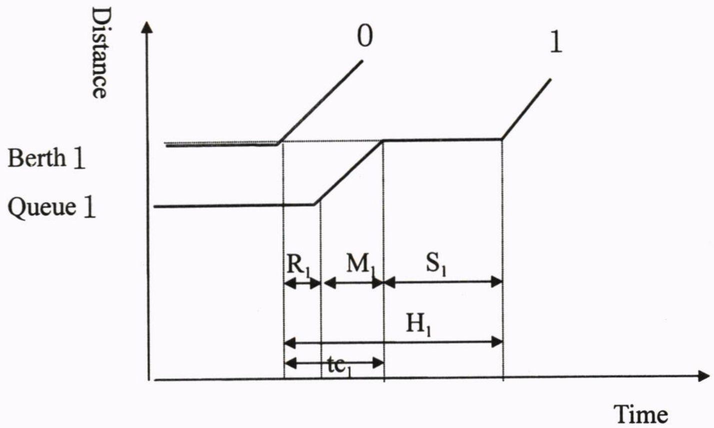

Figure 2. Bus Trajectories at One Berth Bus Stop

Remark：R_i : Reaction time of i bus (s) M_i : Move time of i bus(s)

S_i : Dwell time of i bus (s) tc_i : Clearance time of i bus (s)

H_i: Time Headway of i bus (s) C_j: Capacity of j berths(veh/hr)

E( ) : Expectation value

$E(H_1) = E(R_1) + E(M_1) + E(S_1) = E(tc_1) + E(S_1)$

$$C_1 = 3600/E(H_1) \tag{5}$$

2. Estimation at a 2-berth stop

There are two kinds of time space diagrams at two berths bus stop. One is the bus trajectory under unblocked by front bus, s. Figure 3; the other is the bus trajectory under blocked by the front bus, s. Figure 4.

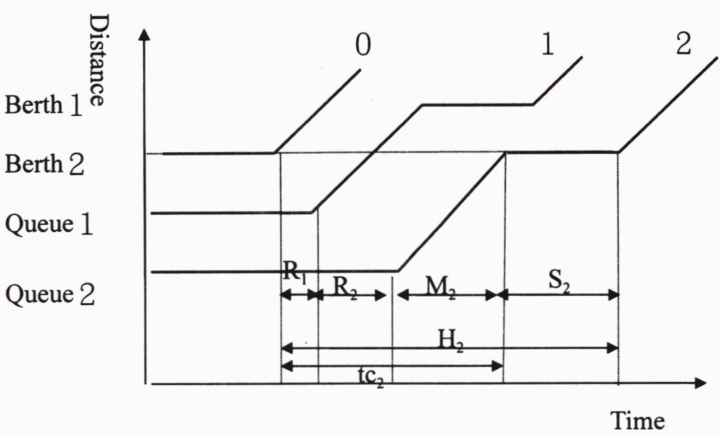

Figure 3. Unblocked bus trajectories at a 2-berth bus stop

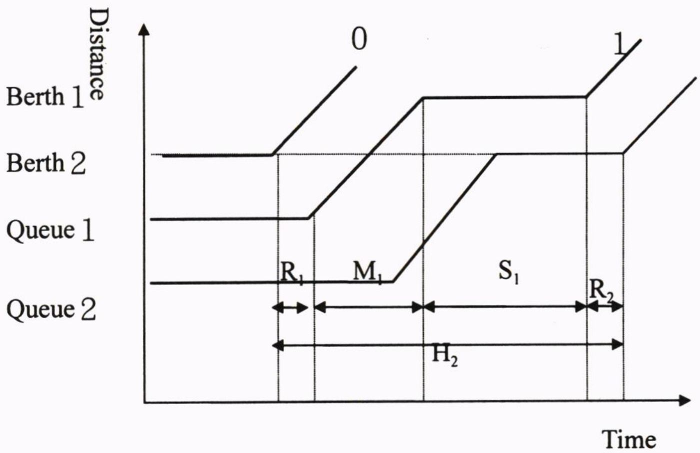

Figure 4. Blocked bus trajectories at 2-berth bus stop

The following equations are to calculate the bus headway of unblocked and blocked traffic flow conditions.

Unblocked headway： $H_2' = R_1 + (R_2 + M_2 + S_2)$

Blocked headway： $H_2'' = (R_1 + M_1 + S_1) + R_2$

Therefore， headway(H_2) can be replaced by following equations：

$$\begin{aligned} H_2 &= \mathrm{Max}\,(H_2', H_2'') \\ &= \mathrm{Max}\,(R_1 + (R_2 + M_2 + S_2),\ (R_1 + M_1 + S_1) + R_2) \\ &\approx R + \mathrm{Max}\,(R_2 + M_2 + S_2,\ R_1 + M_1 + S_1) \\ &\approx tc_2 + \mathrm{Max}\,(S_2, S_1) \end{aligned}$$

$$E(H_2) = E(tc_2) + E(\mathrm{Max}(S_2, S_1))$$

$$= E(tc_2) + \int_0^\infty [1 - P(S_2 < t)P(S_1 < t)]dt$$

$$C_2 = 2 \times 3600 / E(H_2) \qquad (6)$$

Where $P(S_i<t)$ is the probability of the dwell time of i bus less than t.

3. Estimation at a multi-berth stop

By the same way, if S_1, S_2 ...and S_n are i.i.d., bus lane capacity under unsignalized condition is showed in equation (7). For signalized traffic condition, the dwell time will be discounted by g/C ratio. The bus lane capacity with a n-berth stop at signalized junctions will be equation (8).

Unsignalized：

$$E(H_n) = E(tc_n) + E(Max(S_n,\ldots,S_2,S_1))$$

$$= E(tc_n) + \int_0^{\infty}\left[1 - P(S < t)^n\right]dt$$

$$\text{Capacity}(C_n) = \frac{3600}{E(H_n)} \times n \tag{7}$$

Signalized：

$$E(H_n) = E(tc_n) + (g/C)\,E(Max(S_n,\ldots,S_2,S_1))$$

$$= E(tc_n) + (g/C)\int_0^{\infty}\left[1 - P(S < t)^n\right]dt$$

$$\text{Capacity}\ (C_n) = \frac{3600(g/C)}{E(H_n)} \times n \tag{8}$$

3.2 Estimation for Effective Berth Number

In order to analyze the bus lane capacity effected by bus stopping position influenced by passenger alighting and boarding location. The first bus will not always stop on the first berth each times. This study uses field observation data to develop a distribution for describing the behavior of berth choosing. For example, if there are four berths, the distribution will be defined as table 3.

Table 3. The Distribution of Berth Choosing

Stopping position / Probability	Berth1 (x=1)	berth2 (x=2)	berth3 (x=3)	berth4 (x=4)
$f(x \mid y = empty)$	$f(x=1 \mid y=0)$	$f(x=2 \mid y=0)$	$f(x=3 \mid y=0)$	$f(x=4 \mid y=0)$
$f(x \mid y = berth1)$		$f(x=2 \mid y=1)$	$f(x=3 \mid y=1)$	$f(x=4 \mid y=1)$
$f(x \mid y = berth2)$			$f(x=3 \mid y=2)$	$f(x=4 \mid y=2)$
$f(x \mid y = berth3)$				$f(x=4 \mid y=3)$

Where:

Y is a random variable of stopping position of front bus;

y= empty, berth1, berth2,berth3

X is a random variable of stopping position of following bus;

x= berth1, berth2, berth3,berth4

Therefore, the equation (9) will be the effective berth number (n') of four berths bus stop.

$$\begin{aligned}\text{FffectiveBerth Number} = {} & 4 \times \left[f(x=1 \mid y=0) f(x=2 \mid y=1) f(x=3 \mid y=2) f(x=4 \mid y=3)\right] + \\ & 3 \times [f(x=1 \mid y=0) f(x=3 \mid y=1) f(x=4 \mid y=3) \\ & \quad + (f(x=1 \mid y=0) f(x=2 \mid y=1) f(x=4 \mid y=2) \\ & \quad + (f(x=2 \mid y=0) f(x=3 \mid y=2) f(x=4 \mid y=3)] + \\ & 2 \times [f(x=1 \mid y=0) f(x=4 \mid y=1) + f(x=2 \mid y=0) f(x=4 \mid y=2) \\ & \quad + f(x=3 \mid y=0) f(x=4 \mid y=3)] + \\ & 1 \times f(x=4 \mid y=0) \qquad (9)\end{aligned}$$

3.3 Bus Lane Capacity Equation

Combining the results of section 3.1 and section 3.2, a bus lane capacity equation is developed. It is showed in equation (10).

$$\text{Capacity}(C_n) = \frac{3600(g/C)}{E(H_n)} \times n' \qquad (10)$$

Where n' : Effective berth number

4. CALCULATION AND APPLICATION OF CAPACITY

To verify the model, the real bus lane operation data are collected as the input to apply the new model. Consequently, this study summarizes some conclusions comparing with the results of HCM model.

4.1 Surveys on Bus Lane

For the sake of understanding bus lane operation, the bus lane traffic flow in Taipei was observed, and the measurements of the traffic flow were carried out at four berths bus stop during the morning peak hours to make some statistics analyses for these variables.

1. Dwell time

A survey of dwell time shows the frequency distribution of dwell time, as illustrated in figure 5, with mean of 20.7 (seconds) and standard deviation of 18.6(seconds).

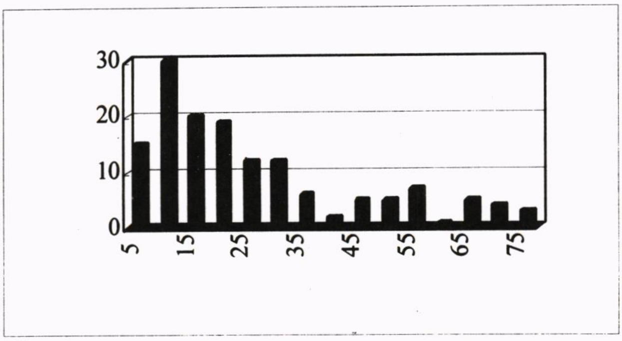

Figure 5. The Frequency Distribution of Dwell Time

2. Berth Choosing Behavior

The whole 143 buses per hour were counted on this bus lane during the peak hour. The berth choice probability is showed in table 4. It indicates that the number of effective berths will reduce with increasing berth number.

Table 4 The distribution of berth choice

Stopping Position	Berth1 (x=1)	berth2 (x=2)	berth3 (x=3)	berth4 (x=4)
$f(x \mid y=0)$	0.5476	0.3334	0.0714	0.0476
$f(x \mid y=1)$		0.8077	0.1538	0.0385
$f(x \mid y=2)$			1.0	0.0
$f(x \mid y=3)$				1.0

3. Total clearance time under multi-berths

The survey result shows the bus clearance time dependent on the berth number, as equation 11. From equation 11, the clearance time will increase with increasing berth number.

$$Y = 9.66 + 4.45(X-1) \qquad (R^2=0.97) \qquad (11)$$

Where Y : Clearance Time (sec.).

X : The Number of Berth

4.2 Calculation of Capacity

Applying the results of section 4.1, this study developed a cumulative distribution to calculate the expectation of $\max(S_1,\ldots,S_n)$. The expectation equals the area above the frontier of $F(\max(S_1,\ldots,S_n))$ between t=0 and t=∞ (s. Fig. 6). Therefore, the total stop time of different berth number can be estimated.

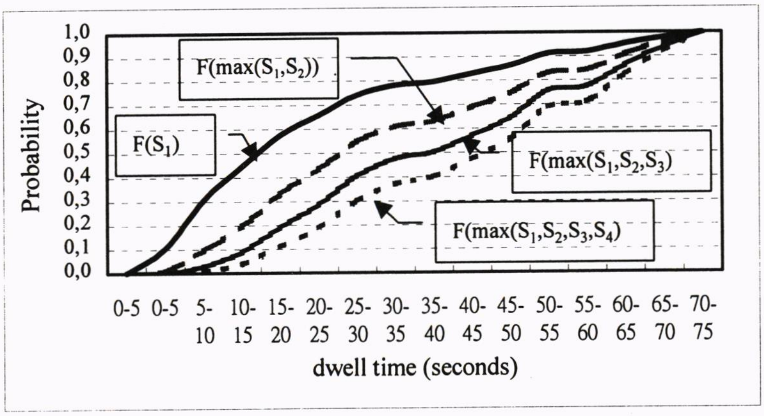

Figure 6. Cumulative distribution of Max $(S_1,\ldots,S_n)$

According to table 4, figure 6 and equation 11, bus lane capacity can be estimated under different berth numbers. Table 5 summarizes the results of capacity calculation.

Table 5. Bus lane capacity of different berth numbers

The Number of Berth	1		2		3		4	
g/C	0.5	1.0	0.5	1.0	0.5	1.0	0.5	1.0
Dwell & waiting time(s.)	10.4	20.7	15.4	30.9	18.7	37.4	21.0	42.1
Clearance time(s.)	9.7	9.7	14.1	14.1	18.6	18.6	23.0	23.0
$E(H_n)$ (s.)	20.0	30.4	29.5	45.0	37.3	56.0	44.0	65.1
Effective Berth Number	1.0	1.0	2.0	2.0	2.8	2.8	3.3	3.3
Capacity(C_n) (bus/hr)	89.9	118.5	121.8	160.1	133.8	178.2	134.9	182.5

5. COMPARISON WITH HCM MODEL

Comparing with the results of HCM model, the results are summarized at table 6, figure 7, and figure 8.

Table 5 Capacity Comparison of Different Model

Berth Number	1		2		3		4	
(g/C)	0.5	1.0	0.5	1.0	0.5	1.0	0.5	1.0
HCM	74.9	98.7	131.1	172.8	168.6	222.2	183.6	241.9
HCM Revised	68.4	83.8	126.6	155.1	167.7	205.4	181.4	222.2
Model 1	89.9	118.5	121.8	160.1	144.9	193.0	163.5	221.2
Model 2	89.9	118.5	121.8	160.1	133.8	178.2	134.9	182.5

Note: HCM is equation (1).

HCM Revised is equation (4).

Model 1 is equation (8).

Model 2 is equation (10).

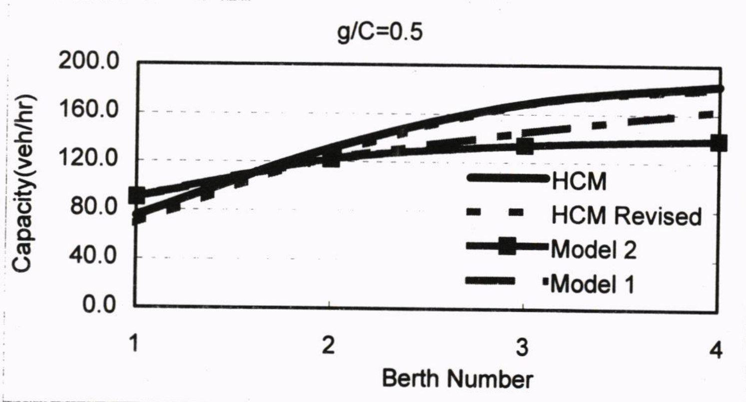

Figure 7 Capacity of Different Model with Signalized Junction

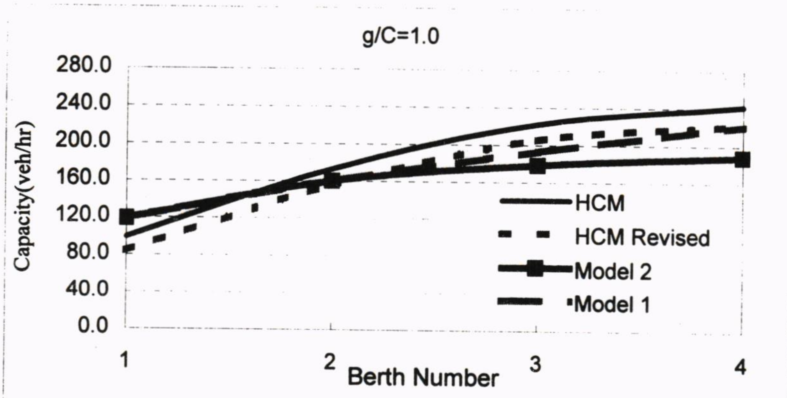

Figure 8 Capacity of Different Model with Unsignalized Junction

According to the results of figure 7 and figure 8, some conclusions are summarized as follow：

1. Figure 7 indicates the results of HCM model (equation 1) and HCM revised model (equation 4) are similar.
2. Figure 8 demonstrates the results of HCM revised model (equation 4) and model 1 (equation 4) are similar.
3. The results of model 1 and model 2 are lower than the values of HCM and HCM revised model.
4. Comparing model 1 (without consideration of berth choosing behavior) with model 2(with consideration of berth choosing behavior), it indicates that berth choosing behavior has a big impact on bus lane capacity.
5. No matter what method is, the marginal capacity value will decrease with increasing berth number.

6. CONCLUSION

A new approach to analyze bus lane capacity is developed. Five major conclusions resulted from the study are listed as following:

1. The standard deviation of dwell time will be affected by the g/C ratio, the revised formula for HCM should be discussed.
2. This study proposes a new capacity model. It not only can reflect the dwell time variability, but also there is no limitation of berth number. Therefore, it can estimate the capacity of bus lane, if the number of berths is more than five.
3. The new formula developed in this study can reflect that bus lane capacity affected by bus stopping position. The effective number of berths can be estimated more precisely and used to estimate the capacity more accurately.
4. The berth choice behavior has a big impact on bus lane capacity. It should be considered into the capacity estimation of bus lane.
5. No matter what method is, the marginal capacity value will decrease with increasing berth number.

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