BUS CAPACITY ANALYSIS

William F. Hoey and Herbert S. Levinson, Wilbur Smith and Associates

This paper provides an initial input for updating the section on bus capacity in the Highway Capacity Manual and identifies parameters, principles, and procedures for estimating the capacity of bus facilities and systems. It reviews available data on bus capacities, suggests design assumptions for bus system planning and analysis, and outlines further research needs. The studies demonstrate that (a) the critical element governing system capacity is the bus station platform or bus stop rather than the busway; (b) at stations, capacity is determined by the number of door channels on the bus and fare collection practices; and (c) bus capacity should be viewed in terms of people transported rather than buses moved per hour.

•BUS capacity values differ widely according to the basic type of operation: in terminals, on arterial streets, or along exclusive busways. This paper concentrates on capacity analysis of bus lanes and busways because terminal capacity depends heavily on the specific mode and pattern of operation (i.e., extent of intercity operations, layover times, and fare collection practices). Results of previous studies are summarized, basic analytical relationships are presented, and capacity ranges and planning guidelines are suggested in an effort to update previous reports (1, 2). The ability of buses to move people under preferential conditions is examined; that is, the impedance of other vehicles in mixed traffic is not considered quantitatively.

PREVIOUS STUDIES AND EXPERIENCES

The number of buses that can operate past a point in a given period of time varies widely according to specific roadway and operating conditions. Previous theoretical studies and actual operating experience provide the basis for subsequent analyses.

Theoretical Values

Ranges in bus capacities or volumes based on theoretical studies are given in Table 1 (3). These studies have primarily investigated the effect of buses on the capacity of mixed traffic roadways (4, 5). When buses do not stop, bus lane capacity is essentially that of equivalent passenger cars. Thus, assuming normal freeway vehicle headways, theoretical capacities of ≥900 buses/lane/hour could be achieved on exclusive bus roadways with uninterrupted flow.

Theoretical simulation studies, based on buses that have 30-sec dwell times and that operate in platoons of six between stations 0.3 mile (0.5 km) apart, result in capacities ranging from 350 to 400 buses/hour on an exclusive grade-separated busway (6).

Operational Experience

Observed bus volumes on heavily used freeways and city streets are given in Table 2 (3). The highest volumes, 735 buses/lane/hour in the Lincoln Tunnel and on the Port Authority Bus Terminal access ramp, are achieved on a completely exclusive right-of-way where vehicles make no stops. Where bus stops or layovers are involved, reported volumes are much less.

Table 1. Theoretical bus volumes.

Source or Facility	Buses per Hour	Headway (sec)	Average Bus Stop Spacing (ft)	Average Bus Speed (mph)	Equivalent Passengers per Hour[a]
General Motors Proving Ground					
Uninterrupted flow	1,450[b]	2.5	No stops	33	72,500
Highway Capacity Manual					
Freeway level of service D	940	3.8	No stops	33	47,000
Freeway level of service C	690	5.2	No stops	40 to 60	34,500
General Motors Proving Ground					
Six-bus platoons, 30-sec on-line stops	400	9.0	Variable	15 to 20	20,000
1965 Highway Capacity Manual					
Arterial streets, 25-sec loading and 25-sec clearance	72	50	Not cited	Not cited	3,600
Toronto Transit Commission					
Planning criteria	60	60	500 to 600	10	3,000

Note: 1 ft = 0.3 m. 1 mph = 1.6 km/h.
[a]50 passengers/bus.
[b]Subsequent studies have reported bus volumes of 900 to 1,000 vehicles/lane/hour; these are consistent with reported flows.

Table 2. Observed bus volumes.

Facility	Buses per Hour	Headway (sec)	Average Bus Stop Spacing (ft)	Average Bus Speed (mph)	Equivalent Passengers per Hour
Lincoln Tunnel—uninterrupted flow	735	4.9	No stops	30	32,560
I-495 (New Jersey) exclusive bus lane—uninterrupted flow	485	7.3	No stops	30 to 40	21,600
San Francisco-Oakland Bay Bridge	350	10.3	No stops	30 to 40	13,000
South Michigan Avenue, Chicago—5-min rate and some multiple lane use	228	16	Not cited	Not cited	11,400[a]
Hillside Avenue, New York City—multiple lane use and lightly patronized stops	170	21	530	Not cited	8,500[a]
Shirley Highway Busway and Fourteenth Street bus lanes	160	23	900[b]	35[c] 6 to 12[b]	8,000[a]
State Street, Chicago; Market Street, Philadelphia; and Market Street, San Francisco—multiple lanes	150	24	300 to 600	6 to 10	6,100 to 9,900
K Street, Washington, D.C.	130	28	500	5 to 8	6,500[a]
Downtown streets in various cities—single lane with stops	90 to 120	30 to 40	500	5 to 10	4,500 to 6,000[a]

Note: 1 ft = 0.3 m. 1 mph = 1.6 km/h.
[a]50 passengers/bus. [b]In CBD. [c]On freeway.

Bus Stops

Stopping a bus to pick up or discharge passengers limits the capacity of a bus lane. Time must be allowed for acceleration, deceleration, stop clearance, and periods when the doors are open. Observed volumes for lanes with intermediate stops rarely exceed 120 buses/hour, although volumes of ≥180 buses/hour are feasible where buses use two or more lanes and where stopped vehicles can be overtaken if there is careful management and control of bus operations. [Maximum streetcar volumes on city streets 50 years ago approached 150 cars/track/hour when there was extensive queuing and platoon loading at heavy stops (7).]

Busways

The only existing example of a downtown grade-separated busway is in Runcorn, England; this busway operates well within its potential capacity. The intermediate stations on the San Bernardino Freeway Busway in Los Angeles are off-line; the El Monte station of the busway operates as a terminal, and downtown Los Angeles distribution is by on-street bus lanes. Volumes approach 80 buses/hour on the busway.

BERTH CAPACITY FOR BUSES

Reviewing experience suggested that theoretical analysis of bus stop and station operation could be useful for estimating realistic capacities of busways.

Basic Variables and Relationships

The number of buses per lane per hour and the number of people they carry depend on the following:

1. The roadway or guideway, for which capacity depends on the number of lanes, their occupancy, signalization, and flow restrictions (or interferences);
2. The vehicle, for which capacity depends on its size and internal circulation capability;
3. The interface between buses and pedestrians at a bus station platform or bus loading zone, for which capacity depends on the number and organization of boarding and alighting channels; and
4. The required clearance times between buses.

Various analytical relationships were derived to show how these factors influence the capacity of a downtown busway. The analyses establish ranges in typical time requirements for each of the sequent operations at a bus berth and identify relationships among bus passenger line-haul capacity, boarding and alighting volumes, and major parameters or equipment and facilities. They focus on the peak 10 to 15 min in the rush hour, since this time period usually represents the maximum boarding (or alighting) volumes and the maximum line-haul loading.

The basic variables used in the analyses are given below.

- A = alighting passengers per bus in peak 10 to 15 min;
- a = alighting service time in seconds per passenger;
- B = boarding passengers per bus in peak 10 to 15 min;
- b = boarding service time in seconds per passenger;
- C = clearance time between successive buses in seconds (time between closing of doors on first bus and opening of doors on second bus);
- D = bus dwell time at a stop in seconds per bus (time when doors are open and bus is stopped);
- f = bus frequency in buses per hour (all routes using a facility) at maximum load point (if all buses stop at all stations, f = number of effective berths × f′);
- h = bus headway on facility in seconds at maximum load point, 3,600/f;
- f′ = maximum peak bus frequency at a berth in buses per hour;
- h′ = minimum bus headway at a berth in seconds, 3,600/f′;
- G = boarding passenger capacity per berth per hour;
- H = alighting passenger capacity per berth per hour;
- J = passengers boarding per hour at heaviest stop or maximum load point;
- K = passengers alighting per hour at heaviest stop or maximum load point;
- L = peak-hour load factor in passengers per bus seat per hour at the maximum load point;
- N = number of effective berths at a station or bus stop, i.e., (N′)(u);
- N′ = number of berth spaces provided in a multiberth station;
- P = line-haul capacity of bus facility in total persons per hour past the maximum load point (hourly flow rate based on peak 10 to 15 min);
- S = seating capacity of bus, varies with design;
- u = berth use factor (an efficiency factor applied to total number of berths to estimate realistic capacity of a multiberth station, i.e., N/N′);
- X = percentage of maximum load-point passengers boarding at heaviest stop, J/P; and
- Y = percentage of maximum load-point passengers alighting at heaviest stop, K/P.

Equations for the basic relationships for a single station are as follows:

$$h' = Bb + C \tag{1}$$

$$f' = \frac{3,600}{h'} = \frac{3,600}{Bb + C} \tag{2}$$

$$G = f'B = \frac{3,600B}{Bb + C} \tag{3}$$

$$N = \frac{J}{G} = \frac{J(Bb + C)}{3,600B} \tag{4}$$

$$f = f'N = \frac{J}{B} \tag{5}$$

The capacity of any system is governed by the number of passengers (a) boarding or alighting at the heaviest stop or (b) traveling past the maximum load point (between stops), whichever is less. Accordingly, equations 6 through 10 show how maximum load point and heaviest station parameters relate. These relationships assume that loading conditions govern; a similar set of equations could be derived on the assumption that passenger alighting (or passenger interchange) governs.

$$f = \frac{P}{S} \tag{6}$$

$$B = X(S) \tag{7}$$

$$h' = bB + C = X(S)b + C \tag{8}$$

$$f' = \frac{3,600}{h'} = \frac{3,600}{X(S)b + C} \tag{9}$$

$$N = \frac{f}{f'} = \frac{P}{S}\left[\frac{X(S)b + C}{3,600}\right] = \frac{P[X(S)b + C]}{3,600S} \tag{10}$$

The sequence of analyses is as follows:

1. Maximum load-point demand establishes bus frequency requirements in the corridor;
2. Bus frequency and boarding volumes determine minimum headway per berth (for planned systems, where no boarding counts are available, the percentage of passengers boarding at the heaviest stop is a key parameter of total passenger capacity);
3. The maximum bus frequency per berth depends on this minimum headway; and
4. Berth needs are derived from the required bus frequency at the maximum load point and the maximum bus frequency that can load at the heaviest berth.

Assuming that boarding conditions govern, the analytical approach leads to the following equation:

$$P = \frac{3{,}600\ NS}{bB + C} \tag{11}$$

Or since the variable of boarding passengers per bus depends on bus frequency f,

$$P = \frac{3{,}600\ N}{Xb + C/S} \tag{12}$$

This relationship can also be expressed in terms of the passenger capacity per berth as follows:

$$P = \frac{NG}{X} = fS \tag{13}$$

These equations indicate that the number of bus berths required at the heaviest stop varies directly with the total passengers to be served at that point, the boarding and alighting service times required per passenger, and the clearance times between buses.

Bus system capacities can be increased (or alternatively berthing requirements can be reduced) by (a) increasing the number of downtown stations, thereby reducing the number of boarding and alighting passengers at the heaviest stop; (b) reducing the loading and unloading times for passengers through multiple doors on buses, prepayment, or selective separation of loading and unloading; and (c) using larger buses to reduce the clearance interval time losses between successive vehicles. In summary, the person capacity of a bus lane appears to depend greatly on the number of doors per bus and the methods of fare collection.

Parameter Estimation

Application of the preceding relationships requires estimating key parameters and providing necessary safety factors.

Bus Headways

The minimum headway of a stop consists of the station dwell time, when the bus doors are open for boarding and alighting, and clearance times between buses.

Field observations of clearance times are limited. A British study (9) reported a dead time (standing at a stop with the doors closed) of 2 to 5 sec. Scheel and Foote (8) indicate that bus start-up times (the time, depending on acceleration and traffic conditions, for a bus to travel its own length after starting ranges from 5 to 10 sec) should also range from 2 to 5 sec. Accordingly, clearance time per bus is estimated at 10 to 20 sec.

Station Dwell Times

Station dwell times may be governed by boarding demand (e.g., in the p.m. peak when substantially empty buses arrive at a heavily used stop), alighting demand (e.g., in the a.m. peak at the same location), or total interchanging passenger demand (e.g., at a major transfer point on the system). In all cases, dwell time is proportional to boarding or alighting volumes times passenger service time.

Observed ranges in passenger service times for various procedures for bus operation and fare collection are given in Tables 3 (11, 12) and 4 (2, 10) for both American and European experience (9).

Boarding service times are usually greater than alighting times. However, some of the equations for stop time in Table 3 relate to total passenger interchange. Differences among cities reflect door configurations, fare collection practices, and one-person versus two-person operations. Some equations reflect the time losses resulting from opening and closing doors (13).

American experience with single-door buses shows passenger boarding times ranging from 2 sec for single-coin fares to >8 sec for multiple-zone fares collected by the driver (Table 5). Alighting times range from about $1\frac{1}{2}$ to $2\frac{1}{2}$ sec for typical urban conditions to ≥6 sec when baggage is involved.

Suggested ranges in bus service times in relation to door width, methods of operation, and fare collection practices are given in Table 5 (2, 3). These bus service times, based on current experiences, were subsequently used to derive relationships between bus and person capacity. They assume that prepayment before entering buses would reduce passenger service times.

Passenger Service Times

Passenger service times decrease as the number of door channels available to passengers increases. The time values in Table 5 reflect the inefficiencies in using additional doorway capacity. For example, one passenger may occupy a double door, and passengers do not distribute themselves uniformly among doorway openings. The time values, however, do not reflect doorway and aisle turbulence at points of heavily simultaneous boarding and alighting.

Figure 1 shows how berth capacity can be increased by changing downtown fare collection practices on a standard versus an urban transit bus. The example shown in Figure 1 is based on the following assumptions: clearance interval, 15 sec/bus; service time with single-coin fare, 3 sec; service time with double doors and prepaid fare, 1.2 sec; and volumes, 10- to 15-min peak flow rates, stated in hourly terms (i.e., with no peak-hour factor). Figure 1 also indicates how increasing the number of passengers boarding per bus tends to decrease frequency of buses that can load at a berth. If the boarding passenger volumes are distributed over several stops so that peak boarding averages 10 passengers/bus at the heaviest stop, from 80 to >140 buses could be scheduled, depending on fare structure, door availability, and the number of alighting passengers. At outlying stops where boarding or alighting averages less than 5 passengers/bus, >120 buses/berth/hour can be scheduled when single-coin fare and single-door entry are used. Conversely, where the entire bus fills up at a given stop, only 20 to 48 buses/hour could be served.

Theoretical Berth Capacities

The theoretical bus berth capacities in persons per hour resulting from the preceding bus analyses are given in Table 6. The following conclusions can be made:

1. Conventional bus loading through a single front door and a single-coin fare would limit berth capacity to a maximum of approximately 1,000 persons/hour;
2. Prepayment of fares and the use of two doors result in berth capacities of 1,500 to 2,400 persons/hour; and
3. Prepayment of fares with 4 doorway channels/bus could result in berth capacities of 2,500 to 3,400 persons/hour.

Table 3. Bus boarding and alighting times in selected urban areas.

Location	Boarding and Alighting Method	Fare Type	Fare Method of Collection	Boarding and Alighting Relationships[a]
Louisville, Kentucky	Alighting only	Flat	Driver	T = 1.8 + 1.1 F
	Boarding only	Flat	Driver	T = -0.1 + 2.6 N
	Simultaneous	Flat	Driver	T = 1.8 + 1.0 F + 2.3 N - 0.02 FN
London, England	Consecutive	Graduated	Conductor[b]	T = 1.3 + 1.5 (N + F)
	Consecutive	Graduated	Driver	T = 8 + 6.9 N + 1.4 F
	Simultaneous	Flat, single-coin	Mechanical	T = 7 + 2.0 N
		Flat, two-coin	Mechanical	T = 5.7 + 3.3 N - Peak, T = 5.7 + 5.0 N - off-peak
Toronto, Canada	Simultaneous	Zonal	Fare box	T = 1.7 N, T = 1.25 F, T = 1.4 (N + F)
Copenhagen, Denmark	Simultaneous	Flat	Split entry, driver and machine	T = 2.2 N
Dublin, Ireland	Consecutive	Graduated	Conductor[b]	T = 1.4 (N + F)
	Consecutive	Graduated	Driver	T = 6.5 N + 3.0 F
Bordeaux, France	Simultaneous	Flat	Driver	T = 15 + 3 N
Toulouse, France	Simultaneous	Flat	Driver	T = 11 + 4.6 N
Paris, France	Simultaneous	Graduated	Driver	T = 4 + 5 N
	Simultaneous	Graduated	Conductor[b]	T = 2.3 N

[a]T = stop time in seconds, N = number of passengers boarding, and F = number of passengers alighting for each bus. These variables do not correspond to those given in this paper.
[b]Buses are operated by two people; all others by one person.

Table 4. Passenger service times on and off buses.

Operation	Conditions	Time (sec)
Unloading	Small amount of hand baggage and parcels and few transfers	1.5 to 2.5
	Moderate amount of hand baggage or many transfers	2.5 to 4
	Considerable baggage from racks (intercity runs)	4 to 6
Loading[a]	Single coin or token fare box	2 to 3
	Odd-penny cash fares, multiple zone fares	3 to 4
	Prepurchased tickets and registration on bus	4 to 6
	Multiple zone fares and cash, including registrations on bus	6 to 8
	Prepayment before entering bus or payment when leaving bus	1.5 to 2.5

[a]Add 1 sec where fare receipts are involved.

Table 5. Bus passenger boarding and alighting service times for selected bus types.

Bus Type	Available Doors or Channels: Number	Location	Boarding Times[a] (sec): Prepayment[b]	Single-Coin Fare[c]	Alighting Times (sec)
Conventional	1	Front	2.0	2.6 to 3.0	1.7
	1	Rear	2.0	–	1.7
	2	Front	1.2	1.8	1.0 to 1.2
	2	Rear	1.2	–	1.0 to 1.2
	2	Front and rear[d]	1.2	–	0.9
	4	Front and rear[e]	0.7	–	0.6
Articulated	3	Front, rear, center	0.9[e]	–	0.8
	2	Rear	1.2[f]	–[f]	–
	2	Front and center[d]	–	–	0.6[f]
	6	Front, rear, center[g]	0.5	–	0.4
Special single unit	6	Three double doors[h]	0.5	–	0.4

[a]Interval between successive boarding or alighting passengers. Does not allow for clearance times between successive buses or dead time at stop.
[b]Also applies to payment-on-leaving or free-transfer situations.
[c]Not applicable with rear-door boarding.
[d]One each.
[e]Less use of separated doors for simultaneous loading and unloading.
[f]Double-door rear loading with single exits, typical European design. Provides one-way flow within vehicle, reducing internal confusion. Desirable for line-haul, especially if two-person operation is feasible. May not be best configuration for busway operation.
[g]Two double doors each.
[h]For example, Neoplan TR-40 Mobile Lounge for airport apron use.

Figure 1. Bus berth capacities versus passenger boarding volumes.

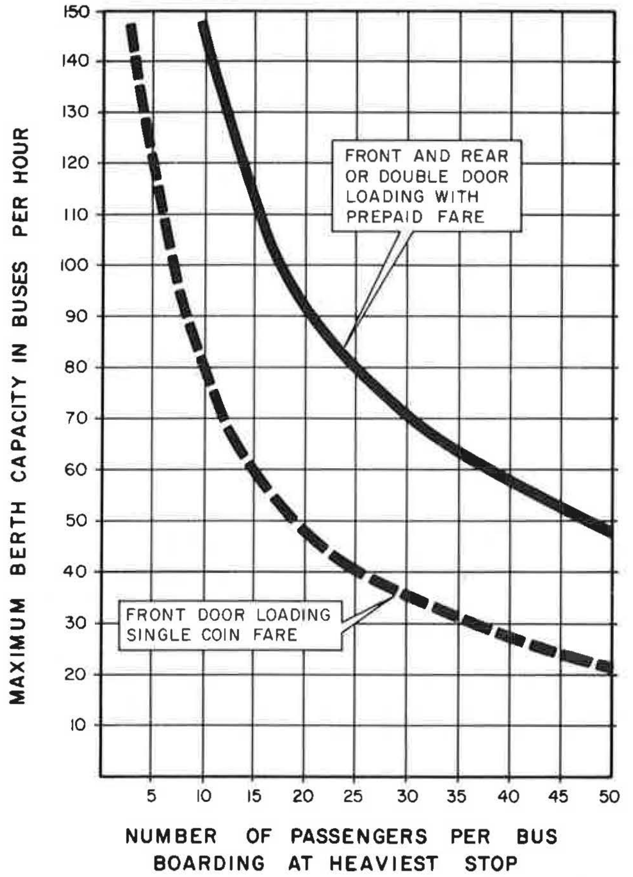

Table 6. Theoretical bus berth capacities related to door channels and fare collection.

				Berth Boarding Capacity (passengers/hour)		
Frequency (buses/hour)	Bus Capacity[a] (persons/hour)	Total Clearance Time[b] (sec/hour)	Total Available Dwell Time[c] (sec/hour)	Single-Coin Fare, 1 Front Door[d]	Fare Prepayment, 2 Doorways[e]	Fare Prepayment, 4 Doorways[f]
20	1,000	300	3,300	—[g]	—[g]	—[g]
30	1,500	450	3,150	1,050	—[g]	—[g]
40	2,000	600	3,000	1,000	—[g]	—[g]
50	2,500	750	2,850	950	2,375	—[g]
60	3,000	900	2,700	900	2,250	—[g]
70	3,500	1,050	2,550	850	2,125	—[g]
80	4,000	1,200	2,400	800	2,000	3,430
90	4,500	1,350	2,250	750	1,875	3,210
100	5,000	1,500	2,100	700	1,750	3,000
110	5,500	1,650	1,950	650	1,625	2,790
120	6,000	1,800	1,800	600	1,500	2,570
130	6,500	1,950	1,650	550	1,375	2,360
140	7,000	2,100	1,500	500	1,250	2,140
150	7,500	2,250	1,350	450	1,125	1,930

[a] 50 passengers/bus. This rate is usually 30 to 70 percent above achievable peak-hour volume because of passenger load variation within the peak hour.
[b] Clearance interval of 15 sec/bus.
[c] 3,600 sec less clearance time.
[d] 1 passenger/3.0 sec.
[e] 1 passenger/1.2 sec.
[f] 1 passenger/0.7 sec.
[g] Single-berth capacity exceeds bus capacity.

Adjusted Berth Capacities

Adjusted berth capacities should be reduced in planning and design to allow for random variations in bus arrivals and for boarding and alighting passenger turbulence. A 25 percent reduction is suggested in applying these factors. Typical resulting values are about 750 passengers/berth/hour for single-coin fare and one-door loading; 1,500 passengers/berth/hour for prepayment and two-door loading; and 2,100 passengers/ berth/hour for prepayment and four-door loading.

Berth Use Factors

Bus route schedules may not permit an even distribution of scheduled buses among berths or an even distribution of passengers among loading positions. Further research is necessary to develop typical use factors because experience with high-volume exclusive bus facilities is limited. The use factors in Table 7 (14) are suggested as a guideline.

Bus Use

The number of people per bus will depend on (a) the size of vehicles (50 seats/conventional bus and 60 seats/articulated bus) and (b) operating policies with regard to standees. To provide an acceptable level of comfort for express bus commuters and a minimum nonstop run of 3 to 5 miles (4.8 to 8 km), the load factor in the peak 10- to 15-min period should not exceed 1.00; i.e., there should be a seat available for each passenger. (Higher load factors are acceptable on short, local bus routes.) When total hourly flows are considered, a lower load factor should be assumed, and, depending on land use and work schedules, load factors of 0.6 or 0.7 may not be unreasonable. Such a conservative load factor also will minimize on-vehicle turbulence at bus stops.

Passenger Distribution at Downtown Stops

A reasonable design assumption is that 50 percent of the maximum load-point volume is served at the heaviest downtown stop, assuming a minimum of three stops in the CBD. (The Washington Street-State Street subway station in Chicago accounts for about half of all boarding passengers at the three downtown stops on the State Street line.)

GUIDELINES AND IMPLICATIONS

Suggested busway capacity guidelines for central urban areas are shown in Figure 2 and given in Table 8 for a variety of bus types and service conditions. Figure 2 shows how door configuration and number of berths increase maximum load-point capacity. The left vertical scale applies to typical through-station operations; the right scale applies to a single-station situation.

Table 8 gives the steps and assumptions used in deriving capacities. These computations assume that

1. Passengers per bus at maximum load point is 50 for conventional buses and 60 for articulated buses,
2. Fifty percent of the maximum load-point passengers board at the heaviest CBD stop,
3. There are three loading berths for both on-line and off-line boarding (for alternate station sizes, see Figure 2),
4. An adjustment factor of 0.75 is used to allow for on-vehicle turbulence and

Table 7. Use factors for multiple-berth operations in linear stations.

	On-Line Stations[a]			Off-Line Stations		
Berth Number	Efficiency (percent)	Capacity Factor (cumulative)	Use Factor	Efficiency (percent)	Capacity Factor (cumulative)	Use Factor
1	100	1.00	1.000	100	1.00	1.000
2	75	1.75	0.875	85	1.85	0.925
3	50	2.25	0.750	75	2.60	0.867
4	25	2.50	0.625	65	3.25	0.812
5	—[b]	2.50	0.500	50	3.75	0.750

[a]Buses do not overtake each other. [b]Negligible.

Figure 2. Downtown busway line-haul service volumes.

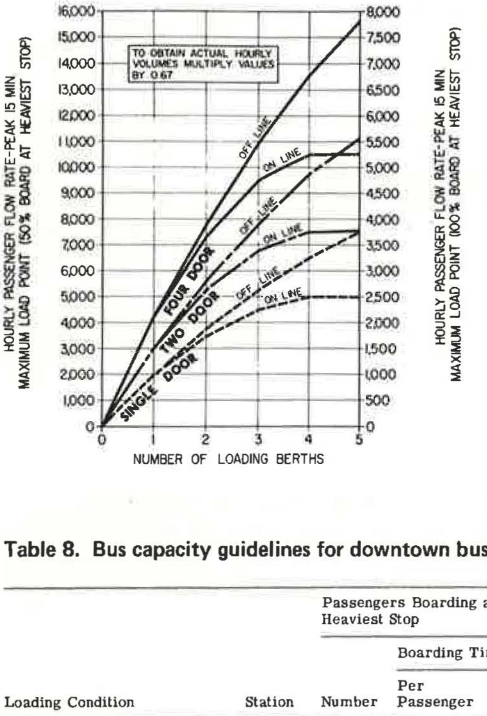

Table 8. Bus capacity guidelines for downtown busways.

		Passengers Boarding at Heaviest Stop			Berth Use (buses/hour)				Passengers/Hour at Heaviest Stop	
			Boarding Time (sec)							
Loading Condition	Station	Number	Per Passenger	Total[a]	Maximum per Berth	Use Factor (3 berths)	Total All Berths	Adjusted All Berths[b]	Peak[c]	Average[d]
Single-door conventional bus, simultaneous loading and unloading	On-line	25	2.0	65	55	2.25	124	93	4,650	3,115
	Off-line	25	2.0	65	55	2.60	143	107	5,350	3,570
Two-door conventional bus, both doors loading or double-stream doors simultaneously loading and unloading	On-line	25	1.2	45	80	2.25	180	135	6,750	4,520
	Off-line	25	1.2	45	80	2.60	208	156	7,800	5,200
Four-door conventional bus, all double-stream doors loading	On-line	25	0.7	32.5	111	2.25	250	188	9,400	6,300
	Off-line	25	0.7	32.5	111	2.60	289	217	10,850	7,230
Six-door articulated bus, all doors loading	On-line	30	0.5	30	120	2.25	270	200	12,000	8,040
	Off-line	30	0.5	30	120	2.60	312	234	14,040	9,360

[a]Includes 15-sec bus clearance.
[b]Adjusted by a factor of 0.75 to account for turbulence, schedule irregularity, and the like.
[c]From Figure 2.
[d]Adjusted by a factor of 0.67 to convert from peak.

schedule irregularity,

5. A peak-hour load factor of 0.67 is used to convert from peak 10- to 15-min flow rates to overall average hourly volumes, and

6. Fares are prepaid (no fares collected on bus in CBD).

Implications for Busway Planning

1. Busway capacity should be expressed in terms of persons per hour, rather than vehicles per hour. The governing factor will be the peak boarding and alighting volumes at the heaviest (downtown) stop.

2. The number of bus berths required at the maximum CBD stop largely depends on (a) the proportion of total busway passengers using the stop, which relates to system layout; (b) the boarding service times per passenger, which depend on operating patterns, door configurations, and bus seating capacities; and (c) the ability to develop off-line stations, which relates to facility design and level of investment.

3. Capacities provided by conventional urban buses can be more than doubled by separation of loading and unloading operations and use of buses with double-stream doors.

4. Articulated buses, with three sets of double doors available for passenger loading, can approximate capacities attained by single-unit streetcars (up to 140 cars/hour in the Philadelphia subway during concentrated loading conditions).

5. Off-line stations can increase capacity, especially where multiple berths are provided. This sometimes may be difficult or costly to achieve in a downtown environment, especially where underground construction is involved and building setback lines are limited.

6. Busway planning should try to provide at least three stops in the central area, and the maximum stop should not serve more than 50 percent of the total entering or leaving peak-hour passenger volume.

Research Directions

Additional information should be obtained on passenger interchange (simultaneous boarding and alighting) and its effect on passenger service times and the efficiency of the bus berth as a function of the number and configuration of berths. Some research has been done in these areas, but it should be expanded to reflect European experience with double-door vehicles.

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DISCUSSION

V. R. Vuchic and F. B. Day, University of Pennsylvania

Capacity, being an important characteristic of transportation modes, has always received considerable attention in professional literature. Unfortunately, understanding of this rather complex concept has not been steadily progressing. Following the extremely valuable reports by Rainville et al. (15) and by the Institute of Traffic Engineers (16), there have been a number of studies, data collections, and computerized models based on inadequate experience with urban transportation modes. Often influenced by some promotional feelings, these studies produced highly erroneous figures and created considerable confusion. The paper by Hoey and Levinson represents a refreshing return to reality. It brings out several important relationships, although some of its analyses justify additional comments.

There are three basic facts that must be understood and correctly treated in capacity analysis.

1. Station capacity C_s and way capacity C_w are two different concepts. Capacity of a transit line C is equal to the smaller of the two:

$$C(\text{per hour}) = \text{Min}(C_s, C_w)$$

As Hoey and Levinson point out, station capacity is critical under nearly all conditions since the minimum headway between successive vehicles is much longer at stations than between moving vehicles. Increase in line capacity can be achieved only by reducing vehicle times at stations or increasing the number of stopping positions.

The critical station is the one that has the highest boarding and alighting passenger volumes per vehicle. That is not necessarily related to the maximum load section (the commonly used concept of the maximum load point is incorrect because the maximum load occurs on a section between stations rather than at a station).

Three major factors cause slow bus-boarding rates on most U.S. systems: single-channel doors, on-board fare collection, and low platform boarding. The first two can be corrected respectively by different vehicle design and application of modern fare systems (flash passes, honor fare collection, or ticket-selling machines at stops). Low platform boarding cannot be overcome; it is inherent in bus technology. Hoey and Levinson's suggestion that separation of alighting and boarding can significantly increase capacity is applicable only at terminal points; at stops along the lines, this type of operation is usually inadvisable since it would result in major delays and disturbances of service.

2. There is a great difference between theoretical computations or fully controlled tests of line capacity and actual capacities achievable by real, operating systems. Computed capacities are usually much higher particularly for systems without centralized control of vehicle travel. However, for systems, such as rapid transit, that have the highest degree of control, computations may show that frequencies of well over 40 trains/hour are possible; however, most systems can achieve only 36, 38, or, exceptionally, 40 trains/hour. This paper does not point out this important fact; some of the entries in Table 1 have no realistic validity and may cause confusion.

3. Capacity must be considered with service quality. Some literature mentions passenger comfort (seating versus standing) and running speed as service elements, but such important factors as safety and reliability are usually ignored. A system transporting 10,000 persons/hour at 9 mph (15 km/h) in vehicles so closely spaced that chain collisions are possible is drastically different from the system carrying the same passenger volume at 18 mph (30 km/h) on an automatically controlled, fail-safe system. Again, this paper does not put sufficient emphasis on these considerations.

Disregard of all these three facts has led to widespread quotations of much higher capacity figures than actual systems can ever achieve. Most common exaggerations have been found with respect to buses and personal rapid transit systems. One example of all three errors combined is the result of the General Motors Proving Ground test of buses running on freeways (Table 1). First, uninterrupted flow that was tested never determines capacity: Stops, terminals, or ramps are the bottlenecks. The closest case to reaching way capacity is the Lincoln Tunnel approach in New York City, in which the bus lane leads into a terminal with 184 berths, certainly a situation atypical for any transit line. Second, the conditions prevailing during the tests were artificial; they do not exist on any freeway. Third, an analysis of the quoted flow of 1,450 buses/hour (Table 1) at 33 mph (53 km/h) through application of basic equations of vehicle traction and dynamic behavior clearly shows that such a flow can occur only under conditions at which safety is well below the minimum safety required for any transit system. Thus, the capacity of 76,850 seated persons/hour for buses, similar to the quoted personal rapid transit capacities of ≥6,000 to 10,000 passengers/hour (capsules following each other at various fractions of a second!), is without any realistic or scientific value. These figures only lead to confusion.

The average hourly passenger volumes, ranging between 3,100 and 9,350, as reported in this paper, are realistic. However, under what conditions can the claimed 50 percent higher 15-min rate be achieved? Such conditions may not be common.

The attempt to develop equations is a step in the right direction, although the given equations can be somewhat improved. For example, passenger boarding and alighting volumes should be given as absolute numbers rather than percentages of vehicle capacity.

In conclusion, the paper presents some refreshing, realistic views; it contains useful data and raises important questions that, as the authors also point out, need considerable further study.

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AUTHORS' CLOSURE

We appreciate the pertinent discussion of Vuchic and Day. Many of their comments are reflected in this paper. For example, Table 1 only contained theoretical bus performance; Table 2 gave only observed (actual) data.

We agree with Vuchic and Day that way and station capacity are different concepts and that the smaller of the two determines system capacity. Their comment correctly highlights and clarifies this important fact. However, they believe that the maximum load-point volume and capacity remain useful concepts; every major transit property conducts maximum load-point checks to assist in route and schedule planning.

In regard to separation of alighting and boarding within stations, we foresee selective application, such as at major interchange stations where a large proportion of passengers transfer between routes. These stations would have the characteristics of a bus terminal, except that through passengers would not be forced to change buses to continue their journey. Such applications of separate boarding and alighting generally would be exceptions to the operating procedures suggested by Vuchic and Day.

We separated the theoretical computations of capacity from observed volumes because the former were not based on real-world experience. (The capacities of stations, car doors, junctions, and terminal train-reversing facilities usually limit rapid transit line capacity—just as station capacity usually limits bus systems.)

We consider 1,450 buses/lane/hour to be analogous to the lane capacity of 2,000 passenger cars/hour (2) for ideal conditions. In actuality, as Vuchic and Day point out, this theoretical lane volume is academic because either demand or station capacity is limiting. Most urban bus fleets operate at a substantially lower volume.

Service quality, particularly service reliability, is indeed implicit in bus capacity assumptions. The capacity analysis in the paper sought to establish the maximum number of people who can be accommodated without risking serious disruption of service. The paper recognized this in the following ways:

1. By using 15-min peak flows, rather than peak-hour totals, as a basis for investigation;
2. By reducing theoretical station volumes derived in the analysis by 25 percent; and
3. By recommending use of seating capacity only (rather than seating and standing room combined) in bus capacity calculation.

The ability of the system to accommodate 15-min peak loads at 1.5 times the hourly rate depends on such nonphysical factors as staggering of work hours within buildings, radio communication between bus drivers and dispatchers, and the ability of bus system management to compensate for perturbations in bus schedules that may result from breakdowns and other incidents.

Accordingly, the findings in this paper represent real-world conditions that can be applied in practice and that could complement the capacity charts, nomograms, and tabulations presented in the Highway Capacity Manual (2).

We agree that further research will be needed, particularly in regard to the impact of on-vehicle turbulence on dwell times. Although we discussed the effects of boarding and alighting on dwell times, the impact of simultaneous interchanging of large passenger volumes requires additional study. A third area to be explored is the effect of comfort and load factors on the attractiveness of bus service.