Bus Capacity Under Mixed Traffic Conditions

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On the basis of a field observation and analysis of traffic phenomena, models to estimate bus capacities under various traffic conditions are proposed. The bus stop is often the critical section that confines bus capacity. Two types of bus stops are introduced: one is a road section stop and the other is an intersection stop near a signalized intersection. In the latter case, buses' parking maneuvers will be affected by the queue length before the stopline of the intersection. According to these two types of bus stop, various road and traffic conditions are considered while bus capacities are calculated.

In China's major cities, besides the bicycle, the bus is an important transportation tool. In Shanghai there are 375 bus lines, including 160 lines in urban areas. More than 15 million passengers ride 6,000 buses every day (14.2 million in urban areas). Although the scheduled speed of buses is 14 km/hr, most of the buses cannot reach this speed. The majority of these buses are articulated vehicles, which are 14.05 m long and can accommodate 146 passengers each. More than 3,000 bus stops are spread along all kinds of streets in urban Shanghai. Because of the narrow streets and the interference caused by the great number of bicycles and pedestrians, bus capacity is severely affected. Therefore, bus capacity under mixed traffic conditions is of substantial importance for improving the levels of bus operation, management, and bus line planning.

On the basis of a field observation and analysis of traffic phenomena, this paper proposes the models to estimate bus capacities under various traffic conditions. The bus stop is often the critical section that confines bus capacity. For this paper, two types of bus stop are introduced: one is a road section stop and the other is an intersection stop, which is near a signalized intersection. In the latter case, buses' parking maneuvers will be affected by the queue length before the stopline of the intersection. According to these two types of bus stop, various road and traffic conditions are considered while the bus capacities are calculated.

BUS CAPACITY MODELS

In urban areas of Shanghai, there are many narrow motor vehicle lanes and walkways. In a street without separate facilities for motor vehicle and bicycle lanes, buses can park only on the bicycle lanes (curb lanes) for passengers' boarding and alighting. As a result, the travel time of all kinds of motor vehicles and bicycles that want to go through the section where the bus stops will be seriously affected. Here, capacity models of two types of stop are discussed: (a) the bus capacity models at road section stops, and (b) the bus capacity models at intersection stops.

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Road Section Stops

Usually, the road section on which a bus stop sits is the critical section that confines the bus capacity. In fact, the critical section is generally contained in a certain length of the lane. On the road section, the bus will slow down when entering the bus stop and come to a complete stop for passengers' boarding and alighting; then the bus starts and accelerates until normal running speed is reached. In this process, various other motor vehicles and bicycles that follow the bus will be influenced unavoidably. These vehicles are delayed and capacity is lowered. This influence is composed of the following two parts: (a) the bus deceleration-acceleration maneuver, and (b) the effective width of the lane, through which other vehicles go, becomes narrower when a bus stops at the stop. Figure 1 shows a typical traffic situation at a bus stop.

In Figure 1, Section I is the section on which a bus starts decelerating, and Section II is the section on which the bus completes its acceleration and reaches the normal speed. When a bus parks at the bus stop, the capacity on Section II is affected and suffers a loss. The loss is composed of $L(h)$, travel time loss caused by the vehicle that closely follows the parking bus, and $L(f)$, headway increasing losses among the vehicles following the parking bus.

Therefore, the capacity of motor vehicles (not including buses) on Section II is given by

$$Q = \frac{3{,}600 - [L(h) + L(f) * T + h\ (b)] * N}{h} \qquad (1)$$

where

Q = capacity of various motor vehicles (not including buses) on Section II (veh/hr);

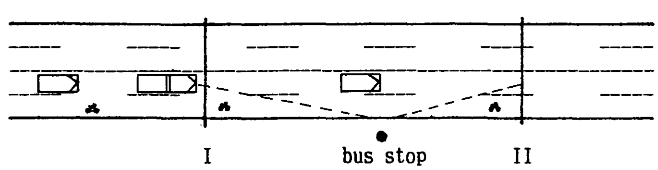

FIGURE 1 Traffic phenomenon at bus stop.

N = buses that stop (veh/hr);
T = average time taken by a bus traveling from Section I to Section II, including time spent at a bus stop (min);
h = average saturation headway of mixed motor traffic flow (sec);
$h(b)$ = bus saturation headway (sec);
$L(h)$ = time loss that results from decreasing speed of vehicle that closely follows bus (sec); and
$L(f)$ = time loss that results from increasing headways among vehicles after bus (sec/min).

If Q is the actual traffic flow rate in vehicles per hour and N is bus capacity on Section II, from Equation 1, bus capacity is estimated by

$$N = \frac{3{,}600 - h * Q}{L(h) + L(f) * T + h(b)} \quad (2)$$

In some cases, bus capacity is confined by berth capacity [similar to the model the 1985, *Highway Capacity Manual* (*1*)].

$$N = \frac{3{,}600 * n}{t(s) + t(c) * n} \quad (3)$$

where

n = maximum number of buses that can stop at the same time,
$t(s)$ = dwell time at bus stop (sec), and
$t(c)$ = clearance between successive buses (sec).

Thus, the bus capacity on a road section stop should be estimated by the lower calculating value obtained from either Equation 2 or Equation 3:

$$N = \min\left\{\frac{3{,}600 - h * Q}{L(h) + L(f) * T + h(b)}, \frac{3{,}600 * n}{t(s) + t(c) * n}\right\} \quad (4)$$

According to the result obtained by Tang, dwell time $t(s)$ can be determined by

$$t(s) = 0.41 * AN * LC + 0.73 * BN * LC + 9.3$$

where

AN = number of alighting passengers,
BN = number of boarding passengers, and
LC = passengers/146.

Here, LC is the load coefficient of a bus and 146 is the maximum number that an articulated bus can theoretically accommodate.

Intersection Stops

The bus capacity at the stop near an intersection is restricted by either the bus stop or the capacity of the stopline at a signalized intersection. The model of the bus capacity restricted by bus stop near a signalized intersection can be expressed by following equation:

$$N = \frac{3{,}600 * n * (g/c)}{(g/c) * t(s) + t(c) * n} \quad (5)$$

where g/c is the green time–cycle time ratio.

Variables $t(s)$, $t(c)$, and n are the same as those in Equation 3, but the factors affecting $t(c)$ in Equation 5 are different from the factors affecting $t(c)$ in Equation 3.

The bus capacity restricted by the stopline of a signalized intersection is given by

$$N = [3{,}600 * (g/c) * s - Q]/1.3 \quad (6)$$

where s is the mixed saturation flow rate in vehicles per hour and Q is the mixed motor vehicle flow rate (not including buses) in vehicles per hour.

The conversing coefficient from a bus to mixed motor vehicles is 1.3. The value roughly reflects the average composition of various kinds of vehicles in urban areas of Shanghai. In a certain case, this value can be calculated according to the percentages of different kinds of vehicles.

Similarly, the bus capacity at the stop near a signalized intersection is estimated by the smaller value obtained from either Equation 5 or Equation 6, that is

$$N = \min\left\{\frac{3{,}600 * n * (g/c)}{(g/c) * t(s) + t(c) * n}, [3{,}600 * (g/c) * s - Q]/1.3\right\} \quad (7)$$

PARAMETER CALIBRATION AND BUS CAPACITY CALCULATION

Road Section Stops

The bus capacity at the road section stop can be estimated from Equation 4:

$$N = \min\left\{\frac{3{,}600 - h * Q}{L(h) + L(f) * T + h(b)}, \frac{3{,}600 * n}{t(s) + t(c) * n}\right\}$$

The parameters in this equation are obtained by the statistical processing of field data. Some parameters are listed in Table 1 and the following:

Level	*Traffic Condition*	*Factor Index*
A	Poor	More than 0.52
B	Average	Between 0.36 and 0.52
C	Favorite	Less than 0.36

The factor index (FI) is introduced to describe the traffic state in a street. Vehicle and bicycle traffic along with the effects of parking buses are considered in determining FI.

$$FI = (X1 + X2 + X3)/3 \quad (8)$$

where

$X1$ = vehicle volume per hour (single direction) divided by 900, 720, or 600 allowing the width of streets to vary from 14 to 12 to 10 m;

TABLE 1 Part of Parameters

parameters	FI level	width 14m	12m	10m
L(h) (sec.)	A B C	7 4 0	19 9 2	26 15 3
L(f) (sec.)	A B C	32 16 4	37 24 7	43 32 10
stopping & starting delay(sec.)	A B C	26 15 6	26 15 6	26 15 6
t(c) (sec.)	A B C	15 11 8	15 11 8	15 11 8

$X2$ = bicycle volume per hour (single direction) divided by 3,600; and
$X3$ = average number of parking buses between Sections I and II (see Figure 1) divided by 3.

On a road stop, $X1$, $X2$, and $X3$ do not have much difference in their contribution to determine the FI; here, these three factors are considered to have a equal weight. For example, on a street 10 m wide without separation, motor vehicle flow is 300 veh/hr, bicycle flow is 2,100 veh/hr, and average bus dwell time at the stop is 30 sec. Then,

$$FI = (X1 + X2 + X3)/3$$
$$= (300/600 + 2{,}100/3{,}600 + 1/3)/3 = 0.47$$

FI pertains to Level B. Consequently, according to Table 1, $L(h)$ = 15 sec and $L(f)$ = 32 sec. The bus capacity at the stop is

$$N = \frac{3{,}600 - h * Q}{L(h) + L(f) * T + h(b)}$$
$$= \frac{3{,}600 - 6 * 300}{15 + 32 * (30 + 15 + 18)/60 + 6} = 33 \text{ buses per hour}$$

Here $h = h(b)$ = 6 sec, the average saturation headway between successive vehicles; 30 sec is average dwell time at the stop; 15 sec is the acceleration and deceleration losses; and 18 sec is the uninterrupted travel time from Section I to Section II.

In the example, if bicycle traffic is prohibited, the FI will be

$$FI = (300/600 + 1/3)/3 = 0.28$$

FI pertains to Level C, thus $L(h)$ = 3 sec, $L(f)$ = 10 sec, and bus capacity changes as follows:

$$N = \frac{3{,}600 - 6 * 300}{3 + 10 * (30 + 6 + 18)/60 + 6}$$
$$= 100 \text{ buses per hour}$$

Bus capacity being up to 100 per hour, the FI should be changed as the average number of parking buses between Sections I and II varies. Then,

$$X3 = [(30 + 6 + 18) * 100/3{,}600]/3 = 0.5$$

$$FI = (300/600 + 0.5)/3 = 0.33$$

FI still pertains to Level C, and the bus capacity remains unchanged. In some cases, it needs iterative calculations while bus capacity is estimated. Table 2 gives the bus capacities under various road and traffic conditions. A bus dwell time at a stop is 30 sec. The bus capacity values in brackets are calculated by Equation 3.

In Table 2 "equivalence" means that a parking bus has the equivalent value conversing to other vehicles when the capacity on the street is concerned.

Intersection Stops

Bus capacity at an intersection stop can be estimated from Equation 7:

$$N = \min\left\{\frac{3{,}600 * n * (g/c)}{(g/c) * t(s) + t(c) * n}, [3{,}600 * g/c) * s - Q]/1.3\right\}$$

All parameters have been defined before, except the parameter $t(c)$. Similar to the method dealing with road section stops, the FI of an intersection is also used to determine $t(c)$.

$$t(c) = \begin{cases} 28 \text{ sec} & \text{when } FI(i) \geq 0.64 \\ 18 \text{ sec} & \text{when } 0.42 \leq FI(i) < 0.64 \\ 14 \text{ sec} & \text{when } FI(i) < 0.42 \end{cases} \quad (9)$$

Here, $FI(i)$ is calculated by following equation:

$$FI(i) = 0.42 * (1 - g/c) + 0.25 * X(v) + 0.33 * X(b) \quad (10)$$

TABLE 2 Bus Capacities in Buses per Hour

width	FI level	other vehicle flow rates (veh/h) 100	200	300	400	500	equivalence
14m	A B C	62 124 (157)	55 109 (157)	47 93 (157)	39 78 (157)	31 62 (157)	12.8 6.5 2.2
12m	A B C	44 78 (157)	37 65 (157)	30 53 152	23 40 116	16 28 79	14.3 7.9 2.8
10m	A B C	35 55 (157)	28 44 133	21 32 100	14 22 67	7 11 33	14.5 9.0 3.0

TABLE 3 Bus Capacities at Intersection Stops in Buses per Hour

	motor traffic flow (veh/h)			
X(b)	100	200	300	400
.30	83	70	70	(38)
.60	70	70	70	(38)
.90	70	70	50	(38)

where

$X(v)$ = saturation ratio of motor vehicle;
$X(b) = Q(b)/[1{,}800 * W(b) * (g/c)]$, saturation ratio of bicycles;
$Q(b)$ = bicycle traffic flow per hour; and
$W(b)$ = width of bicycle lane (m).

Maximum flow rate is 1,800 bicycles per green hour time per meter wide.

Table 3 gives some calculating results of intersection bus capacities under certain traffic conditions. In Table 3, the parameters are as follows: $g/c = 0.50$, and $t(s) = 30$ sec.

The capacity of mixed traffic flow at the stopline is 450 vehicles per hour. Values in brackets show that the stopline is a critical section to the bus capacity, that is, the bus capacity $N = [3{,}600 * (g/c) * S - Q]/1.3$.

For estimating the bus capacity at the intersection stop without bicycle interference, Equation 7 can also be used. In this case, there is no need to calculate FI(i). The parameter $t(c)$ is 14 sec.

CONCLUSION

Because of the complexity of precisely estimating the bus capacity at a bus stop, and in order to apply the bus capacity models conveniently, the road and traffic condition variables such as the width of a street, separate conditions, and motor vehicle and bicycle flows (timing factor at intersection stops) are used to classify the FI into three levels. Accordingly, the bus capacity values calculated are discontinuous. This gives practical users a scope in which to calibrate calculated capacity values against the actual traffic conditions.

Bus stops have a great deal of interference on road capacity. In streets without separation, when the traffic condition is poor, average, or favorite—that is, the FI pertains to Level A, B, or C, respectively—a parking bus has equivalent value about 15, 8, or 2.8 conversing to other vehicles, accordingly, as the capacity on the road is concerned.

The effect of the changing width of bus capacity at a bus stop is significant: add 2 m of width and the bus capacity may be doubled.

If bicycle traffic is prohibited or has a separate right-of-way, the bus capacity may be increased by 200 percent. With the variations of traffic conditions and bicycle flow rates, the effects on bus capacity caused by prohibiting bicycle traffic are varied.

The paper discusses the bus capacity only within a critical road section. The bus capacity of a whole bus line is much more complicated and needs further research.

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