CHAPTER 27

TRANSIT

CONTENTS

EXHIBITS

I. INTRODUCTION

For background and concepts, see Chapter 14

This chapter presents methodologies for calculating the vehicle and person capacities of transit modes that operate on street, namely, buses, streetcars, and light rail. Procedures are presented for bus loading areas, bus stops, busways and freeway high-occupancy-vehicle (HOV) lanes, exclusive arterial street bus lanes, mixed-traffic lanes used by buses, and rail lines. Furthermore, this chapter presents procedures for calculating bus and rail travel speeds and gives guidance on sizing passenger waiting areas at transit stations.

In addition, procedures for calculating transit quality-of-service measures for transit service from the passenger's point of view are presented for transit stops and route segments. Unlike the highway-oriented chapters in the HCM, which address individual roadway facilities and generally present a single service measure for determining level of service (LOS), this chapter addresses all on-street transit facilities and operations and as a result presents four service measures.

This chapter should be used in conjunction with Chapter 14, Transit Concepts, which describes basic concepts and definitions, not repeated in this chapter. Transit capacity and quality-of-service procedures and applications related to multimodal corridor and system analysis are presented in Chapters 29 and 30, "Corridor Analysis" and "Areawide Analysis." Capacity and speed estimation methods for off-street transit modes as well as more detailed information about transit capacity and quality-of-service procedures may be found in the *Transit Capacity and Quality of Service Manual* published by the Transportation Research Board (*1*).

RELATIONSHIP TO OTHER ANALYTICAL PROCEDURES

Capacity estimation methods and concepts provided in other HCM chapters are required in some of the methods given in this chapter for estimating the capacity of on-street transit operations. Methodologies in Chapters 15, 16, and 17, "Urban Streets," "Signalized Intersections," and "Unsignalized Intersections," in particular, should be reviewed when on-street transit operations are analyzed. Methodology in Chapter 23, "Basic Freeway Segments," is also useful in evaluating busway and HOV-lane capacity.

The effect of transit on roadway operations is addressed in many of the other chapters in Part III of this manual, usually in the form of a passenger vehicle equivalence factor for buses. The method in Chapter 16, "Signalized Intersections," also accounts for the number of buses stopping at an intersection.

Transit passengers are usually also pedestrians, bicyclists, or motorists at one or both ends of their transit trip. Chapters 18, "Pedestrians," and 19, "Bicycles," should be consulted regarding the availability of pedestrian and bicycle facilities and the LOS provided. Methodologies in Chapter 18 can also be used in sizing passenger waiting areas at bus stops and transit stations.

For guidelines on multimodal analyses of a system, see Part IV

The interactions of automobiles, transit, and other modes and their joint role in moving people as part of a transportation system are addressed in Part IV of this manual, where methods for assessing multimodal facilities, corridors, and larger areas may be found. Finally, comparisons of the capacity, speed, and quality of service offered by on-street transit modes with those offered by off-street modes may be found in the *Transit Capacity and Quality of Service Manual* (*1*).

The methods presented in this chapter are reflective of North American transit capacity and quality-of-service experience and are not necessarily reflective of conditions in other parts of the world. Experience in Europe and Asia, in particular, indicates that greater maximum person capacities are possible than those presented in this chapter. These greater capacities create greater levels of crowding and a lower quality of service for passenger loads.

LIMITATIONS OF THE METHODOLOGY

This chapter presents methodologies for bus and light rail operations within the limits of highway rights-of-way and for off-street operations only to the extent that off-street capacity constrains on-street capacity. It does not address transit operations that have their own exclusive dedicated facilities. The chapter also does not provide procedures for the analysis of oversaturated conditions.

II. METHODOLOGY

The methodology in this chapter is for the analysis of capacities of transit modes like buses, streetcars, and light rail in on-street operation.

QUALITY OF SERVICE

This section presents transit quality-of-service measures for transit availability and comfort and convenience of transit stops and route segments, as well as other performance measures that analysts may want to consider for specific applications. These measures are presented to give all users of the HCM an understanding of the overall magnitude of and interrelationships within transit quality of service (*1*).

The four service measures related to transit facilities (transit stops and route segments) per the transit quality-of-service framework presented in Chapter 14 are service frequency, hours of service, passenger loads, and reliability. Two other performance measures relating to transit systems, service coverage, and transit or automobile travel time and their application to corridor and areawide analysis are discussed in Chapters 29 and 30 of this manual.

Each quality-of-service measure has been divided into six LOS, each representing a range of values defined by the characteristics of a particular service measure. Where appropriate, descriptions of the changes in conditions that occur at LOS thresholds are provided with each service measure.

Availability Measures

Transit service availability can be used as a measure of quality of service. Availability measures for transit stops and route segments are described in the following sections.

Service Frequency at Transit Stops

From the transit user's perspective, transit service frequency determines the number of times an hour a user has access to the transit mode, assuming that transit service is provided within acceptable walking distance (measured by service coverage) and at the times the user wishes to travel (measured by hours of service). Service frequency also is a measure of the convenience of transit service to choice riders and is one component of overall transit trip time (helping to determine how long one waits for a transit vehicle).

Because of the different characteristics of urban scheduled transit service, paratransit service, and intercity scheduled transit service, these characteristics are used to define the LOS for each. Frequency LOS can vary by time of day or week: for example, a service may operate at LOS B during peak hours, LOS D at midday, and LOS F at night. Similarly, paratransit service may operate at LOS D on weekdays but at LOS F on weekends if no service is offered.

Urban Scheduled Transit Service

Urban scheduled transit service includes all scheduled service within a city as well as service between cities within a larger metropolitan area. Deviated-route bus service is included in this category because the basic service is scheduled, even if specific stops are not. For the purpose of determining service frequency LOS, commuter rail is treated as intercity service.

Urban scheduled transit service includes deviated fixed-route bus service

The service frequency LOS measure for urban scheduled transit service is headway; however, for convenience, Exhibit 27-1 shows LOS both by headway and by the corresponding number of vehicles per hour. It should be emphasized that although headways are given as continuous ranges for the purposes of determining LOS, passengers find it easier to understand schedules when clock headways are used (headways that are evenly divisible into 60). When clock headways are used, transit vehicles arrive at the same times each hour. The threshold between LOS E and F is service once an hour; this service corresponds to the typical analysis period and to the minimum service frequency applied when hours-of-service LOS is determined.

Headway determines service frequency LOS for urban scheduled transit service

EXHIBIT 27-1. SERVICE FREQUENCY LOS FOR URBAN SCHEDULED TRANSIT SERVICE

LOS	Headway (min)	Veh/h	Comments
A	< 10	> 6	Passengers don’t need schedules
B	≥ 10–14	5–6	Frequent service; passengers consult schedules
C	> 14–20	3–4	Maximum desirable time to wait if bus/train missed
D	> 20–30	2	Service unattractive to choice riders
E	> 30–60	1	Service available during hour
F	> 60	< 1	Service unattractive to all riders

Service frequency LOS is determined by destination from a given transit stop, since several routes may serve a given stop but not all may serve a particular destination. Some judgment must be applied for bus stops located near timed transfer centers. There is a considerable difference in service from a passenger’s perspective between a bus that arrives every 10 min and three buses that arrive in sequence from a nearby transfer center every 30 min, even though both scenarios result in six buses per hour serving the stop. In general, buses on separate routes serving the same destination that arrive at a stop within 3 min of each other should be counted as one bus for the purposes of determining service frequency LOS. Exhibit 27-1 gives LOS ranges for scheduled service.

Paratransit Service

Paratransit includes all unscheduled transit service obtained by notifying the service provider that a pickup is desired. However, as noted above, deviated fixed-route service, which is scheduled, is evaluated using the urban scheduled transit service procedures.

The measure of service frequency for paratransit service is access time, the minimum amount of time from when a passenger requests service to the time a pickup can be guaranteed to occur. Standing reservations, where a passenger is picked up every day at a given time unless the service provider is notified otherwise, are convenient for the passenger and potentially require less work on the part of the service provider; however, random reservations are assumed in calculating access time. Exhibit 27-2 summarizes LOS thresholds for service frequency of paratransit service. The threshold between LOS E and F is one day’s advance notice for obtaining a ride. At a higher LOS, service can be provided the day it is requested.

Service frequency LOS is measured by access time for paratransit operation

EXHIBIT 27-2. SERVICE FREQUENCY LOS FOR PARATRANSIT SERVICE

LOS	Access Time (h)	Comments
A	0.0–0.5	Fairly prompt response
B	> 0.5–1.0	Acceptable response
C	> 1.0–2.0	Tolerable response
D	> 2.0–4.0	Poor response, may require advance planning
E	> 4.0–24.0	Requires advance planning
F	> 24.0	Service not offered every weekday or at all

Intercity Scheduled Transit Service

Intercity transportation services help fill the mobility needs of smaller communities

Transportation services between communities can be just as important as services within communities, especially for rural areas where medical, educational, and other services may not be readily available. Intercity transportation services, whether bus, train, or ferry, help to fill these mobility needs by linking smaller communities to larger communities and to other transportation modes.

The number of transit vehicles per day between one community and another establishes the LOS for intercity service. Exhibit 27-3 summarizes LOS thresholds for service frequency of intercity scheduled transit service. The threshold between LOS E and F is a minimum of two round trips per day, allowing a return to one's origin the same day with sufficient time in the destination city for the trip to be useful. With just one round trip a day, a transit vehicle would likely return to its origin soon after arriving, not allowing time for a passenger to do anything useful in the destination community and still return home that day.

EXHIBIT 27-3. SERVICE FREQUENCY LOS FOR INTERCITY SCHEDULED TRANSIT SERVICE

LOS	Veh/Day	Comments
A	> 15	Numerous trips throughout the day
B	12–15	Midday and frequent peak-hour service
C	8–11	Midday or frequent peak-hour service
D	4–7	Minimum service to provide choice of travel times
E	2–3	Round trip in one day is possible
F	0–1	Round trip in one day is not possible[a]

Note:
a. Technically, a round trip might be possible, but the transit vehicle would likely return to its origin soon after arriving at its destination, not allowing any time for errands.

Accessibility at Transit Stops

Pedestrian, bicycle, automobile, and ADA (Americans with Disabilities Act of 1990) accessibility to transit stops is difficult to quantify. An evaluation of pedestrian accessibility should consider whether sidewalks are provided, the condition of the sidewalks, terrain, traffic volumes on streets that pedestrians must cross to access a transit stop and the kind of traffic control provided on those streets, and whether out-of-direction travel is required. Sidewalks are usually needed on arterial or collector routes used by buses, especially at the bus stop. Sidewalks are less critical on low-volume local streets with bus service. One possible measure could be pedestrian travel time to a stop from a certain point, with different walking times assigned to different walking environments and with delays involved in waiting for a Walk indication at signalized intersections and waiting for a sufficiently large gap in traffic in order to cross a street at an unsignalized intersection accounted for. *The Manual on Uniform Traffic Control Devices* (*2*) and the

ITE *Manual of Transportation Engineering Studies* (*3*) provide guidance on pedestrian travel speeds and assessing gaps in traffic.

ADA accessibility to transit

Research has provided a method for assessing the ADA accessibility of bus stops and the routes leading to bus stops (*4*). (Since the ADA regulations may change in the future, this method should be used for guidance in developing accessible routes for bus stops, but the current version of the regulations should be relied on for determining legal compliance with ADA.)

Bicycle accessibility

Assessment of bicycle access should consider the availability and condition of bicycle facilities on the roadways leading to a transit stop, traffic volumes on the roadways leading to transit stops, the provision of bicycle racks on buses and whether demand exceeds rack capacity, the provision of bicycle storage lockers at high-volume boarding locations, and the ability to load bicycles onto rail vehicles during peak periods.

Automobile accessibility

Assessment of automobile access should consider the capacity of park-and-ride or transit station parking lots relative to demand and the pedestrian environment within parking lots and between lots and the transit stop. For transit systems that use a zone-based fare system, consideration should be given to the parking requirements of transit stops located near a zone boundary where a drop in fare occurs.

Passenger Loads at Transit Stops

Passenger loads can be a transit availability concern when too few vehicles are scheduled or at locations with strong passenger peaking characteristics

Although passenger loads are generally more of a comfort and convenience factor than a transit availability factor, when a transit vehicle is full as it arrives at a stop, passengers waiting at the stop are unable to board and transit service is not available to those passengers at that time. Transit vehicle scheduling should provide sufficient frequency along routes to accommodate peak passenger demand volumes and avoid passing up waiting passengers. Special consideration should be given to providing sufficient transit vehicles to locations with strong peaking characteristics (such as airports, sports stadiums, or concert venues), when many people will want to board transit vehicles at the same time. Unusual weather conditions, such as snow and ice in some areas, can cause people who normally drive to use transit instead, resulting in overcrowded conditions.

Route Segment Hours of Service

Hours of service, also known as service span, is simply the number of hours during the day when transit service is provided along a route, a segment of a route, or between two locations. It plays as important a role as frequency and service coverage in determining the availability of transit service to potential users.

Exhibit 27-4 summarizes hours-of-service LOS thresholds for a transit route. Hours-of-service LOS is measured similarly for fixed-route and paratransit services. For fixed-route service, LOS is based on the number of hours per day when transit service is provided at least once an hour (corresponding to a minimum LOS E for service frequency and compatible with a typical 1-h analysis period). For paratransit service, LOS is based on the number of hours per day when service is offered. As with frequency, hours-of-service LOS can vary by day. Hours-of-service LOS is intended only for transit service provided within cities; intercity service should use only the frequency LOS measure, which is based on the number of trips provided per day.

Route Segment Accessibility

The same accessibility considerations that apply to transit stops also apply to route segments. A potential measure of pedestrian, bicycle, and ADA accessibility for a route segment could include the percentage of transit stops along the segment that meet certain accessibility criteria. Assessment of automobile access should also consider the frequency of park-and-ride lots along a route, to minimize the number of vehicle-kilometers traveled on the area's roadway system by motorists traveling to transit.

EXHIBIT 27-4. HOURS-OF-SERVICE LOS

LOS	Hours per Day	Comments
A	> 18–24	Night or owl service provided
B	> 16–18	Late evening service provided
C	> 13–16	Early evening service provided
D	> 11–13	Daytime service provided
E	> 3–11	Peak-hour service/limited midday service
F	0–3	Very limited or no service

Notes:
Fixed route: number of hours per day when service is provided at least once an hour.
Paratransit: number of hours per day when service is offered.

Comfort and Convenience Measures

Comfort and convenience measures of transit service quality are described in the following sections.

Passenger Loads at Transit Stops

From the passenger's perspective, passenger loads reflect the comfort level of the on-board vehicle portion of a transit trip both in terms of being able to find a seat and in terms of overall crowding levels within the vehicle. From a transit operator's perspective, a poor LOS may indicate the need to increase service frequency or vehicle size in order to reduce crowding and to provide a more comfortable ride for passengers. A poor passenger load LOS indicates that dwell times will be longer for a given passenger boarding and alighting demand at a transit stop and, as a result, travel times and service reliability will be negatively affected.

Passenger loads are measured as space per person

Passenger load LOS for bus and rail uses the same measure—square meters per passenger—but the ranges used to determine the LOS differ between the two modes because of differences in the level of crowding that passengers will tolerate and because most rail modes (with the notable exception of commuter rail) provide more standing area than do buses. Passenger load LOS can be measured by time of day (e.g., LOS D peak, LOS B off peak) or by the amount of time a certain condition occurs (e.g., some passengers must stand for up to 10 min).

The *Transit Capacity and Quality of Service Manual* (*1*) can be used to estimate the passenger area provided within different kinds of transit vehicles. Alternatively, the load factors (passengers per seat) shown in Exhibit 27-5 can be used to estimate LOS.

EXHIBIT 27-5. PASSENGER LOAD LOS

	Bus		Rail		
LOS	m^2/p	p/seat[a]	m^2/p	p/seat[a]	Comments
A	> 1.20	0.00–0.50	> 1.85	0.00–0.50	No passenger need sit next to another
B	0.80–1.20	0.51–0.75	1.30–1.85	0.51–0.75	Passengers can choose where to sit
C	0.60–0.79	0.76–1.00	0.95–1.29	0.76–1.00	All passengers can sit
D	0.50–0.59	1.01–1.25	0.50–0.94	1.01–2.00	Comfortable loading for standees
E	0.40–0.49	1.26–1.50	0.30–0.49	2.01–3.00	Maximum schedule load
F	< 0.40	> 1.50	< 0.30	> 3.00	Crush loads

Note:
a. Approximate values for comparison. LOS is based on area per passenger.

Amenities at Transit Stops

The amenities provided at transit stops are usually a matter of agency policy, based on the number of boarding riders that would benefit from a particular amenity as well as other factors. Exhibit 27-6 lists typical amenities, daily boarding volumes, and other factors to consider.

EXHIBIT 27-6. TYPICAL TRANSIT STOP AMENITIES

Amenity	Typical Daily Boarding Volumes at Stop	Other Factors to Consider
Shelter	10 (rural)	Number of transfers at a stop
	25 (suburban)	Available space to place shelter
	50–100 (urban)	ADA requirements
		Availability of alternative shelter
		Average passenger waiting time
Bench	Somewhat lower than shelter thresholds	Insufficient space for shelter
		Walls, stairs, etc., that attract passengers onto adjacent property
		Stops used by elderly/disabled
Landing pad	--	Wheelchair deployments at stop
		Muddy waiting areas
		Waiting areas damaging adjacent property
Information signs	100	Major trip generators and transfer points
		Number of routes using a stop
		Room to install display
Trash receptacles	--	Evidence of litter problem at a stop
		Availability of sponsor for maintenance
		Room to install adjacent to the bus stop

Source: References *5–7*.

Route Segment Reliability

Several different measures of reliability are used by transit systems. The most common of these are

- On-time performance,
- Headway adherence (the consistency or evenness of the interval between transit vehicles),
- Missed trips, and
- Distance traveled between mechanical breakdowns.

Headway adherence is important for frequent service, since bunched vehicles lead to overcrowding and longer waits than expected

On-time performance is the most widely used measure in the transit industry. It is a measure to which users can relate and encompasses several of the factors listed earlier that influence transit reliability. However, when vehicles run at frequent intervals, headway adherence becomes important to passengers, especially when vehicles arrive in bunches, causing overcrowding on the lead vehicle and longer waits than expected.

Most transit systems define a fixed-route transit vehicle as late when it is more than 5 min behind schedule (*8, 9*). Some systems consider transit vehicles to be on time when they depart 1 to 3 min early, but the majority of systems consider an early departure as not being on time. From the perspective of a passenger waiting for a transit vehicle, an early departure is often equivalent to a vehicle's being late by the amount of one headway. Reliability LOS considers on-time performance for fixed-route service as a departure from a published time point 0 to 5 min after the scheduled time or an arrival at the end of the route no more than 5 min after the scheduled time. Early departures are not considered on time.

In the case of deviated fixed-route service, in which a bus travels to the rider rather than the riders traveling to meet a bus, early arrivals and departures are not as critical. Also, maintaining a consistent schedule from day to day is more difficult. Therefore, reliability LOS considers on-time performance for deviated fixed-route service as a pickup within 10 min of the scheduled time. The only paratransit on-time performance measure identified in the literature (*8*) defines a pickup within 20 min of the scheduled time as on time, and this is the criterion used for the reliability LOS for paratransit service.

Exhibit 27-7 lists reliability LOS grades for transit service operating with frequencies of fewer than six buses/h scheduled. The LOS thresholds are based on the systemwide on-time performance reported by 83 transit properties (*8*).

EXHIBIT 27-7. RELIABILITY LOS FOR ON-TIME PERFORMANCE

LOS	On-Time Percentage	Comments[a]
A	97.5–100.0	1 late bus per month
B	95.0–97.4	2 late buses per month
C	90.0–94.9	1 late bus per week
D	85.0–89.9	
E	80.0–84.9	1 late bus per direction per week
F	< 80.0	

Notes:
Applies to routes with frequencies of fewer than 6 buses/h scheduled.
a. User perspective, based on 5 round trips/week of their travel on a particular transit route with no transfers.
On-time = 0-5 min late departing published time point (fixed route)
arrival within 10 min of scheduled pickup time (deviated fixed route)
arrival within 20 min of scheduled pickup time (paratransit)

For transit service operating at frequencies of six buses/h scheduled or more, headway adherence is used to determine reliability. The measure is based on the coefficient of variation of headways of transit vehicles serving a particular route arriving at a stop, c_v, which is calculated by Equation 27-1.

$$c_v = \frac{\text{standard deviation of headways}}{\text{scheduled headway}} \qquad (27\text{-}1)$$

Exhibit 27-8 summarizes headway adherence LOS thresholds by coefficient of variation.

EXHIBIT 27-8. RELIABILITY LOS FOR HEADWAY ADHERENCE

LOS	Coefficient of Variation
A	0.00–0.10
B	0.11–0.20
C	0.21–0.30
D	0.31–0.40
E	0.41–0.50
F	> 0.50

Note:
Applies to routes with frequencies greater than or equal to 6 buses/h scheduled.

Route Segment Travel Speed

Travel speed is a measure useful for analyzing systems

Travel speed is a useful route segment performance measure because it reflects how long a trip may take without depending on how long a route segment might be. Transit priority measures, improvements to fare collection procedures, use of low-floor buses, and other similar actions implemented along a route segment will be reflected as improvements in travel speed. The methods presented later in this chapter can be used to estimate transit travel speeds along a route segment. Research has provided suggested LOS ranges based on bus speeds for buses operating on arterial bus lanes (*10*).

PARAMETERS OF BUS FACILITIES

Regardless of the kind of bus facility—loading area, bus stop, or bus lane—being analyzed, there are some fundamental components common to each that are required to calculate the facility's vehicle and person capacity. Dwell time is the most important of these, but all have some effect on capacity. This section presents procedures for calculating each of these components.

Dwell Time

Dwell time is the amount of time a bus spends while stopped to serve passengers. When buses operate in mixed traffic and stop in a travel lane, the reduction in the roadway capacity is directly related to the amount of time the buses stop. It is the time required to serve passengers at the busiest door plus the time required to open and close the doors. A value of 2 to 5 s for door opening and closing is reasonable for normal operations.

Dwell time, t_d, can be measured in the field. Field measurement of dwell time is best suited for determining the capacity and LOS of an existing transit line. In the absence of other information, dwell time can be assumed to be 60 s for central business district (CBD), transit center, major on-line transfer point, or major park-and-ride stops; 30 s for major outlying stops; and 15 s for typical outlying stops (*11*).

Equation 27-2 can be used to compute dwell time.

$$t_d = P_a t_a + P_b t_b + t_{oc} \tag{27-2}$$

where

t_d = dwell time (s),
P_a = alighting passengers per bus through busiest door during peak 15 min (p),
t_a = passenger alighting time (s/p),
P_b = boarding passengers per bus through busiest door during peak 15 min (p),
t_b = passenger boarding time (s/p), and
t_{oc} = door opening and closing time (s).

Peak Passenger Volumes

Estimates of hourly passenger volume are required for the highest-volume stops. The peak-hour factor is used to adjust hourly passenger volumes to reflect 15-min conditions (see Equations 27-3 and 27-4).

$$PHF = \frac{P}{4P_{15}} \tag{27-3}$$

$$P_{15} = \frac{P}{4(PHF)} \tag{27-4}$$

where

PHF = peak-hour factor,
P = passenger volume during peak hour (p), and
P_{15} = passenger volume during peak 15 min (p).

If buses operate at frequencies longer than four buses/h scheduled, the denominator of Equations 27-3 and 27-4 should be adjusted accordingly. Typical PHFs range from 0.60 to 0.95 for transit service (*12, 13*), with a value close to 1.0 indicating possible underservice of the route.

Boarding and Alighting Times

Boarding and alighting times for base conditions are determined using the values in Exhibit 27-9. Note that if standees are present, 0.5 s should be added to the boarding times shown. For certain special conditions, the base values are multiplied by 1.2 (*12*), 0.6 (*14,15*), and 0.9 (*16*) for heavy two-way flow through a single door or double-stream door and for a low-floor bus, respectively.

EXHIBIT 27-9. TYPICAL BUS PASSENGER BOARDING AND ALIGHTING SERVICE TIMES FOR SELECTED BUS TYPES AND DOOR CONFIGURATIONS

Bus Type	Available Doors or Channels		Typical Boarding Service Times[a] (s/p)		Typical Alighting Service Times (s/p)
	Number	Location	Prepayment[b]	Single Coin Fare	
Conventional (rigid body)	1	Front	2.0	2.6 to 3.0	1.7 to 2.0
	1	Rear	2.0	NA	1.7 to 2.0
	2	Front	1.2	1.8 to 2.0	1.0 to 1.2
	2	Rear	1.2	NA	1.0 to 1.2
	2	Front, rear[c]	1.2	NA	0.9
	4	Front, rear[d]	0.7	NA	0.6
Articulated	3	Front, rear, center	0.9[d]	NA	0.8
	2	Rear	1.2[e]	NA	-----
	2	Front, center[c]	-----	-----	0.6
	6	Front, rear, center[c]	0.5	NA	0.4
Special single unit	6	3 double doors[f]	0.5	NA	0.4

Notes:
NA: data not available.
a. Typical interval in seconds between successive boarding and alighting passengers. Does not allow for clearance times between successive buses or dead time at stop. If standees are present, 0.5 s should be added to the boarding times.
b. Also applies to pay-on-leave or free transfer situation.
c. One each.
d. Less use of separated doors for simultaneous loading and unloading.
e. Double-door rear loading with single exits, typical European design. Provides one-way flow within vehicle, reducing internal congestion. Desirable for line-haul, especially if two-person operation is feasible. May not be best configuration for busway operation.
f. Examples: Denver 16th Street Mall shuttle; airport buses used to shuttle passengers to planes. Typically low-floor buses with few seats serving short, high-volume passenger trips.
Source: Cuntill and Watts (*17*).

Wheelchair Accessibility Adjustment

All new transit buses in the United States are equipped with wheelchair lifts or ramps. When a lift is in use, the door is blocked from use by other passengers. Typical wheelchair lift cycle times are 60 to 200 s, and the ramps used in low-floor buses reduce the cycle times to 30 to 60 s (including the time required to secure the wheelchair inside the bus). The higher cycle times relate to a minority of inexperienced or severely disadvantaged users. When wheelchair users regularly use a bus stop to board or alight, the wheelchair lift time should be added to the dwell time.

Bicycle Adjustment

Some transit systems provide folding bicycle racks on buses. When no bicycles are loaded, the racks typically fold upright against the front of the bus. (Some systems also use rear-mounted racks, and a very few allow bikes on board on certain long-distance routes.) When bicycles are loaded, passengers deploy the bicycle rack and load their bicycles into one of the available loading positions (typically two are provided). The process takes approximately 20 to 30 s. When bicycle rack usage at a stop is frequent enough to warrant special treatment, the dwell time of a bus is determined using the greater of the passenger boarding and alighting time or the bicycle loading and unloading time.

Coefficient of Variation of Dwell Times

The effect of variability in bus dwell times is reflected by the coefficient of variation of dwell times, which is the standard deviation of dwell time observations divided by the mean. On the basis of reported field observations of bus dwell times in several U.S. cities, the coefficient of variation of dwell times typically ranges from 40 to 80 percent, with 60 percent suggested as an appropriate value in the absence of field data (*10*).

The coefficient of variation of dwell times is the standard deviation of dwell times divided by the mean dwell time

Clearance Time

Clearance time defined

Clearance time includes two components, the time for a bus to start up and travel its own length while exiting a bus stop and (for off-line stops only) the reentry delay associated with the wait for a sufficient gap in traffic to allow a bus to pull back into the travel lane. Various studies have looked at these factors, either singly or together. Research has found that bus start-up times range from 2 to 5 s (*5*). The time for a bus to travel its own length after stopping is approximately 5 to 10 s, depending on acceleration and traffic conditions. Other research recommends a range of 10 to 15 s for clearance time (*10*).

Start-up and exiting time may be assumed to be 10 s. Reentry delay can be measured in the field or, at locations where buses reenter a traffic stream, may be estimated from Exhibit 27-10 on the basis of traffic volumes in the adjacent travel lane. If buses must wait for a queue from a signal or for traffic to clear before they can reenter the street or if traffic arrives randomly, values from Exhibit 27-10 should not be used; instead, reentry delay should be estimated using the average queue length (in vehicles), the saturation flow rate, and the start-up lost time (see Chapter 16).

EXHIBIT 27-10. AVERAGE BUS REENTRY DELAY INTO ADJACENT TRAFFIC STREAM (RANDOM VEHICLE ARRIVALS)

Adjacent-Lane Mixed-Traffic Volume (veh/h)	Average Reentry Delay (s)
100	0
200	1
300	2
400	3
500	4
600	5
700	7
800	9
900	11
1000	14

Exhibit 27-10 applies only to off-line stops and only where buses must yield to other traffic when they reenter a street, traffic arrives randomly, and the stop is located away from the influence of a queue

Some states have passed laws requiring that other traffic yield to transit vehicles that are signaling to exit a stop. In these locations, the reentry delay can be reduced or even eliminated, depending on how well motorists comply with the law. Transit priority measures, such as queue jumps at signals, can also eliminate reentry delay.

Reentry delay can be reduced or eliminated by using on-line stops, queue jumps at signals, or laws requiring traffic to yield to buses

Failure Rate

One-tail normal variate, Z_a

The probability that a queue of buses will not form behind a bus stop, or failure rate, can be derived from basic statistics. Z_a represents the area under one tail of the normal curve beyond the acceptable levels of probability that a queue will form at a bus stop. Typical values of Z_a for various failure rates are listed in Exhibit 27-11. A design failure rate should be chosen for use in calculating a loading area capacity. Higher design failure rates increase bus stop capacity at the expense of schedule reliability. Capacity occurs under normal conditions at a 25 percent failure rate (*18,19*).

EXHIBIT 27-11. VALUES OF PERCENT FAILURE ASSOCIATED WITH Z_a

Failure Rate (%)	Z_a
1.0	2.330
2.5	1.960
5.0	1.645
7.5	1.440
10.0	1.280
15.0	1.040
20.0	0.840
25.0	0.675
30.0	0.525
50.0	0.000

Suggested values of Z_a are the following (*12*):

• CBD stops: Z_a values of 1.440 down to 1.040 should be used. They result in probabilities of 7.5 to 15 percent, respectively, that queues will develop.

• Outlying stops: A Z_a value of 1.960 should be provided wherever possible, especially when buses must pull into stops from the travel lane. This value results in queues beyond bus stops only 2.5 percent of the time. Z_a values down to 1.440 are acceptable, however.

Passenger Loads

Load factor defined

Passenger loads are the number of passengers in a single transit vehicle. The occupancy of the vehicle is typically related to the number of seats, expressed as a load factor. A factor of 1.0 means that all of the seats are occupied. The importance of vehicle loading varies by the type of transit service. In general, bus transit provides a load factor at or below 1.0 for long-distance commute trips and high-speed, mixed-traffic operations. Inner-city service can approach a load factor of 1.5 to 2.0.

Maximum schedule loads defined

Maximum schedule load is synonymous with capacity, assuming a reasonable number of standees. It represents the upper limit for scheduling purposes. Maximum scheduled loads are typically 125 to 150 percent of seating capacity (e.g., 54 to 64 passengers on a typical 14-m bus).

Crush loads defined

Crush loads, typically loads above 150 percent of seating capacity, subject standees and other passengers to unreasonable discomfort. Such loads are unacceptable to passengers. Crush loads prevent circulation of passengers at intermediate stops, induce delay, and reduce vehicle capacity. Although crush loading represents the theoretically offered capacity, it cannot be sustained on every bus for any given period, and it exceeds the maximum utilized capacity. Therefore, crush loads should not be used for transit capacity calculations. Note, however, that when maximum schedule loads are used, some buses will experience crush loading because of the peaking characteristics of passenger demand.

Minimum passenger space requirements

Design guidelines for seats and passenger areas in transit vehicles are based on human factors. For buses, comfortable loading for design should provide at least 0.50 m^2/passenger and maximum schedule loads should provide a minimum of 0.40 m^2/p where relatively short trips allow standees (*20*). High-speed express bus service should not allow standees, and scheduling should be guided by the number of seats provided.

Skip-Stop Operation

Capacity adjustment for availability of adjacent lane

When buses stop at every curbside bus stop in an on-line loading area arrangement, use of the adjacent lane becomes necessary only to pass obstructions in the curb lane. The ability to spread out stops, alternating route stop patterns along an urban street, can substantially improve bus speeds and capacities.

Many large transit systems have instituted two- or three-block stop patterns for bus stops along urban streets. This block-skipping pattern allows for a faster trip through the section and reduces the number of buses stopping at each bus stop.

These alternating block stopping patterns enable the bus lane capacity to nearly equal the sum of the capacities of the stops involved. Thus, an urban street with an alternating two-block stopping pattern would ideally have a capacity equal to the sum of the two stops, assuming unimpeded use of the adjacent lane. In reality, this capacity may not always be achievable because of the irregularity of bus arrivals and traffic signal delays.

DETERMINING LOADING AREA CAPACITY

The maximum number of buses per loading area per hour, B_{bb}, is given by Equation 27-5.

$$B_{bb} = \frac{3{,}600\left(\frac{g}{C}\right)}{t_c + \left(\frac{g}{C}\right)t_d + Z_a c_v t_d} \tag{27-5}$$

where

- B_{bb} = maximum number of buses per berth per hour (buses/h),
- g/C = effective green time per signal cycle (1.0 for a stop not at a signalized intersection),
- t_c = clearance time between successive buses (s),
- t_d = average dwell time (s),
- Z_a = one-tail normal variate corresponding to probability that queues will form behind bus stop, and
- c_v = coefficient of variation of dwell times.

These maximum capacities assume adequate loading area and bus stop geometry. Guidelines for the spacing, location, and geometric design of bus stops are given in TCRP Report 19 (*6*).

DETERMINING BUS STOP CAPACITY

Sawtooth and other nonlinear designs are more effective than linear loading areas when four or five loading areas are required

As shown in Exhibit 27-12, increasing the number of linear loading areas at a bus stop has an ever-decreasing effect on capacity as the number of loading areas increases. Doubling the number of linear loading areas at a bus stop does not double capacity because the linear loading areas of multiple-berth stops typically are not used equally. When more than three loading areas are required, sawtooth, pull-through, or other nonlinear designs should be considered.

The values suggest that four or five on-line linear loading areas have the equivalent effectiveness of three loading areas. Note that to provide two effective on-line loading areas, three physical loading areas would have to be provided, since partial loading areas are never built. All other types of multiple loading areas are 100 percent efficient: the number of effective loading areas equals the number of physical loading areas.

Person capacity of a bus stop is related to number of people boarding and alighting

The vehicle capacity of a bus stop in buses per hour is given by Equation 27-6.

$$B_s = N_{eb}B_{bb} = N_{eb}\frac{3{,}600\left(\frac{g}{C}\right)}{t_c + \left(\frac{g}{C}\right)t_d + Z_a c_v t_d} \tag{27-6}$$

where

- B_s = maximum number of buses per bus stop per hour, and
- N_{eb} = number of effective loading areas, from Exhibit 27-12.

EXHIBIT 27-12. EFFICIENCY OF MULTIPLE LINEAR LOADING AREAS AT BUS STOPS

	On-Line Loading Areas		Off-Line Loading Areas	
Loading Area No.	Efficiency, %	No. of Cumulative Effective Loading Areas	Efficiency, %	No. of Cumulative Effective Loading Areas
1	100	1.00	100	1.00
2	85	1.85	85	1.85
3	60	2.45	75	2.60
4	20	2.65	65	3.25
5	5	2.70	50	3.75

Note: On-line values assume that buses do not overtake each other.
Source: References *19*, *21*, and *22*.

BUS FACILITIES ON FREEWAY HOV LANES AND BUSWAYS

Freeway HOV lanes are designed to increase the person capacity of a freeway by reserving one or more lanes, either part time or full time, for the use of vehicles with a multiple number of occupants. When the regular freeway lanes experience congestion, vehicles in the HOV lane should still travel freely. As a result, persons in the HOV lane are provided a time-savings benefit compared with those in general traffic.

Exclusive busway vehicle capacity can be computed using appropriate assumptions regarding the type of bus used, maximum allowable bus loading, the distribution of ridership among stops, the peak-hour factor, and the type of loading area. Chapter 14 presents typical busway vehicle capacities in CBD areas.

Capacity of a busway depends on the capacity of major stops

The person capacity of a busway or HOV lane at its maximum load point may be computed by multiplying the product of number per hour of each type of vehicle and the number of seats available per vehicle by a peak-hour factor. However, the vehicle capacity and therefore the person capacity will be constrained by bus stop capacity. High-speed bus service on busways and HOV lanes should not allow standees, so capacity calculations should assume that every passenger is seated. Chapter 14 provides illustrative busway person capacities at the maximum load point.

Exhibit 27-13 shows how the number of channels, or doors, and number of loading areas increase the maximum load point capacity. This exhibit can be used to estimate the number of passengers per hour that can be accommodated by various numbers and types of loading areas. The exhibit assumes that passenger loading is concentrated in the CBD area as opposed to being dispersed along the busway. Note that increasing the number of doors available for boarding (e.g., by using prepaid fares at busway stations or through use of smart card technology) greatly increases the person capacity of a busway.

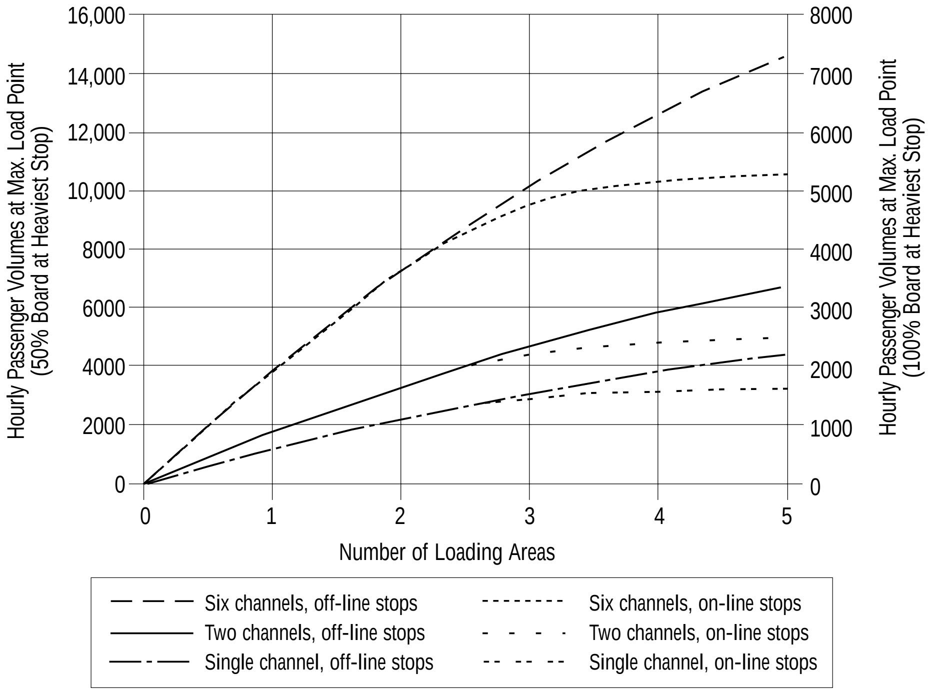
Average bus speed is determined by
- running speed,
- stop spacing, and
- dwell time.

The average speed of a bus operating on a busway or freeway HOV lane depends on three factors: the running speed of the bus in the lane, bus stop spacing, and dwell time at bus stops.

Chapter 23, “Basic Freeway Segments,” may be used to estimate the running speed of a bus in a busway or freeway HOV lane given the free-flow speed of the lane, the traffic volume in the lane, and the mix of passenger vehicles and buses using the lane. The time required to travel through a given length of busway or HOV lane without stopping can be calculated from this running speed.

Bus stop spacing affects the number of times a bus must dwell as well as the number of times the bus experiences added delay due to acceleration and deceleration. A rate of 1.2 m/s^2 may be assumed for acceleration and deceleration in the absence of local data (*10*). Exhibit 27-14 lists average travel speeds in kilometers per hour for a selection of running speeds, dwell times, and off-line bus stop spacings. As would be expected, average bus speeds decrease as the stop spacing increases or as the average dwell time per stop increases.

EXHIBIT 27-13. TYPICAL BUSWAY LINE-HAUL PASSENGER VOLUMES



Note: Six-channel configurations assume 60-passenger (seated) articulated buses.

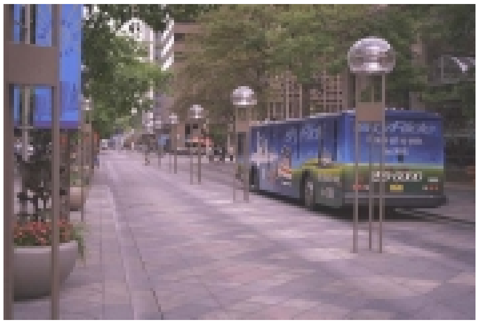
EXHIBIT 27-14. ESTIMATED AVERAGE SPEEDS OF BUSES OPERATING IN FREEWAY HOV LANES

Stop Spacing (km)	Dwell Time (s) 15	30	45	60
	80-km/h Running Speed			
1.5	53.4	46.6	41.2	37.0
2.5	61.6	55.9	51.1	47.1
3.0	64.1	58.9	54.4	50.6
4.0	67.4	63.0	59.1	55.7
5.0	69.6	65.8	62.4	59.3
	90-km/h Running Speed			
1.5	56.4	48.7	42.9	38.4
2.5	66.3	59.7	54.3	49.8
3.0	69.3	63.2	58.1	53.8
4.0	73.5	68.3	63.8	59.8
5.0	76.3	71.8	67.7	64.1
	100-km/h Running Speed			
1.5	58.6	50.4	44.2	39.4
2.5	70.3	62.8	56.9	52.0
3.0	73.9	67.0	61.3	56.5
4.0	79.1	73.0	67.9	63.4
5.0	82.5	77.2	72.5	68.4

Note:
Values are in kilometers per hour.
Assumes constant 1.2-m/s^2 acceleration-deceleration rate as buses enter and exit the freeway from off-line stops.

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. These types of bus lane treatments are described in Chapter 14. Illustrations 27-1 through 27-3 depict Types 1, 2, and 3 exclusive bus lanes, respectively.



Denver, Colorado

Los Angeles, California

Illustration 27-1. Examples of Type 1 exclusive bus lane.

Portland, Oregon

Montreal, Canada

Illustration 27-2. Examples of Type 2 exclusive bus lane.

New York, New York

Miami, Florida (single lane with off-line stops)

Illustration 27-3. 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.

If no special bus operational procedures, such as skip-stop, are used and if right turns by nontransit vehicles are prohibited, the bus lane vehicle capacity is simply the vehicle capacity of the critical bus stop along the bus lane. However, when skip-stop operation is used or when right turns are allowed, adjustments must be made to this base vehicle capacity.

Adjustment for Right Turns

Capacity adjustment for effects of right-turning traffic

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, far-side, 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, f_r, may be estimated using Equation 27-7.

$$f_r = 1 - f_l\left(\frac{v_r}{c_r}\right) \qquad (27\text{-}7)$$

where

f_r = right-turn adjustment factor;
f_l = bus stop location factor, from Exhibit 27-15;
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, f_l, are listed in Exhibit 27-15. 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. These factors reflect the likely ability of buses to move around right-turn queues.

EXHIBIT 27-15. 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*).

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 nonplatooned arrivals and the effects of high volumes of vehicular traffic in the adjacent lane. Equation 27-8 represents the factors that impede buses from fully utilizing the added capacity provided by skip-stop operations (*10*).

$$f_k = \frac{1 + Ka(N_s - 1)}{N_s} \qquad (27\text{-}8)$$

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 27-9; and
N_s = number of alternating skip stops in sequence.

$$a = 1 - 0.8\left(\frac{v}{c}\right)^3 \qquad (27\text{-}9)$$

where

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

These values result in added capacity with skip stops, even when the adjacent lane is fully utilized by passenger vehicles, since nonstopping buses have zero dwell time at the stop. When there is no spreading of stops, no increase in capacity is rendered by the adjacent lane.

Exhibit 27-16 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. Exhibit 27-17 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.

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:

Exclusive urban street bus lane vehicle capacity

$$\text{Non-skip-stop operation: } B = B_1 = B_{bb} N_{eb} f_r \qquad (27\text{-}10)$$

$$\text{Skip-stop operation: } B = f_k(B_1 + B_2 + \ldots + B_n) \qquad (27\text{-}11)$$

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
$B_1, \ldots, B_n$ = vehicle capacities of each set of routes at their respective critical bus stops that use the same alternating skip-stop pattern (buses/h).

Several bus stops may have to be tested to determine the critical bus stop, because either dwell times or right-turning volume may control

The capacities B_1, B_2, B_n used in Equation 27-11 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.

EXHIBIT 27-16. TYPICAL VALUES OF ADJUSTMENT FACTOR, f_k, FOR AVAILABILITY OF ADJACENT 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*).

EXHIBIT 27-17. VALUES OF ADJUSTMENT FACTOR, f_K, FOR TYPE 2 BUS LANES WITH ALTERNATING TWO-BLOCK SKIP STOPS

	Arrival Pattern		
Adjacent Lane v/c	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*).

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 27-12. The factor is applied to saturation flow similar to the other saturation flow adjustments, including the factor for bus blockage.

Saturation flow adjustment factor for bus use of adjacent lane

$$f_p = 1 - \left(4\frac{N_p}{3{,}600}\right) \tag{27-12}$$

where

f_p = bus-passing activity factor, and
N_p = number of buses making maneuver from curb lane to adjacent lane, from Equation 27-13.

Bus lane person capacity at the maximum load point is the product of
- bus lane vehicle capacity,
- allowed passenger loads, and
- peak-hour factor.

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 (*10*) 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 27-13.

$$N_p = \frac{N_s - 1}{N_s} v_b \left(\frac{v_b}{c_b}\right)^3 \qquad (27\text{-}13)$$

where

N_s = number of stops skipped,
v_b = volume of buses in bus lane (buses/h), and
c_b = bus vehicle capacity of bus lane (buses/h).

As expressed in Equation 27-13, the number of buses in the adjacent lane would be half the total bus flow when an alternating two-block skip-stop operation approaches capacity. Two-thirds of the buses would use the adjacent lane for a three-block pattern. However, these impacts would not take full effect until the bus volumes approached capacity.

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 27-10 or Equation 27-11, as appropriate, and the allowed passenger loads on board an individual bus by a peak-hour factor.

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 27-14, which can be used to estimate bus travel speed, S_t, on urban streets. Bus running time is determined from Exhibits 27-18 and 27-19, 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.

$$S_t = \left(\frac{60}{t_{r,0} + t_{r,1}}\right) f_s f_b \qquad (27\text{-}14)$$

where

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.

EXHIBIT 27-18. 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*).

EXHIBIT 27-19. 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*).

Bus Travel Time Rates

Exhibits 27-18 and 27-19 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 (*23*). First, a base bus running time is determined from Exhibit 27-18. This running time reflects the speed buses would travel without signal or traffic delays. Next, running time losses are determined from Exhibit 27-19, 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 Exhibit 27-19. The two running times are added and divided into 60 to determine a base bus speed for use in Equation 27-14.

Average speeds can be calculated for any distance and series of stop patterns. When a corridor is examined, the length of the study area, the number of bus stops, and the dwell times at each stop will affect the speed results. The capacity calculation should be made at the critical point along the urban street, where the combination of dwell time and dwell variation results in the lowest calculated capacity. Sections chosen for analysis should have generally homogeneous characteristics in terms of street geometry, bus lane features, stop frequency, and dwell times. The average dwell times and v/c ratios in each section should be used in estimating speeds. Ideally, each section should be at least 400 m long.

In applying Exhibit 27-19, the additional running time loss selected from a possible range of losses should consider both signal timing and enforcement efforts (or the lack thereof) to keep nonauthorized vehicles out of an exclusive bus lane.

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. This ability depends on the availability of the adjacent lane or the provision of an off-line bus stop. Where dual bus lanes or off-line bus stops are provided, the anticipated bus speed can be calculated using the distance between the bus stops served. Where congestion in the adjacent lane results in essentially no passing-lane availability, the buses will progress as if they were stopping at each stop with a zero dwell time at the intermediate stops. When partial use of the adjacent lane is available, the bus speed will be somewhere in between.

Equation 27-15 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.

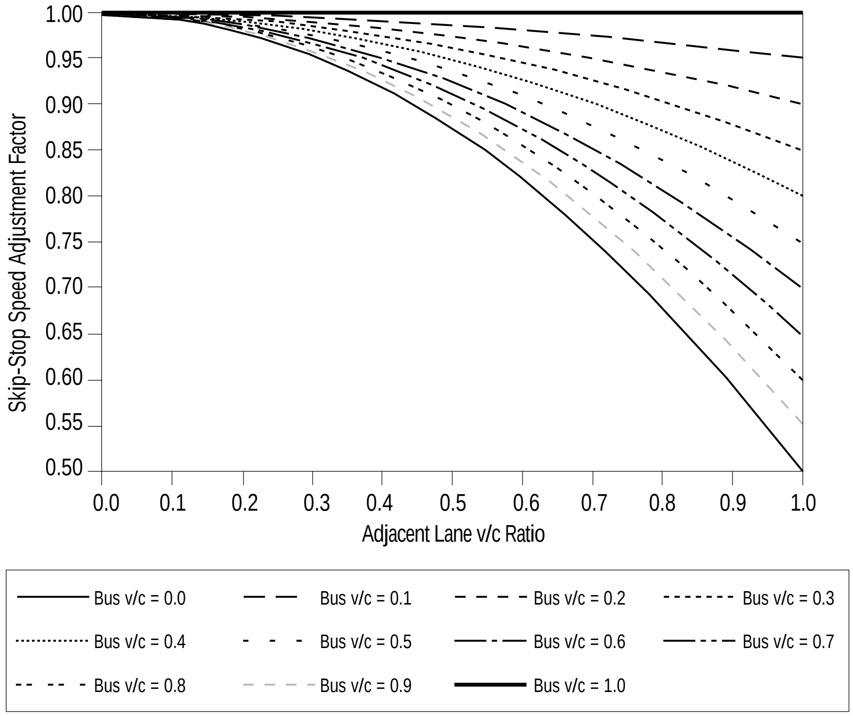
$$f_s = 1 - \left(\frac{L_1}{L_2}\right)\left(\frac{v}{c}\right)^2\left(\frac{v_b}{c_b}\right) \qquad (27\text{-}15)$$

where

- 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).

Exhibit 27-20 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.

EXHIBIT 27-20. SKIP-STOP SPEED ADJUSTMENT FACTOR, f_s



Note: Assumes two-block skip-stop pattern.

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. Research (*22*) and field observations have shown a sharp drop in bus speeds as bus volumes approach capacity (*10*). Exhibit 27-21 lists values of the speed adjustment factor for bus-bus interference.

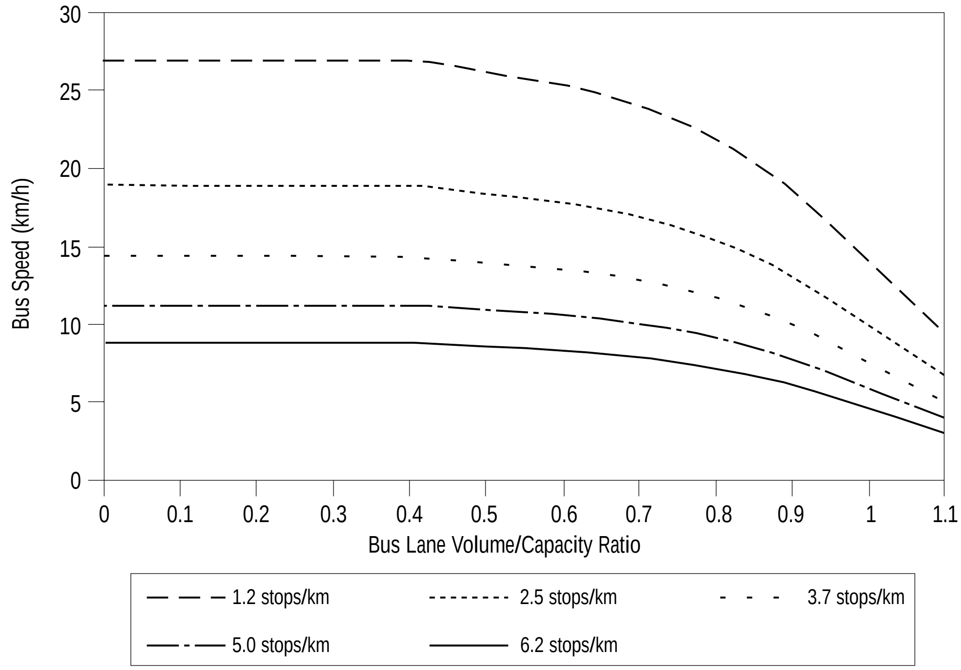
Exhibit 27-22 shows the effects of increasing bus lane volumes on bus speeds. There is little effect on bus speeds until approximately 70 percent of the bus lane capacity is being used.

EXHIBIT 27-21. 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*).

EXHIBIT 27-22. BUS LANE VOLUMES AND SPEEDS



Note: Assumes suburban conditions, 30-s dwell times, and a single bus lane.

MIXED-TRAFFIC BUS FACILITIES

Buses in mixed-traffic situations represent the most common operating scenario in North American cities and rural areas for small and large buses, both standard and articulated, and for both fixed-route and demand-responsive services. The unusual exceptions occur in larger cities with very high capacity routes, which may lend themselves to busways or downtown bus lanes.

Mixed-traffic bus capacity is calculated in a similar manner as that for exclusive urban street bus lanes, except that the interference of other traffic sharing a lane with buses must be accounted for

Because a bus operates much like other vehicles in a traffic lane, its impact on the overall vehicle capacity of the lane may be calculated as if it were another vehicle, using methods given in other chapters in this manual. Bus vehicle capacity is calculated in a similar manner as that for exclusive urban street bus lanes, except that the interference of other traffic on bus operations must be accounted for. This traffic interference is greatest when off-line stops are used and buses must wait for a gap in traffic to merge back into the street.

Bus Lane Types

Type 1 mixed-traffic lanes have one traffic lane in the direction the bus operates, shared by buses and other vehicles. Type 2 mixed-traffic lanes have two or more traffic lanes in the direction the bus operates. Traffic can use any lane, but buses typically operate in the curb lane. There are no Type 3 mixed-traffic bus lanes. Illustration 27-4 depicts Type 1 and Type 2 mixed-traffic bus lanes.

Type 1 (Portland, OR)

Type 2 (Portland, OR)

ILLUSTRATION 27-4. Mixed-traffic bus lane types.

Vehicle and Person Capacity

Delay to buses from other vehicles that slow entry into, or departure from, a bus stop is accounted for in the estimate of clearance time

The volume of mixed traffic sharing the curb lane with buses affects bus vehicle capacity in two ways: (a) the interference caused by other traffic in the lane, particularly at intersections, may block buses from reaching a stop or may delay a bus blocked behind a queue of automobiles, and (b) for off-line stops, the additional reentry delay encountered when buses leave a stop and reenter traffic may affect capacity. The latter source of delay is incorporated into the clearance time used to calculate bus stop capacity. The former is accounted for by the mixed-traffic adjustment factor, f_m, calculated using Equation 27-16.

$$f_m = 1 - f_l\left(\frac{v}{c}\right) \tag{27-16}$$

where

f_m = mixed-traffic adjustment factor,
f_l = bus stop location factor,
v = curb-lane volume at critical bus stop, and
c = curb-lane capacity at critical bus stop.

The mixed-traffic bus capacity procedures are an extension of the exclusive bus lane capacity procedures developed by Project TCRP A7-A. A theoretical basis exists for the mixed-traffic procedure, but it has not yet been validated in the field.

The mixed-traffic adjustment factor is essentially the same as the right-turn adjustment factor presented in Equation 27-7 for exclusive urban street bus lanes. The difference is that in a mixed-traffic situation, the nontransit traffic will be greater and it may not just be turning right; it could also be going straight or even left, and thus bus vehicle capacity will be lower in a mixed-traffic situation than in an exclusive bus lane. Chapters 15 and 16 should be used to determine the vehicle capacity of the curb lane. Equation 27-17 is used to calculate the bus vehicle capacity of a mixed-traffic lane in which buses operate.

$$B = B_{bb} N_{eb} f_m \tag{27-17}$$

where

B = mixed-traffic bus lane capacity (buses/h),
B_{bb} = maximum number of buses at critical bus stop (buses/h),
N_{eb} = number of effective loading areas at critical bus stop, and
f_m = mixed-traffic adjustment factor at critical bus stop.

The person capacity of buses operating in mixed traffic at the lane's maximum load point may be calculated by multiplying the product of vehicle capacity and the maximum passenger load allowed by policy by a peak-hour factor. The mixed-traffic bus capacity procedures are an extension of the exclusive bus lane capacity procedures developed by the TCRP A-7A project. A theoretical basis exists for the mixed-traffic procedure, but the procedure has not yet been validated in the field.

Measure bus speeds directly whenever possible

Speed

The best way to determine bus travel speeds is to measure them directly. If this is not possible (for example, in planning future service), speeds can be estimated by driving the route or by using Equation 27-14 to estimate bus speeds. The bus-bus interference adjustment factor, f_b, should be set to 1.0 in mixed-traffic situations because the additional running time losses obtained from Exhibit 27-19 already account for the interference of other traffic sharing the lane with buses. The value selected from the range of values presented in Exhibit 27-19 should consider signal timing and the volume of traffic using the bus lane relative to its capacity.

SIZING STATION AREAS

The methodologies in Chapter 18, "Pedestrians," can be used to size passenger waiting areas at transit stops and stations. Given a desired LOS for the waiting area, based on the amount of space provided per passenger, and estimates of maximum boarding passenger volumes per vehicle per route at the stop, Equation 27-18 can be used to estimate the required size of the passenger waiting area, A. Greater detail on sizing station areas can be found in the *Transit Capacity and Quality of Service Manual* (*1*).

$$A = (P_{b1} + P_{b2} + ... + P_{bn})a_p \qquad (27\text{-}18)$$

where

A = passenger waiting area size (m^2),
$P_{b1}, \ldots, P_{bn}$ = boarding passenger volume per transit vehicle for each route served by waiting area during peak 15 min (p), and
a_p = design pedestrian area occupancy (m^2/p).

PARAMETERS OF LIGHT RAIL AND STREETCAR FACILITIES

Of the many varieties of rail transit—streetcars, light rail, rail rapid transit, commuter rail, and automated guideway—only streetcars and light rail can operate on urban streets. Streetcars often operate in mixed traffic and have characteristics similar to those of buses under these circumstances. Modern light rail systems running on street usually operate in reserved lanes and have significantly different characteristics from buses.

This section presents methods and procedures for estimating the vehicle and person capacity of streetcars and light rail vehicles operating on street. The *Transit Capacity and Quality of Service Manual* should be consulted for similar procedures for off-street rail modes. Determining on-street rail transit capacity is a three-step process: determining the dwell time at the stop with the highest passenger volumes, determining the track section providing the minimum headway, and calculating capacity based on the minimum headway.

Dwell Time

The dwell time, t_d, is the time required to serve passengers at the busiest door divided by the number of available doors, or channels (most light rail doors are dual stream, having two channels) plus the time required to open and close the doors (typically 5 s for modern light rail vehicles, 10 s if folding or sliding steps are involved) (*24*). Time spent waiting at a station with the doors closed is incorporated into the operating margin. Equation 27-19 is used to calculate dwell time.

$$t_d = \frac{P_d t_{pf}}{N_{cd}} + t_{oc} \qquad (27\text{-}19)$$

where

t_d = dwell time (s),
N_{cd} = number of channels per door for moving passengers,
t_{oc} = door opening and closing time (s),

P_d = alighting passengers per rail through busiest door (p), and
t_{pf} = passenger flow time (s/p), from Exhibit 27-23.

EXHIBIT 27-23. RAIL TRANSIT AVERAGE PASSENGER FLOW TIMES (SINGLE STREAMS)

Car Entry	Passenger Flow Time t_{pf} for Flow Type (s/p) Mainly Boarding	Mainly Alighting	Mixed Flow
Level	2.0	1.5	2.5
Steps	3.2	3.7	5.2

Note:
Add 1 s to mixed flow and either boarding or alighting times if fares are collected on board.
Source: Parkinson and Fisher (*24*).

Peak Passenger Volumes

Some regional transportation models produce a.m. or p.m. peak flows for a 2-h period. In this case, either the model's peak-hour conversion factor or a typical value of 60 percent is used to arrive at a peak-hour passenger volume. Next, the station with the highest passenger volume, either into or out of the station, is selected and the flow is classified as mainly boarding (70 percent or more of the passengers boarding), mainly alighting (70 percent or more of the passengers alighting), or mixed (all other situations). If the maximum load point station is downtown, it is likely that the flow will be primarily alighting in the morning and primarily boarding in the afternoon. If the station is also an interchange with another rail transit line, flows could be mixed.

Morning peak usually defines controlling headway

Unless station flows are also available for the afternoon peak period, this process assumes that the morning peak period defines the controlling headway and thus maximum capacity. Morning peaks tend to be sharper, whereas afternoon peaks are more dispersed as some passengers pursue other activities between work and the trip home.

The hourly passenger flows are adjusted for peak 15-min passenger flows. Unless there is sufficient similarity with an existing operation (see Equation 27-4), the recommended PHF for light rail is 0.75 (*24*).

Number of Doors Available

The number of doors available, D, is given by Equation 27-20 and is related to the number of trains scheduled per hour, the average number of cars per train, and the number of doors per car. The number of cars per train is limited by the station length (typically one city block in CBD areas).

Deduct any door not available for passengers, such as a door blocked by wheelchair lifts

$$D = \frac{3{,}600 D_c N_c}{h_s} \tag{27-20}$$

where

D = number of doors available in peak hour,
D_c = number of doors per car,
N_c = number of cars per train, and
h_s = scheduled headway (s).

Passenger Flow at Controlling Door

Except on heavily loaded rail lines operating close to capacity (a situation in which this method is not appropriate), passengers do not tend to spread evenly along a station platform, and uneven doorway utilization results. A value of 1.5 is recommended for light rail for the ratio of busiest door usage to average door usage. Equation 27-21 calculates passenger volume at the busiest door.

$$P_d = \frac{R_d P}{D(PHF)} = \frac{R_d P h_s}{3{,}600 D_c N_c (PHF)} \qquad (27\text{-}21)$$

where

P_d = passenger volume through busiest door during peak 15 min (p), and
R_d = ratio of busiest door usage to average door usage.

Operating Margins

When dwell times are calculated, it is not possible to account for every variable that may affect dwell times. Passenger volumes may vary within the 15-min peak, especially at transfer stations where passengers may arrive in surges following the arrival of connecting buses or trains. Trains may run faster or slower than scheduled, because of either equipment problems or differences among train operators. A late train has additional passenger movement, because more passengers have accumulated at each station since the previous train. Consequently, a late train has a longer station dwell time and becomes progressively later until it interferes with the schedule of the following train. Similarly, a train running early results in longer dwell times for the following train, because more passengers than normal have accumulated in the time between the two trains.

Operating margin defined

An operating margin is the extra time added to a transit line's headway to allow for irregular operation and ensure that one train does not delay the following train. It is suggested that a range be considered for the operating margin. When capacity is not an issue, 25 s or more is recommended. If necessary to provide sufficient service to meet the estimated demand, the operating margin can be reduced to 20 or even 15 s (*24*).

Adjustment for Wheelchair Accessibility

The accessibility of light rail transit to wheelchairs and other mobility devices (considered together with wheelchairs in this section) is a major issue for such systems. Boarding and alighting times with nonlevel loading of wheelchairs tend to be highly variable, depending on the skill of the passenger. There are five primary ways to provide wheelchair accessibility: car-mounted lifts, platform-mounted lifts, mini-high platforms, high platforms, and low-floor cars. Those are described in greater detail in TCRP Report 13 (*24*).

To adjust for wheelchair accessibility, doors blocked by wheelchair lifts should be deducted from the total when Equation 27-19 is used to calculate dwell time.

Minimum Headways

An important element in calculating on-street light rail and streetcar vehicle and passenger capacity is determining the minimum headway possible between trains on an off-street block-signaled section, h_{min}. This calculation is complicated by the variety of rights-of-way that can be employed. Most light rail transit lines use a combination of right-of-way types, which can include on-street operation (often in reserved lanes) and private right-of-way with grade crossings. The line capacity is determined by the weakest link; this link could be a traffic signal with a long cycle length but is more commonly the minimum headway possible on an off-street block-signaled section. Although this chapter focuses on on-street rail operations, the capacity of an on-street section may be constrained by a block-signaled or single-track section elsewhere on the line rather than by conditions in the section being analyzed (*24*).

The train headway used for calculating capacities is the largest of the three potential controlling headways: on-street, block-signaled, and single-track headways. Equation 27-22 defines this relationship.

$$h_{min} = \max \begin{Bmatrix} h_{os} \\ h_{bs} \\ h_{st} \end{Bmatrix} \quad (27\text{-}22)$$

where

h_{min} = minimum train headway (s),
h_{os} = minimum on-street section train headway (s),
h_{bs} = minimum block-signaled section train headway (s), and
h_{st} = minimum single-track section train headway (s).

On-Street Operation

It is difficult to encompass all the variables that affect on-street light rail and streetcar operation in a single formula. However, the capacity of on-street light rail may be greater in certain circumstances than on grade-separated, signalized rights-of-way, where higher speeds force the separation between trains to be increased. Variability due to traffic congestion has been reduced as a factor, since almost all recently built on-street light rail lines operate on reserved lanes. A number of older streetcar systems still operate extensively in mixed traffic and are subjected to the variability in train throughput caused by traffic queuing, left turns, and parallel parking (*24*).

The minimum headway between trains operating on street, h_{os}, can be determined from Equation 27-23. For typical streetcar operations, where more than one streetcar can be present in a city block, or for light rail operations where the dwell time at the critical stop is long in comparison with the cycle length, dwell times and the effective green time control the minimum headway. For light rail operation where the length of two trains exceeds one city block, the closest sustainable headway should be at least twice the longest traffic signal cycle on the on-street portions of the line. This headway minimizes the chance that two adjacent trains can block an intersection (*25*).

The closest possible headway for multiple-car light rail trains in on-street operation is often taken to be twice the longest traffic signal cycle

$$h_{os} = \max \begin{Bmatrix} \dfrac{t_c + \left(\dfrac{g}{C}\right) t_d + Z_a c_v t_d}{\left(\dfrac{g}{C}\right)} \\ 2C_{max} \end{Bmatrix} \quad (27\text{-}23)$$

where

h_{os} = minimum on-street section train headway (s),
g = effective green time, reflecting reductive effects of on-street parking and pedestrian movements (mixed-traffic operation only) as well as any impacts of traffic signal preemption (s),
C = cycle length at stop with highest dwell time (s),
C_{max} = maximum cycle length in line's on-street section (s),
t_d = dwell time at critical stop (s),
t_c = clearance time between successive trains, defined as sum of minimum clear spacing between trains (typically 15 to 20 s or signal cycle time) and time for cars of a train to clear a station (typically 5 s per car) (s);
Z_a = one-tail normal variate corresponding to probability that queues of trains will form, from Exhibit 27-11; and
c_v = coefficient of variation of dwell times (typically 40 percent for light rail operation in an exclusive lane and 60 percent for streetcar operation in mixed traffic).

Some transit agencies use the signal cycle time (C) as the minimum clearance time

Block-signaled sections, rather than an on-street section, may constrain a light rail or streetcar line's capacity

Block Signaling

Many light rail lines operate predominantly in private right-of-way with grade crossings or grade separations. These lines can take the form of routes that do not follow existing streets or that run in the medians of roads. Trains are physically separated from other traffic except at crossings, operate with full signal preemption of cross-street traffic, and run at higher speeds than in on-street sections. To ensure safe separations between trains, track sections are divided into blocks, with signals used to control train entry into each block. Many light rail lines are not signaled with the minimum possible headway in mind but more economically for the minimum planned headway. This operation can easily make signaled sections the dominant capacity constraint on a light rail line (*24*).

Single-track sections used for two-way operation (as opposed to single tracks operating in one-way couplets) can constrain light rail and streetcar capacity

Single-Track Sections

Single-track sections greater than 400 to 500 m used for two-way operations are potentially the most restrictive capacity constraint for light rail. Single-track sections are used primarily as a cost-saving measure, both in areas where the right-of-way will permit double tracking at a future date and in areas where widening the right-of-way or a structure is cost-prohibitive.

Equation 27-24 computes the time to cover a single-track section, t_{st}. This computation includes the time required to traverse the single-track section plus one train length at the maximum track section speed; time losses during acceleration, deceleration, and station stops; a speed margin to adjust for equipment not operating to performance specifications and train operators who do not push to the edge of the operating envelope (i.e., do not operate at the maximum permitted speed); and an operating margin to allow for off-schedule trains (*24*).

$$t_{st} = SM\left[\frac{(N_s + 1)}{2}\left(\frac{3S_{max}}{d_s} + t_{jl} + t_{br}\right) + \frac{L_{st} + L}{S_{max}}\right] + N_s t_d + t_{om} \qquad (27\text{-}24)$$

where

t_{st} = time to cover single-track section (s);
L_{st} = length of single-track section (m);
L = train length (m);
N_s = number of stations on single-track section;
t_d = station dwell time (s);
S_{max} = maximum speed reached (m/s);
d_s = deceleration rate (m/s^2) also used as a surrogate for twice average acceleration from 0 to v_{max};
t_{jl} = jerk-limiting time (s);
t_{br} = operator and braking system reaction time (s);
SM = speed margin (constant); and
t_{om} = operating margin time (s).

Jerk-limiting time is an allowance for equipment features that taper the braking rate at the beginning and end of brake application to provide a smooth stop

The minimum headway on a single-track section is twice the time required for a train to cover the single-track section and is given by Equation 27-25.

$$h_{st} = 2t_{st} \qquad (27\text{-}25)$$

where

h_{st} = minimum single-track section train headway (s).

Light Rail and Streetcar Capacity

Vehicle Capacity

The maximum capacity of a light rail or streetcar line, in terms of the number of trains, T, is determined from the minimum headway by Equation 27-26.

$$T = \frac{3{,}600}{h_{min}} \tag{27-26}$$

where

T = maximum number of trains per hour.

Person Capacity

The maximum person capacity, P, of light rail and streetcar lines is the number of trains multiplied by their length, the number of passengers per meter of length set by policy, and a peak-hour factor. Alternatively, maximum person capacity can be determined by Equations 27-27 and 27-28 using the number of trains multiplied by the number of cars per train, the maximum allowed passenger load per car, and a peak-hour factor.

Trains operating on street should be no more than one block long to avoid blocking intersections when trains stop. Consequently, this length constrains maximum person capacity.

A light rail loading level of 5 passengers per meter of train length is recommended for calculating maximum person capacity of new systems. It provides 0.4 m^2 per standing passenger.

$$P = TLP_m(PHF) = \frac{3{,}600 LP_m(PHF)}{h_{min}} \tag{27-27}$$

where

P = maximum single-track capacity in passengers per peak-hour direction (p),
L = train length (m),
P_m = loading level (p/m), and
PHF = peak-hour factor.

$$P = TN_cP_c(PHF) = \frac{3{,}600 N_cP_c(PHF)}{h_{min}} \tag{27-28}$$

where

N_c = number of cars per train, and
P_c = maximum allowed passenger load per car (p).

Speed

Light rail and streetcar travel time is influenced by the following factors.

- Running time required to travel the analysis section if no stops are made. For off-street sections, the maximum operating speed should be used. For on-street streetcar operations (where streetcars share a lane with other traffic), the procedures in Chapter 15, "Urban Streets," should be used. For on-street rail operations in an exclusive lane, either the posted speed for the street or the speed dictated by signal progression should be used, whichever is lower. If rail vehicles do not benefit from either traffic signal progression or traffic signal priority, traffic signal delays should be accounted for when running times are calculated.
- Dwell time at stops.
- Acceleration and deceleration time at stops for boarding and alighting passengers.

For existing light rail and streetcar operations, travel time can be determined either through a series of travel time measurements or by using the scheduled time between points. For the purposes of planning future transit service, travel time can be estimated by the procedures defined in Equations 27-29 through 27-32.

Running time, t_r, is related to distance traveled and the average free-flow speed (FFS) for the section being analyzed. FFS is taken to be the posted speed limit for on-street operations and the maximum section operating speed for off-street operations. When these values vary over the transit route section being analyzed, a weighted average FFS can be calculated by multiplying the FFS for each section by the length of that section, summing these values, and dividing the result by the total length. A speed margin is used to adjust the running time to account for variations in transit equipment and the fact that drivers may not drive consistently at the FFS.

$$t_r = 3{,}600 SM \frac{L}{S_f} \tag{27-29}$$

where

- t_r = running time (s);
- SM = speed margin, assumed to be 1.1;
- L = analysis section length (km); and
- S_f = free-flow speed of train (km/h).

The acceleration and deceleration time, t_a, is given by Equation 27-30 (*24*).

$$t_a = \frac{3S_f}{d_s} + t_{jl} + t_{br} \tag{27-30}$$

where

- d_s = deceleration rate (m/s^2) also used as a surrogate for twice the average acceleration from 0 to v_f;
- t_{jl} = jerk-limiting time (s); and
- t_{br} = operator and braking system reaction time (s).

Total travel time, t_t, is computed by Equation 27-31.

$$t_t = t_r + (N - 1)(t_d + t_a) \tag{27-31}$$

where

- t_t = total travel times (s), and
- N = number of stops or stations in analysis section.

Finally, average travel speed, S_t, is computed by Equation 27-32.

$$S_t = \frac{L}{t_t} \tag{27-32}$$

III. APPLICATIONS

The methodology in this chapter is used for analyzing the capacity of transit modes that operate on street, namely, buses, streetcars, and light rail trains. To apply the methodology, the analyst must address two fundamental questions. First, the primary output must be identified. The outputs that are typically produced are capacity and speed.

Second, the analyst must identify the default values or estimated values for use in the analysis. The analyst has three main sources of input data: (a) default values found in this manual, (b) estimates and locally derived default values developed by the analyst, and (c) values derived from field measurements and observation. For each of the input variables, a value must be supplied to calculate the outputs, both primary and secondary.

Specific and commonly used applications are computations of capacity and speed of an existing facility or of a changed facility in the near term or distant future. This type of application is termed operational. Another general type of analysis can be termed planning. This type uses estimates, HCM default values, and local default values for inputs. As outputs, LOS or capacity can be determined. The difference between a planning analysis and an operational analysis is that for planning, most or all of the input values come from estimates or default values, whereas operational analyses tend to utilize field-measured values or known values.

COMPUTATIONAL STEPS

For operational analysis, all input data are collected or computed. Depending on the type of transit facility, different capacities and speeds are computed.

Exhibit 27-24 summarizes the input factors that are used in the capacity and speed procedures, the results of the various procedures, and the measures that can be taken to improve both the input factors and the results.

PLANNING APPLICATIONS

Procedures for planning applications directly correspond to those described for operational analysis. The criterion that characterizes these as planning applications is the use of estimates and HCM default values or local default values, or both, for inputs.

QUALITY OF SERVICE

There are several measures of quality of service for transit as discussed in this chapter. The availability measures are policy-based, but a low LOS grade should indicate the need to review service to determine whether the amount of service provided to an area is consistent with the area population and job density.

EXHIBIT 27-24. FACTORS INFLUENCING TRANSIT CAPACITY AND SPEED

Factor	Ways To Improve Each Factor or Result
Input Factors	
Dwell time	• Make greater use of prepaid fares • Use low-floor vehicles • Encourage one-way door flows on two-door buses • Provide multiple-stream doors for boarding and alighting • Increase bus frequency to reduce the number of standees • Implement proof-of-payment fare collection
Clearance time	• Use on-line stops rather than off-line stops[a] • Enact and enforce laws requiring vehicles to yield to buses reentering a street • Implement queue jumps at traffic signals
Coefficient of variation	• Keep generally constant for a given area
Failure rate	• Increase the number of loading areas per stop • Schedule fewer buses per hour using the stop[b]
Operating margin	• Use policy basis[a]
Calculated Results	
Loading area capacity	• Reduce dwell time • Implement transit priority treatments • Increase the accepted failure rate[a]
Bus stop capacity	• Increase loading area capacity • Use off-line loading areas[a] • Use sawtooth or pull-through loading areas • Increase the number of loading areas
Bus lane capacity	• Increase the capacity of the critical stop • Reserve lanes for buses • Platoon buses • Implement skip-stop operation • Prohibit right turns by automobiles
Rail capacity	• Reduce dwell time • Reduce the operating margin[a] • Eliminate single-track sections • Increase the number of cars per train
Bus speeds	• Reduce dwell time • Implement transit priority treatments • Balance the number of stops with passenger convenience and demand • Implement skip-stop operation
Rail speeds	• Reduce dwell time • Balance the number of stops with passenger convenience and demand

Notes:
a. Measure that may negatively affect other items on the list if implemented.
b. Measure that improves the failure rate but decreases capacity.

IV. EXAMPLE PROBLEMS

No.	Description
1	Bus dwell time calculation
2	Bus vehicle capacity in mixed traffic (near-side stops)
3	Bus vehicle capacity in mixed traffic (far-side stops)
4	Bus vehicle capacity in mixed traffic (skip-stop operation)
5	Person capacity
6	Bus speeds
7	Light rail capacity on street

Bus dwell time calculation

EXAMPLE PROBLEM 1

The Situation An express route is planned along an arterial from a suburb to the CBD with 10 stops, including one at a transit center midway (Stop 5). The route will operate in mixed traffic in the CBD (Stops 7 to 10).

The Question What will the average dwell times be at the 10 stops and how might they affect how the route is developed?

The Facts

√ The route will use 42-seat buses,
√ Exact fare is required on boarding,
√ The door opening and closing time is 4 s,
√ All passengers board through the front door and alight through the back door, and
√ The transit agency has estimated potential ridership for the route and predicts the following average number of boarding and alighting passengers per stop.

Stop number	1	2	3	4	5	6	7	8	9	10
Alighting passengers	0	0	3	2	14	6	16	19	15	11
Boarding passengers	20	16	11	12	16	8	2	1	0	0

Comments

√ Assume 3.0-s boarding time per passenger (3.5 s with standees), and
√ Assume 2.0-s alighting time per passenger.

Outline of Solution All input parameters are known. Since there are two doors, one used by boarding passengers and the other by alighting passengers, boarding and alighting times will be calculated separately for each stop to determine which governs dwell time. The total number of passengers on board the bus will be tracked to determine the stops where standees will be present on the bus.

Steps

1. Determine the stops where the bus arrives with standees.	There will be more than 42 passengers on the bus when it arrives at Stops 4 to 7. The last passenger to board at Stop 3 will encounter a single standee, but this can be neglected.
2. Calculate the boarding time.	The boarding time is the number of boarding passengers times 3.0 or 3.5 s, depending on whether standees are present.
3. Calculate the alighting time.	The alighting time is the number of alighting passengers times 2.0 s.
4. Determine the dwell time.	The dwell time is the larger of the boarding and alighting times at each stop plus the 4-s door opening and closing time.

The Results Estimated dwell times are shown below for each stop:

Stop number	1	2	3	4	5	6	7	8	9	10
Dwell time (s)	64	52	37	46	60	32	36	42	34	26

Boarding times govern at Stops 1 to 7, and alighting times govern at Stops 8 to 10. Stop 8 is the critical bus stop for this route within the CBD area.

Because of the long dwell times at Stops 1 to 5 in the suburban portion of the corridor, off-line stops (pullouts) should be considered at these locations to avoid substantial traffic delays to other vehicles in the curb lane. At the same time, to minimize delays to the express buses reentering the arterial, transit priority treatments such as queue jumps should also be considered at these locations.

The dwell time at Stop 5 required to serve passenger movements is 60 s. However, since this stop is located at a transfer center, buses will likely need to occupy the berth for longer periods of time to allow for connections between routes. This extra berth occupancy time needs to be accounted for in sizing the transfer center.

Having standees on board a long-distance express bus is not desirable for quality of service; thus, increasing service frequency so that all riders may have a seat should be considered.

Mixed-traffic-lane bus vehicle capacity with near-side stops

EXAMPLE PROBLEM 2

The Situation A transit operator wants to consolidate its outbound downtown bus routes, which currently use several streets, onto a single three-lane one-way street with four signalized intersections.

The Question How will the street operate with the added buses?

The Facts

- √ Four signalized intersections;
- √ g/C = 0.45 on the one-way street at each of the four signalized intersections;
- √ Cycle length = 90.0 s at each signalized intersection;
- √ 40 buses per hour will use the street; all 40 are assumed to stop at each bus stop;
- √ Bus stops are located at each signal, none are located between signals;
- √ 1,200 automobiles per hour will also use the street, plus 40 buses;
- √ To reduce walking distances for passengers from the shelter to the bus door and thus minimize dwell times, the transit operator desires to limit the number of loading areas to two per stop;
- √ Near-side, on-line stops located at the four signalized intersections;
- √ No on-street parking, no grades, 3.6-m travel lanes; and
- √ Dwell times, curb lane automobile right-turn and through volumes, and conflicting pedestrian movements as follows.

Stop No.	Dwell Time (s)	Curb Lane Right-Turn Auto Volume (veh/h)	Curb Lane Through Auto Volume (veh/h)	Conflicting Ped Volume (p/h)
1	30	350	50	100
2	35	200	100	300
3	40	100	100	500
4	20	300	50	200

Comments

- √ Assume base saturation flow rate, s_0, is 1,900 pc/h/ln (from Chapter 10);
- √ The computed bus blockage factor, f_{bb}, is 0.840 (from Exhibit 16-7 for a lane group with one lane and 40 buses per hour stopping);
- √ The heavy-vehicle factor, f_{HV}, is given in the summary table below (from Exhibit 16-7 and 40 buses, no trucks, per hour, and E_T = 2.0);
- √ The area factor is 0.90 for a CBD (from Exhibit 16-7);
- √ The bus stop location factor, f_l, is 0.9 (Type 2 lane, near-side stop), from Exhibit 27-15;
- √ For on-line stops, assume a 10-s clearance time (from Clearance Time section, Chapter 27);
- √ Z_a = 1.440 for 7.5 percent failure rate, from Exhibit 27-11;
- √ Assume 60 percent coefficient of variation of dwell times (from Coefficient of Variation of Dwell Times section, Chapter 27); and
- √ For two linear on-line loading areas, the number of effective loading areas, berths, N_{EB}, is 1.85, from Exhibit 27-12.

Outline of Solution All input parameters are known. The critical bus stop will determine the bus lane capacity. Because of the variety of dwell times, right-turn volumes, and conflicting pedestrian volumes, the critical stop is not immediately obvious. The vehicle capacity of each stop is found and then modified by the number of effective loading areas at each stop and the mixed-traffic interference factor. Note that the solution is based on operations in the rightmost (curb) lane. The adjustment factors related to bus blockage and heavy vehicles are computed solely on the basis of the curb lane.

Steps

1. Calculate the right-turn saturation adjustment factor, f_{RT}, and the pedestrian adjustment factor for right-turn movements, f_{Rpb}, for each stop, using the procedures from Chapter 16, "Signalized Intersections."	For Stop 1: $f_{RT} = 1.0 - 0.15P_{RT}$ $f_{RT} = 1.0 - 0.15\left(\frac{350}{440}\right) = 0.881$ f_{Rpb} = 0.948 (from Chapter 16, Appendix D)
2. Calculate the right-turn lane capacity, c.	For Stop 1: $c = s_0(g/C)f_{bb}\,f_{HV}\,f_a\,f_{RT}\,f_{Rpb}$ c = (1,900)(0.45)(0.840)(0.917)(0.90)(0.881)(0.948) c = 495 veh/h
3. Calculate the mixed-traffic interference factor (use Equation 27-16).	For Stop 1: $f_m = 1 - f_l\left(\frac{v}{c}\right)$ $f_m = 1 - 0.9\left(\frac{440}{495}\right)$ $f_m = 0.200$
4. Calculate the loading area capacity (use Equation 27-5).	For Stop 1: $B_{bb} = \frac{3{,}600\left(\frac{g}{C}\right)}{t_c + \left(\frac{g}{C}\right)t_d + Z_a c_v t_d}$ $B_{bb} = \frac{3{,}600(0.45)}{10 + (0.45)(30) + (1.44)(0.60)(30)}$ B_{bb} = 33 buses/h
5. Calculate the curb lane bus capacity at this bus stop (use Equation 27-17).	For Stop 1: $B = B_{bb}N_{eb}f_m$ B = (33)(1.85)(0.200) B = 12 buses/h

Summary table for all stops:

Stop No.	P_{RT}	f_{RT}	f_{Rpb}	f_{HV}	c	v	f_m	B_{bb}	B
1	0.795	0.881	0.948	0.917	495	440	0.200	33	12
2	0.588	0.912	0.898	0.894	473	340	0.353	29	19
3	0.417	0.938	0.883	0.857	459	240	0.529	26	25
4	0.769	0.885	0.908	0.907	471	390	0.255	45	21

The Results Although bus Stop 3 has the highest dwell time and the lowest individual loading area vehicle capacity, the curb lane bus capacity is actually greatest at this stop because right-turn interferences are greater at the other stops. The critical bus stop for determining the vehicle capacity is Stop 1. The capacity at Stop 1 is 12 buses per hour, which is insufficient to accommodate the proposed number of buses.

The simplest way, if space permits, to add capacity to a one- or two-berth bus stop is to add another berth. However, in this case, the transit operator desires to minimize pedestrian walking distances by limiting the number of loading areas to two. Another option is to increase the allowed failure rate; however, this option decreases schedule and headway reliability and should be avoided. Therefore, the analyst will need to evaluate other potential solutions. These solutions are the subject of subsequent example problems.

Mixed-traffic-lane bus vehicle capacity with far-side stops

EXAMPLE PROBLEM 3

The Situation The CBD street from Example Problem 2 is used. Having determined that a mixed-traffic lane with near-side stops will not provide sufficient capacity, the transit operator would like to try using far-side stops to avoid some of the right-turn interferences.

The Question How will the street operate under this scenario?

The Facts

√ Same assumptions as in Example Problem 2 except that stops are now far-side.

Outline of Solution As in Example Problem 2, all input parameters are known and the critical bus stop will determine the bus lane capacity. The only factor that changes is the location factor, f_l, which is 0.5 for a Type 2 mixed-traffic-lane with far-side stops as shown in Exhibit 27-15.

Summary table for all stops:

Stop No.	P_{RT}	f_{RT}	f_{Rpb}	f_{HV}	c	v	f_m	B_{bb}	B
1	0.795	0.881	0.948	0.917	495	440	0.556	33	34
2	0.588	0.912	0.898	0.894	473	340	0.641	29	34
3	0.417	0.938	0.883	0.857	459	240	0.739	26	36
4	0.769	0.885	0.908	0.907	471	390	0.586	45	49

The Results Bus lane vehicle capacity improves substantially as a result of using far-side stops but is still below the required value of 40 buses per hour. If only one stop was the constraint on capacity, a right-turn prohibition at that intersection might be considered, but in this case three of the four stops have insufficient vehicle capacity.

EXAMPLE PROBLEM 4

Mixed-traffic-lane bus vehicle capacity with skip-stop operation

The Situation The CBD street from Example Problems 2 and 3 is used. The transit operator would next like to try a skip-stop operation to improve capacity.

The Question How will the street operate under this scenario?

The Facts

- √ Same assumptions as in Example Problem 2; and
- √ Half of the buses will use A-pattern stops, which are the same ones used in Example Problem 3. The other half will use B-pattern stops in the alternate blocks. For this example, the critical B stop has the same characteristics as the critical A stop, Stop 1.

Comments

- √ Random bus arrivals are assumed,
- √ Automobile volumes in the left two lanes are assumed to be evenly distributed, and
- √ Adjustment factor K for random arrivals, from Exhibit 27-16, is 0.50.

Outline of Solution As in Example Problems 2 and 3, all input parameters are known. The critical A and B bus stops will determine the bus lane capacity. The v/c ratio of the adjacent lane is calculated to determine how well buses can use that lane to skip stops. The bus lane capacity will be the sum of the capacities of the A and B stop patterns times an adjustment factor for the effect of random bus arrivals and the impedance of other traffic in the adjacent lane. Note that there are no heavy vehicles other than buses skipping stops in two adjacent lanes. Thus, f_{HV} is 1.000.

Steps

1. Calculate the adjacent-lane capacity.	At Stop 1: $v = \left(\frac{1{,}200 - 350 - 50}{2}\right) = 400$ veh/h/ln $c = s_0(g/C)f_{HV}\,f_a$ c = (1,900)(0.45)(1.000)(0.90) = 770 veh/h
2. Calculate the adjacent-lane impedance factor (use Equation 27-9).	At Stop 1: $a = 1 - 0.8\left(\frac{v}{c}\right)^3$ $a = 1 - 0.8\left(\frac{400}{770}\right)^3$ a = 0.888
3. Calculate the skip-stop adjustment factor (use Equation 27-8).	$f_k = \frac{1 + Ka(N_s - 1)}{N_s}$ $f_k = \frac{1 + (0.50)(0.888)(2 - 1)}{2}$ f_k = 0.722
4. The A-pattern bus lane capacity, from Example Problem 3, is 34 buses per hour. The B-pattern capacity is assumed to be the same. Calculate the total bus vehicle capacity of the street (use Equation 27-11).	$B = f_k(B_1 + B_2 + ... + B_n)$ B = 0.710 (at Stop 2)(34 + 34) B = 48 buses/h

The Results If skip stops are implemented and bus stops are placed on the far sides of intersections, there will be sufficient capacity for the proposed 40 buses per hour, with some excess capacity to accommodate more buses in the future.

EXAMPLE PROBLEM 5

Bus person capacity

The Situation The CBD street from Example Problems 2, 3, and 4 is used.

The Question How many persons can be carried at the maximum load point?

The Facts

- √ Same assumptions as in Example Problem 3;
- √ All buses are 43-passenger buses;
- √ Ten buses are express buses operating on freeways; the operator's policy is to not allow standees on these buses; and
- √ The remaining local buses allow standees.

Comments

- √ Assume maximum schedule loads for the local buses; a load factor of 1.50 is also assumed; and
- √ The peak-hour factor is 0.75.

Outline of Solution The person capacity at the maximum load point is equal to the bus vehicle capacity times the allowed passenger load per bus times the peak-hour factor. From Example Problem 4, the bus vehicle capacity is 48 buses per hour.

Steps

1. Calculate the bus person capacity at its maximum load point under the proposed operation.	P = [(10 * 43) + (30 * 43 * 1.50)] * 0.75 P = 1,774 persons
2. Calculate the maximum bus person capacity at its maximum load point.	P = [(10 * 43) + (48 * 43 * 1.50)] * 0.75 P = 2,645 persons

The Results Under the proposed operation, the street can carry 1,774 persons per hour in buses at its maximum load point. If the street's bus vehicle capacity of 48 buses per hour were to be scheduled, the person capacity would be 2,645 at the maximum load point.

EXAMPLE PROBLEM 6

The Situation The CBD street from Example Problems 2, 3, 4, and 5 is used.

The Question What will the average speed of buses be under the skip-stop scenario?

The Facts

√ Same assumptions as in Example Problem 4, and

√ Blocks are 125 m long.

Comments

√ Since buses stop every two blocks, the stop frequency is $\frac{1}{2(0.125)}$ = 4.0 stops/km.

Outline of Solution Buses operate in mixed traffic. The speed estimation procedure involves identifying the base bus running time using Exhibit 27-18 and additional running time losses for mixed-traffic operations using Exhibit 27-19. The estimated speed is adjusted to account for the inability of buses to fully utilize the additional potential speed gained from the skip-stop operations. Normally, speeds would be calculated for each skip-stop pattern. However, because both skip-stop patterns have the same capacity and the same volume, both patterns will operate at the same speed.

Steps

1. Identify the base bus running time (use Exhibit 27-18). The average dwell time for the four stops is 31.25 s, so interpolate between the 30-s and 40-s values.	$t_{r,0}$ = 4.24 min/km
2. Identify additional running time losses (use Exhibit 27-19). Because the v/c ratio of the bus lane is relatively high (0.833, from Example Problem 3), a value toward the higher end of the range is selected.	$t_{r,1}$ = 2.3 min/km
3. Calculate the skip-stop adjustment factor (use Equation 27-15). Average values for the v/c ratios of the bus lane and the adjacent lane are obtained from Example Problem 4.	$f_s = 1 - \left(\frac{L_1}{L_2}\right)\left(\frac{v}{c}\right)^2\left(\frac{v_b}{c_b}\right)$ $f_s = 1 - \left(\frac{125}{250}\right)(0.406)^2\left(\frac{40}{48}\right) = 0.931$
4. Calculate the bus travel speed (use Equation 27-14). Because the bus running speed accounts for time losses due to vehicle and bus interferences, f_b is set to 1.0.	$S_t = \left(\frac{60}{t_{r,0} + t_{r,1}}\right) f_s f_b$ $S_t = \left(\frac{60}{4.24 + 2.3}\right)(0.931)(1.0) = 8.5$ km/h

The Results The average travel speed of buses operating in mixed traffic on this street will be 8.5 km/h. Speeds and capacity could be increased by implementing an exclusive bus lane and prohibiting right turns from the bus lane.

EXAMPLE PROBLEM 7

Maximum light rail capacity for on-street operation with signalized intersections and one- or three-car trains

The Situation A light rail line operates within a city street median through signalized intersections.

The Question What is the maximum passenger carrying capacity without limits on the total number of light rail cars in service?

The Facts

- √ Service is provided by single cars or by three-car trains, with each car 28 m long,
- √ Initial acceleration is 1.0 m/s^2,
- √ Blocks are 135 m long,
- √ The g/C ratio is 0.50,
- √ The maximum cycle time at any one intersection is 90 s,
- √ The passenger dwell times are 35 s,
- √ The transit authority maintains a peak-hour loading service standard of five passengers per meter of car, and
- √ The peak-hour factor is 0.75.

Comments

- √ It is assumed that there are no single-track sections on the line and no limitations imposed by any signaled sections of the line,
- √ The coefficient of variation of dwell times is typically 0.40 for light rail operations, and
- √ Capacity typically occurs at 25 percent failure rate, Z_a = 0.675.

Outline of Solution The single-car and three-car train situations require different approaches. Each approach determines the maximum number of trains per hour, which is then multiplied by the train capacity.

Steps

(a) Single-car trains	
1. Determine the total train clearance time including minimum separation between trains and the time for a train to clear the stop. The minimum spacing between trains is estimated at 20 s. The time for the train to clear a stop equals the train length divided by the average speed.	$\sqrt{\dfrac{2(\text{train length})}{(\text{acceleration})}}$ $\sqrt{\dfrac{2(28\text{ m})}{(1.0\text{ m/s}^2)}} = 7.5\text{ s}$ Total train clearance time = 7.5 s + 20 s = 27.5 s
2. Determine the maximum number of trains per hour (use Equation 27-23). Because more than one one-car train can occupy a block or stop at the same time without blocking other vehicles, the traffic signal cycle time component of the equation is not considered. In transit operations, headways should be rounded up to an even interval of 1 h, in this case to 120 s or 2 min, equivalent to 30 trains per hour.	$h_{os} = \dfrac{t_c + \left(\dfrac{g}{C}\right)t_d + Z_a c_v t_d}{\left(\dfrac{g}{C}\right)}$ $h_{os} = \dfrac{(27.5) + (0.5)(35) + (0.675)(0.4)(35)}{(0.5)}$ h_{os} = 108.9 s, round to 120 s 3,600/120 = 30 trains/h

(b) Three-car trains	
3. Since a three-car train is 84 m long, only one train can fit in the 135-m block length. In this case the closest headway is twice the longest intersection cycle time of 90 s. This results in a 3-min headway, or 20 trains per hour.	$h_{os} = 2(90) = 180$ s $\frac{3{,}600}{180} = 20$ trains/h
4. The final step is to multiply the number of trains per hour by their person capacity and the peak-hour factor.	$28\,\frac{\text{m}}{\text{car}} * 5\,\frac{\text{passengers}}{\text{m}} = \frac{140\text{ passengers}}{\text{car}}$ Single-car operation maximum person capacity: $= \left(30\,\frac{\text{trains}}{\text{h}}\right)\left(1\,\frac{\text{car}}{\text{train}}\right)\left(140\,\frac{\text{passengers}}{\text{car}}\right)(0.75)$ = 3,150 passengers Three-car operation maximum person capacity: $= \left(20\,\frac{\text{trains}}{\text{h}}\right)\left(3\,\frac{\text{car}}{\text{train}}\right)\left(140\,\frac{\text{passengers}}{\text{car}}\right)(0.75)$ = 6,300 passengers

The Results The one-car operation has a maximum capacity of 3,150 passengers, the three-car operation twice as much. The maximum capacity of three-car trains is effectively restricted to ensure that, in irregular operation, two bunched trains do not cause a backup that blocks an intersection.

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