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Method for calculating the capacity of bus bay

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Abstract: The bus operating characteristics are analyzed at the bus bay using the trajectories depending on the current status of buses. On this basis, a method for calculating the capacity of the bus bay is developed, which considers the queue probability, the dwell time distribution and the waiting time for a gap in the traffic stream at the curb lane. Then, the distribution model of the dwell time is developed using the survey data of Hangzhou city. And the log-normal distribution shows the best fitting performance. The capacities of the bus bay are computed with the Matlab program under different distribution parameters of the dwell time and different traffic volumes at the curb lane. The results show a large range of traffic capacity as the distribution parameters and traffic volumes change. Finally, the proposed model is validated by measurement and simulation, and the average relative errors between the calculated values and the measured and simulated values are 8.78% and 5.28%, respectively.

Key words: bus bay; capacity; dwell time; log-normal distribution

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A bus stop is an area where one or more buses load and unload passengers and the most common forms of loading areas are curbside bus stops and bus bays, among which bus bays can reduce the effects of the stopped buses on the capacity of the neighboring lane. Therefore, bus bays have been introduced in a lot of bus stops when roads are constructed. However, with the rapid development of public transport, bus stops face increasing pressure, especially, during peak hours, their efficiency decreases continuously, and even serious traffic congestion occurs frequently. So, to some extent, the bus stop even becomes a stumbling block in an urban road network. Therefore, it is necessary to make an intensive study on the capacity of the bus stop based on the current operating characteristics of urban road traffic.

The most widely used calculation method with regard to the capacity of bus stops is presented in the transit capacity and the quality of the service manual[1] and HCM2000[2]. The HCM2000 adopts the following model for estimating the capacity of a bus stop:

$$B_{\mathrm{s}} = N_{\mathrm{eb}} \frac{3\,600(g/C)}{t_{\mathrm{c}} + (g/C)t_{\mathrm{d}} + ZC_{\mathrm{v}}t_{\mathrm{d}}}$$

where B_{s} is the maximum number of buses per bus stop per hour; N_{eb} is the number of effective loading areas; g/C is the effective green time per signal cycle; t_{c} is the clearance time between successive buses (s); t_{d} is the average dwell time (s); Z is the one-tail normal variation corresponding to the probability that queues will form behind the bus stop; c_{v} is the coefficient of variation of dwell times.

The above formula is straightforward and rests on empirical values of the seven parameters coming from case studies at stops in the USA. It is assumed that the number of the effective berths of a uniform bus stop is constant. The average dwell time is used as its expectations, and the influence of other factors on the number of effective berths and the differences in the distribution of dwell time are ignored, which makes the HCM model inaccurately reflect the bus stop capacity in different locations and at different times.

According to the highway capacity analysis in China, the capacity of a bus stop is given by[3]

$$C = \frac{3\,600}{t}$$

where t is the average time of bus stops occupied by buses. In this model, it is assumed that buses can be serviced immediately when arriving at a bus stop. According to the survey of bus stops in Hangzhou city, however, the percentage that a queue of buses exists behind stops is 50% to 70%. It is obvious that the serving process of queuing buses is different, compared with non-queuing buses.

In addition, Yang et al.[4] studied the capacity reduction factor of outside lanes when buses move in and out of a bus stop using the queuing theory and the gap acceptance theory. Since the efficiency of bus berths is different, it is unreasonable to directly use the queuing theory to study the capacity of bus bays.

In a word, the existing models cannot meet the current requirements for the design of bus stops. Therefore, this paper first uses trajectories to describe the vehicle operat-

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ing characteristics at bus bays by taking full account of the process of buses queuing up at bus stops. Then, the calculation model of the bus bay capacity is derived by considering its influencing factors including the dwell time and the delay of buses moving out of bus stops. Finally, the model is verified by measured and simulated data.

1 Theoretical Analysis of Capacity of Bus Bays

Some surveys show that the probability of overtaking is very small at bus bays, because the flexibility of buses is poor, and the bus bay's space is not enough. When pulling out of the bus bays, buses must wait for a gap in the stream at the curb lane. So the total time that a bus occupies the bus bay includes the reaction time of bus drivers, the move-up and positioning time, the dwell time and the waiting time for a gap. In this paper, the capacities of one- and two-berth bus bays are studied. Three assumptions are adopted in the formula derivation:

1) All the drivers have the same characteristics, i. e., the same reaction times;

2) Suppose that buses speed up with a constant acceleration a_1, and then slow down with a constant deceleration a_2, during the process of moving from the waiting position to the service position;

3) The minimum headway between buses is the length of one berth when buses move into the bus bay.

1.1 Model for calculating one-berth bus bay capacity

Many factors affect the operation and the capacity of bus bays. Commonly considered factors include the number of berths, dwell time, clearance time, signal control, and operator policy[5-6]. The operating characteristics of buses at one-berth bus bays is analyzed using trajectories and taking full consideration of the bus stop queue process of vehicles, as shown in Fig. 1.

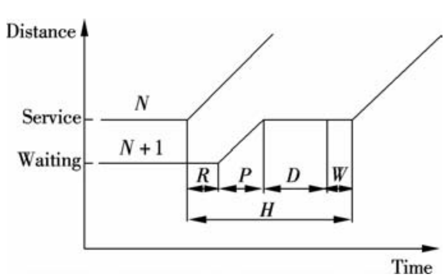

Fig. 1 Trajectories at a bus bay with one loading area

At a bus bay with one loading area except skip-stop running, buses overtaking will not happen. So the capacity of bus bays is then given by

$$C_1 = \frac{1}{E(H)} \tag{1}$$

where $E(H)$ is the mathematical expectation of the headway between buses.

As shown in Fig. 1, the headway between bus N and bus $N+1$ is the sum of R, P, D and W[7].

$$E(H) = E(R) + E(P) + E(D) + E(W) \tag{2}$$

where R is the reaction time of drivers; D is the dwell time; W is the waiting time for a gap at the curb lane; P is the boarding time and it can be calculated by

$$P = \beta P_1 + (1-\beta) P_2 \tag{3}$$

where β is the percentage of a queue of buses which exists behind bus bays; P_1 and P_2 represent the positioning time of queuing and non-queuing buses, respectively.

$$P_1 = \sqrt{\frac{2d}{a_1 + a_2}}\left(\sqrt{\frac{a_2}{a_1}} + \sqrt{\frac{a_1}{a_2}}\right),\ P_2 = \sqrt{\frac{2d}{a_2}}$$

Then,

$$P = \beta \sqrt{\frac{2d}{a_1 + a_2}}\left(\sqrt{\frac{a_2}{a_1}} + \sqrt{\frac{a_1}{a_2}}\right) + (1-\beta)\sqrt{\frac{2d}{a_2}} \tag{4}$$

where d is the minimum headway between buses at bus bays.

1.2 Model for calculating two-berth bus bay capacity

There are two possible scenarios at two-berth bus bays: 1) Bus $N+1$ finishes its service before bus $N+2$; 2) Bus $N+2$ finishes its service before bus $N+1$ (see Fig. 2).

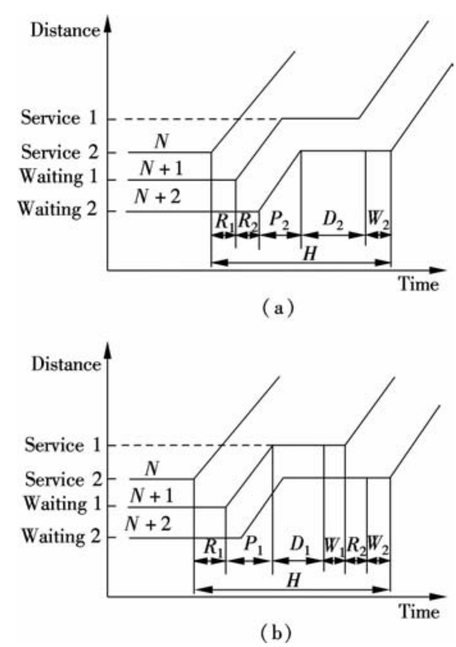

Fig. 2 Trajectories at a two-berth bus bay (a) Scenario 1); (b) Scenario 2)

The headway in the two cases is calculated by

$$H' = R_1 + R_2 + P_2 + D_2 + W_2 \tag{5}$$

$$H'' = R_1 + R_2 + P_1 + D_1 + W_1 + W_2 \tag{6}$$

Generally, the greater headway representing the corresponding case happens. So, the headway is the maximum value between H' and H''.

$$H = \max\{R_1 + R_2 + P_2 + D_2 + W_2, R_1 + R_2 + P_1 + D_1 + W_1 + W_2\} \tag{7}$$

According to the above assumptions, $R_1 = R_2$. The length of two berths is $2d$, so P is calculated by

$$P = 2\beta\sqrt{\frac{d}{a_1 + a_2}}\left(\sqrt{\frac{a_2}{a_1}} + \sqrt{\frac{a_1}{a_2}}\right) + 2(1-\beta)\sqrt{\frac{d}{a_2}} \quad (8)$$

In fact, the values of R, D, P, W are random variables. However, reaction and positioning times are relatively uniform, depending on driver response, acceleration, and type of vehicles. Thus, for the sake of simplicity, they are considered as fixed values. The dwell time depends on the demand (boarding and alighting), the opening and closing gates time, and it can be described by the probability distribution function. Waiting time depends on the traffic volume at the curb lane and the distribution function of the headway, and it can be studied using the gap acceptance theory. The headway between buses and its mathematical expectation at two-berth bus bays can be calculated by

$$H \approx 2R + P + W_2 + \max(D_1 + W_1, D_2) \quad (9)$$

$$E(H) \approx 2R + P + E(W) + E(\max(D_1 + W_1, D_2)) \quad (10)$$

The capacity of the bus bay is then given by

$$C_2 = \frac{2}{E(H)} \quad (11)$$

Assume that the cumulative distribution function and the probability density function of D and W are $u(x)$, $U(x)$, $v(x)$ and $V(x)$, respectively. The cumulative distribution function and the probability density function of $(D+W)$ are

$$f_{D+W}(t) = P(D + W = t) = \int_0^t u(x)v(t-x)\,\mathrm{d}x$$

$$F_{D+W}(t) = P(D + W \leqslant t) = \int_0^t u(x)V(t-x)\,\mathrm{d}x$$

The cumulative distribution function of $\max(D_1 + W_1, D_2)$ is

$$F_{\max(D_1+W_1,D_2)}(t) = P[\max(D_1 + W_1, D_2) \leqslant t] = P[D_1 + W_1 \leqslant t]P[D_2 \leqslant t] = F_{D+W}(t)U(t) \quad (12)$$

And the probability density function of $\max(D_1 + W_1, D_2)$ is

$$f_{\max(D_1+W_1,D_2)}(t) = \frac{\mathrm{d}}{\mathrm{d}x}F_{\max(D_1+W_1,D_2)}(t) = F_{D+W}(t)u(t) + f_{D+W}(t)U(t) \quad (13)$$

The mathematical expectation is then given by

$$E(\max(D_1 + W_1, D_2)) = \int_0^{+\infty} tf_{\max(D_1+W_1,D_2)}(t)\,\mathrm{d}t = 2\int_0^{+\infty}\int_0^t t[u(t)u(x)V(t-x) + U(t)u(x)v(t-x)]\,\mathrm{d}x\mathrm{d}t \quad (14)$$

2 Determination of Distribution Function

2.1 Distribution function of dwell time

Field data are collected at three single bus bays from 7:00 to 9:30 in the morning on July 20 to 22, 2011, and they are fitted with normal, log-normal and Weibull distributions, respectively[8]. The dwell time distribution fitting results are shown in Tab. 1.

From Tab. 1, it can be seen that the log-normal distribution describes the collected data best. The fitting curve of the histogram and the cumulative distribution at Qingfeng bus stop are shown in Fig. 3.

Suppose that the dwell time is distributed log-normally, the distribution and the density functions of the dwell time are

$$u(t) = \frac{1}{t\sigma\sqrt{2\pi}}\exp\left(\frac{(\ln(t) - u)^2}{2\sigma^2}\right)$$

$$U(t) = \int_0^t \frac{1}{x\sigma\sqrt{2\pi}}\exp\left(\frac{(\ln(x) - u)^2}{2\sigma^2}\mathrm{d}x\right)$$

Tab. 1 The dwell time distribution fitting (Qingfeng stop)

Period	Normal distribution		Log-normal distribution		Weibull distribution	
	Function	K-S value	Function	K-S value	Function	K-S value
7:30—8:30	(19.68, 9.47)	0.116 6	(2.823, 0.443)	0.050 6	(22.27, 2.19)	0.095 3
8:30—9:30	(17.57, 4.11)	0.145 5	(2.848, 0.273)	0.083 9	(19.21, 4.31)	0.136 7

2.2 Distribution function of waiting time

According to the revised monograph on the traffic flow theory, the M3 model proposed by Cowan is a better headway model for gap acceptance among the distributions[9]. This headway model has a cumulative probability distribution:

$$P(h \leqslant t) = \begin{cases} 1 - \alpha \mathrm{e}^{-\lambda(t-\tau)} & t \geqslant \tau \\ 0 & t < \tau \end{cases}$$

where α is the proportion of free vehicles; λ is the decay constant.

When headways are assumed to have a Cowan M3 distribution, the proportion of drivers stopped for more than a short period t is given by the empirical equation[9]:

$$P(W > t) = P(0,t) + A[1 - P(0,t)]\rho + (1-A)[1 - P(0,t)]\rho^2 + (1-A)(1-B)(1-\rho)\rho$$

where

$$B = 1 - (1 - t/t_{\mathrm{f}})(1 - t_{\mathrm{m}}q)\mathrm{e}^{-\lambda(t_{\mathrm{c}} - t_{\mathrm{m}})}$$

$$A = 1 - a_0\mathrm{e}^{-\lambda(t_{\mathrm{c}} - t_{\mathrm{m}})}$$

$$\lambda = \alpha q/(1 - t_{\mathrm{m}}q)$$

$$P(0,t) = 1 - (1 - t_{\mathrm{m}}q + t\alpha q)\mathrm{e}^{-\lambda(t_{\mathrm{c}} - t_{\mathrm{m}})}$$

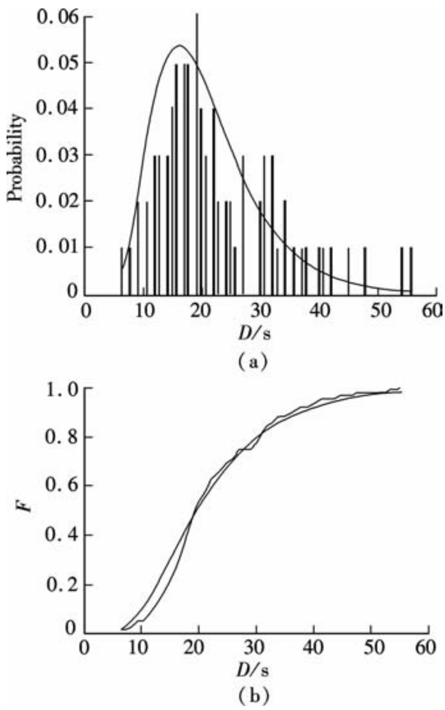

Fig. 3 Dwell time distribution fitting (μ = 2.823, σ^2 = 0.443). (a) Histogram; (b) Cumulative probability distribution

q is the traffic volume at the curb lane; t_m is the minimum headway between vehicles; t_c is the critical gap time when buses enter the traffic stream at the curb lane, $t_c = 7$ s; t_f is the follow-up time, $t_f = 4$ s; ρ is the degree of saturation; a_0 equals 1.25 if the major stream is random, and 1.15 for bunched major stream traffic.

Then, the distribution function of W is

$$F_W(t) = 1 - P(W > t) = P(0,t) + A[1 - P(0,t)]\rho + (1-A)[1-P(0,t)]\rho^2 + (1-A)(1-B)(1-\rho)\rho \quad (15)$$

3 Calculated Results

According to the urban road design manual, the length of one bus and one berth are 12 and 15 m, respectively[10]. In this paper, the acceleration and deceleration are assumed to be 1.2 m/s[1], the reaction time of drivers is 2 s[11], β is 50%. The capacity of bus bays is calculated with the method of numerical integration in Matlab software, as shown in Fig. 4.

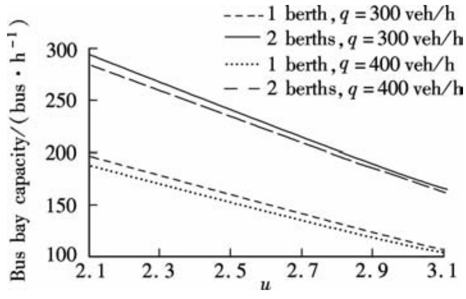

Fig. 4 Bus bay capacity ($\sigma^2 = 0.43$)

Fig. 4 shows the high variability of the capacity of bus bays depending on the expectation of the dwell time and the traffic volume at the curb lane. In other words, the capacity of uniform bus bays varies greatly in different locations and different periods, so the number of effective berths at a bus bay is not constant.

4 Model Validation

First, the proposed model is validated using measured data at two bus bays of Pingshui street in Hangzhou city. The number of buses that can be served by stops under saturated conditions are surveyed. Then the number of buses are derived from an hourly volume, which are the measured capacity of the bus bays, as shown in Tab. 2.

Tab. 2 Comparison of the calculated and measured values of bus bay capacity

Bus stop	Number of berths	Distribution of dwell time (μ, σ^2)	Traffic volume at curb lane/ (veh · h^{-1})	Calculated values/ (bus · h^{-1})	Measured values/ (bus · h^{-1})	Relative error/ %
Jingzhou road stop	2	(2.856, 0.325)	360	199	184	8.15
Gudun road stop	2	(2.931, 0.414)	420	186	170	9.41

As shown in Tab. 2, the average relative error between the calculated and the measured values of the bus bay capacity is 8.78%. It shows that the proposed model can effectively reflect the operating characteristics of bus bays.

Secondly, simulation analyses are conducted to verify the effectiveness of the model. The required input data for the VISSIM model to simulate the operations of bus bays are: free speeds of buses, acceleration and deceleration characteristics of buses, the distribution function of the dwell time. In the simulation, the frequency of buses is set to a value which is close to the bus bay capacity and the capacity of the bus bay is estimated as the maximum flow rate that buses can depart from a bus bay. In order to improve the reliability of the VISSIM model, the simulations are made with the random number seeds ranging from 41 to 45 and the average of the output values is taken as the final model output.

As can be seen in Tab. 3, the average relative error between the calculated and the simulated values of the bus bay capacity is 5.28%.

5 Conclusion

A method for calculating the capacity of bus bays is developed with the consideration of the queue probability, the dwell time distribution and the waiting time for a gap in the traffic stream at the curb lane. The calculated results show a large range of traffic capacities depending on

Tab. 3 Comparison of the calculated and simulated values of bus bay capacity

Number of berths	Distribution of dwell time (μ,σ^2)	Traffic volume at curb lane/ ($veh \cdot h^{-1}$)	Calculated values/ ($bus \cdot h^{-1}$)	Simulated values/ ($bus \cdot h^{-1}$)	Relative error/ %
1	(2.823,0.443)	300	125	123	1.63
	(2.814,0.377)	300	128	122	4.92
	(2.901,0.398)	300	120	120	1.70
	(2.848,0.273)	300	128	122	4.92
	(2.823,0.443)	400	121	117	3.42
	(2.814,0.377)	400	124	118	5.08
	(2.901,0.398)	400	117	113	3.54
	(2.848,0.273)	400	124	116	6.89
2	(2.823,0.443)	300	201	192	4.68
	(2.814,0.377)	300	208	195	6.67
	(2.901,0.398)	300	196	185	5.94
	(2.848,0.273)	300	214	204	4.90
	(2.823,0.443)	400	196	185	5.95
	(2.814,0.377)	400	203	188	7.98
	(2.901,0.398)	400	192	177	8.47
	(2.848,0.273)	400	209	194	7.73
Average					5.28

the expectation of the dwell time and the traffic volume at the curb lane. With this methodology, the capacity is obtained easily if knowing the characteristics of the dwell time distribution, the queue probability and the traffic volume at the curb lane in different locations and at different periods. Although a log-normal distribution is used, other probability functions can be rapidly implemented using the methodology described in this paper.

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港湾式公交停靠站通行能力计算方法

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摘要:针对目前城市的公交运行现状,使用时空分布图分析了港湾式公交停靠站的车辆运行特性,并在此基础上建立了公交停靠站通行能力计算模型,该模型综合考虑了站点排队概率、停靠时间分布和汇入间隙的等待时间. 利用杭州市的调查数据对公交车辆的站点停靠时间进行了分布拟合,结果表明对数正态分布的拟合效果最优. 使用 Matlab 编程求出了不同停靠时间分布参数和外侧车道流量下的站点通行能力,结果显示随着分布参数和外侧车道流量的变化,站点通行能力的变化范围较大. 最后,使用实测和仿真方法对模型进行了验证,模型计算值与实测数据、仿真数据的平均相对误差分别为 8.78% 和 5.28%.

关键词:港湾式公交停靠站; 通行能力; 停靠时间; 对数正态分布

中图分类号:U491.51