Exclusive Urban Street Bus Facilities

Exclusive urban street bus facility capacity and speed determination processes are given in the following sections. The procedure applies for three lane types, namely, Type 1, bus lanes with no adjacent lane; Type 2, bus lanes with partial use of an adjacent lane; and Type 3, bus lanes with two lanes for the exclusive use of buses. Illustrations in Figure (1) through (3) depict Types 1, 2, and 3 exclusive bus lanes, respectively.

Figure(1): Examples of Type 1 Exclusive Bus Lane.

Figure(2): Examples of Type 2 Exclusive Bus Lane.

Figure(3): Examples of Type 3 Exclusive Bus Lane.

Vehicle Capacity

The vehicle capacity of an exclusive bus lane depends on several factors:

- Bus lane type,
- Whether skip-stop operation is used,
- Whether buses using the lane are organized into platoons,
- Volume to capacity ratio of the adjacent lane for Type 2 bus lanes, and
- Bus stop location and right-turning volumes from the bus lane.

1. Adjustment for Right Turns

Right-turning traffic physically competes with buses in the bus lane for space at an intersection. The traffic generally turns from the bus lane, although in some cases right turns are made from the adjacent lane. Vehicles may queue behind buses at a near-side bus stop to make a right turn. Conversely, right-turning traffic may block buses or preempt green signal time. The interference of right-turning traffic on bus operations can be further magnified by significant pedestrian crossing volumes blocking right-turn movements. The placement of the bus stop at the intersection, whether near-side, farside, or midblock, can also influence the amount of delay induced by, and to, the right turning traffic.
The effects of right turns on bus lane vehicle capacity can be estimated by multiplying the bus lane vehicle capacity without right turns by an adjustment factor.
The values of this adjustment factor, fr, may be estimated using Equation (1):

$$f_r = 1 - f_l\left(\frac{v_r}{c_r}\right) \quad \text{....................} \ (1)$$

where:

f_r = right-turn adjustment factor;

f_l= bus stop location factor, from Table (1);

v_r = volume of right turns at specific intersection (veh/h); and

c_r = capacity of right turns at specific intersection (veh/h).

Suggested factors for the bus stop location factor, fl, are listed in table (1). Where right turns are allowed, the factors range from 0.5 for a far-side stop with the adjacent lane available for buses to 1.0 for a near-side stop with all buses restricted to a single lane. A factor of 0.0 is used for Type 3 lanes, since right turns by nontransit vehicles are not allowed from this type of bus lane.

Table (1): Bus Stop Location Factors.

Bus Stop Location	Bus Lane Type		
	Type 1	Type 2	Type 3
Near-side	1.0	0.9	0.0
Midblock	0.9	0.7	0.0
Far-side	0.8	0.5	0.0

Note:
f_l = 0.0 for contraflow bus lanes and median bus lanes regardless of bus stop location or bus lane type, since right turns are either prohibited or do not interfere with bus operations.
Source: St. Jacques and Levinson (*10*).

2. Adjustment for Skip-Stop Operation

The total number of buses per hour that can be accommodated by a series of skip stops represents the sum of the capacities of bus routes using each stop multiplied by an impedance factor, f_k, reflecting non-platooned arrivals and the effects of high volumes of vehicular traffic in the adjacent lane. Equation (2) represents the factors that impede buses from fully utilizing the added capacity provided by skip-stop operations .

$$f_k = \frac{1+Ka(N_s-1)}{N_s} \quad \text{.........................} \ (2)$$

where:
f_k = capacity adjustment factor for skip-stop operations;
K = adjustment factor for ability to fully utilize bus stops in a skip-stop operation: 0.50 for random arrivals, 0.75 for typical arrivals, and 1.00 for platooned arrivals;
a = adjacent-lane impedance factor, from Equation (3); and
N_s = number of alternating skip stops in sequence.

$$a = 1 - 0.8\left(\frac{v}{c}\right)^3 \quad \text{...............................} \ (3)$$

where:
v = traffic volumes in adjacent lane (veh/h), and
c = capacity of adjacent lane (veh/h).

Table (2) gives representative values for the impedance factor, f_k, for various types of bus lanes and stopping patterns. As indicated previously, these factors are applied to the sum of the capacities in the sequence of bus stops. Thus, they reflect the actual dwell times at each stop. Table (3) gives adjustment factors for a Type 2 bus lane with alternating two-block stops. In general, the traffic impacts of the adjacent lane only become significant when that lane operates above 75 percent of its capacity.

Table(2): Typical Values of Adjustment factor , f_k , for Availability of Adjustment Lanes.

Condition	Arrivals	Adjacent Lane v/c	a	N_s - 1	K	f_k
			Type 1 Bus Lane			
Stops every block	-	0 to 1	0 to 1	0	0	1.00
			Type 2 Bus Lane			
Stops every block	-	*0 to 1*	*0 to 1*	*0*	*0*	*1.00*
Alternating 2-block stops	Random	0	1	1	0.50	0.75
		1	0.2[a]	1	0.50	0.55
Alternating 2-block stops	Typical	0	1	1	0.75	0.88
		1	0.2[a]	1	0.75	0.58
Alternating 2-block stops	Platooned	0	1	1	1.00	1.00
		1	0.2[a]	1	1.00	0.60
			Type 3 Bus Lane			
Alternating 2-block stops	Random	0	1	1	0.50	0.75
Alternating 2-block stops	Random	0	1	1	0.75	0.88
Alternating 2-block stops	Random	0	1	1	1.00	1.00
Alternating 3-block stops	Random	0	1	2	0.50	0.67
Alternating 3-block stops	Random	0	1	2	0.75	0.83
Alternating 3-block stops	Random	0	1	2	1.00	1.00

Note:
a. Approximate.
Source: St. Jacques and Levinson (*10*).

Table(3): Values of Adjustment Factor, f_k, for Typical 2 Bus Lanes with Alternating Two-Block Skip Stops.

Adjacent Lane v/c	Arrival Pattern		
	Random	Typical	Platooned
0.0	0.75	0.88	1.00
0.5	0.72	0.84	0.95
0.6	0.71	0.81	0.92
0.7	0.68	0.77	0.87
0.8	0.65	0.71	0.80
0.9	0.60	0.65	0.71
1.0	0.55	0.58	0.60

Source: St. Jacques and Levinson (*10*).

The set of adjustment factors for skip-stop operations and the impact of right turns define the following equations for estimating exclusive urban street bus lane vehicle capacity:

Non-skip-stop operation: $B = B_1 = B_{bb} N_{eb} f_r$ .... (4)

Skip- stop Operation: $B = f_k(B_1 + B_2 + B_3)$ .... (5)

where:
B = bus lane vehicle capacity (buses/h),
B_{bb} = bus loading area vehicle capacity at critical bus stop (buses/h),
N_{eb} = number of effective loading areas at critical bus stop,
f_r = capacity adjustment factor for right turns at critical bus stop,
f_k = capacity adjustment factor for skip-stop operations, and
B_1,..., B_n = vehicle capacities of each set of routes at their respective critical bus stops that use the same alternating skip-stop pattern (buses/h).

The capacities B1, B2, Bn used in Equation (5) are calculated separately for each set of routes using Equation 27-10. When the critical stop or stops are determined, several bus stops may have to be tested to determine which one controls the bus lane vehicle capacity, because one stop may have high dwell times but another may have severe right-turning traffic interference.

3. Bus Effects on Adjacent- lane Capacity

The introduction of single or dual bus lanes reduces vehicle capacity for other traffic. The extent of this reduction is determined by the bus lane type, the number of buses using the bus lane, and whether the bus lane replaces a curb parking lane.

The effects of bus lane operations on the adjacent general travel lane can be expressed by multiplying the adjacent-lane vehicle capacity by the adjustment factor given in Equation (6):

$$f_p = 1 - \left(4 \frac{N_p}{3,600}\right) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(6)}$$

where:
f_p = bus-passing activity factor, and
N_p = number of buses making maneuver from curb lane to adjacent lane,
from Equation (7).

The delay to through traffic in the adjacent lane is minimal unless buses leave the bus lane. Therefore, an adjustment is needed to determine the actual number of buses, N_p, that would pass other buses using the curb lane. Simulations and field observations indicate that when buses operate at less than one-half the vehicle capacity of the bus lane, they have little need to pass each other even in a skip-stop operation because of the low arrival headways relative to capacity. Bus use of the adjacent lane increases at an increasing rate as bus activity approaches capacity. Thus, N_p may be approximated using Equation (7).

$$N_p = \frac{N_s - 1}{N_s} V_p \left(\frac{V_p}{C_p}\right)^3 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(7)}$$

where:
N_s= number of stops skipped,
V_p= volume of buses in bus lane (buses/h), and
C_p = bus vehicle capacity of bus lane (buses/h).

4. Person Capacity

The person capacity at the maximum load point of an urban street bus lane can be determined by multiplying the product of bus lane vehicle capacity given by Equation (4) or Equation (5), as appropriate, and the allowed passenger loads on board an individual bus by a peak-hour factor.

5. Speed

The best way to determine bus travel speeds on urban street bus lanes is to measure them directly. When this is not possible (for example, in planning future service), speeds can be estimated by driving the route and making an average number of stops with simulated dwells, with two or three runs during both peak and off-peak times, or by scheduling buses on similar routes and adjusting running times as needed on the basis of operating experience. Alternatively, the analytical method described below can be used to estimate speeds.

Bus speeds on exclusive urban street bus lanes are influenced by bus stop spacing, dwell times, delays due to traffic signals and right-turning traffic, skip-stop operations, and interference caused by other buses. These factors are reflected in Equation (8),which can be used to estimate bus travel speed, St, on urban streets.
Bus running time is determined from Tables (4) and (5), accounting for the effects of stop spacing, dwell times, and traffic and signal delays. This running time is then converted into a speed and adjusted to account for the effects of skip-stop operations and the interference of other buses operating in the lane.

$$S_t = \left(\frac{60}{t_{r,0}+t_{r,1}}\right) f_s f_b \quad \text{.................................... (8)}$$

<u>where:</u>
S_t = bus travel speed (km/h),
$t_{r,0}$ = base bus running time (min/km),
$t_{r,1}$ = bus running time losses (min/km),
f_s = skip-stop speed adjustment factor, and
f_b = bus-bus interference adjustment factor.

Table(4): Estimated Base Bus Running Time, $t_{r,0}$.

Dwell Time (s)	Stops per km							
	1	2	3	4	5	6	7	8
10	1.39	1.82	2.29	2.83	3.46	4.18	5.04	5.91
20	1.55	2.15	2.79	3.49	4.29	5.19	6.20	7.24
30	1.72	2.49	3.29	4.16	5.12	6.18	7.37	8.58
40	1.89	2.82	3.78	4.82	5.96	7.18	8.54	9.91
50	2.06	3.15	4.28	5.49	6.80	8.18	9.70	11.24
60	2.22	3.48	4.77	6.15	7.63	9.18	10.87	12.58

Notes:
Values are in minutes per kilometer.
Data based on field measurements.
Interpolation between shown values of dwell time is done on a straight-line basis.
Source: St. Jacques and Levinson (23).

Table(5):Estimated Bus Running Time Losses, $t_{r,1}$.

Condition	Bus Lane	Bus Lane No Right Turns	Bus Lane with Right-Turn Delays	Bus Lanes Blocked by Traffic	Mixed-Traffic Flow
Central Business District					
Typical		0.7	1.2	1.5–1.8	1.8
Signals set for buses		0.4	0.8		
Signals more frequent than bus stops		0.9–1.2	1.5–1.8	1.8–2.1	2.1–2.4
Streets Outside the CBD					
Typical	0.4				0.6
Range	0.3–0.6				0.4–0.9

Notes:
Values are in minutes per kilometer.
Data based on field measurements. Traffic delays shown reflect peak conditions.
Source: St. Jacques and Levinson (23).

6. Bus Travel Time Rates

Table (4) and (5) together provide an estimate of bus running times as a function of stop spacing, average dwell time per stop, and operating environment. These values were derived from field observations . First, a base bus running time is determined from Table (4). This running time reflects the speed buses would travel without signal or traffic delays. Next, running time losses are determined from Table(5) , accounting for the effects of signals and other traffic sharing the bus lane. If actual observed delays are available, they could be used in lieu of the estimates given in Table(5). The two running times are added and divided into 60 to determine a base bus speed for use in Equation (8).

7. Adjustment for Skip- Stop Operation

Skip-stop operations spread buses out among a series of bus stops, allowing for an increase in speeds. The analytical method accounts for skip-stop operations by considering only the bus stops in the skip-stop pattern. For example, if bus stops are located 125 m apart at each intersection, a two-block skip-stop pattern provides 250 m between stops for a bus using that pattern.

A bus with a two-block pattern would be able to proceed at about twice the speed of a bus with a one-block stop pattern and a bus with a three-block stop pattern at about three times the speed, assuming uniform block distances and dwell times. The ability of buses to leave the curb bus lane to pass stopped buses becomes a factor in the ability to attain the two- or threefold increase in speed.
Equation (9) expresses the speed adjustment factor for skip-stop operation, f_s, as a function of both the traffic in the adjacent lane and the buses in the curb lane (*10*). This factor reduces the faster base running time that results from the longer distance between stops used in the skip-stop pattern. If skip stops are not used, f_s = 1.0, and the base running speed is based on the actual stop spacing.

$$f_s = 1 - \left(\frac{L_1}{L_2}\right)\left(\frac{v}{c}\right)^2\left(\frac{v_b}{c_b}\right) \quad \text{.........................} \quad (9)$$

<u>where:</u>
f_s = skip stop speed adjustment factor,
L_1 = distance for one-block stop pattern (m),
L_2 = distance for multiple-block stop pattern (m),
v = volume in adjacent lane (veh/h),
c = vehicular capacity of adjacent lane (veh/h),
v_b = volume of buses in bus lane (buses/h), and
c_b = bus vehicle capacity of a single bus lane (buses/h).

Figure (1) illustrates the effects of increasing bus v/c ratio and general traffic v/c ratio in the adjacent lane on the skip-stop speed adjustment factor. The exhibit assumes a two-block skip-stop pattern. It can be seen that until the volume of the adjacent lane becomes more than about 50 percent of the bus lane capacity, the ability to achieve the twofold increases in speed is not reduced, regardless of the bus lane v/c ratio. At higher v/c ratios, both the bus lane volumes and the adjacent-lane volumes play an important role in determining bus speeds. When skip-stop operations are used, speeds should be calculated separately for each skip-stop pattern used.

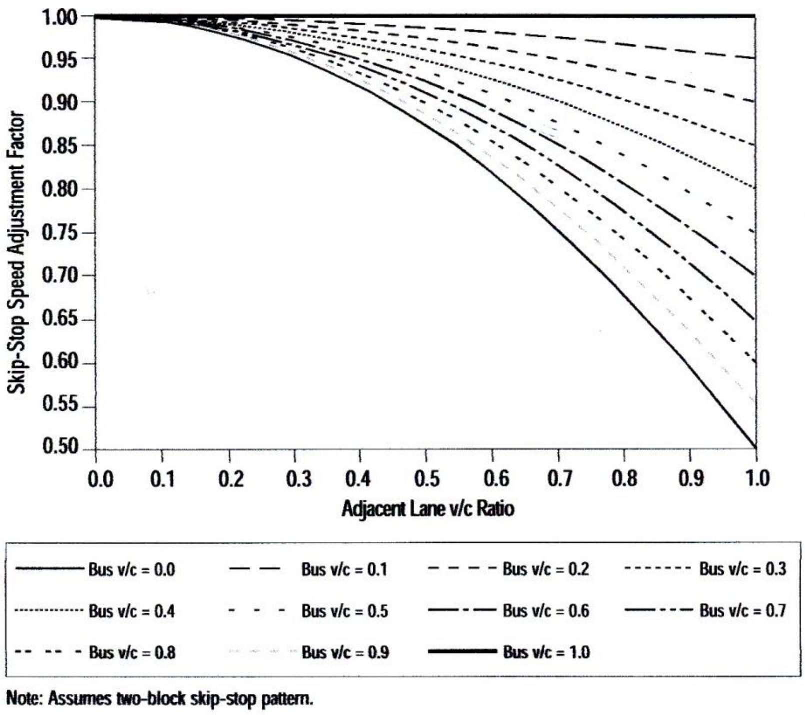

Figure (1): Skip-Stop Speed Adjustment Factors, f_s.

8. Adjustment for Bus-Bus Interference

Bus speeds within a bus lane along an urban street decline as the lane becomes saturated with buses because as the number of buses using the lane increases, there is a greater probability that one bus will delay another bus, either by using available loading areas or by requiring passing and weaving maneuvers. Table (6) lists values of the speed adjustment factor for bus-bus interference. Figure (2) shows the effects of increasing bus lane volumes on bus speeds. There is little effect on bus speeds until approximately 70 percent of the bus lane capacity is being used.

Table (6): Bus- Bus Interference Factor, f_b.

Bus Lane v_b/c_b Ratio	Bus-Bus Interference Factor
< 0.5	1.00
0.5	0.97
0.6	0.94
0.7	0.89
0.8	0.81
0.9	0.69
1.0	0.52
1.1	0.35

Source: St. Jacques and Levinson (*10*).

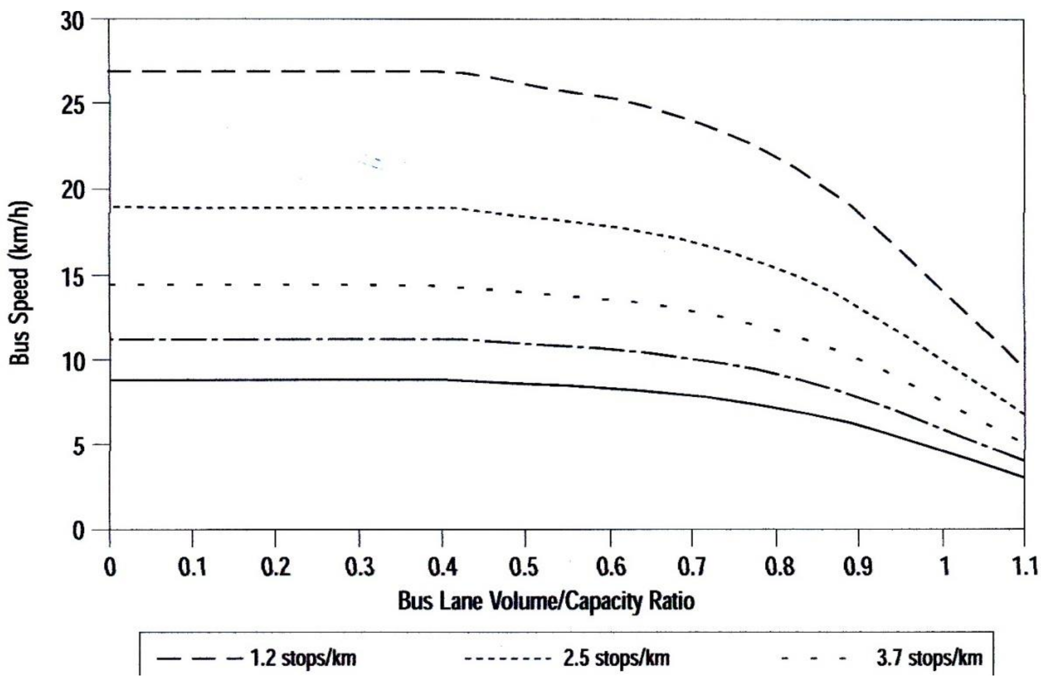

Figure (2): Bus Lane Volumes and Speeds.