# PART 2
# BUS TRANSIT CAPACITY

## CONTENTS

## LIST OF EXHIBITS

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# 1. BUS CAPACITY BASICS

## OVERVIEW

*Bus capacity is complex, incorporating a number of factors.*

Bus capacity is a complex topic: it deals with the movement of both people and vehicles, depends on the size of the buses used and how often they operate, and reflects the interaction between passenger traffic concentrations and vehicle flow. It also depends on the operating policy of the service provider, which normally specifies service frequencies and allowable passenger loadings. Ultimately, the capacities of bus routes, bus lanes, and bus terminals, in terms of persons carried, are generally limited by (1) the ability of stops or loading areas to pick up and discharge passengers, (2) the number of vehicles operated, and (3) the distribution of boardings and alightings along a route.

*Passenger service times at major bus stops, and the number of vehicles operated, usually determine bus route and lane person capacity.*

*Organization of Part 2.*

Part 2 of the *Transit Capacity and Quality of Service Manual* presents methods for calculating bus capacity and speed for a variety of facility and operating types.

- *Chapter 1* introduces the basic factors and concepts that determine bus capacity.
- *Chapter 2* discusses bus and roadway operating issues that influence bus capacity.
- *Chapters 3-6* present capacity and speed calculation procedures for four facility and operating categories. The *Types of Bus Facilities and Service* section below discusses these categories in further detail.
- *Chapter 7* contains references for material presented in Part 2 which may be consulted for further information on how the procedures were developed.
- *Chapter 8* presents example problems that illustrate how to apply the procedures introduced in Part 2 to "real world" situations.
- *Appendix A* provides a procedure for collecting bus dwell time data in the field.
- *Appendix B* provides substitute exhibits in U.S. customary units for Part 2 exhibits that use metric units.

*Exhibits also appearing in Appendix B are indicated by a marginal note such as this.*

### Definitions

*Vehicle vs. person capacity.*

Throughout Part 2, the distinction is made between *vehicle* and *person* capacity. Vehicle capacity reflects the number of buses that can be served by a loading area, bus stop, bus lane, or bus route during a specified period of time. Person capacity reflects the number of people that can be carried past a given location during a given time period under specified operating conditions without unreasonable delay, hazard, or restriction, and with reasonable certainty.

*As the length of time that passengers remain on a bus affects how many passengers may be carried over the length of a route, person capacity is often measured at a route's maximum load point, rather than measured for the route as a whole.*

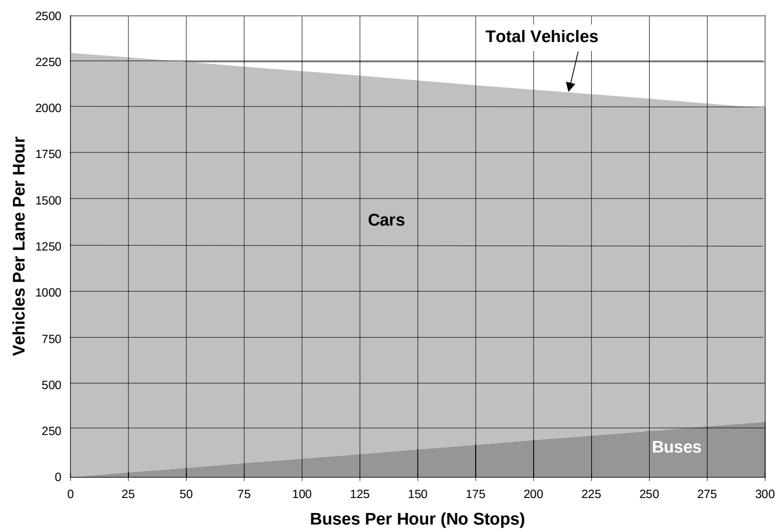
This definition of person capacity is less absolute than definitions of vehicle capacity, because it depends on the allowable passenger loading set by operator policy and the number of buses operated. Because the length of time that passengers remain on a bus affects the total number of passengers that may be carried over the entire length of a route, person capacity is often measured at a route's maximum load point. For example, an express bus may have most of its passengers board in a suburb and disembark in the CBD. In this situation, the number of passengers carried at the maximum load point will be close to the total number of boarding passengers. For a local bus, with a variety of potential passenger trip generators along the length of the route, the number of persons carried over the length of the route will be significantly greater than the express bus, although both bus' passenger loads at their respective maximum load points may be quite similar.

Exhibit 2-1 illustrates the relationship between vehicle and person capacity, using a freeway lane as an example. The number of buses operated is set by the service provider. The number of cars that can operate in the lane used by buses reflects the passenger vehicle capacity of the freeway lane after deducting the vehicle equivalencies of the buses. The total person capacity thus represents the number of people that can be carried by the specified number of buses and the remaining passenger vehicles.

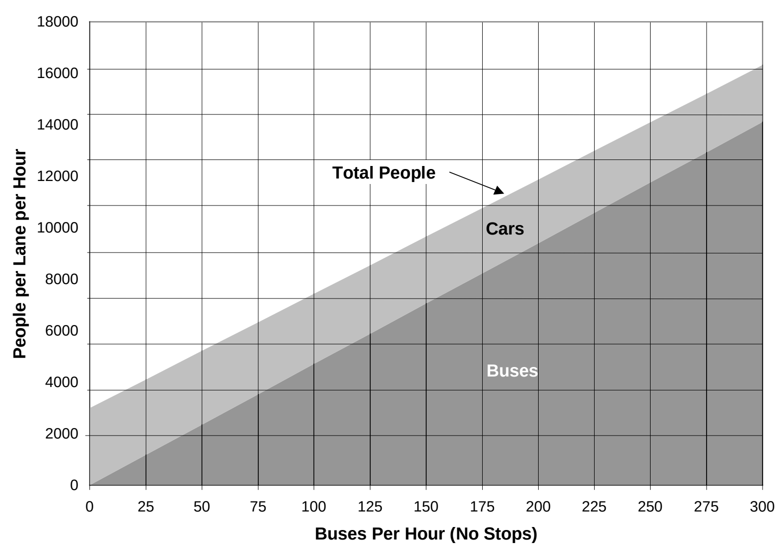
For the purposes of this example, the capacity of the freeway lanes are assumed to be 2,300 passenger vehicles per hour per lane (without buses), one bus is assumed to be the equivalent of 2 passenger vehicles, buses are assumed not to stop along the freeway, and buses and passenger vehicles are assumed to have average occupancies of 47 and 1.3, respectively, corresponding to typical major-city vehicle occupancies. It can be seen that as the number of buses using a freeway lane increases to 300, the person capacity of that lane increases from about 3,000 to over 16,800, while the vehicle capacity drops only from 2,300 to 2,000 (1,700 passenger vehicles plus 300 buses). Note that this figure only refers to capacity, not to demand or actual use.

*Buses generally form a small percentage of the total vehicular volume on a roadway…*

Exhibit 2-1
Examples of Freeway Vehicle and Person Capacity




*…but have the ability to carry most of the people traveling on a roadway.*



## TYPES OF BUS FACILITIES AND SERVICE

The capacity procedures presented in Part 2 categorize bus service by the kinds of facilities that buses operate on, and, in the case of demand-responsive service, by the special operating characteristics that influence capacity. These procedures will be presented in order from the most exclusive kinds of facilities used by buses to the least exclusive.

The most exclusive facilities, and often the facilities where buses can achieve the highest speeds, are *busways* and *freeway high-occupancy vehicle (HOV) lanes.* Busways are special roadways designed for exclusive use by buses. A busway may be constructed at, above, or below grade and may be located either within a separate right-of-way or within a highway corridor. Exhibit 2-2 depicts two examples of North American busways. Buses share freeway HOV lanes with carpools and vanpools, but are able to avoid congestion in the regular freeway lanes.

Exhibit 2-2
Busway Examples

Ottawa, Ontario　　　　Seattle Bus Tunnel

*Ottawa, Ontario has North America's most extensive busway system, with five busways totaling 32.2 km (19.3 mi).*

*The five-station, 2.1-km (1.3-mi) downtown Seattle bus tunnel serves dual-powered (electric and diesel) trolleybuses and was designed to accommodate future light rail.*

Another form of bus facility is *exclusive arterial street bus lanes*, typically found along downtown streets. These lanes are reserved primarily for buses, either all day or during specified periods. Depending on local regulations, they may be used by other traffic under certain circumstances, such as by vehicles making turns, or by taxis, motorcycles, carpools, or other vehicles that meet certain requirements. Exhibit 2-3 shows an example of an arterial street bus lane, the downtown Portland, Oregon bus mall.

Exhibit 2-3
Exclusive Arterial Street Bus Lane Example (Portland, OR)

The most common operating environment for buses is in *mixed traffic,* where buses share roadways with other traffic. In this environment, capacity procedures must account for the interactions between buses and other traffic and whether or not buses stop in the traffic lanes (*on-line stops*) or out of the traffic lanes (*off-line stops*). Exhibit 2-4 illustrates a typical mixed-traffic condition.

Exhibit 2-4
Mixed Traffic Example (Portland, OR)

The final category of bus service is *demand-responsive service.* Unlike the other categories, which address the capacity of facilities, demand-responsive capacity depends mostly on operating factors, including the number of vehicles available, the size of the service area, and the amount of time during which service is offered (See Exhibit 2-5).

Exhibit 2-5
Typical Demand-Response Vehicle

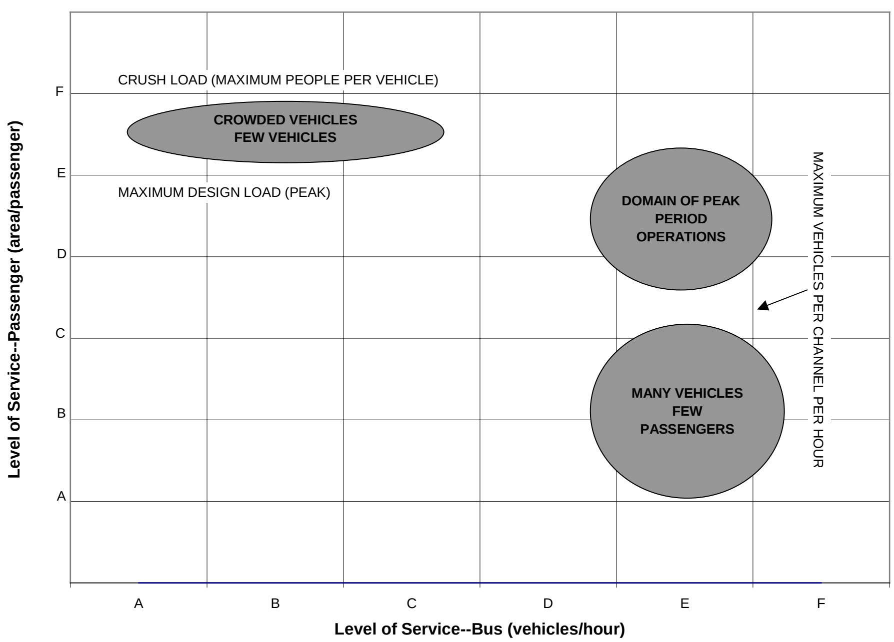
## FACTORS INFLUENCING BUS CAPACITY

This section presents the primary factors that determine bus vehicle and person capacity. These concepts will be used throughout the remainder of Part 2. Although many of the individual factors influencing vehicle capacity are different than those influencing person capacity, this section will show that there are strong connections between vehicle and person capacity, as well as between capacity in general and the concept of quality of service introduced in Part 5.

*Relationship of person and vehicle capacity.*

Exhibit 2-6 illustrates the two-dimensional nature of urban bus capacity. It can be seen that it is possible to operate many buses, each carrying few passengers. From a highway capacity perspective, the number of vehicles could be at or near capacity, even if they run nearly empty. Alternatively, few vehicles could operate, each overcrowded. This represents a poor quality of service from the passenger perspective, and long waiting times would further detract from user convenience. Finally, the domain of peak-period operations in large cities commonly involves a large number of vehicles, each heavily loaded.

Exhibit 2-6
Relationship Between Person and Vehicle Capacity




### Vehicle Capacity

Vehicle capacity is commonly calculated for three locations:

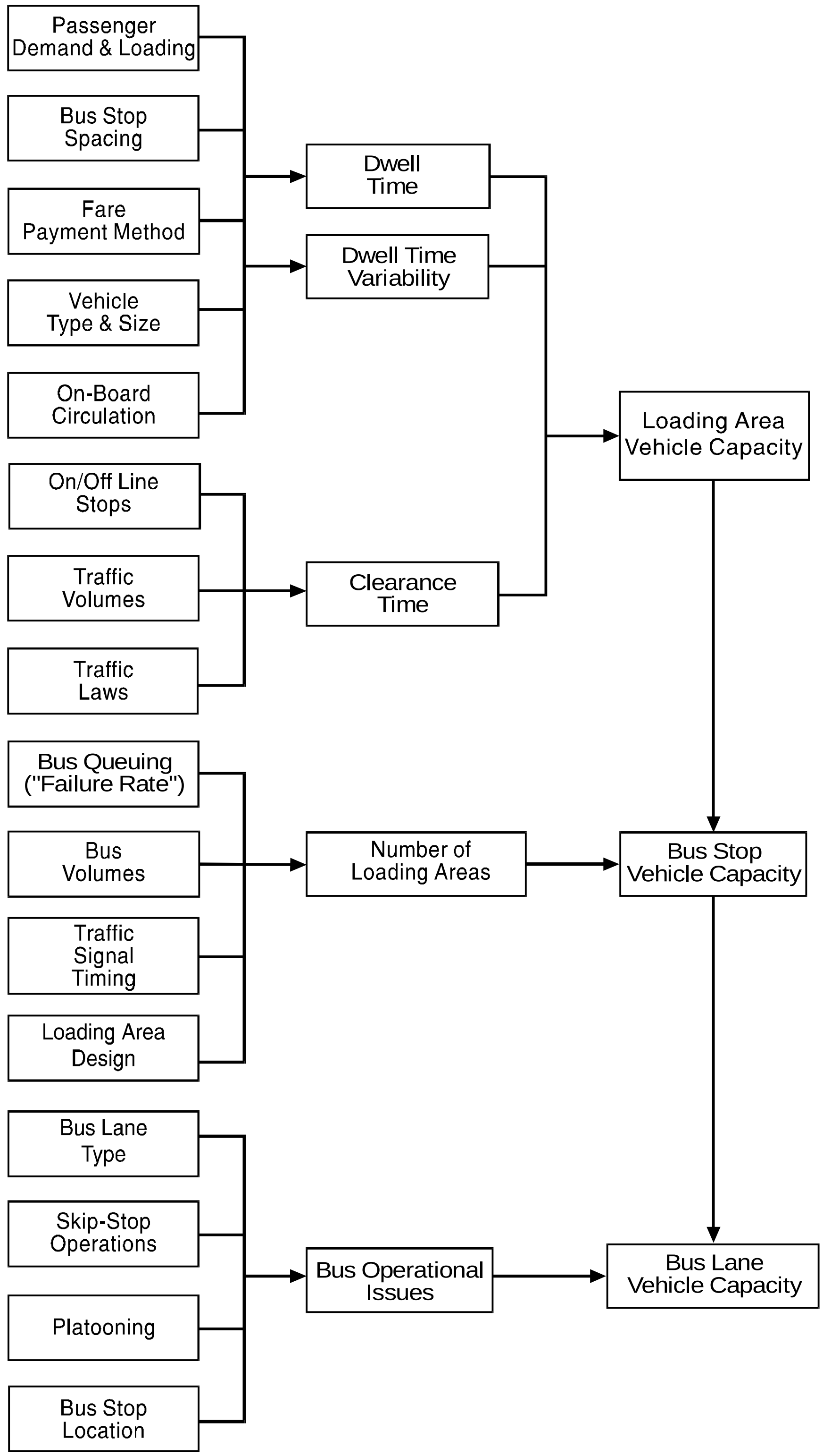
- loading areas (bus berths);
- bus stops; and
- bus lanes.

Each of these locations has one or more elements that determines its capacity, and each of these elements has a number of factors that further influence capacity. Exhibit 2-7 illustrates the key factors that affect vehicle capacity.

*Vehicle capacity is commonly calculated at three locations: loading areas (bus berths), bus stops, and bus lanes.*

*The capacity of each of these locations is influenced by one or more elements (middle column), each of which in turn is influenced by a number of factors (left column).*

Exhibit 2-7
Bus Vehicle Capacity Factors



### Loading Areas

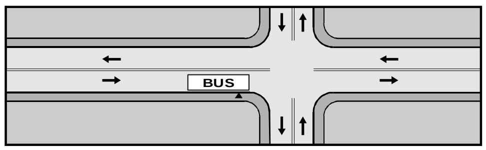
A loading area, or bus berth, is a space for buses to stop and board and discharge passengers. Bus stops, discussed below, contain one or more loading areas.

*On-line vs. off-line loading areas.*

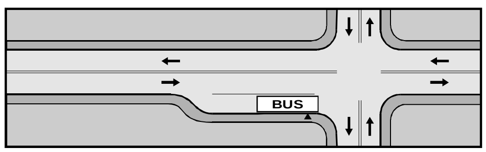
The most common form of loading area is a linear bus stop along a street curb. In this case, loading areas can be provided in the travel lane (*on-line*), where following buses may not pass the stopped bus, or out of the travel lane (*off-line*), where following buses may pass stopped vehicles. Exhibit 2-8 depicts these two types of loading areas.

Exhibit 2-8
On-Line and Off-Line Loading Areas(R6)

**On-Line**




**Off-Line**




*Elements affecting loading area vehicle capacity.*

*Dwell time is the single most important factor affecting vehicle capacity.*

The main elements affecting loading area vehicle capacity are the following:

- *Dwell Time***.** Dwell time is the single most important factor affecting vehicle capacity. It is the time required to serve passengers at the busiest door, plus the time required to open and close the doors.
- *Dwell Time Variability.* The variations in dwell time among different buses using the same loading area affect capacity. The greater the variation, the lower the vehicle capacity.
- *Clearance Time.* Clearance time is the average time between one bus leaving a stop and a following bus being able to enter the stop.

Each of these elements is addressed in more detail below.

#### Dwell Time

Just as dwell times are key to determining vehicle capacity, passenger demand volumes and passenger service times are key to determining dwell time. Dwell times may be governed by boarding demand (e.g., in the p.m. peak period when relatively empty buses arrive at a heavily used stop), by alighting demand (e.g., in the a.m. peak period at the same location), or by total interchanging passenger demand (e.g., at a major transfer point on the system). In all cases, dwell time is proportional to the boarding and/or alighting volumes times the service time per passenger. Dwell time can also influence a bus operator’s bottom line: if average bus speeds can be increased by reducing dwell time, fewer vehicles may be required to provide the same service frequency on a route, if the cumulative change in dwell time exceeds the existing route headway.

As shown in Exhibit 2-7, there are five main factors that influence dwell time. Two of these relate to passenger demand, while the other three relate to passenger service times:

- *Passenger Demand and Loading.* The number of people boarding and/or alighting through the *highest-volume* door is the key factor in how long it will take for all passengers to be served. If standees are present on-board a bus as it arrives at a stop, or if all seats become filled as passengers board, service times will be higher than normal because of congestion in the bus aisleway. The mix of alighting and boarding passengers at a stop also influences how long it takes all passenger movements to occur.

- *Bus Stop Spacing.* The fewer the stops, the greater the number of passengers who will need to board at a given stop. A balance is required between too few stops (which increase the distance riders must walk to access transit and increase the amount of time an individual bus occupies a stop) and too many stops (which reduce overall travel speeds due to the time lost in accelerating, decelerating, and possibly waiting for a traffic signal every time a stop is made).
- *Fare Payment Procedures.* The amount of time passengers must spend paying fares is a major factor in the total time required per boarding passenger. This time can be reduced by minimizing the number of bills and coins required to pay a fare; encouraging the use of pre-paid tickets, tokens, passes, or smart cards; using a proof-of-payment fare-collection system; or developing an enclosed, monitored paid-fare area at high-volume stops. In addition to eliminating the time required for each passenger to pay a fare on-board the bus, proof-of-payment fare collection systems also allow boarding passenger demand to be more evenly distributed between doors, rather than being concentrated at the front door.
- *Vehicle Types.* Low-floor buses decrease passenger service time by eliminating the need to ascend and descend steps. This is particularly true when a route is frequently used by the elderly, persons with disabilities, or persons with strollers or bulky carry-on items.
- *On-Board Circulation.* Encouraging people to exit via the rear door(s) on buses with more than one door decreases passenger congestion at the front door and reduces passenger service times.

*Wheelchair and bicycle boarding times may also need to be considered when calculating dwell time.*

In certain locations, dwell time can also be affected by the time to board and disembark passengers in wheelchairs, and for bicyclists to load and unload bicycles onto a bus-mounted bicycle rack.

Combinations of these factors can substantially reduce dwell times. Denver's 16th Street Mall shuttle operation is able to maintain 75-second peak headways with scheduled 12.5-second dwell times, despite high peak passenger loads on its 70-passenger buses.[1] This is accomplished through a combination of fare-free service, few seats (passenger travel distances are short), low-floor buses, and three double-stream doors on the buses.

### Dwell Time Variability

Not all buses stop for the same amount of time at a stop, depending on fluctuations in passenger demand between buses and between routes. The effect of variability in bus dwell times on bus capacity is reflected by the *coefficient of variation of dwell times*, which is the standard deviation of dwell time observations divided by the mean dwell time. Dwell time variability is influenced by the same factors that influence dwell time.

[1] Denver's Regional Transit District (RTD) planned to switch to 128-passenger buses in 1999 to accommodate growing passenger demand for this service.

### Clearance Time

Once a bus closes its doors and prepares to depart a stop, there is a period of time, known as the *clearance time,* during which the loading area is not available for use by the following bus. Part of this time is fixed, consisting of the time for a bus to start up and travel its own length, clearing the stop. For on-line stops, though, this is the only component of clearance time. For off-line stops, however, there is another component to clearance time: the time required for a suitable gap in traffic to allow the bus to re-enter the traffic stream and accelerate. This re-entry delay is variable and depends on the traffic volume in the travel lane adjacent to the stop and increases as traffic volumes increase. The delay also depends on the platooning effect from upstream traffic signals. Some states have passed laws requiring motorists to yield to buses re-entering a roadway; depending on how well motorists comply with these laws, the re-entry delay can be reduced or even eliminated. Many bus operators avoid using off-line stops on busy streets in order to avoid this re-entry delay.

*The time required for a bus to start up and travel its own length is fixed; re-entry delay for off-line stops is dependent on traffic volumes in the curb lane.*

## Bus Stops

A bus stop is an area where one or more buses load and unload passengers. It consists of one or more loading areas. Bus stop vehicle capacity is related to the vehicle capacity of the individual loading areas at the stop, the bus stop design, and the number of loading areas provided. Off-line bus stops provide greater vehicle capacity than do on-line stops for a given number of loading areas, but in mixed-traffic situations, bus speeds may be reduced if heavy traffic volumes delay buses exiting a stop. The design of off-street bus terminals and transfer centers entails additional considerations.

### Bus Terminals

The design of a bus terminal or “transit center” involves not only estimates of passenger service times of buses that will use the center, but also a clear understanding of how each bus route will operate. Therefore, such factors as schedule recovery times, driver relief times, and layovers to meet scheduled departure times become the key factors in establishing loading area requirements and sizing the facility. In addition, good operating practice suggests that each bus route, or geographically compatible groups of routes, should have a separate loading position to provide clarity for passengers.

*Bus stop design for bus terminals must consider passenger factors and take into account longer loading area occupancies by buses.*

Loading area space requirements should recognize the specific type of transit operations, fare collection practices, bus door configurations, passenger arrival patterns, amount of baggage, driver layover-recovery times, terminal design, and loading area configuration. They should reflect both scheduled and actual peak period bus arrivals and departures, since intercity bus services regularly run “extras” during the busiest seasonal travel periods.

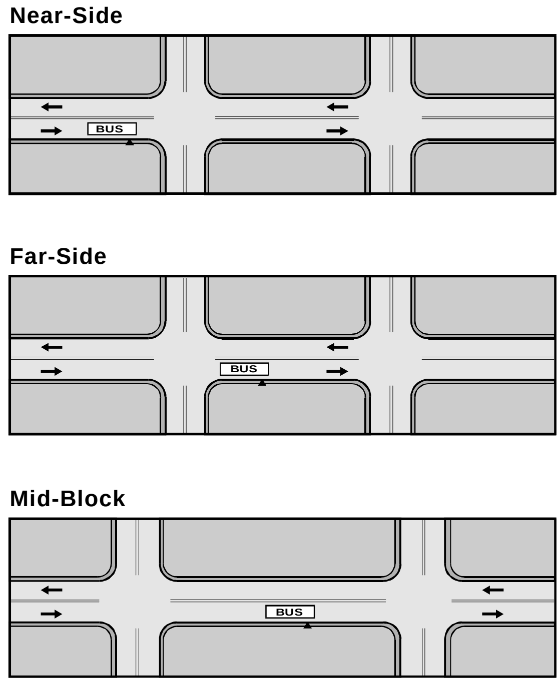
Bus route and service patterns also influence loading area requirements. Good operating practice calls for a maximum of two distinct routes (i.e., “services”) per loading position. Part 4 of this manual describes sizing bus terminals in greater detail.

### On-Street Bus Stops

On-street bus stops are typically located curbside in one of three locations: (1) *near-side,* where the bus stops immediately prior to an intersection, (2) *far-side,* where the bus stops immediately after an intersection, and (3) *mid-block,* where the bus stops in the middle of the block between intersections. Under certain circumstances, such as when buses share a stop with streetcars running in the center of the street, or when exclusive bus lanes are located in the center of the street, a bus stop may be located on a boarding island within the street rather than curbside. When boarding islands are used, pedestrian safety and ADA accessibility issues should be carefully considered. Exhibit 2-9 depicts typical on-street bus stop locations.

*The three typical on-street bus stop locations are near-side, far-side, and mid-block.*

Exhibit 2-9
On-Street Bus Stop Locations(R6)




*Freeway bus stops.*

Special bus stops are sometimes located along freeway rights-of-way, usually at interchanges or on parallel frontage roads. Examples include stops in Marin County, California and in Seattle, where they are known as "flyer stops." These stops are used to reduce travel time for buses by eliminating delays associated with exiting and re-entering freeways. Freeway stops should be located away from the main travel lanes and adequate acceleration and deceleration lanes should be provided. To be successful, attractive, well-designed pedestrian access to the stop is essential.(R5)

*Far-side stops have the most beneficial effect on bus stop vehicle capacity, but other factors must also be considered when siting bus stops*

The bus stop location influences vehicle capacity, particularly when passenger vehicles are allowed to make right turns from the curb lane (as is the case in most situations, except for certain kinds of exclusive bus lanes). Far-side stops have the least effect on capacity (when buses are able to use an adjacent lane to avoid right-turn queues), followed by mid-block stops, and near-side stops.

However, vehicle capacity is not the only factor which must be considered when selecting a bus stop location. Potential conflicts with other vehicles operating on the street, transfer opportunities, the distances passengers must walk to and from the bus stop, locations of passenger generators, signal timing, driveway locations, physical obstructions, and the potential for implementing transit preferential measures must also be considered.

For example, near-side stops are preferable when curb parking is allowed, since there is more space for buses to re-enter the moving traffic lane. They are also desirable at intersections where buses make a right turn and at intersections with one-way streets moving from right to left. Where buses operate in the curb lane and/or right-turning traffic is heavy, far-side stops are preferable. Far-side stops are also used at intersections where buses make left turns and at intersections with one-way streets moving from left to right. Mid-block stops are typically only used at major passenger generators or where insufficient space exists at adjacent intersections.(R5)

Exhibit 2-10 compares the advantages and disadvantages of each kind of bus stop location.

Exhibit 2-10
On-Street Bus Stop Location Comparison(R6)

*Advantages and disadvantages of near-side, far-side, and mid-block stops.*

| Location | Advantages | Disadvantages |
|---|---|---|
| Far-Side | • Minimizes conflicts between right turning vehicles and buses<br>• Provides additional right turn capacity by making curb lane available for traffic.<br>• Minimizes sight distance problems on intersection approaches<br>• Encourages pedestrians to cross behind the bus<br>• Creates shorter deceleration distances for buses, since the intersection can be used to decelerate<br>• Buses can take advantage of gaps in traffic flow created at signalized intersections | • May result in intersections being blocked during peak periods by stopped buses<br>• May obscure sight distance for crossing vehicles<br>• May increase sight distance problems for crossing pedestrians<br>• Can cause a bus to stop far side after stopping for a red light, interfering with both bus operations and all other traffic<br>• May increase the number of rear-end crashes since drivers do not expect buses to stop again after stopping at a red light<br>• Could result in traffic queued into intersection when a bus stops in the travel lane |
| Near-Side | • Minimizes interferences when traffic is heavy on the far side of the intersection<br>• Allows passengers to access buses closest to crosswalk<br>• Intersection width available for bus to pull away from the curb<br>• Eliminates potential for double stopping<br>• Allows passengers to board and alight while bus stopped for red light<br>• Allows driver to look for oncoming traffic, including other buses with potential passengers | • Increases conflicts with right turning vehicles<br>• May result in stopped buses obscuring curbside traffic control devices and crossing pedestrians<br>• May cause sight distance to be obscured for side street vehicles stopped to the right of the bus<br>• Increases sight distance problems for crossing pedestrians |
| Mid-Block | • Minimizes sight distance problems for vehicles and pedestrians<br>• May result in passenger waiting areas experiencing less pedestrian congestion. | • Requires additional distance for no-parking restrictions<br>• Encourages passengers to cross street mid-block (jaywalking)<br>• Increases walking distance for passengers crossing at intersections |

As mentioned previously, the vehicle capacity of a bus stop depends primarily on the following two elements:

1. the vehicle capacity of the individual loading areas that comprise the bus stop, and
2. the number of loading areas provided and their design.

The vehicle capacity of loading areas was discussed in the previous section. The factors that determine how many loading areas need to be provided at a given bus stop were shown in Exhibit 2-7 and are examined in more detail below.

### Bus Stop Loading Area Requirements

The key factors influencing the number of loading areas that are required at a bus stop are the following:

- *Bus Volumes.* The number of buses that are scheduled to use a bus stop during an hour directly affects the number of buses that may need to use the stop at a given time. If insufficient loading areas are available, buses will queue behind the stop, decreasing its vehicle capacity. In this situation, passenger travel times will increase, and the on-time reliability experienced by passengers will decrease, both of which negatively affect quality of service.

*Failure rate.*

- *Probability of Queue Formation.* The probability that queues of buses will form at a bus stop, known as the *failure rate,* is a design factor that should be considered when sizing a bus stop.

*Linear loading areas are less efficient than other loading area designs.*

- *Loading Area Design.* Loading area designs other than linear (sawtooth, drive-through, etc.) are 100% effective: the bus stop vehicle capacity equals the number of loading areas times the vehicle capacity of each loading area, since buses are able to maneuver in and out of the loading areas independently of other buses. Linear loading areas, on the other hand, have a decreasing effectiveness as the number of loading areas increases, because it is not likely that the loading areas will be equally used. Buses may also be delayed in entering or leaving a linear loading area by buses stopped in adjacent loading areas.

- *Traffic Signal Timing.* The amount of green time provided to a street that buses operate on affects the maximum number of buses that could potentially arrive at a bus stop during an hour.

## Bus Lanes

A bus lane is any lane on a roadway in which buses may operate. It may be used exclusively by buses, or it may be shared with other traffic. The vehicle capacity of a bus lane is influenced by the capacity of the critical bus stop located along the lane, which typically is the stop with the highest volume of passenger movements. However, the critical stop might also be a stop with an insufficient number of loading areas. Bus lane capacity is also influenced by the following operational factors:

- *Bus Lane Type.* The vehicle capacity procedures define three bus lane types.[R29] *Type 1* bus lanes have no use of the adjacent lane, *Type 2* bus lanes have partial use of the adjacent lane, which is shared with other traffic, and *Type 3* bus lanes provide for exclusive use of two lanes by buses. The curb lane of Type 1 and 2 lanes may or may not be shared with other traffic. The greater the degree of exclusivity of the bus lane and the greater the number of lanes available for buses to maneuver, the greater the bus lane capacity. Bus lane types are illustrated and discussed in more detail in Chapter 4, *Exclusive Arterial Street Bus Lanes,* and in Chapter 5, *Mixed Traffic.*

- *Skip-Stop Operation.* Bus lane capacity can be increased by spreading out bus stops, so that only a portion of the routes using the bus lane stop at a particular set of stops. (Skip-stop operation is different than limited stop service, where certain buses on a particular route do not stop at selected stops.) This block skipping pattern allows for a faster trip and reduces the number of buses stopping at each bus stop, although it also increases the complexity of the bus system to new riders and may also increase passenger walking distances to bus stops. Skip-stop operation is discussed further in Chapter 2, *Operating Issues.*

- *Platooning.* When skip stops are used, forming buses into platoons at the start of the skip-stop section maximizes the efficiency of the skip-stop operation. Each platoon is assigned a group of stops in the skip-stop pattern to use. The platooned buses travel as "trains" through the skip-stop section. The number of buses in each platoon ideally should equal the number of loading areas provided at each stop used by the platoon of buses.

- *Bus Stop Location.* As discussed in the bus stop section above, far-side stops allow for the highest bus lane capacity, but other factors must also be considered when siting bus stops.

### Person Capacity

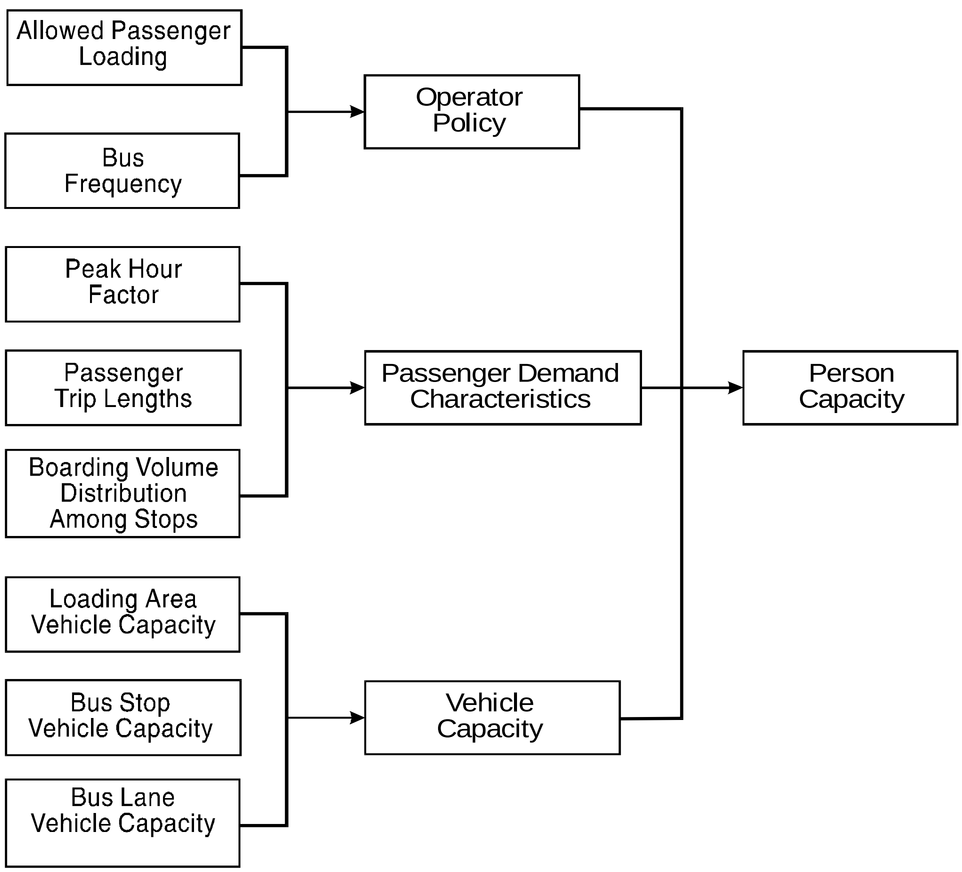
*Person capacity is commonly calculated for bus stops and for the maximum load point of a bus route or bus lane.*

Person capacity is commonly calculated for three locations:

- bus stops;
- bus routes, at the maximum load point; and
- bus lanes, at the maximum load point.

As Exhibit 2-11 shows, in addition to the factors discussed in the previous section relating to vehicle capacity, there are other factors which must be considered when calculating person capacity.

Exhibit 2-11
Person Capacity Factors



### *Operator Policy*

*Increasing the maximum allowed passenger load increases person capacity, but decreases quality of service.*

Two factors directly under the control of the bus operator are the maximum *passenger load* allowed on buses and the *service frequency*. An operator whose policy requires all passengers to be seated will have a lower potential passenger capacity for a given number of buses, than one whose policy allows standees. (The quality of service experienced by passengers, though, will be higher with the first operator.) The bus frequency determines how many passengers can actually be carried, even though a bus stop or lane may be physically capable of serving more buses than are actually scheduled.

### *Passenger Demand Characteristics*

How passenger demand is distributed spatially along a route and how it is distributed over time during the analysis period affects the number of boarding passengers that can be carried. The spatial aspect of passenger demand, in particular, is why passenger capacity must be stated *for a given location,* not for a route or a street as a whole.

During the period of an hour, passenger demand will fluctuate. The *peak hour factor* reflects passenger demand volumes over (typically) a 15-minute period during the hour. A bus system should be designed to provide sufficient capacity to accommodate this peak passenger demand. However, since this peak demand is not sustained over the entire hour and since not every bus will experience the same peak loadings, actual person capacity during the hour will be less than that calculated using peak-within-the-peak demand volumes.

The average *passenger trip length* affects how many passengers may board a bus as it travels its route. If trip lengths tend to be long (passengers board near the start of the route and alight near the end of the route), buses on that route will not board as many passengers as a route where passengers board and alight at many locations. However, the total number of passengers on board buses on each route at their respective maximum load points may be quite similar.

The *distribution of boarding passengers* among bus stops affects the dwell time at each stop. If passenger boardings are concentrated at one stop, the vehicle capacity of a bus lane will be lower, since that stop's dwell time will control the vehicle capacity (and, in turn, the person capacity) of the entire lane. Vehicle capacity (and person capacity at the maximum load point) is greater when passenger boarding volumes (and, thus, dwell times) are evenly distributed among stops.

### *Vehicle Capacity*

The vehicle capacity of various facilities used by buses—loading areas, bus stops, and bus lanes—set an upper limit to the number of passengers that may use a bus stop or may be carried past a bus route's or bus lane's maximum load point.

The relationship between the vehicle capacity of bus facilities and the elements of person capacity described above is illustrated in Exhibit 2-12:

*Bus stop and bus lane person capacities are constrained by the maximum vehicle capacities of those locations. Bus route person capacity is usually constrained by the service frequency set by the transit operator.*

Exhibit 2-12
Person Capacity Calculation Process

| | | | | | | |
|---|---|---|---|---|---|---|
| Bus Lane Vehicle Capacity | X | Allowed Passenger Loading | X | Peak Hour Factor | = | Bus Lane Person Capacity at Maximum Load Point |
| Route Frequency | X | Allowed Passenger Loading | X | Peak Hour Factor | = | Bus Route Person Capacity at Maximum Load Point |
| Bus Stop Vehicle Capacity | X | Peak 15-min Passenger Interchange Volume per Vehicle | X | Peak Hour Factor | = | Bus Stop Person Capacity |

## FUNDAMENTAL CAPACITY CALCULATIONS

Regardless of the kind of bus facility being analyzed, there are some fundamental capacity calculations common to each. This section presents these calculation procedures, which will be used throughout Chapters 3-5.

### Vehicle Capacity

#### *Dwell Time*

Three methods can be used to determine bus dwell times:

1. *Field measurements.* This method is best suited for determining the capacity of an existing bus route.
2. *Default values.* This method is best suited for future planning when reliable estimates of future passenger boarding and alighting volumes are not available.
3. *Calculation.* This method is suitable for estimating dwell times when passenger boarding and alighting counts or estimates are available.

##### *Method 1: Field Measurements*

The most accurate way to determine bus dwell times at a stop is to measure them directly. An average (mean) dwell time and its standard deviation can be determined from a series of observations. Appendix A presents a methodology for measuring bus dwell times in the field.

*Best for evaluating existing bus routes. See Appendix A for details.*

##### *Method 2: Default Values*

If field data or passenger counts are unavailable for a bus stop, the following representative values can be used to estimate dwell time: 60 seconds per CBD, transit center, major on-line transfer point, or major park-and-ride stop, 30 seconds per major outlying stop, and 15 seconds per typical outlying stop.(R20)

*Best for future planning when reliable passenger estimates are unavailable.*

##### *Method 3: Calculation*

*Suitable when passenger counts or estimates are available.*

This method requires that passenger counts or estimates be available, categorized by the number of boarding and alighting passengers.

*Step 1: Obtain hourly passenger volume estimates.* These estimates are required only for the highest-volume stops. When skip-stop operations are used, estimates are needed for the highest-volume stops in each skip-stop sequence.

*Step 2: Adjust hourly passenger volumes for peak passenger volumes.* Equation 2-1 shows the peak hour factor (PHF) calculation method. Typical peak-hour factors range from 0.60 to 0.95 for transit lines.(R9,R13) A PHF close to 1.0 may well indicate system overload (underservicing) and reveal the potential for more service. If buses operate at less than 15-minute headways, the denominator of Equation 2-1 should be adjusted appropriately (e.g., $3P_{20}$ for 20-minute headways). Equation 2-2 adjusts hourly passenger volumes to reflect peak-within-the-peak conditions.

$$PHF = \frac{P}{4P_{15}}$$

Equation 2-1

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

Equation 2-2

where:

| | | |
|---|---|---|
| *PHF* | = | peak hour factor; |
| *P* | = | passenger volume during the peak hour (p); and |
| $P_{15}$ | = | passenger volume during the peak 15 minutes (p). |

*Step 3: Determine the base passenger boarding and alighting time.* This time can be estimated using values given in Exhibit 2-13 or by using the following values for typical operating conditions—single-door loading, pay on bus:

*Boarding*
2.0 seconds pre-payment (includes bus pass, free transfer, pay-on-leave)
2.6 seconds single ticket/token
3.0 seconds exact fare
Add 0.5 seconds to the above boarding times if standees are present on the bus.

*Alighting*
1.7 to 2.0 seconds

Exhibit 2-13
Typical Bus Passenger Boarding and Alighting Service Times for Selected Bus Types and Door Configurations (Seconds per Passenger)(R4)

| Bus Type | Available Doors or Channels | | Typical Boarding Service Times [a] (s) | | Typical Alighting Service Times (s) |
|---|---|---|---|---|---|
| | 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 [d] | 1.2 | NA | 0.9 |
| | 4 | Front, Rear [f] | 0.7 | NA | 0.6 |
| Articulated | 3 | Front, Rear, Center | 0.9[f] | NA | 0.8 |
| | 2 | Rear | 1.2[g] | NA | ----- |
| | 2 | Front, Center [d] | ----- | ----- | 0.6 |
| | 6 | Front, Rear, Center [e] | 0.5 | NA | 0.4 |
| Special Single Unit | 6 | 3 Double Doors [h] | 0.5 | NA | 0.4 |

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.
[b] Also applies to pay-on-leave or free transfer situation.
[c] Not applicable with rear-door boarding. Higher end of range is for exact fare.
[d] One each.
[e] Two double doors each position.
[f] Less use of separated doors for simultaneous loading and unloading.
[g] 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.
[h] 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.

*Step 4: Adjust the passenger boarding and alighting times for special conditions.* Multiply the base boarding and/or alighting times, as appropriate, by the following factors if the corresponding condition occurs:

- Heavy two-way flow through a single door: 1.2 [R9]
- Double-stream door: 0.6 [R17,R18]
- Low-floor bus: 0.85 [R15]

*Step 5: Calculate the dwell time.* The dwell time 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 seconds for door opening and closing is reasonable for normal operations.[R4,R19] The number of boarding and alighting passengers per bus through the busiest door during the peak-within-the-peak (typically 15 minutes), $P_b$ and $P_a$, are determined by the proportions of boarding and alighting passengers per bus during the peak period.

$$t_d = P_a t_a + P_b t_b + t_{oc}$$

Equation 2-3

where:

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

#### Impact of Wheelchair Accessibility on Dwell Time

All new transit buses in the U.S. 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 seconds, while the ramps used in low-floor buses reduce the cycle times to 30 to 60 seconds (including the time required to secure the wheelchair inside the bus). The higher cycle times relate to a small 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.

#### Impact of Bicycles on Dwell Time

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 seconds. When bicycle rack usage at a stop is frequent enough to warrant special treatment, a bus' dwell time is determined using the greater of the passenger boarding/alighting time or the bicycle loading/unloading time.

### Clearance Time

*Door opening and closing time is incorporated into the dwell time, rather than the clearance time.*

Clearance time includes two components, (1) the time for a bus to start up and travel its own length while exiting a bus stop, and for off-line stops, (2) the re-entry delay associated with waiting for a sufficient gap in traffic to allow a bus to pull back into the travel lane. Various studies have evaluated these factors, either singly or as a whole. Scheel and Foote found that bus start-up times range from 2 to 5 seconds.[R30] The time for a bus to travel its own length after stopping is approximately 5 to 10 seconds, depending on acceleration and traffic conditions. TCRP Report 26 recommends a range of 10-15 seconds for clearance time.(R29)

*Clearance time is the sum of start-up and exiting time and re-entry delay.*

Start-up and exiting time may be assumed to be 10 seconds. Re-entry delay can be measured in the field or, at locations where buses re-enter a traffic stream, may be estimated from Exhibit 2-14, based on traffic volumes in the adjacent travel lane. If buses must wait for a queue from a signal to clear before they can re-enter the street, Exhibit 2-14 should not be used; instead, re-entry delay should be estimated using the average queue length (in vehicles), the saturation flow rate, and the start-up lost time.

*Exhibit 2-14 applies only to off-line stops where buses must yield to other traffic when re-entering a street, and only when the stop is located away from the influence of a queue from a signalized intersection.*

Exhibit 2-14
Average Bus Re-Entry Delay into Adjacent Traffic Stream (Random Vehicle Arrivals)

| Adjacent Lane Mixed Traffic Volume (veh) | Average Re-Entry Delay (s) |
|---|---|
| 100 | 0 |
| 200 | 1 |
| 300 | 2 |
| 400 | 3 |
| 500 | 4 |
| 600 | 5 |
| 700 | 7 |
| 800 | 9 |
| 900 | 11 |
| 1,000 | 14 |

SOURCE: Computed using 1997 HCM unsignalized intersection methodology (minor street right turn at a stop sign), assuming a critical gap of 7 seconds and random vehicle arrivals. Delay based on 12 buses stopping per hour.

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

Some states in the U.S. have passed laws requiring other traffic to yield to transit vehicles that are signaling to exit a stop. In these locations, the re-entry 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 (see Chapter 2), can also reduce or eliminate re-entry delay.

### Coefficient of Variation of Dwell Times

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

Based on field observations of bus dwell times in several U.S. cities reported in TCRP Report 26,(R29) the *coefficient of variation of dwell times* (the standard deviation of dwell times divided by the mean dwell time) typically ranges from 40% to 80%, with 60% recommended as an appropriate value in the absence of field data.

### 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. The value $Z_a$ represents the area under one "tail" of the normal curve beyond the acceptable levels of probability of a queue forming at a bus stop. Typical values of $Z_a$ for various failure rates are shown in Exhibit 2-15. A design failure rate should be chosen for use in calculating a loading area's capacity. Higher design failure rates increase bus stop capacity at the expense of schedule reliability. Capacity occurs under normal conditions at a 25% failure rate.(R9,R23)

Exhibit 2-15
Values of Percent Failure Associated With $Z_a$[R29]

| 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 design failure rates.*

Suggested values of $Z_a$ are the following:[R29]

- *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 results in queues beyond bus stops only 2.5 percent of the time. $Z_a$ values down to 1.440 are acceptable, however.

### *Loading Areas*

*Loading area vehicle capacity.*

The maximum number of buses per loading area per hour is:[R29]

$$B_{bb} = \frac{3{,}600(g/C)}{t_c + (g/C)t_d + Z_a c_v t_d}$$

Equation 2-4

where:

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

Exhibit 2-16 presents the estimated number of buses that can use a bus loading area for $g/C$ ratios of 0.5 and 1.0 (the ratio of green signal time to the total traffic signal cycle length). Values are tabulated for dwell times ranging from 15 to 120 seconds. Values for $g/C$ times between 0.5 and 1.0 can be interpolated; values for $g/C$ times less than 0.5 and for other dwell times can be computed directly from Equation 2-4. 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.[R6] These guidelines must be carefully applied to assure both good traffic and transit operations.

Exhibit 2-16
Estimated Maximum Capacity of Loading Areas (Buses/h)

| Dwell Time (s) | *g/C* = 0.5 | *g/C* = 1.0 |
|---|---|---|
| 15 | 63 | 100 |
| 30 | 43 | 63 |
| 45 | 32 | 46 |
| 60 | 26 | 36 |
| 75 | 22 | 30 |
| 90 | 19 | 25 |
| 105 | 16 | 22 |
| 120 | 15 | 20 |

NOTE: Assumes 15-second clearance time, 25% queue probability, and 60% coefficient of variation of dwell times.

### Bus Stops

As shown in Exhibit 2-17, increasing the number of loading areas at a *linear* bus stop has an ever-decreasing effect on capacity as the number of loading areas increases (doubling the number of loading areas at a linear bus stop *does not* double capacity). When more than three loading areas are required, sawtooth, pull-through, or other non-linear designs should be considered.

*Sawtooth and other non-linear designs are more effective than linear loading areas when four or five loading areas are required.*

Exhibit 2-17
Efficiency of Multiple Linear Loading Areas at Bus Stops[R19,R21,R23]

| | On-Line Loading Areas | | Off-Line Loading Areas | |
|---|---|---|---|---|
| Loading Area # | Efficiency % | # of Cumulative Effective Loading Areas | Efficiency % | # 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.

The off-line loading area efficiency factors given in Exhibit 2-17 are based on experience at the Port Authority of New York and New Jersey's Midtown Bus Terminal. The on-line loading efficiency factors are based on simulation[R23] and European experience.[R16] The exhibit suggests 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 need to be provided, since partial loading areas are never built. Once again, it should be noted that Exhibit 2-17 applies only to *linear* loading areas. All other types of multiple loading areas are 100% efficient—the number of effective loading areas equals the number of physical loading areas.

The vehicle capacity of a bus stop in buses per hour is given by Equation 2-5:

$$B_s = N_{eb} B_{bb} = N_{eb} \frac{3{,}600(g/C)}{t_c + (g/C)t_d + Z_a c_v t_d}$$

Equation 2-5

where:

$B_s$ = maximum number of buses per bus stop per hour; and

$N_{eb}$ = number of effective loading areas, from Exhibit 2-17.

Exhibit 2-18 provides estimated capacities of on-line bus stops. This exhibit shows the number of buses per hour for various numbers of loading areas, dwell times, and *g*/*C* ratios. The maximum capacities attainable are 3.0 times those of a single loading area.

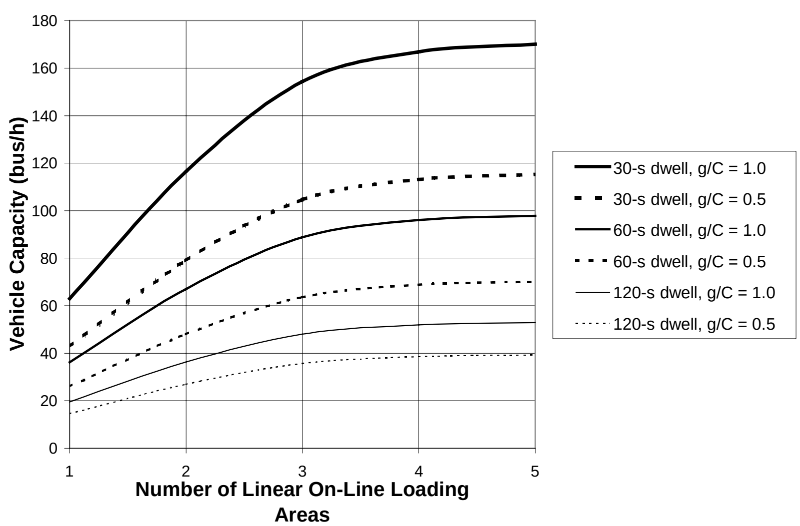
Exhibit 2-18
Estimated Maximum Capacity of On-Line Linear Bus (bus/h)

| Dwell Time (s) | Number of On-Line Linear Loading Areas | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | | 2 | | 3 | | 4 | | 5 | |
| | *g*/*C* 0.50 | *g*/*C* 1.00 | *g*/*C* 0.50 | *g*/*C* 1.00 | *g*/*C* 0.50 | *g*/*C* 1.00 | *g*/*C* 0.50 | *g*/*C* 1.00 | *g*/*C* 0.50 | *g*/*C* 1.00 |
| 30 | 43 | 63 | 79 | 117 | 105 | 154 | 113 | 167 | 115 | 170 |
| 60 | 26 | 36 | 48 | 67 | 64 | 89 | 69 | 96 | 70 | 98 |
| 90 | 19 | 25 | 35 | 47 | 46 | 62 | 49 | 67 | 50 | 69 |
| 120 | 15 | 20 | 27 | 36 | 36 | 48 | 39 | 52 | 39 | 53 |

NOTE: Assumes 15-second clearance time, 25% queue probability, and 60% coefficient of variation of dwell times. To obtain the vehicle capacity of non-linear on-line bus stops, multiply the one-loading-area values by the number of loading areas provided.

Exhibit 2-19 provides a further guide for estimating on-line linear bus stop capacity. It shows the number of buses per hour for selected dwell times and *g*/*C* ratios based on a 15-second clearance time. *Increasing the number of linear loading areas has a much smaller effect on changes in capacity than reducing dwell times.* Note that for dwell times greater than 60 seconds, the differences between a *g*/*C* of 0.5 and 1.0 are small.

Exhibit 2-19
Bus Stop Maximum Vehicle Capacity
Related to Dwell Times and Number of Loading Areas



### Bus Lanes

Bus lane vehicle capacity procedures vary, depending on the facility type. Chapters 3-5 present bus lane capacity procedures for busways and freeway HOV lanes, exclusive arterial street bus lanes, and mixed traffic situations.

## Person Capacity

### Bus Stops

The person capacity of a bus stop is related to the number of people boarding and alighting at the bus stop, which influences the vehicle capacity of the bus stop. Equation 2-6 shows this relationship:

$$P_s = B_s P_{15}$$

Equation 2-6

where:

| | | |
|---|---|---|
| $P_s$ | = | person capacity of a bus stop (p/h); |
| $B_s$ | = | vehicle capacity of the bus stop (buses/h), from Equation 2-5; and |
| $P_{15}$ | = | peak 15-minute passenger interchange per bus (p/bus). |

### Bus Routes and Bus Lanes

The person capacity of a bus route or bus lane *at its maximum load point* under prevailing conditions is determined by the allowed passenger loading set by operator policy and by the number of buses operated during the analysis period (typically one hour):

$$P_{mlp} = P_{max} f_{mlp} (PHF)$$

Equation 2-7

where:

| | | |
|---|---|---|
| $P_{mlp}$ | = | person capacity of a bus route or bus lane at its maximum load point under prevailing conditions (p/h); |
| $P_{max}$ | = | maximum allowed passenger loading per bus (p/bus); |
| $f_{mlp}$ | = | bus frequency on the route or the bus lane at its maximum load point (buses/h); and |
| $PHF$ | = | peak hour factor. |

The person capacity of a bus route or bus lane, in terms of number of boarding passengers during the analysis period, may be considerably greater than the person capacity given by Equation 2-7, if typical passenger trip lengths are short relative to the length of the bus route or bus lane.

The *maximum* person capacity of a bus lane at its maximum load point is determined by the bus lane's maximum vehicle capacity:

$$P_{mlp,max} = P_{max} B(PHF)$$

Equation 2-8

where:

| | | |
|---|---|---|
| $P_{mlp,max}$ | = | maximum person capacity of a bus route or bus lane at its maximum load point (p/h); and |
| $B$ | = | bus lane vehicle capacity (bus/h), from the appropriate Chapter 3, 4, 5 procedure. |

## PLANNING APPLICATIONS

Exhibit 2-20 summarizes the bus vehicle and person capacity factors and calculations identified in this chapter and suggests ways that each can be improved to provide additional capacity. Note that in some cases, increasing capacity requires a trade-off with decreased quality of service.

Exhibit 2-20
Factors Influencing Bus Capacity

| Item | Ways To Improve Each Item |
|---|---|
| **CAPACITY FACTORS** | |
| Dwell Time | • Greater use of pre-paid fares<br>• Use low-floor vehicles<br>• Encourage one-way door flows on two-door buses<br>• Provide multiple-stream doors for boarding and alighting<br>• Increase bus frequency to reduce the number of standees<br>• Implement proof-of-payment fare collection |
| Clearance Time | • Use on-line stops*<br>• Enact and enforce laws that require cars to yield to buses re-entering a street<br>• Implement queue jumps at traffic signals |
| Coefficient of Variation | • Generally constant for a given area |
| Failure Rate | • Increase the number of loading areas at a stop<br>• Schedule fewer buses per hour using the stop** |
| **CALCULATED RESULTS** | |
| Loading Area Capacity | • Reduce dwell time<br>• Implement transit priority treatments<br>• Increase the accepted failure rate* |
| Bus Stop Capacity | • Increase loading area capacity<br>• Use off-line loading areas*<br>• Use sawtooth or pull-through loading areas<br>• Increase the number of loading areas |
| Bus Lane Capacity | • Increase the capacity of the critical stop<br>• Reserve lanes for buses<br>• Platoon buses<br>• Implement skip-stop operation<br>• Prohibit right turns by automobiles |
| Bus Speeds | • Reduce dwell time<br>• Implement transit preferential treatments<br>• Balance the number of stops with passenger convenience and demand<br>• Implement skip-stop operation |

*Measures that may negatively affect other items in the list if implemented.
**Measure that improves the failure rate, but decreases capacity.

The observed peak-hour bus movements along freeways and city streets, and to or from bus terminals provide guidelines for estimating the capacity of similar facilities. They also provide means of checking or verifying more detailed capacity calculations. General guidelines for planning purposes follow:

*Roadway bus capacity.*

Suggested arterial street bus service volume varies based on actual operating experience. Suggested service volumes are given in Exhibit 2-21. This table gives representative service volumes for downtown streets and arterial streets leading to the city center for each level of service. Where stops are not heavily patronized, as along outlying arterial streets, volumes could be increased by about 25 percent.

*These service volumes may be used for planning purposes. More precise values for operations and design purposes should be computed from the capacity relationships and procedures presented later in Part 2.*

*The values for forced flow conditions should not be used for planning or design. They are merely given for comparative purposes.*

Exhibit 2-21
Suggested Bus Flow Service Volumes for Planning Purposes
(Flow Rates For Exclusive or Near-Exclusive Lane)(R12,R14)

| Description | Service Volume bus/lane/h | Average bus/lane/h |
|---|---|---|
| **ARTERIAL STREETS** | | |
| Free Flow | 25 or less | 15 |
| Stable Flow, Unconstrained | 26 to 45 | 35 |
| Stable Flow, Interference | 46 to 75 | 60 |
| Stable Flow, Some Platooning | 76 to 105 | 90 |
| Unstable Flow, Queuing | 106 to 135 | 120 |
| Forced Flow, Poor Operation | over 135* | 150* |
| **CBD STREETS** | | |
| Free Flow | 20 or less | 15 |
| Stable Flow, Unconstrained | 21 to 40 | 30 |
| Stable Flow, Interference | 41 to 60 | 50 |
| Stable Flow, Some Platooning | 61 to 80 | 70 |
| Unstable Flow, Queuing | 81 to 100 | 90 |
| Forced Flow, Poor Operation | over 100* | 110* |

*Results in more than one-lane operation.

*Person capacity.*

The people per hour that can be served by varying bus flow rates and passenger load factors are given in Exhibit 2-22. This table provides a broad person-capacity planning guide assuming that key boarding points are sufficiently dispersed to achieve these bus loads. It suggests *maximum* person-flow rates of about 6,450 people per hour per lane on downtown streets and 8,700 people per hour per lane on arterial streets. Corresponding maximum values for *seated* passenger flow rates are 4,300 and 5,800 people respectively. Exclusive use of articulated buses would increase these values by 15 to 20 percent.

Exhibit 2-22
Maximum Bus Passenger Service Volumes For Planning Purposes
(Hourly Flow Rates Based on 43 Seats Per Bus)

| Buses per Hour | Passengers/Seat | | | | |
|---|---|---|---|---|---|
| | 0.00-0.50 | 0.51-0.75 | 0.76-1.00 | 1.01-1.25 | 1.26-1.50 |
| **ARTERIAL STREETS** | | | | | |
| 25 or less | 535 | 805 | 1,075 | 1,340 | 1,610 |
| 26 to 45 | 965 | 1,450 | 1,935 | 2,415 | 2,900 |
| 46 to 75 | 1,610 | 2,415 | 3,225 | 4,030 | 4,835 |
| 76 to 105 | 2,255 | 3,385 | 4,515 | 5,640 | 6,770 |
| 106 to 135 | 2,900 | 4,350 | 5,805 | 7,255 | 8,705 |
| **CBD STREETS** | | | | | |
| 20 or less | 430 | 645 | 860 | 1,075 | 1,290 |
| 21 to 40 | 860 | 1,290 | 1,720 | 2,150 | 2,580 |
| 41 to 60 | 1,290 | 1,935 | 2,580 | 3,225 | 3,870 |
| 61 to 80 | 1,720 | 2,580 | 3,440 | 4,300 | 5,160 |
| 81 to 100 | 2,150 | 3,225 | 4,300 | 5,375 | 6,450 |

*Peak-hour factor.*

These person-flow rates indicate the number of people that can be carried, assuming uniform flow during the peak hour. Appropriate peak hour factors should be used to discount these values to reflect flow variations within the 15-minute peak period.

# 2. OPERATING ISSUES

## INTRODUCTION

This chapter presents operating issues that influence the results of the capacity procedures presented in the remainder of Part 2. Factors under the direct control of bus operators are the allowed passenger loads on a bus and whether or not a skip-stop pattern is used on streets with high bus volumes. Bus preferential treatments at intersections and on roadway segments, in order to be implemented, require the cooperation of bus operators and the agencies responsible for streets and roads.

## BUS OPERATIONS

### Passenger Loads

From a *capacity* perspective, the allowed passenger load on a bus (set by policy) constrains the number of people that a given number of buses can carry. From a *passenger*'s perspective, loading reflects the comfort level of the on-board portion of a bus trip—both in terms of being able to find a seat and in overall crowding levels within the bus. From a *transit operator*'s perspective, liability concerns and the desire to provide every customer with a seat for high-speed or long-distance services may cause the operator to set the allowed loading at levels lower than what riders might tolerate.

The impacts of all three of these perspectives on transit capacity are addressed in this section. The quality of service impacts of passenger loading are addressed in Part 5 of this manual.

#### *Guidelines*

*Load factor.*

The *passenger load* is simply the number of passengers on a single transit vehicle. Much work uses the occupancy of the vehicle relative 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 service. In general, bus transit provides load factors below 1.0 for long-distance commute trips and high-speed, mixed-traffic operations. Inner-city service can approach a load factor of 2.0 (but more typically 1.5), while other services are in between. Typical bus vehicle types, dimensions, and passenger capacities are given in Exhibit 2-23.

*An alternative table using U.S. customary units appears in Appendix B.*

Exhibit 2-23
Characteristics of Bus Transit Vehicles—United States and Canada

| Bus Type | Length (m) | Width (m) | Typical Capacity: Seats | Standees | Total |
|---|---|---|---|---|---|
| Small Bus/Minibus | 5.6-9.1 | 2.0-2.4 | 8-30 | 0-10 | 8-40 |
| Transit Bus | 10.7 | 2.4-2.6 | 30-35 | 20-30 | 50-60 |
| | 12.2 | 2.6 | 35-50 | 30-40 | 65-75 |
| (low floor) | 12.2 | 2.4 | 30-40 | 25-40 | 55-70 |
| (articulated) | 18.3 | 2.4-2.6 | 65 | 55 | 120 |

NOTE: In any transit vehicle, the total passenger capacity can be increased by removing seats and by making more standing room available; however, this lowers the passengers' quality of service. The upper ends of the total capacity ranges represent crush capacity and should not be used for transit capacity calculations.

A typical 12-meter (40-foot) urban transit bus can normally seat 43 passengers and can carry up to 37 additional standees if all of the aisle circulation space is filled. Similarly, an 18-meter (60-foot) articulated bus can carry 65 seated passengers and 55 standees. However, bus operator policy often limits the number of standees to levels below this theoretically offered, or *crush capacity.*

*Maximum schedule loads.*

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 a bus' seating capacity (e.g., 54-64 passengers on a typical 12-meter or 40-foot bus).

*Crush loads.*

Crush loads, typically loads above 150 percent of a bus' 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 and so 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, due to 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. Part 5 addresses the quality of service aspects of passenger loading. For buses, comfortable loading for design should provide at least 0.50 $m^2$/passenger (5.4 $ft^2$/p) and maximum schedule loads should provide a minimum of 0.40 $m^2$/p (4.3 $ft^2$/p), where relatively short trips allow standees.[R9] The "comfortable loading" figure provides a reasonable balance between operating economy and passenger comfort and is consistent with the value suggested by Pushkarev and Zupan for a realistic passenger capacity for rapid transit lines.[R27] However, high-speed express bus service should not allow standees; hence, their scheduling should be guided by the number of seats provided.

## Skip-Stop Operation

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

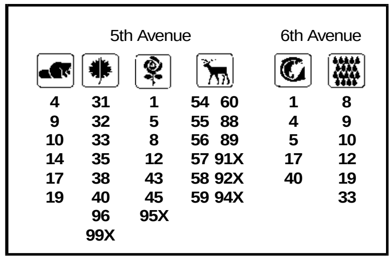
Many large transit systems have instituted two- or three-block stop patterns for bus stops along arterial streets. This block skipping pattern allows for a faster trip through the section and reduces the number of buses stopping at each bus stop.

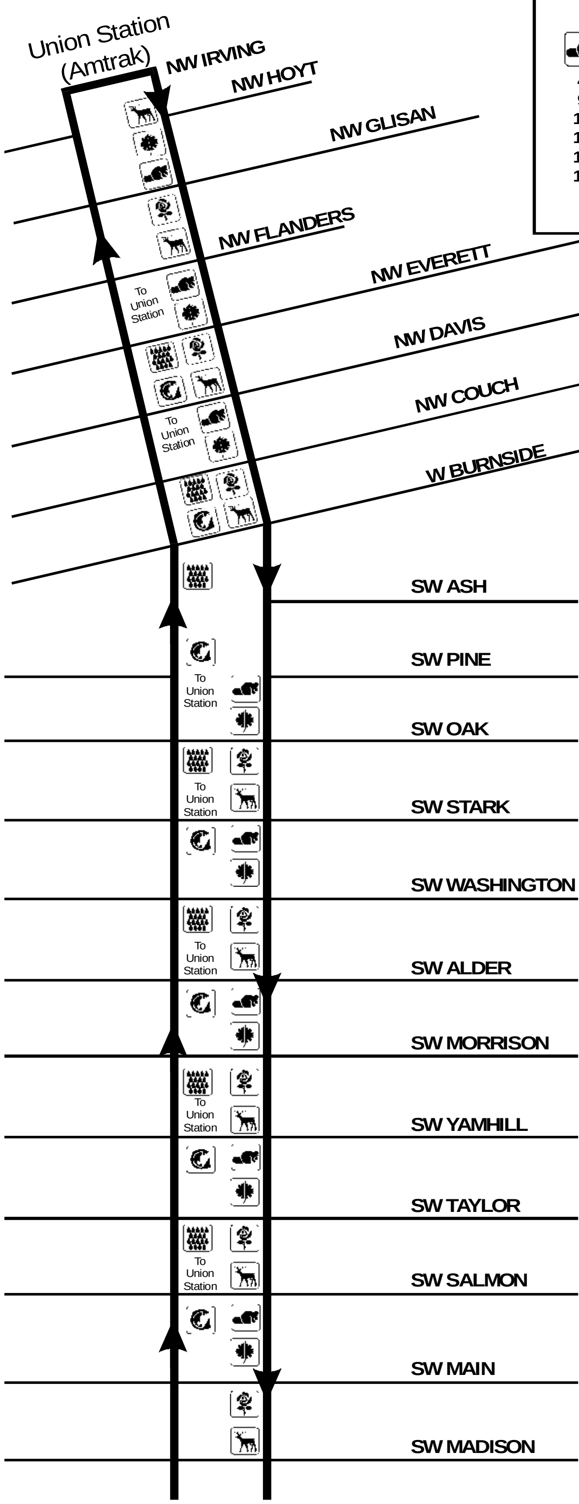
Exhibit 2-24 illustrates the skip-stop pattern used by Tri-Met in Portland, Oregon on its Fifth and Sixth Avenue Transit Mall in 1997. Each street uses a repeating pattern of three or four bus stops. Each bus stop contains two loading areas. All routes headed for a particular portion of the metropolitan area use a particular set of stops, which are designated by a colored symbol (for example, a brown beaver) on bus stop signs, bus schedules, and maps. As shown in Exhibit 2-24, other bus stop signing systems can also be used, such as Denver's "X-Y-Z" system.

*Capacity adjustment for the availability of the adjacent lane.*

These alternate block stopping patterns enable the bus lane capacity to nearly equal the sum of the capacities of the stops involved. Thus an arterial with an alternate 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 may not always be possible because of the irregularity of bus arrivals and traffic control delays. (To effectively double the capacity of a segment with a 3-bus loading area capacity at each stop by instituting a two-block A-B stop pattern, three A-pattern buses must arrive at the upstream entry to the section during one signal cycle, followed by three B-pattern buses.) Buses alternating stops must also be able to utilize the adjacent traffic lane to bypass stopped buses. They may be impeded in this maneuver when the adjacent lane operates at or near capacity.

Exhibit 2-24
Example Skip-Stop Pattern and Bus Stop Signing
Portland, Oregon 5th and 6th Avenue Bus Mall





*The Portland 5th and 6th Avenue Bus Mall is depicted on the map (1997 configuration). All buses heading to a particular portion of the Portland area use the same stop, which is indicated by a colored symbol on maps and bus stops, such as the "orange deer" pictured.*

*Local buses stop every two blocks, with four sets of stops southbound on Fifth Avenue (two in each block) and three sets of stops northbound on Sixth Avenue. Express buses (routes ending in "X") stop every four blocks.*

*The number of buses using the "orange deer" stops decreased in the fall of 1998, following the opening of the Westside MAX light rail extension, which replaced many of the routes using those stops.*

*Other systems for designating bus stops in a skip-stop sequence are also possible, such as Denver's X-Y-Z system pictured to the left.*

## ROADWAY OPERATIONS

Much attention has been paid to expediting transit flow by providing various forms of priority treatment. Such treatments are aimed at improving schedule adherence and reducing travel times and delays for transit users. They may attract new riders, increase transit capacity, and/or improve the transit quality of service.

Successful priority measures are usually characterized by:

- an intensively developed downtown area with limited street capacity and high all-day parking costs,
- a long-term reliance on public transport,
- highway capacity limitations on the approaches to downtown,
- major water barriers that limit road access to the CBD and channel bus flows,
- fast non-stop bus runs for considerable distances,
- bus priorities on approaches to or across water barriers,
- special bus distribution within the CBD (often off-street terminals), and
- active traffic management, maintenance, operations, and enforcement programs.(R21)

### Bus Preferential Treatments at Intersections

When buses operate in mixed traffic, as is typical, the interference caused by general traffic decreases bus speeds and lowers overall bus vehicle and person capacity. The bus preferential treatments described in this section compensate for these interferences by removing or reducing sources of delay, resulting in increased bus speeds. When considering implementing bus preferential treatments, the total change in person-delay (including both passengers in buses and motorists) should be taken into account.

#### *Signal Priority*

Bus signal priority measures include *passive* systems, pre-timed modifications to the signal system adjusted manually to determine the best transit benefit while minimizing the impact to other vehicles, and *active* systems, which adjust the signal timing after sensing the arrival of a bus. Exhibit 2-25 lists common bus signal priority systems.

Exhibit 2-25
Bus Signal Priority Systems(R1)

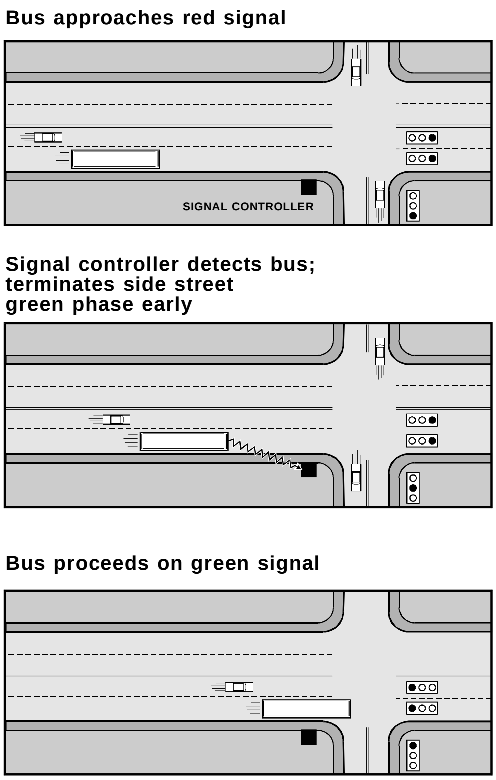
| Treatment | Description |
|---|---|
| **Passive Priority** | |
| Adjust cycle length | Reduce cycle lengths at isolated intersections. |
| Split phases | Apply multiple phases while maintaining original cycle length. |
| Areawide timing plans | Preferential progression for buses through signal offsets. |
| Bypass metered signals | Buses use special reserved lanes, special signal phases, or are rerouted to non-metered signals. |
| **Active Priority*** | |
| Phase extension | Increase phase time. |
| Early start | Reduce other phase times. |
| Special phase | Addition of a bus phase. |
| Phase suppression | Skipped non-priority phases. |
| Preemption (Unconditional) | Bus phase begins when all other intervals are satisfied. |
| Preemption (Conditional) | Same as above except certain conditions are used to determine when the bus phase should begin. |

*Occurs after bus detection.

Active priority should only be implemented at intersections operating at less than capacity, so that the changes to signal timing that occur each time a bus passes through the intersection do not significantly worsen the intersection's level of service. Automated systems that do not require bus driver intervention are preferable, as bus drivers may not always remember to activate the system at the intersections equipped with signal priority equipment. When coupled with two-way data communication and automatic vehicle location (AVL) equipment, on-bus signal priority systems can be set to activate signal priority only when a bus is behind schedule.(R3)

Exhibit 2-26 illustrates one way that active signal priority can be implemented. Streetside equipment can detect the bus (for example, using a transponder) or bus-mounted equipment can transmit a request for priority to the signal controller.

Exhibit 2-26
Bus Signal Priority Concept(R3)




### *Queue Jump*

Queue jump treatments allow buses to avoid long queues of vehicles at signalized intersections by using right-turn lanes or long off-line bus stops to move past much of the queue. Buses are exempted from any right-turn requirements at the intersection.

A special right-lane signal provides a green indication for a brief period of time before the adjacent regular traffic lanes. During this time, the bus exits the right lane and merges into the lane to the left ahead of the other traffic that had stopped for the signal. Alternatively, the bus pulls into the right lane on a red signal and proceeds to a far-side off-line bus stop on green, resulting in reduced delay waiting for the queue in the regular lanes to clear the intersection. Exhibit 2-27 illustrates a typical queue jump design, while Exhibit 2-28 shows an actual application of a queue jump. In Exhibit 2-28, the bus receives priority from a bus lane that ends at a near-side bus stop at the intersection. In this application, a special transit signal (the vertical bar indication adjacent to the regular traffic signal) is used to give the bus priority, rather than a regular traffic signal.

Exhibit 2-27
Bus Queue Jump Concept

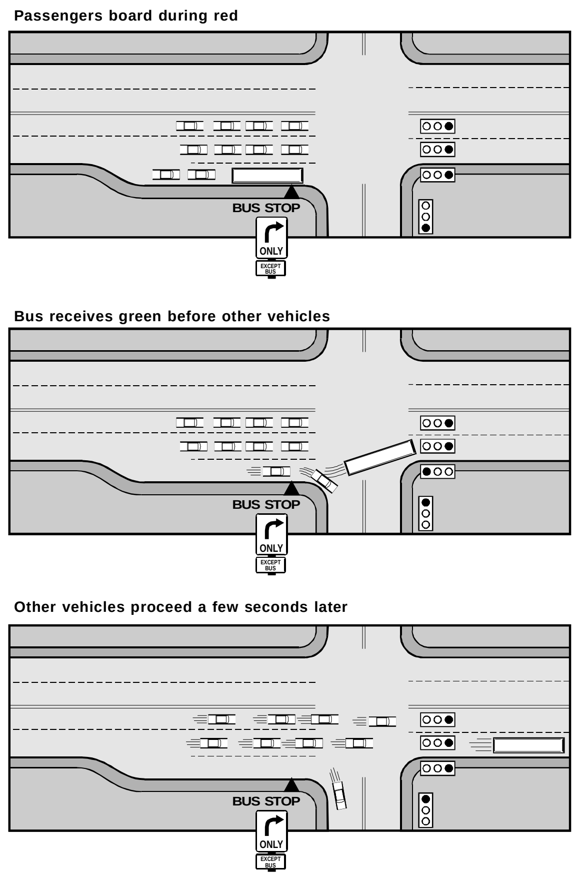


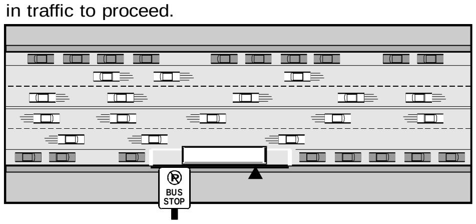

Exhibit 2-28
Bus Queue Jump Example (Copenhagen, Denmark)

### *Curb Extensions*

Where streets have curbside parking and high traffic volumes, it may not be desirable for a bus to pull to the curb to stop, because of the delays involved in waiting for a sufficiently large gap in traffic that will allow the bus to pull back into the travel lane. In these situations, the curb can be extended into the parking lane to allow buses to stop in the travel lane to pick up and discharge passengers. The additional area curbside can be used to provide an ADA-compliant clear area to load and unload wheelchair passengers, to provide a bus shelter in a location that otherwise would not have enough space, and to provide more room for passengers to stand while waiting for the bus. Curb extensions can also create more on-street parking, as the area prior to the bus stop previously used by buses to pull to the curb can now be used for additional parking. At intersections, curb extensions also benefit all pedestrians by reducing the street width that must be crossed. If bicycle lanes exist, they may need to be routed around the curb extension, creating potential bicycle/pedestrian conflicts. Exhibit 2-29 and Exhibit 2-30 illustrate the use of curb extensions.

Exhibit 2-29
Curb Extension Concept(R3)

**Before**
Bus pulls to curb at bus stop: must wait for gap in traffic to proceed.




**After**
Curb extended into parking lane, bus stops in travel lane; more curbside parking available.

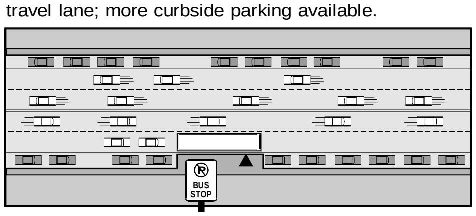


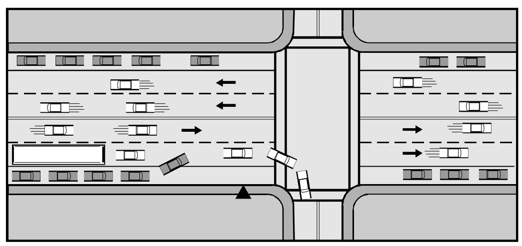

Exhibit 2-30
Curb Extension Example (Vienna, Austria)

### Boarding Islands

Where significant parking activity, stopped delivery vehicles, heavy right-turning traffic volumes and other interferences slow traffic in the right lane of a street with multiple lanes in the same direction, buses may be able to travel faster in the lane to the left. Boarding islands allow bus stops to be located between travel lanes so that buses can use a faster lane without having to merge into the right lane before every stop. Pedestrian safety issues must be addressed when considering the use of boarding islands. Exhibit 2-31 and Exhibit 2-32 illustrate the concept and application of this treatment.

Exhibit 2-31
Boarding Island Concept(R3)

**Before**
Traffic congestion in curb lane due to parking and turning maneuvers.



**After**
Bus travels in faster lane, passengers load and unload at boarding island.

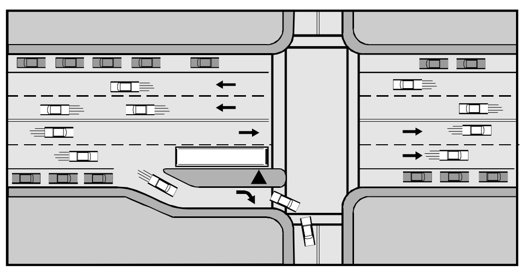


Exhibit 2-32
Boarding Island Example (San Francisco)

### Other Measures

Other transit preferential treatments at intersections include the following:[R3]

- **Parking Restrictions.** These are used in areas where high parking turnover interferes with the flow of traffic on a street. Restricting parking will improve transit and traffic flow, but the impacts to adjacent land uses from the loss of on-street parking must also be considered. Parking restrictions are sometimes applied during peak hours only, often in conjunction with bus lane operations.
- **Bus Stop Relocation.** On streets with good traffic signal progression for passenger vehicles, moving a bus stop from the near-side of an intersection to the far-side (or vice versa) may allow buses to use the signal timing to their advantage, passing through intersections on a green signal and dwelling on a red signal.
- **Turn Restriction Exemptions.** The most direct route for a bus may not be possible because of left-turn restrictions at intersections, particularly where there is insufficient room to develop left-turn lanes. If the restriction is due to traffic congestion, rather than safety, it may be feasible to exempt buses from the restriction without unduly impacting intersection operations.

## Bus Preferential Treatments on Roadway Segments

### Arterial Bus Lanes

Where there is a relatively high volume of buses operating on a roadway, coupled with a high degree of bus and automobile congestion, exclusive bus lanes may be considered to provide more attractive and reliable bus service. Most bus lanes take the form of reserved bus lanes on city streets, usually in the same direction as the general traffic flow. There are a number of bus-only streets, such as Denver's 16th Street, Portland's Fifth and Sixth Avenue Transit Mall, and Vancouver's Granville Mall. Contraflow center lanes in Montréal, with center median waiting, are unusual but have been successful.

Policy and cost considerations generally set the lower limit for bus volumes that warrant priority treatments on arterials, while bus vehicle capacity sets the upper limit. A study of bus operations in Manhattan recommended the following desirable maximum a.m. peak hour bus volumes for arterial street bus lanes:[R22]

- Two lanes exclusively for buses: 180 buses/hour
- One lane exclusively for buses, partial use of adjacent lane: 100 buses/hour
- One lane exclusively for buses, no use of adjacent lane: 70 buses/hour
- Buses in curb lane in mixed traffic: 60 buses/hour

Exhibit 2-33 presents general planning guidelines for bus priority treatments on arterial streets. A comparison of person volumes on buses operating in mixed traffic with person volumes in other vehicles operating on the street can also be used to help decide when to dedicate one or more lanes to exclusive bus use.

Exhibit 2-33
General Planning Guidelines for Bus Priority Treatments—Arterials[R21,R31]

| Treatment | Minimum One-Way Peak Hour Bus Volumes | Minimum One-Way Peak Hour Passenger Volumes | Related Land Use and Transportation Factors |
|---|---|---|---|
| Bus Streets or Malls | 80-100 | 3,200-4,000 | Commercially oriented frontage. |
| CBD curb bus lanes, main street | 50-80 | 2,000-3,200 | Commercially oriented frontage. |
| Curb bus lanes, normal flow | 30-40 | 1,200-1,600 | At least 2 lanes available for other traffic in same direction. |
| Median bus lanes | 60-90 | 2,400-3,600 | At least 2 lanes available for other traffic in same direction; ability to separate vehicular turn conflicts from buses. |
| Contraflow bus lanes, short segments | 20-30 | 800-1,200 | Allow buses to proceed on normal route, turnaround, or bypass congestion on bridge approach. |
| Contraflow bus lanes, extended | 40-60 | 1,600-2,400 | At least 2 lanes available for other traffic in opposite direction. Signal spacing greater than 150-meter (500-foot) intervals. |
| Bus preemption of traffic signals | 10-15 | 400-600 | Wherever not constrained by pedestrian clearance or signal network constraints. |
| Special bus signals and signal phase, bus-activated | 5-10 | 200-400 | At access points to bus lanes, busways, or terminals; or where special bus turning movements must be accommodated. |
| Special bus turn provisions | 5-10 | 200-400 | Wherever vehicular turn prohibitions are located along routes. |

### *Busways and Freeway HOV Lanes*

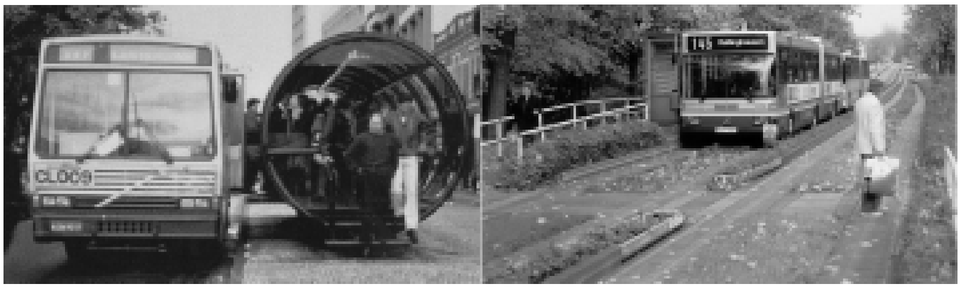
In North America, busways and reserved lanes on freeways are mainly found in larger cities, usually with a large downtown employment and heavy peak-hour bus ridership. However, busways have found wide application internationally as a substitute for or supplement to rail systems.

Brazil (Curitiba and São Paulo) has pioneered efficient busways with high-level, pre-paid stations, as shown in Exhibit 2-34. Dwell times are similar to rail transit, resulting in higher average speeds and higher vehicle utilization. Bi-articulated buses capable of carrying up to 270 passengers are operated on the city's five express busways. Larger terminals located at the termini of the busways, and smaller terminals located approximately every 2 km (1.2 mi) along the busways, provide transfer opportunities to inter-district and local feeder buses. These terminals are also pre-paid areas, so passengers do not have to pay a separate fare or show a fare receipt when transferring between buses, similar to a transfer station on a rail transit system.

Curitiba's distinctive high-level "tube stations" are equipped with wheelchair lifts, allowing passengers in wheelchairs to roll directly onto the bus when it arrives. Passengers pay an attendant at the tube station when they enter, so that no fares need be collected on-board the bus.[R24,R28]

Essen, Germany and Adelaide, Australia are among the few cities to date worldwide that have developed guided busways, which allow buses to operate in narrower rights-of-way and require less steering on the part of the driver. An extra set of wheels provides lateral guidance for the bus, as shown in Exhibit 2-34. One advantage of the lateral guidance is that only the wheel tracks need be paved, allowing a grass strip to be planted in the middle of the lane, improving the lane's aesthetics.

Exhibit 2-34
International Busway Examples



High-Level (Curitiba, Brazil) Guided Busway (Essen, Germany)

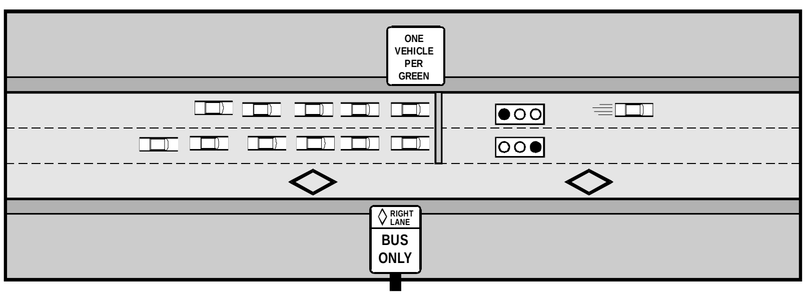
### *Queue Bypasses*

*Queue bypasses.*

Queue bypasses are a form of priority treatment that allow buses to avoid queues of vehicles (such as those that develop at freeway ramp meters) by providing a special lane that avoids the queue. Exhibit 2-35 depicts a typical queue bypass design on a freeway on-ramp and Exhibit 2-36 shows an actual application.

Exhibit 2-35
Freeway Ramp Queue Bypass Concept

**Cars queue at ramp meter**




**Bypass lane allows bus to avoid queue**

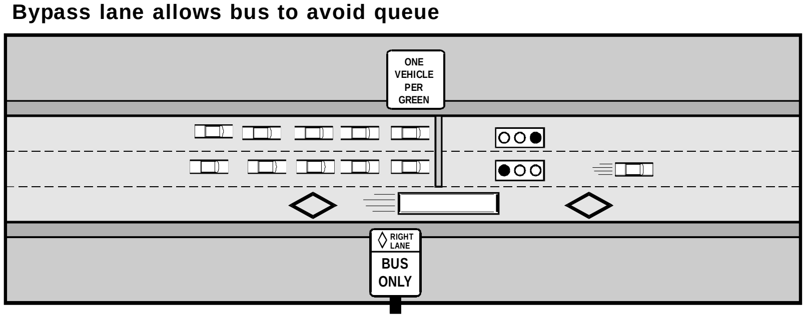


Exhibit 2-36
Freeway Ramp Queue Bypass Example (Los Angeles)


As with arterial street bus lanes, policy and cost considerations usually dictate the lower limit for bus volumes that warrant busway or freeway HOV lane treatments. Lower minimum vehicle thresholds can be expected, and are usually accepted, with busways than with HOV lanes; however, the minimum vehicle threshold may be higher in a heavily congested corridor than in one with lower levels of congestion. Non-users in heavily congested areas may be much more vocal about a facility they feel is under-utilized than commuters in a corridor where congestion is not at serious levels. Whenever considering providing busway or HOV facilities, the perceptions of commuters and the public, as well as any unique local conditions, should be considered when developing minimum operating thresholds.(R31)

Exhibit 2-37 presents typical minimum freeway HOV lane operating thresholds in vehicles per hour per lane, based on U.S. experience.

Exhibit 2-37
Typical Busway and HOV Lane Minimum Operating Thresholds (veh/h/lane) (R31)

| **Facility Type** | **Minimum Operating Threshold** |
|---|---|
| Separate right-of-way, HOV | 800-1,000 |
| Freeway, exclusive two-directional | 400-800 |
| Freeway, exclusive reversible | 400-800 |
| Freeway, concurrent flow | 400-800 |
| Freeway, contraflow HOV | 400-800 |
| HOV queue bypass lanes | 100-200 |

Exhibit 2-38 presents general planning guidelines for busways and bus priority treatments associated with freeways. For more information on busway and freeway HOV facility planning guidelines, design and operation, consult the *HOV Systems Manual*,(R31) published by TRB.

Exhibit 2-38
General Planning Guidelines for Bus Priority Treatments—Freeways[R21]

| Treatment | Minimum One-Way Peak Hour Bus Volumes | Minimum One-Way Peak Hour Passenger Volumes | Related Land Use and Transportation Factors |
|---|---|---|---|
| Busways on special right-of-way | 40-60 | 1,600-2,400 | Urban population: 750,000; CBD employment: 50,000; 1.85 million $m^2$ CBD floor space; congestion in corridor; save buses 0.6 min/km (1 min/mi) or more. |
| Busways within freeway right-of-way | 40-60 | 1,600-2,400 | Freeways in corridor experience peak-hour congestion; save buses 0.6 min/km (1 min/mi) or more. |
| Busways on railroad right-of-way | 40-60 | 1,600-2,400 | Potentially not well located in relation to service area. Stations required. |
| Freeway bus lanes, normal flow | 60-90 | 2,400-3,600 | Applicable upstream from lane drop. Bus passenger time savings should exceed other road user delays. Normally achieved by adding a lane. Save buses 0.6 min/km (1 min/mi) or more. |
| Freeway bus lanes, contraflow | 40-60 | 1,600-2,400 | Freeways with six or more lanes. Imbalance in traffic volumes permits freeway LOS D in off-peak travel direction. Save buses 0.6 min/km (1 min/mi) or more. |
| Bus lane bypasses at toll plazas | 20-30 | 800-1,200 | Adequate reservoir on approach to toll plaza. |
| Exclusive bus access to non-reserved freeway or arterial lane | 10-15 | 400-600 | |
| Bus bypass lane at metered freeway ramp | 10-15 | 400-600 | Alternate surface street route available for metered traffic. Express buses leave freeways to make intermediate stops. |
| Bus stops along freeways | 5-10 | 50-100* | Generally provided at surface street level in conjunction with metered ramp. |

*Boarding or alighting passengers in the peak hour.

## Person Delay Considerations

*The net change in person delay is an important factor to consider before implementing transit priority measures.*

In many cases, providing transit priority treatments involves tradeoffs among the various users of a roadway facility. Providing a bus queue jump at a traffic signal, for example, provides a time-savings benefit for bus passengers, while causing additional delay for motorists, their passengers, bicyclists, and some pedestrians. When considering implementing transit priority treatments, one factor to consider should be the net change in person delay to all roadway users as a result of the priority treatment. Of course, other factors, such as cost, change in transit quality of service, and local policies encouraging greater transit use should also be considered. An example problem in Chapter 8 illustrates how to evaluate the net change in person delay resulting from implementing a transit signal priority measure.

## Roadway Operations Summary

Exhibit 2-39 summarizes the advantages and disadvantages of the transit preferential treatments presented in this chapter.

Exhibit 2-39
Bus Preferential Treatments Comparison(R3)

| Treatment | Advantages | Disadvantages |
|---|---|---|
| Signal Priority | • Reduces control delay<br>• Improves reliability | • Risks interrupting coordinated traffic signal operation<br>• Risks lowering intersection LOS, if intersection is close to capacity<br>• Requires on-going inter-jurisdiction coordination<br>• Buses on the cross-street may experience added delay greater than the time saved by the favored routes |
| Queue Bypass | • Reduces delay from queues at ramp meters or other locations | • Bus lane must be available and longer than the back of queue |
| Queue Jump | • Reduces delay due to queues at signals<br>• Buses can leap-frog stopped traffic | • Right lane must be available and longer than the back of queue<br>• Special transit signal required<br>• Reduces green time available to other intersection traffic<br>• Bus drivers must be alert for the short period of priority green time |
| Curb Extensions | • Reduces delay due to merging back into traffic<br>• Increases riding comfort because buses don't need to pull in and out of stops<br>• Increases on-street parking by eliminating need for taper associated with bus pullouts<br>• Increases space for bus stop amenities<br>• Reduces pedestrian street crossing distances | • Requires at least two travel lanes in bus' direction of travel to avoid blocking traffic while passengers board and alight<br>• Bicycle lanes require special consideration |
| Boarding Islands | • Increases bus speed by allowing buses to use faster-moving left lane | • Requires at least two travel lanes in bus' direction of travel and a significant speed difference between the two lanes<br>• Requires more right-of-way than other treatments<br>• Pedestrian and ADA accessibility, comfort, and safety issues must be carefully considered |
| Parking Restrictions | • Increases bus speed by removing delays caused by automobile parking maneuvers<br>• Increases street capacity and reduces traffic delays | • May significantly impact adjacent land uses (both business and residential)<br>• Requires on-going enforcement |
| Bus Stop Relocation | • Uses existing signal progression to bus' advantage | • May increase walking distance for passengers transferring to a cross-street bus |
| Turn Restriction Exemption | • Reduces travel time by eliminating need for detours to avoid turn restrictions | • Potentially lowers intersection level of service<br>• Safety issues must be carefully considered |
| Exclusive Bus Lanes | • Increases bus speed by reducing sources of delay<br>• Improves reliability<br>• Increases transit visibility | • Traffic/parking effects of eliminating an existing travel or parking lane must be carefully considered<br>• Requires on-going enforcement |

# 3. BUSWAYS AND FREEWAY HOV LANES

## INTRODUCTION

This chapter presents methodologies for analyzing the operation of buses using busways and freeway HOV lanes. *Busways* are characterized by (1) uninterrupted flow, (2) exclusive use by buses, and (3) lanes separated from other traffic. Some facilities called "busways," such as the South Miami Busway, have interrupted traffic flow due to traffic signals and should be treated as exclusive arterial street bus lanes. Bus stops, if any, along the facility are either located off-line or a passing lane is provided at the stop. Exhibit 2-40 presents examples of North American busways. *High-occupancy vehicle (HOV) lanes* are not necessarily separated from other traffic and may allow passenger vehicles with a designated number of occupants (typically 2 or 3) to use the lanes (See examples in Exhibit 2-41).

*Busways are characterized by at least one separated lane reserved exclusively for buses, and uninterrupted flow.*

*Bus facilities with interrupted flow are treated as exclusive arterial street bus lanes and are addressed in Chapter 4.*

Exhibit 2-40
Busway Examples

Ottawa

Pittsburgh

Seattle Bus Tunnel

Dallas (Southwestern Medical Center)

Exhibit 2-41
Freeway HOV Lane Examples

Shirley Highway, Virginia

New Jersey (Lincoln Tunnel approach)

## CALCULATING VEHICLE CAPACITY

### Freeway HOV Lanes

Freeway HOV lanes are designed to increase the potential person-capacity of a freeway by reserving one or more lanes, either part-time or full-time, for the use of vehicles with multiple 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 to persons driving alone.

In order to maintain this time-savings incentive (and to continue to move more people through the freeway segment than would be possible without the HOV lane), HOV lanes should not operate at or near capacity. The level of service provided to persons traveling in an HOV lane should be better during peak periods than the level of service provided to vehicles traveling in the regular freeway lanes. This level of service can be calculated using the procedures given in the HCM chapters related to freeways.

Calculating the theoretical bus capacity, or *service volume*, for freeway HOV lanes used exclusively by buses is not practical because (1) no North American transit agency schedules so many buses as to come close to the bus vehicle capacity of a basic freeway segment, and (2) the number of buses that can actually be scheduled along a freeway will be constrained by the vehicle capacity of the off-line bus stops along the HOV lane section or by the bus stops located after the end of the HOV lane. For example, the maximum number of buses using an exclusive bus lane in North America, 735 buses per hour, is achieved through an a.m. peak hour contraflow lane serving the Lincoln Tunnel in New York, with no stops along the lane, and with an 210-berth bus terminal to receive these and other buses.[R23]

### Busways

Exclusive busway vehicle and person capacity can be computed using appropriate assumptions regarding the type of bus used, maximum allowable bus loading, the distribution of ridership among CBD stops, the peak hour factor, and the type of loading area.

*Exclusive busways with a limited number of CBD stops have passenger distribution characteristics similar to subways.*

If the busway extends into the CBD (for example, the Seattle Bus Tunnel) and has a limited number of stations in the downtown area, the busway's passenger distribution characteristics will be similar to those of a subway or other rail line. A reasonable design assumption is that 50 percent of the maximum load point volume is served at the heaviest CBD busway station—assuming a minimum of three stops in the downtown area. (For comparison, the Washington-State Street subway station in Chicago accounts for about half of all boarding passengers at the three CBD stops on the State Street subway line.)

Peak hour factors of 0.67 to 0.75 are reasonable for busways, depending on the location and type of operation.

Illustrative CBD busway vehicle and person capacities are given in Exhibit 2-42 for a variety of bus types and service conditions. The key assumptions are:

- Fares are pre-paid at CBD busway stations. This allows all doors to be used for loading, which greatly decreases the service time per passenger, since several passengers can board at the same time.
- Fifty percent of the maximum load point passengers board at the heaviest stop. A peak hour factor of 0.67 is assumed.
- No delays due to signals (grade-separated busway).
- The bus clearance time at stops is 10 seconds. The design failure rate is 7.5% and a 60% coefficient of variation is assumed.

- Three linear loading areas are provided at each station.
- The maximum load point passenger volume is limited to 40 passengers per bus for standard buses and 60 passengers per bus for articulated buses; this corresponds to a load factor of approximately 1.00 and provides a seat for all passengers.

Exhibit 2-42
Illustrative CBD Busway Capacities

| | **Loading Condition** | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | **A** | | **B** | | **C** | | **D** | |
| **Stations: On-Line/Off-Line** | **On** | **Off** | **On** | **Off** | **On** | **Off** | **On** | **Off** |
| *Passengers boarding at heaviest station* | | | | | | | | |
| Boarding passengers per bus | 20 | 20 | 20 | 20 | 20 | 20 | 30 | 30 |
| Boarding time per passenger (s) | 2.0 | 2.0 | 1.2 | 1.2 | 0.7 | 0.7 | 0.5 | 0.5 |
| Dwell time (s) | 40.0 | 40.0 | 24.0 | 24.0 | 14.0 | 14.0 | 15.0 | 15.0 |
| *Vehicle Capacity* | | | | | | | | |
| Loading area capacity (bus/h) | 42 | 42 | 65 | 65 | 100 | 100 | 95 | 95 |
| Effective loading areas | 2.45 | 2.60 | 2.45 | 2.60 | 2.45 | 2.60 | 2.45 | 2.60 |
| Station capacity (bus/h) | 103 | 109 | 159 | 169 | 245 | 260 | 233 | 247 |
| *Passengers/hour—maximum load point* | | | | | | | | |
| Peak—flow rate (15 min x 4) | 4,120 | 4,360 | 6,360 | 6,760 | 9,800 | 10,400 | 13,980 | 14,820 |
| Average—peak hour (with PHF) | 2,760 | 2,920 | 4,260 | 4,530 | 6,570 | 6,970 | 9,370 | 9,930 |

Loading condition A: Single-door conventional bus, simultaneous loading and unloading.
Loading condition B: Two-door conventional bus, both doors loading or double-stream doors simultaneously loading and unloading.
Loading condition C: Four-door conventional bus, all double-stream doors loading.
Loading condition D: Six-door articulated bus, all doors loading.

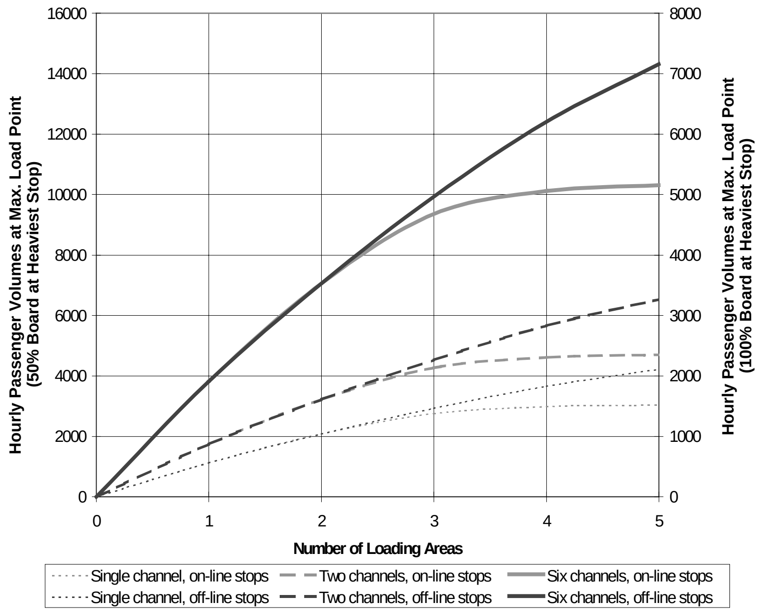
NOTE: Assumes 10-second clearance time, 7.5% failure rate, 60% coefficient of variation, 3 linear loading areas, $g/C$ = 1.0, PHF = 0.67, 50% of passengers board at heaviest CBD station, 40 seats per conventional bus, 60 seats per articulated bus, no standees allowed.

## CALCULATING PERSON CAPACITY

The theoretical person capacity of a busway or HOV lane at its maximum load point may be computed by multiplying the number of each type of vehicle per hour by the number of seats available per vehicle, times a peak hour factor. High-speed bus service on busways and HOV lanes should not allow standees, so capacity calculations should assume that every passenger may be seated. Exhibit 2-42 provides illustrative busway person capacities at the busway's maximum load point.

Exhibit 2-43 shows how the door configuration and number of loading areas increase the maximum load point capacity. The left vertical scale applies to through-station operations where 50 percent of all passengers board at the heaviest stop. The right vertical scale applies to a single-station situation where all riders board at the major stop, such as at a CBD bus terminal. 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. It can be seen that increasing the number of doors available for boarding (e.g., by using pre-paid fares at busway stations or through use of smart card technology) greatly increases a busway's person capacity.

Exhibit 2-43
Typical Busway Line-Haul Passenger Volumes




NOTE: PHF = 0.67. Six-channel configurations assume 60-passenger articulated buses.

## CALCULATING SPEED

The average speed of a bus operating on a busway or freeway HOV lane depends on three factors:

1. the running speed of the bus in the lane;
2. bus stop spacing; and
3. dwell time at bus stops.

The *Highway Capacity Manual* 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. (Note that this estimated speed assumes that the lane is operating below capacity.) 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 deceleration and acceleration into and out of stops. A rate of 1.2 m/s$^2$ (4.0 ft/s$^2$) may be assumed for an acceleration and deceleration rate, in the absence of local data.[R29] Exhibit 2-44 presents average travel speeds for a selection of running speeds, dwell times, and 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 2-44
Estimated Average Speeds of Buses Operating in Freeway HOV Lanes (km/h)

| 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: Assumes constant 1.2 $m/s^2$ acceleration/deceleration rate.

*An alternative table using U.S. customary units appears in Appendix B.*

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# 4. EXCLUSIVE ARTERIAL STREET BUS LANES

## INTRODUCTION

This chapter presents methodologies for analyzing the operation of buses using exclusive arterial street bus lanes. The key characteristics of this kind of facility are (1) at least one lane reserved exclusively for use by buses (except possibly at intersections), and (2) interrupted flow. Freeway HOV lanes are discussed in Chapter 6 and mixed-traffic situations are discussed in Chapter 7.

*Exclusive arterial street bus lanes are characterized by at least one lane exclusively for buses (except possibly at intersections) and interrupted flow.*

## BUS LANE TYPES

The vehicle capacity procedures used in this chapter define three types of bus lanes. The availability of the adjacent lane for buses to pass other buses, right-turn queues, or other bus lane obstructions is the main difference among the three types of bus lanes.

*Bus lane types described.*

*Type 1* exclusive bus lanes have no use of the adjacent lane; for example, contraflow lane and physically channelized lanes. Exhibit 2-45 depicts Type 1 exclusive bus lanes.

*Type 2* exclusive bus lanes have partial use of the adjacent lane, depending on the use of this lane by other traffic. Right turns may or may not be prohibited. Exhibit 2-46 shows examples of Type 2 exclusive bus lanes.

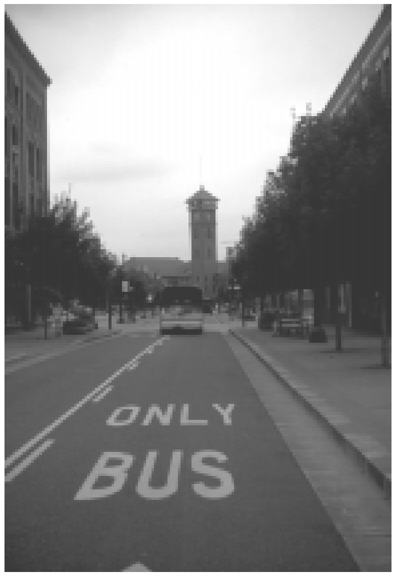
*Type 3* exclusive bus lanes (dual bus lanes) have full use of the adjacent lane, with only occasional use by authorized vehicles other than buses, and right turns are prohibited. Exhibit 2-47 illustrates Type 3 exclusive bus lanes. Single bus lanes with off-line stops and right-turn prohibitions are also considered Type 3 bus lanes, as buses have an unimpeded opportunity to pass stopped buses.

Exhibit 2-45
Type 1 Exclusive Bus Lane Examples

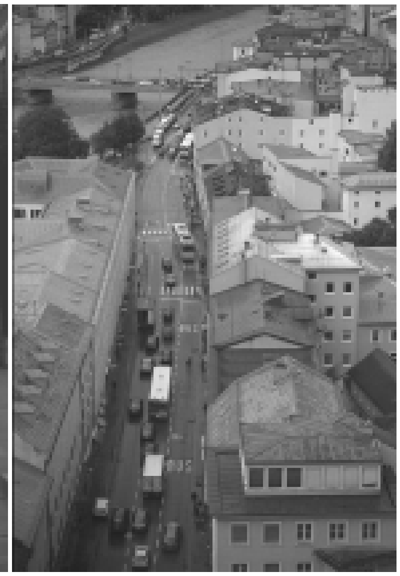
Denver (16th Street Mall)

Los Angeles

Exhibit 2-46
Type 2 Exclusive Bus Lane Examples




Portland, OR



Salzburg, Austria

Exhibit 2-47
Type 3 Exclusive Bus Lane Examples


New York

Miami (single lane with off-line stops)

## CALCULATING VEHICLE CAPACITY

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

- the bus lane type;
- whether or not skip-stop operation is used;
- whether or not buses using the lane are organized into platoons;
- the 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-stops, are used and if right turns are prohibited by non-transit vehicles, then the bus lane vehicle capacity is simply the vehicle capacity of the critical bus stop along the bus lane. However, when skip stops are used or when right turns are allowed, then adjustments must be made to this base vehicle capacity, as described in the following sections.

### Effects of Right Turns

*Capacity adjustment for the 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 (as in Houston) some right turns are made from the adjacent lane. The right turns may queue behind buses at a near-side bus stop to make a right turn. Conversely, right-turning traffic may block buses or preempt signal green time from them. 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 mid-block—can also influence the amount of delay induced by, and to, the right-turning traffic.

The conflicts between buses and right turns are greatest where there is a near-side stop and buses are unable to freely use the bus lane. Automobiles turning right may block access to the bus stop; conversely, buses boarding or discharging passengers on the green signal indication may block right turns. The amount of interference diminishes as the distance between the stop line and bus stop increases. Far-side or mid-block stops therefore minimize the effects of right turns on bus speeds, when buses can use the adjacent lane. Placing stops at locations where there are no right turns can further minimize impacts. Right turns are usually prohibited with dual or contra-flow bus lanes.

Just as right turns across bus lanes can delay buses along the arterial, pedestrians crossing side streets next to the bus lane can cause delays to the right-turning vehicles. This, in turn, can cause increased delays to buses in the bus lane. The delays introduced by pedestrians are concentrated at the beginning of the signal green interval for bus movement on the arterial, when queued groups of pedestrians step off of the curb.

By crossing or utilizing space in the bus lane to execute their turn, right-turning vehicles reduce the bus lane vehicle capacity by preempting a portion of the green time available to buses. Thus, bus lane vehicle capacity will be approached more quickly when right turns occur. For bus volumes at less than half of the bus lane vehicle capacity, there is generally little impact on the resulting speed of bus operations from a moderate volume of right turns unless pedestrian volumes are very heavy. Procedures for estimating the capacity of right turns are given in the *Highway Capacity Manual*.

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 from Equation 2-9:[R29]

*Right turn adjustment factor.*

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

Equation 2-9

where:

$f_r$ = right turn adjustment factor;
$f_l$ = bus stop location factor, from Exhibit 2-48;
$v_r$ = volume of right turns at specific intersection; and
$c_r$ = capacity of right turns at specific intersection.

Suggested factors for the bus stop location factor, $f_l$, are shown in Exhibit 2-48. 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, as right turns are not allowed by non-transit vehicles from this type of bus lane. These factors reflect the likely ability of buses to move around right turns. Note that at critical intersections on some bus lanes all turns can be prohibited and pedestrian walk signals delayed.

*Bus stop location factor.*

Exhibit 2-48
Bus Stop Location Factors, $f_l$ [R29]

| Bus Stop Location | Bus Lane Type | | |
|---|---|---|---|
| | **Type 1** | **Type 2** | **Type 3** |
| Near-side | 1.0 | 0.9 | 0.0 |
| Mid-block | 0.9 | 0.7 | 0.0 |
| Far-side | 0.8 | 0.5 | 0.0 |

NOTE: $f_l$ = 0.0 for contra-flow bus lanes and median bus lanes, regardless of bus stop location or bus lane type, as right turns are either prohibited or do not interfere with bus operations.

### Skip-Stop Adjustment Factor

The total number of buses per hour that can be accommodated by a series of split stops represents the sum of the capacities of bus routes using each stop, multiplied by a impedance factor, $f_k$, reflecting non-platooned arrivals and the effects of high volumes of vehicular traffic in the adjacent lane. Equation 2-10 represents the factors that impede buses from fully utilizing the added capacity provided by skip-stop operations.[R29]

*Impedance factor.*

$$f_k = \frac{1 + Ka(N_s - 1)}{N_s}$$

Equation 2-10

where:

$K$ = adjustment factor for the ability to fully utilize the 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 2-11; and
$N_s$ = number of alternating skip-stops in sequence.

Adjacent lane impedance factor.

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

Equation 2-11

where:
$v$ = traffic volumes in the adjacent lane (veh/h); and
$c$ = capacity of the 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 non-stopping buses have zero dwell time at the stop. When there is no spreading of stops, there is no increase in capacity rendered by the adjacent lane.

Exhibit 2-49 gives representative values for the capacity adjustment 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 2-50 gives factors for a Type 2 bus lane with two-block alternating stops. In general, the traffic impacts of the adjacent lane only become significant when that lane operates above 75% of its capacity.

Exhibit 2-49
Typical Values of Adjustment Factor, $f_k$, for Availability of Adjacent Lanes(R29)

| Condition | 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* | 1 | 0.50 | 0.55 |
| Alternating 2-block stops, typical | 0 | 1 | 1 | 0.75 | 0.88 |
| | 1 | 0.2* | 1 | 0.75 | 0.58 |
| Alternating 2-block stops, platooned | 0 | 1 | 1 | 1.00 | 1.00 |
| | 1 | 0.2* | 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 |

*approximate

Exhibit 2-50
Values of Adjustment Factor, $f_k$, for Type 2 Bus Lanes
with Alternate Two-Block Skip Stops(R29)

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

## Vehicle Capacity

The adjustment factors for skip-stop operations and right-turn impacts define the following equations for estimating exclusive arterial street bus lane vehicle capacity:

Exclusive arterial bus lane vehicle capacity.

non-skip-stop operation: $$B = B_1 = B_{bb} N_{eb} f_r$$

Equation 2-12

skip-stop operation: $$B = f_k (B_1 + B_2 + \ldots + B_n)$$

Equation 2-13

where:

| | | |
|---|---|---|
| $B$ | = | bus lane vehicle capacity (buses/h); |
| $B_{bb}$ | = | bus loading area vehicle capacity at the critical bus stop (buses/h); |
| $N_{eb}$ | = | number of effective loading areas at the critical bus stop; |
| $f_r$ | = | capacity adjustment factor for right turns at the 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, as either dwell times or right-turning volume may control.

The capacities $B_1$, $B_2$, etc. used in Equation 2-13 are calculated separately for each set of routes using Equation 2-12. When determining the critical stop(s), several bus stops may have to be tested to determine which one controls the bus lane's vehicle capacity, as one stop may have high dwell times, but another may have severe right-turning traffic interferences.

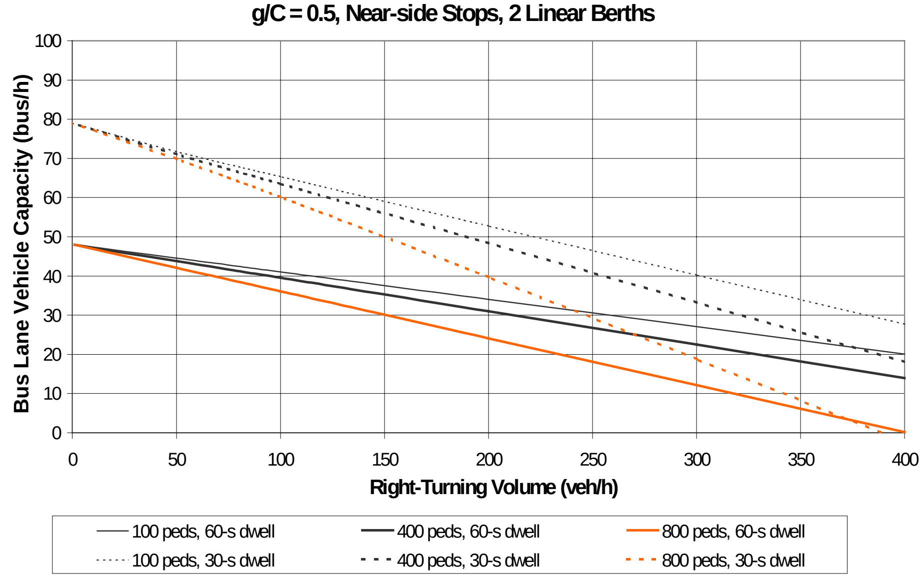
Because of the large number of factors involved, it is not possible to develop summary tables of exclusive bus lane vehicle capacity that cover a comprehensive range of situations. However, it is possible to illustrate the magnitude of the influence of certain factors on bus lane vehicle capacity.

Exhibit 2-51 illustrates the effects of dwell time, right-turning volume from the bus lane, and conflicting pedestrian volumes on bus lane vehicle capacity. It assumes 20 buses scheduled per hour that all use the same stop, conflicting pedestrian volumes ranging from 100-800 per hour, dwell times of 30-60 seconds, and right-turning volumes of 0-400 vehicles, as well as various other assumptions (held constant) that are listed in the exhibit.

It can be seen that as dwell time decreases, bus vehicle capacity increases. Conflicting pedestrian volumes under 200 per hour have little effect on bus vehicle capacity, but have substantial effects at higher conflicting volumes, especially as right-turning volumes increase. However, when right-turn conflicts do not exist, conflicting pedestrian volumes have no impact on vehicle capacity, and the lines for a given dwell time converge to a single point. It can also be seen that the lines for a given pedestrian volume converge towards a point where the right-turn capacity is exceeded and the bus lane vehicle capacity drops to zero. Between these two extremes, bus vehicle capacity steadily declines as right-turning volumes increase until a point is reached where the bus demand volumes exceed the bus lane vehicle capacity.

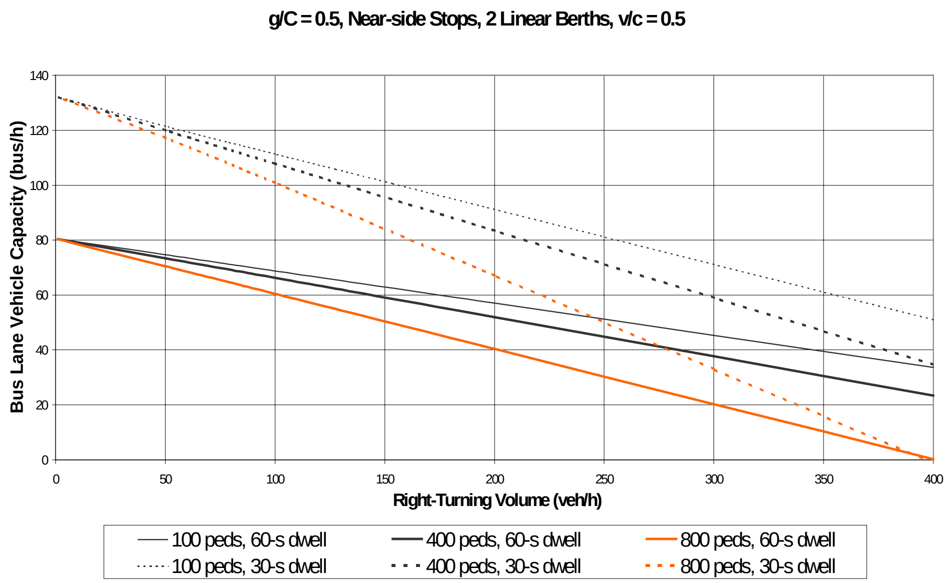
Exhibit 2-52 illustrates the same situations, except that the 20 buses per hour employ a two-stop skip-stop operation, and the adjacent lane is assumed to have a $v/c$ ratio of 0.5. For a given right-turning volume, the corresponding bus lane vehicle capacity is about 67% higher than if skip stops were not used.

Exhibit 2-51
Illustrative Exclusive Bus Lane Vehicle Capacity: Non-Skip Stop Operation




NOTE: Assumes 15-second clearance time, 25% queue probability, 60% coefficient of variation of dwell times, permitted right-turn signal phasing, shared right-turn lane, and bus volumes minimal in relation to right-turn volumes ($P_{RT}$ = 1.0).

Exhibit 2-52
Illustrative Exclusive Bus Lane Vehicle Capacity: Skip-Stop Operation




NOTE: Assumes 15-second clearance time, 25% queue probability, 60% coefficient of variation of dwell times, permitted right-turn signal phasing, shared right-turn lane, and bus volumes minimal in relation to right-turn volumes ($P_{RT}$ = 1.0).

### Bus Effects on Passenger Vehicle Capacity in an Adjacent Lane

The introduction of single or dual bus lanes reduces a roadway's vehicle capacity for other traffic. The extent of this reduction is determined by (1) the bus lane type, (2) the number of buses using the bus lane, and (3) whether or not the bus lane replaces a curb parking lane.

The following impacts are associated with the provision of a single or dual bus lane:(R29)

- If the lane is already used primarily by buses, the vehicle capacity loss will be relatively small. However, when the lane is introduced for relatively low existing bus flows (i.e., fewer than 40 buses per hour), the reduction in vehicle capacity could be as much as 30-50% of one travel lane.
- Introducing a single dedicated curb lane for buses onto a street with no previous bus operations reduces the street vehicle capacity by one lane if buses stay in the lane (Type 1) and right turns are prohibited or made from the second lane. Allowing right turns from a Type 1 bus lane reduces street vehicle capacity by less than one full lane.
- A dual bus lane (Type 3) reduces arterial vehicle capacity by up to two lanes. Because dual lanes usually would be implemented when buses already preempt most of the curb lane, the actual capacity reduction in arterial traffic would be less. The Madison Avenue dual bus lane experience in New York indicates that prohibiting right turns, eliminating weaving movements, and strict enforcement of regulations actually increased general traffic flow and speeds over what was experienced with an existing Type 2 bus lane.
- The effects of a Type 2 bus lane where buses may enter the adjacent lane will be between those of the Type 1 and Type 3 lanes. For low bus volumes, buses entering the mixed traffic lane would have little effect on the capacity of the mixed traffic lane. As bus volumes in a Type 2 lane increase, their impact on the adjacent lane increases to a point where some traffic is discouraged from using the adjacent lane. The passenger vehicle equivalency of a bus traveling without stops is estimated in the *Highway Capacity Manual* at 1.5-2.0 passenger vehicles. However, for Type 2 bus lanes, merging, weaving, and diverging maneuvers could raise this equivalency to 3-4 or more.

The effects of bus lane operations on the adjacent general travel lane can be expressed by multiplying the adjacent lane's vehicle capacity by the adjustment factor given in Equation 2-14, derived from simulation.(R29) 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 an adjacent lane.*

$$f_p = 1 - \left( 4 \frac{N_p}{3600} \right)$$

Equation 2-14

where:

$f_p$ = bus-passing activity factor; and

$N_p$ = number of buses making the maneuver from the curb lane to the adjacent lane, from Equation 2-15.

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[(R29)] 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 by the following relationship:

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

Equation 2-15

where:

| | | |
|---|---|---|
| $N_s$ | = | number of stops skipped; |
| $v_b$ | = | volume of buses in the bus lane; and |
| $c_b$ | = | bus vehicle capacity of the bus lane. |

As expressed in this equation, 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.

## CALCULATING PERSON CAPACITY

The person capacity at the maximum load point of an arterial street bus lane can be determined by multiplying the bus lane vehicle capacity given by Equation 2-12 or Equation 2-13, as appropriate, by the allowed passenger loading on-board an individual bus, times a peak hour factor.

*Bus lane person capacity at the maximum load point is the bus lane vehicle capacity times the allowed passenger loading times the peak hour factor.*

## CALCULATING SPEED

The best way to determine bus travel speeds is to measure them directly. When this is not possible (for example, when planning future service), speeds can be estimated by (1) driving the route making an average number of stops with simulated dwells, making two or three runs during peak and off-peak times, (2) scheduling buses based on similar routes and adjusting running times as needed based on the operating experience, or (3) using the analytical method described below to estimate speeds.

*Bus speeds are best measured directly or estimated based on local conditions and operating experience.*

Bus speeds on an exclusive arterial street bus lane are influenced by bus stop spacing, dwell times, delays due to traffic signals and right-turning traffic, skip-stop operations, and interferences between buses operating in the lane. These factors are reflected in Equation 2-16. A base bus speed is determined from Exhibit 2-53, which includes the effects of stop spacing, dwell times, and traffic and control delays. The base speed is then modified by adjustment factors accounting for skip-stop operations and bus-bus interferences. These factors are described below.

Bus travel speed calculation

$$V_t = V_0 \, f_s \, f_b$$

Equation 2-16

where:

| | | |
|---|---|---|
| $V_t$ | = | travel speed (km/h or mph); |
| $V_0$ | = | base bus speed (km/h or mph), from Exhibit 2-53 or Appendix B; |
| $f_s$ | = | skip-stop operation adjustment factor, from Equation 2-17; and |
| $f_b$ | = | bus-bus interference adjustment factor, from Exhibit 2-55. |

### Base Bus Speeds

Base bus speed, $V_0$

Exhibit 2-53 provides estimates of base bus speeds on arterial street bus lanes, $V_0$, as a function of stop spacing, average dwell time, and typical traffic signal and right-turn delays, based on field measurements. The exhibit provides data for each of the following situations:

- *Without Traffic Delays.* An exclusive bus lane operating without either signal or traffic delays. The only source of delay is dwell time at stops.
- *Single Normal Flow Bus Lanes.* A single lane exclusive bus lane located along the right curb. Separate values are shown for CBD, central city, and suburban areas, representing different assumed delays per kilometer (mile) due to signal and traffic delays. If the capacity analysis included capacity reductions due to right-turn delays, the dual/contraflow lanes column should be used instead.
- *Dual/Contraflow Bus Lanes.* Either (1) two exclusive bus lanes located adjacent to the right curb, or (2) a *contraflow* lane that operates opposite the normal traffic flow on one-way streets, without vehicle or turning conflicts. The speeds shown in this column include control delays only.

### Right Turn Delays

Right turns from a bus lane can adversely affect bus speeds, especially where both right turns and pedestrian volumes are heavy. These impacts are greatest for near-side stops where buses and turning traffic compete for the same roadway space. These impacts are included in a general way in Exhibit 2-53 for single normal flow bus lanes. These values may be used where buses stop every block and where conflicting right turn impacts are generally light. However, both the bus-bus interference and skip-stop speed adjustment factors, introduced below, include a vehicle capacity component and thus may already reflect the impacts of right turns. *Therefore, the dual flow column should be used for the basic speed estimate when the vehicle capacity adjustment factors have been applied to the calculation of vehicle capacity.*

### Skip-Stop Operations

The analytical method intrinsically accounts for skip-stop operations by considering only the bus stops in the skip-stop pattern. For example, if bus stops are located at each intersection, 125 meters (400 feet) apart, the two-block skip-stop distance is 250 meters (800 feet). Thus, a bus with a two-block stop pattern can proceed along the arterial at about twice the speed of a one-block stop pattern, and a three-block stop pattern at about three times the speed, assuming uniform block distances and dwell times.

Exhibit 2-53
Estimated Arterial Street Bus Speeds, $V_0$ (km/h)[R29]

*An alternative table using U.S. customary units appears in Appendix B.*

| Stops/ km | Without Traffic Delays [a] Delay: 0 min/km | Single Normal Flow Bus Lanes [b] CBD Delay: 1.2 min/km | Central City Delay: 0.4 min/km | Suburbs Delay: 0.3 min/km | Dual/Contraflow Bus Lanes [c] Delay: 0.7 min/km |
|---|---|---|---|---|---|
| **10-second dwell time** | | | | | |
| 1.2 | 40.2 | 21.9 | 32.2 | 33.3 | 26.2 |
| 2.5 | 29.5 | 18.3 | 24.9 | 25.6 | 21.6 |
| 3.7 | 23.0 | 15.6 | 20.1 | 20.6 | 17.5 |
| 5.0 | 18.2 | 13.2 | 16.3 | 16.6 | 14.8 |
| 6.2 | 13.8 | 10.8 | 12.6 | 12.9 | 11.7 |
| **20-second dwell time** | | | | | |
| 1.2 | 35.4 | 20.4 | 29.0 | 29.9 | 24.6 |
| 2.5 | 24.6 | 16.3 | 21.2 | 21.7 | 18.8 |
| 3.7 | 18.5 | 13.4 | 16.6 | 16.9 | 14.8 |
| 5.0 | 14.5 | 11.1 | 13.4 | 13.5 | 12.2 |
| 6.2 | 11.1 | 9.0 | 10.5 | 10.5 | 9.8 |
| **30-second dwell time** | | | | | |
| 1.2 | 31.4 | 19.0 | 26.2 | 27.0 | 22.5 |
| 2.5 | 20.9 | 17.2 | 18.5 | 19.0 | 16.6 |
| 3.7 | 15.6 | 11.7 | 14.2 | 14.5 | 12.9 |
| 5.0 | 12.1 | 9.7 | 11.3 | 11.3 | 10.5 |
| 6.2 | 9.3 | 7.9 | 8.9 | 8.9 | 8.4 |
| **40-second dwell time** | | | | | |
| 1.2 | 28.3 | 17.9 | 24.1 | 24.8 | 20.9 |
| 2.5 | 18.3 | 13.4 | 16.4 | 16.7 | 15.0 |
| 3.7 | 13.4 | 10.5 | 12.4 | 12.6 | 11.4 |
| 5.0 | 10.3 | 8.5 | 9.7 | 9.8 | 9.2 |
| 6.2 | 8.0 | 6.9 | 7.7 | 7.7 | 7.2 |
| **50-second dwell time** | | | | | |
| 1.2 | 25.7 | 16.9 | 22.2 | 22.9 | 19.5 |
| 2.5 | 16.3 | 12.2 | 14.8 | 15.0 | 13.5 |
| 3.7 | 11.7 | 9.5 | 10.9 | 11.1 | 10.1 |
| 5.0 | 9.0 | 7.6 | 8.5 | 8.7 | 8.2 |
| 6.2 | 7.1 | 6.1 | 6.8 | 6.8 | 6.4 |
| **60-second dwell time** | | | | | |
| 1.2 | 23.7 | 15.9 | 20.6 | 21.1 | 28.3 |
| 2.5 | 14.6 | 11.3 | 13.5 | 13.7 | 12.4 |
| 3.7 | 10.5 | 8.7 | 9.8 | 10.0 | 9.2 |
| 5.0 | 8.0 | 6.9 | 7.7 | 7.7 | 7.2 |
| 6.2 | 6.3 | 5.6 | 6.1 | 6.1 | 5.8 |

NOTE: Data based on field measurements. Traffic delays shown reflect peak conditions. Dwell times are average dwell times.
[a] Without traffic or control delays.
[b] Includes signal and right-turn delays.
[c] Includes control delay. This column should also be used for single normal-flow bus lanes where the capacity analysis includes deductions for right-turn interferences.

For alternating skip-stop patterns, 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 three-fold 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 possible, the bus speed will be somewhere in between.

*Skip stop speed adjustment factor, $f_s$.*

Equation 2-17 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.[R29]

$$f_s = 1 - \left(\frac{d_1}{d_2}\right)\left(\frac{v}{c}\right)^2\left(\frac{v_b}{c_b}\right)$$

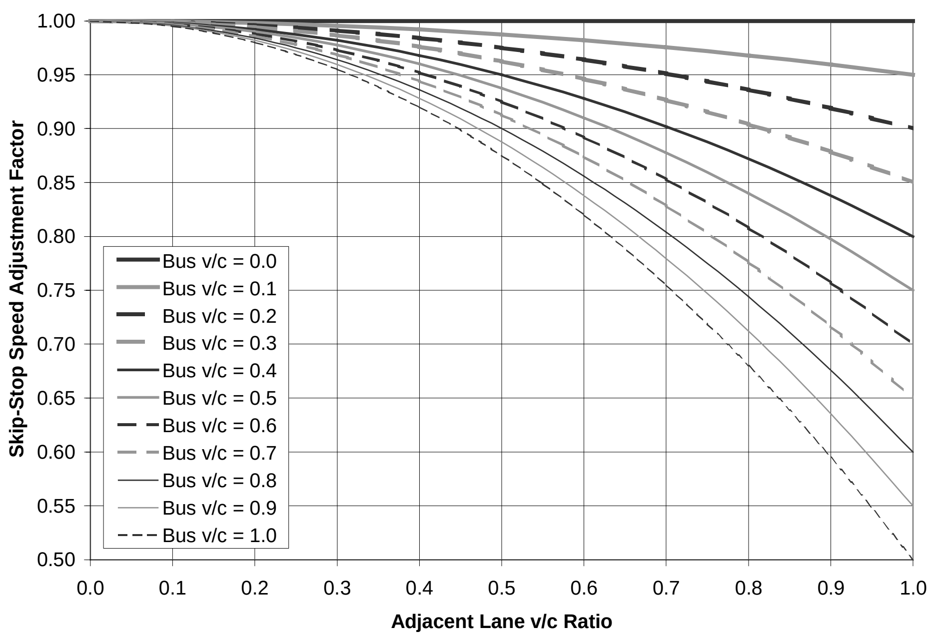
Equation 2-17

where:

| | | |
|---|---|---|
| $f_s$ | = | skip-stop speed adjustment factor; |
| $d_1$ | = | distance for one-block stop pattern (m or ft); |
| $d_2$ | = | distance for multiple-block stop pattern (m or ft); |
| $v$ | = | volume in adjacent lane (veh/h); |
| $c$ | = | vehicular capacity of adjacent lane (veh/h); |
| $v_b$ | = | bus volume in bus lane (buses/h); and |
| $c_b$ | = | capacity of single bus lane (buses/h). |

Exhibit 2-54 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% of the bus lane capacity, the effect on bus speeds is minimal, 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.

Exhibit 2-54
Illustrative Skip-Stop Speed Adjustment Effects




NOTE: Assumes two-block skip-stop pattern.

### Bus-Bus Interference

Speed adjustment factor for bus volumes, $f_b$.

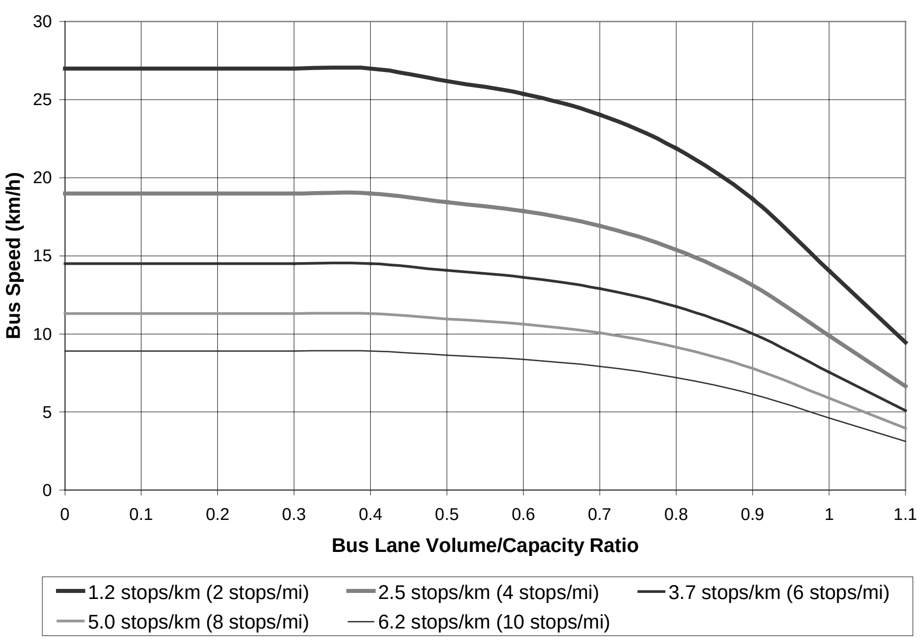
Bus speeds within a bus lane along an arterial street decline as the lane becomes saturated with buses. This is because as the number of buses using the lane increases, there is a greater probability that one bus will delay another bus, either by using available loading areas or by requiring passing and weaving maneuvers. Simulation runs reported in TCRP Report 26,[R29] as well as observations of actual bus lane operations[R26] show a sharp drop in bus speeds as bus volumes approach capacity. Exhibit 2-55 presents the speed adjustment factor for bus volumes. These factors were developed through simulation of Type 1 and Type 2 bus lanes, using an 80-second cycle, a $g/C$ ratio of 0.5, 125-meter (400-foot) block spacing, 20- to 50-second dwell times, and a 33 percent coefficient of dwell time variation.

Exhibit 2-55
Bus-Bus Interference Factor, $f_b$[R29]

| Bus Lane *v/c* 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 |

Exhibit 2-56 illustrates the effects of increasing bus lane volumes on bus speeds. There is little effect on bus speeds until approximately 70% of the bus lane's capacity is being used.

Exhibit 2-56
Illustrative Bus-Bus Interference Factor Effects




NOTE: Assumes suburban conditions, 30-second dwell times, and a single normal flow bus lane.

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# 5. MIXED TRAFFIC

## INTRODUCTION

*Mixed traffic is the most common bus operating environment in North America.*

Buses operating in mixed-traffic situations is the most common operating scenario in North American cities and rural areas, and applies to small and large buses, both standard and articulated, and to 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 similarly to exclusive arterial street bus lanes, except that the interference of other traffic sharing a lane with buses must be accounted for.*

Because buses operate much like other vehicles in a traffic lane, their impact on the overall vehicle capacity of the lane may be calculated as if they were another vehicle, using the procedures given in the *Highway Capacity Manual*, and using a vehicle equivalence of 2.0.[R9] The lane's bus vehicle capacity is calculated in a similar manner as for exclusive arterial 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

*Bus lane types described.*

Similar to exclusive arterial street bus lanes, the capacity procedures in this chapter define two lane types, with the availability of an adjacent lane for buses to pass other vehicles the determining factor.

*Type 1* mixed traffic lanes have one traffic lane in the direction the bus operates, shared by buses and other vehicles. Exhibit 2-57 illustrates a Type 1 mixed traffic bus lane.

*Type 2* mixed traffic lanes have two or more traffic lanes in the direction the bus operates. Traffic can use any of the lanes, but buses typically operate in the curb lane. Exhibit 2-58 illustrates a Type 2 mixed traffic bus lane.

There are no *Type 3* mixed traffic bus lanes.

Exhibit 2-57
Type 1 Mixed Traffic Bus Lane (Portland, OR)

Exhibit 2-58
Type 2 Mixed Traffic Bus Lane (Vancouver, BC)

## CALCULATING VEHICLE CAPACITY

The volume of mixed traffic sharing the curb lane with buses affects bus vehicle capacity in two ways: (1) the interference caused by other traffic in the lane, particularly at intersections, which may block buses from reaching a stop or may delay a bus blocked behind a queue of cars, and (2), for off-line stops, the additional re-entry delay encountered when leaving a stop and reentering traffic. The latter source of delay is incorporated into the clearance time used to calculate bus stop capacity. The former is accounted for by the following capacity adjustment factor:

*Mixed traffic adjustment factor.*

*This mixed traffic bus capacity procedure is an extension of the exclusive bus lane capacity procedures developed by the TCRP A-7 project. The theoretical basis exists for the mixed traffic procedures, but they have not yet been validated in the field.*

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

Equation 2-18

where:

| | | |
|---|---|---|
| $f_m$ | = | mixed traffic adjustment factor; |
| $f_l$ | = | bus stop location factor, from Exhibit 2-48; |
| $v$ | = | curb-lane volume at a specific intersection; and |
| $c$ | = | curb-lane capacity at a specific intersection. |

The mixed traffic adjustment factor is essentially the same as the right turn adjustment factor presented in Equation 2-9 for exclusive arterial street bus lanes. The difference is that in a mixed-traffic situation, the non-transit 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 arterial street bus lane. The most recent version of the *Highway Capacity Manual* should be used to determine the vehicle capacity of the curb lane.

Equation 2-19 may be used to calculate the bus vehicle capacity of a mixed traffic lane in which buses operate.

$$B = B_{bb} N_{eb} f_m$$

Equation 2-19

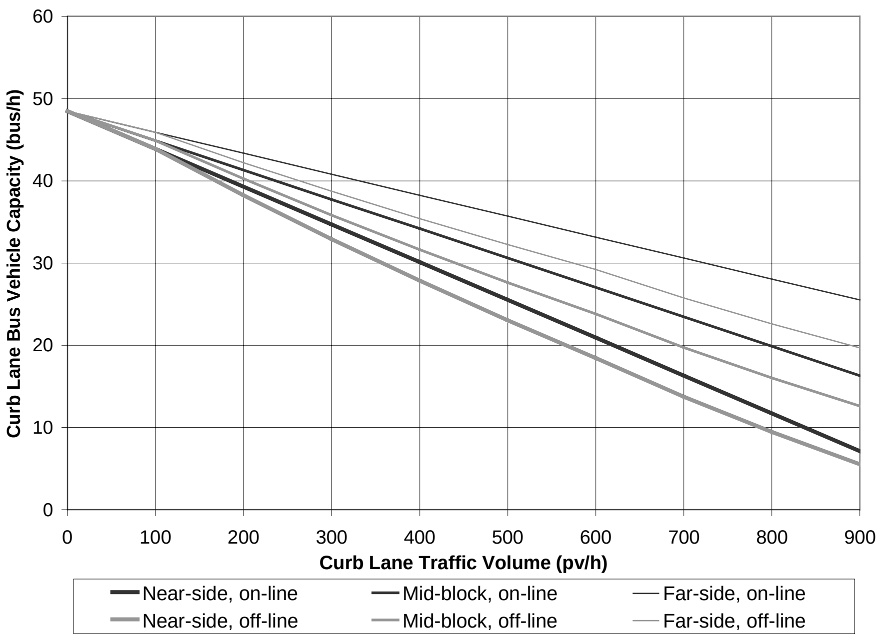
where:

$B$ = mixed traffic bus capacity (buses/h);
$B_{bb}$ = bus loading area capacity at the critical bus stop (buses/h);
$N_{eb}$ = number of effective loading areas at the critical bus stop; and
$f_m$ = capacity adjustment factor for mixed traffic interference at the critical bus stop.

*In mixed traffic situations, on-line stops may provide greater capacity than off-line stops, depending on traffic volumes and the number of loading areas provided.*

Exhibit 2-59 illustrates how bus vehicle capacity declines as curb lane traffic volumes increase and how bus vehicle capacity varies by bus stop location. It should also be noted that in mixed-traffic situations, off-line linear stops may provide less bus vehicle capacity than on-line stops for identical dwell times, as the additional fractional effective loading areas provided by off-line stops are outweighed by the additional delay buses encounter when re-entering traffic.

Exhibit 2-59
Illustrative Mixed Traffic Maximum Bus Vehicle Capacity




NOTE: Assumes a Type 1 mixed bus lane, one linear loading area per stop, $g/C$ = 0.5, 30-second dwell time, 25% failure rate, and a 60% coefficient of variation.

## CALCULATING PERSON CAPACITY

The person capacity of buses operating in mixed traffic at the lane's maximum load point may be calculated by multiplying the vehicle capacity given by Equation 2-19 by the maximum passenger loads allowed by policy times a peak hour factor.

## CALCULATING SPEED

As always, the best way to determine bus travel speeds is to measure them directly. If this is not possible (for example, when planning future service), speeds can be estimated by (1) driving the route making an average number of stops with simulated dwells, making two or three runs during peak and off-peak times, (2) scheduling buses based on similar routes and adjusting running times as needed based on the operating experience, or (3) using the analytical method described below to estimate speeds.

The speeds of buses operating in mixed traffic are influenced by bus stop spacing, dwell times, delays due to traffic signals, and interferences from other traffic operating in the lane. The method used to estimate bus speeds in mixed traffic is similar to that used for exclusive arterial street bus lanes, as indicated by Equation 2-20. The difference is that Exhibit 2-60 should be used for determining the base bus speed, which takes into account the added delay caused by mixed traffic operating in the curb lane.

$$V_t = V_0 \, f_s \, f_b$$

Equation 2-20

where:

| | | |
|---|---|---|
| $V_t$ | = | travel speed (km/h or mph); |
| $V_0$ | = | base bus speed in mixed traffic (km/h or mph), from Exhibit 2-60 or Appendix B; |
| $f_s$ | = | skip-stop speed adjustment factor, from Equation 2-17; and |
| $f_b$ | = | bus-bus interference factor, from Exhibit 2-55. |

Exhibit 2-60
Estimated Bus Speeds, $V_0$ (km/h)—Mixed Traffic[R29]

| Stops/ km | CBD Delay: 1.9 min/km | Central City Delay: 0.6 min/km | Suburbs Delay: 0.4 min/km |
|---|---|---|---|
| **10-second dwell time** | | | |
| 1.2 | 17.9 | 29.3 | 31.2 |
| 2.5 | 15.4 | 23.2 | 24.3 |
| 3.7 | 13.5 | 19.0 | 19.8 |
| 5.0 | 11.6 | 15.4 | 16.1 |
| 6.2 | 9.7 | 12.2 | 12.6 |
| **20-second dwell time** | | | |
| 1.2 | 16.9 | 26.6 | 28.2 |
| 2.5 | 14.2 | 20.0 | 20.9 |
| 3.7 | 11.7 | 15.8 | 16.3 |
| 5.0 | 9.7 | 12.7 | 13.0 |
| 6.2 | 8.2 | 10.1 | 10.3 |
| **30-second dwell time** | | | |
| 1.2 | 15.9 | 24.3 | 25.6 |
| 2.5 | 12.7 | 17.5 | 18.2 |
| 3.7 | 10.5 | 13.5 | 14.0 |
| 5.0 | 8.9 | 10.8 | 11.1 |
| 6.2 | 7.2 | 8.5 | 8.7 |
| **40-second dwell time** | | | |
| 1.2 | 15.1 | 22.5 | 23.5 |
| 2.5 | 11.7 | 15.6 | 16.3 |
| 3.7 | 9.5 | 11.9 | 12.2 |
| 5.0 | 7.9 | 9.5 | 9.7 |
| 6.2 | 6.4 | 7.6 | 7.6 |
| **50-second dwell time** | | | |
| 1.2 | 14.3 | 20.8 | 21.7 |
| 2.5 | 10.8 | 14.2 | 14.6 |
| 3.7 | 8.7 | 10.6 | 10.8 |
| 5.0 | 7.1 | 8.4 | 8.5 |
| 6.2 | 5.8 | 6.6 | 6.8 |
| **60-second dwell time** | | | |
| 1.2 | 13.7 | 19.5 | 20.3 |
| 2.5 | 10.1 | 12.9 | 13.2 |
| 3.7 | 8.0 | 9.5 | 9.7 |
| 5.0 | 6.4 | 7.6 | 7.6 |
| 6.2 | 5.3 | 6.0 | 6.0 |

NOTE: Data based on field measurements. Traffic delays shown reflect peak conditions. Dwell times are average dwell times.

*An alternative table using U.S. customary units appears in Appendix B.*

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# 6. DEMAND-RESPONSIVE

## INTRODUCTION

Demand-responsive services encompass a wide range of transportation services, as shown in Exhibit 2-61. The differences among the types of services include the kinds of vehicles used and their passenger capacity, the locations service is provided to, and how service is provided.

Exhibit 2-61
Characteristics of Different Demand-Responsive Bus Systems[R2]

| | Service Types | Service Configuration | Typical Passenger Loads | Primary Markets | Typical Regulatory Jurisdiction | Degree of Regulatory Restriction |
|---|---|---|---|---|---|---|
| **Commercial Services** | | | | | | |
| **Shared-Ride** *Taxis* | On demand, hail request | Many-to-many | 3-4 | Downtown, airports, train stations | City | High |
| **Dial-a-ride** *Specialized & General* | On demand, phone & hail request | Many-to-many | 6-10 | Elderly, handicapped | City/State | Low |
| *Airport Shuttles* | On demand, phone & hail request | Few-to-one | 6-10 | Air travelers | State, airports | Low to moderate |
| **Jitneys** *Circulators* | Regular route, fixed stops | Fixed route/loop (one-to-one) | 6-15 | Employees, specialized | City | Moderate to high |
| *Transit Feeders* | Regular route, hail request | Many-to-one | 6-15 | Employees, specialized | City | Moderate to high |
| *Areawide* | Semi-regular route, hail request | Many-to-many | 6-15 | Riders not well served by other transit | City | Moderate to high |
| **Commuter Vans** | Pre-arranged, scheduled | Few-to-one | 10-15 | Commuters | State | Low |
| **Employer- and Developer-Sponsored Services** | | | | | | |
| **Shuttles** | Pre-arranged, regular route | Fixed route/loop (often one-to-one) | 15-30 | Commuters, students | Local/State | Low |
| **Vanpools** | Pre-arranged, scheduled | Many-to-one | 6-15 | Commuters | State | Low |
| **Buspools** | Pre-arranged, scheduled | Few-to-one | 30-60 | Commuters | State | Low |

### Vehicle Types

There are a wide variety of vehicles available for demand-responsive services. These vehicles are usually not the articulated or standard buses typically used for fixed-route service. Typically, demand-responsive vehicles are smaller because of the greater variety of roadways upon which they must operate, and the smaller passenger loads that can be served within an acceptable travel time. The following is a list of the kinds of vehicles that are used in demand-responsive service:[R2]

- private automobiles;
- taxi cabs;
- jitney vans and buses;
- commercial vans and buses; and
- paratransit vans and buses.

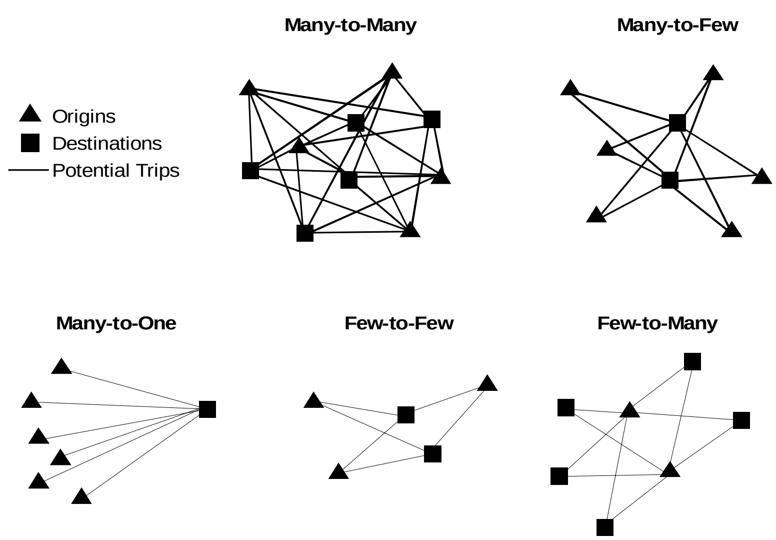
## Operating Scenarios

The following operating scenarios exist for demand-responsive transit:[R2]

- many-to-many;
- many-to-few;
- few-to-many;
- few-to-few; and
- many-to-one.

*Many-to-many* occurs when the provider places no constraints on the type of trips it handles. In other words, the origins and destinations are random and can occur anywhere. *Many-to-few* occurs when the provider has only a couple of popular destinations (hospitals, shopping areas, and the like) and random origins. *Few-to-many* occurs when the reverse happens. *Few-to-few* serves a limited number of origins and destinations. Finally, *many-to-one* occurs when there is only one destination, such as a senior center, and random origins. Exhibit 2-62 shows these five scenarios graphically.

Exhibit 2-62
Demand-Responsive Transit Service Patterns

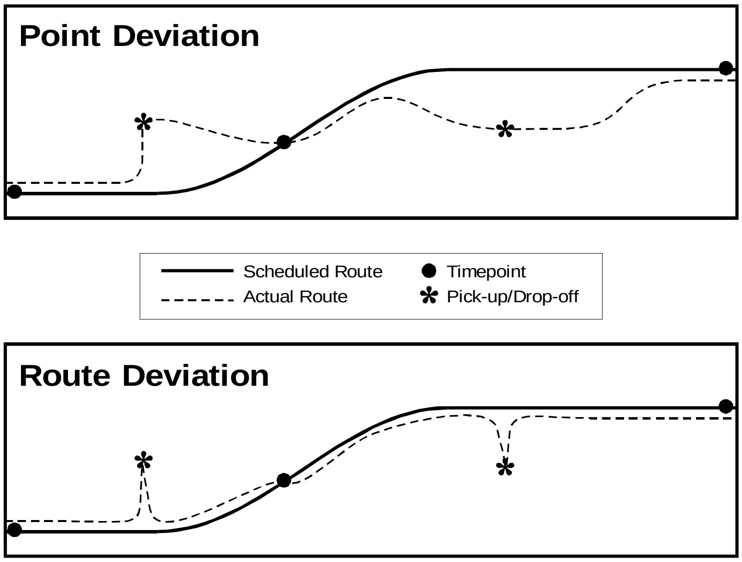



## Deviated Fixed-Route Transit

A variation of fixed-route service that incorporates elements of demand-responsive service is *deviated fixed-route transit.* This form of service is often used to expand the potential service area of a single route in a low-density area, by allowing deviations up to a set distance from the usual route to pick up and drop off passengers. It is also sometimes used by transit systems as a way of meeting Americans with Disabilities Act (ADA) requirements for providing complimentary paratransit service within the service area of a fixed-route bus line. In this latter situation, the fixed-route vehicle also provides the door-to-door ADA service for those passengers who have difficulty traveling on their own to the nearest bus stop.

Two types of deviated fixed-route transit are commonly used. *Route deviation* requires the bus to follow the entire fixed route, so as not to miss potential passengers waiting along the route, but allows the bus to travel off the route a fixed distance to pick up and drop off passengers, as long as the bus returns to the fixed route at the same point it left it. *Point deviation* requires only that a bus be at certain locations at certain times. The bus may follow a set route when no deviations are requested, but it is not obligated to return to the route at the same point it left. (See Exhibit 2-63.)

Exhibit 2-63
Deviated Fixed-Route Service Patterns




## CALCULATING VEHICLE CAPACITY

Demand-responsive service capacity is different than capacity for other kinds of bus service in that the issue is not how many vehicles can a facility accommodate, as the number of vehicles being operated in any given service is generally very small. Rather, the question being asked is how many vehicles are required to accommodate a given passenger demand and service area.

For many-to-one and few-to-one types of service, vehicles are usually assigned to geographical areas, with the number of vehicles assigned to each geographic area depending on the number of passengers from that area that need to be accommodated at a given time. Every passenger should be provided with a seat in demand-responsive service.

For other kinds of service, particularly many-to-many services such as dial-a-ride, the number of vehicles required is dependent on passenger demand and the size of the service area to be covered. Some larger dial-a-ride systems use a hub-and-spoke system, where each vehicle picks up and drops off passengers in a designated geographic area during a specified period of time, then returns to a central location to meet the other vehicles to transfer passengers. This arrangement provides greater person capacity per vehicle, but may not be feasible for systems serving the elderly and persons with disabilities, as these customers should be required to board and alight as little as possible.

*A demand-responsive vehicle's person capacity is inversely related to the vehicle's service area and the number of potential origins and destinations it must serve.*

To date, no national studies have been performed on demand-responsive person capacity, particularly for dial-a-ride types of service, so this chapter does not provide calculation procedures for estimating demand-responsive capacity. However, the following general statement about capacity can be made: *a demand-responsive vehicle's person capacity is inversely related to the size of its service area and also is inversely related to the number of potential origins and destinations it must serve.* The best method for estimating demand-responsive person capacity is to identify a well-used demand-responsive system serving an area similar to one for which service is contemplated, and to identify the number of passengers per hour or per day that system is capable of serving.

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# 8. EXAMPLE PROBLEMS

1. Bus Dwell Time Calculation
2. Number of Bus Berths Required at a Stop
3. Bus Vehicle Capacity and Speed with an Exclusive Bus Lane (Skip-stop Operation)
4. Bus Vehicle Capacity in Mixed Traffic (Near-side Stops)
5. Bus Vehicle Capacity in Mixed traffic (Far-side stops)
6. Bus Vehicle Capacity in Mixed traffic (Skip-stop Operation)
7. Person Capacity
8. Implementing an Exclusive Bus Lane on a CBD Street
9. Implementing a Bus Queue Jump at a Traffic Signal

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 #7-10).

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

***The Facts***

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

| Stop # | 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 seconds boarding time per passenger (3.5 seconds with standees).
- ✓ Assume 2.0 seconds alighting time per passenger.

***Outline of Solution***

All input parameters are known. Method 3 (calculation) will be used to determine dwell times. As there are two doors, one used by boarding passengers and the other by alighting passengers, boarding and alighting times will need to be calculated separately for each stop to determine which governs dwell time. The total number of passengers on board the bus will need to 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 3-7.
2. Calculate the boarding time. — The boarding time is the number of boarding passengers times 3.0 or 3.5 seconds, depending on whether or not standees are present.
3. Calculate the alighting time. — The alighting time is the number of alighting passengers times 2.0 seconds.
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 # | 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 #1-7, while alighting times govern at stops #8-10. Stop #8 is the critical bus stop for this route within the CBD area.

Because of the long dwell times at stops #1-4 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 when re-entering 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 seconds. 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 when sizing the transfer center.

Having standees on-board a long-distance express bus is not desirable from a quality of service point-of-view. Increasing service frequency so that all riders may have a seat should also be considered.

*Number of bus berths required at a stop.*

## Example Problem 2

***The Situation*** A downtown Type 2 exclusive bus lane currently serves 32 buses during the evening peak hour. The transit agency wishes to add another route to the corridor with 10-minute headways during the peak hour.

***The Question*** What is the existing bus vehicle capacity along the corridor? Will additional loading areas be required at the busiest stop, and if so, how many?

***The Facts***
- ✓ The *g*/*C* ratio (the ratio of effective green time to cycle length) along the route is 0.45.
- ✓ All bus stops are on-line and currently have one linear berth each.
- ✓ Average bus dwell time at the critical stop is 30 seconds.
- ✓ The desired bus stop failure rate is 10%.
- ✓ Right turns are prohibited along the street.

***Comments***
- ✓ Assume $C_v$ (the coefficient of variation in dwell times) is 0.60.
- ✓ For on-line stops, assume a 10-second clearance time.

***Outline of Solution***
All input parameters are known. As right turns are prohibited, the vehicle capacity of the critical bus stop will determine the bus lane vehicle capacity (i.e., $f_r$ from Equation 2-9 is 1). The vehicle capacity of a linear bus stop is the vehicle capacity of a loading area times the number of effective loading areas.

***Steps***

1. Calculate the vehicle capacity of a single berth, from Equation 2-4.

$$B_{bb} = \frac{3{,}600(g/C)}{t_c + (g/C)t_d + Z_a c_v t_d}$$

$$B_{bb} = \frac{3{,}600(0.45)}{10 + (0.45)(30) + (1.28)(0.60)(30)}$$

$$B_{bb} = 35 \text{ bus/h}$$

2. One loading area is sufficient to accommodate the existing demand of 32 buses per hour. Adding another route with 10-minute headways will result in six more buses per hour, which will exceed the critical stop's vehicle capacity. Try adding a second linear berth, which from Exhibit 2-17, has the effectiveness of 1.85 berths.

From Equation 2-5:

$$B_s = N_{eb} B_{bb}$$

$$B_s = (1.85)(35)$$

$$B_s = 65 \text{ bus/h}$$

***The Results*** Adding a second linear berth to the critical bus stop will give it sufficient vehicle capacity to accommodate the new route. The new critical bus stop should now be checked to make sure that it, too, can accommodate the proposed additional buses.

As a general rule, most downtown stops should have two or three berths wherever possible.

### Example Problem 3

*Bus vehicle capacity and speed with an exclusive bus lane (skip-stop operation).*

***The Situation*** It has been suggested that implementing skip-stop operations along the street described in Example Problem 2 could eliminate the need to add berths to existing bus stops and would increase bus operating speeds for the future scenario of 38 buses during the peak hour.

***The Question*** Will implementing a two-stop skip-stop pattern provide sufficient vehicle capacity at the critical bus stop without requiring an extra berth? How much room for additional growth in bus volumes will there be? How will bus operating speeds be affected?

***The Facts***

- ✓ Same assumptions as Example Problem 2.
- ✓ There are two groups of routes: NE Metro (25 buses) and NW Metro (13 buses). Buses arrive randomly within each group.
- ✓ 500 veh/h use the adjacent lane.
- ✓ Trucks comprise 2% of the traffic in the adjacent lane.
- ✓ Bus stops are located on the near sides of intersections.
- ✓ Average dwell time for both groups of routes is 30 seconds.
- ✓ Stops are spaced 200 meters apart (5 stops/km).

***Comments***

- ✓ The *Highway Capacity Manual* should be used to determine the capacity of the adjacent lane. The base saturation flow rate, $v_0$, is 1900 passenger vehicles per hour of green. The heavy vehicle saturation adjustment factor, $f_{HV}$, is 0.98. The area saturation flow adjustment factor, $f_a$, is 0.90 for CBDs.

***Outline of Solution***

All input parameters are known. Since the larger of the two groups of buses has 25 buses per hour and the critical stop can accommodate 35 buses per hour (from Example Problem 2), the skip-stop pattern will provide sufficient capacity for each group without requiring additional berths at stops. The bus lane vehicle capacity is equal to the sum of the vehicle capacities of the two bus stop patterns, times an adjustment factor for the effect of random bus arrivals and the impedance of other traffic in the adjacent lane. The speed estimation procedure involves identifying the base bus speed in mixed traffic, from Exhibit 2-53, and modifying this speed by adjustment factors for skip-stop operation and bus-bus interferences.

***Steps***

1. Calculate the capacity of the adjacent lane, using the procedures given in Chapter 16 of the *Highway Capacity Manual.*

$$c = v_0 (g / C) f_{HV} f_a$$
$$c = (1900 \text{ veh/h})(0.45)(0.98)(0.90)$$
$$c = 754 \text{ veh/h}$$

2. Calculate the adjacent lane impedance factor from Equation 2-11.

$$a = 1 - 0.8\left(\frac{v}{c}\right)^3$$
$$a = 1 - 0.8\left(\frac{500}{754}\right)^3$$
$$a = 0.77$$

3. Calculate the skip-stop adjustment factor from Equation 2-10. Arrivals are random; therefore, the *K* factor is 0.50.

$$f_k = \frac{1 + Ka(N_s - 1)}{N_s}$$
$$f_k = \frac{1 + (0.50)(0.77)(2 - 1)}{2}$$
$$f_k = 0.69$$

4. The bus lane vehicle capacity is given by Equation 2-13 and is equal to the sum of the two pattern's critical bus stop vehicle capacities times the factor calculated in Step 3. Because both patterns have the same dwell times and right-turns are prohibited, their critical bus stop vehicle capacities are the same (35 bus/h, from Example Problem 2).

$$B = f_k(B_1 + B_2)$$
$$B = 0.69(35 + 35)$$
$$B = 48 \text{ bus/h}$$

5. Bus speeds under the all-stop scenario can be calculated from Equation 2-16. The skip-stop speed adjustment factor, $f_s$, is 1.0 for this scenario, since skip-stops are not used. The bus-bus interference factor, $f_b$, is determined from Exhibit 2-55: $v/c$ = (38/65) = 0.58, and by interpolation, $f_b$ is 0.95. (This assumes that all bus stops are lengthened to accommodate two berths; otherwise, the capacity should be based on the critical one-berth stop). The base bus speed, $V_0$, is calculated from Exhibit 2-53, using the dual bus lane column since the capacity calculations took right-turn interferences into account.

$$V_t = V_0 f_s f_b$$
$$V_t = (10.5 \text{ km/h})(1.0)(0.95)$$
$$V_t = 10.0 \text{ km/h}$$

6. Under the skip-stop scenario, the skip-stop speed adjustment factor must be calculated from Equation 2-17. The larger of the two patterns' bus $v/c$ ratios should be used in the calculation[R29]; thus, $v_b/c_b$ = (25/35) = 0.71.

$$f_s = 1 - \left(\frac{d_1}{d_2}\right)\left(\frac{v}{c}\right)^2\left(\frac{v_b}{c_b}\right)$$
$$f_s = 1 - \left(\frac{100}{200}\right)\left(\frac{500}{754}\right)^2\left(\frac{25}{35}\right)$$
$$f_s = 0.84$$

7. By interpolation, $f_b$ = 0.88, using the larger of the two patterns' bus $v/c$ ratios. The base bus speed and the bus travel speed under the skip-stop scenario are calculated similarly to Step 5.

$$V_t = V_0 f_s f_b$$
$$V_t = (10.5 \text{ km/h})(0.84)(0.88)$$
$$V_t = 7.8 \text{ km/h}$$

8. For comparison, the existing bus speeds on the street (32 buses and single loading areas) are:

$$V_t = V_0 f_s f_b$$
$$V_t = (10.5 \text{ km/h})(1.0)(0.67)$$
$$V_t = 7.0 \text{ km/h}$$

***The Results***

Both options provide sufficient vehicle capacity to accommodate the proposed route modification and both options increase bus travel speeds above existing levels. Adding an additional berth to each stop has a greater potential effect on speed and capacity than does implementing skip-stop operation. However, if it is possible only to lengthen the critical stop from Example Problem 2, skip-stop operations may have a greater effect, depending on the vehicle capacity of the critical one-berth bus stop.

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

## Example Problem 4

***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.

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

***The Facts***

- ✓ $g/C$ = 0.45.
- ✓ 40 buses per hour will use the street.
- ✓ 1200 automobiles per hour will also use the street.
- ✓ 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 every two blocks.
- ✓ No on-street parking, no grades, 3.6-m (12-ft) travel lanes.
- ✓ Dwell times, curb lane auto right-turn volumes, curb lane auto through volumes, and conflicting pedestrian movements as follows:

| Stop # | Dwell Time (s) | Right-Turn Volume | Through Auto Volume | Conflicting Ped Volume |
|---|---|---|---|---|
| 1 | 30 | 350 | 50 | 100 |
| 2 | 35 | 200 | 100 | 300 |
| 3 | 40 | 100 | 100 | 500 |
| 4 | 20 | 300 | 50 | 200 |

***Comments***

- ✓ The base saturation flow rate, $v_0$, is 1900 pv/hg/ln.
- ✓ The bus blockage factor saturation flow adjustment factor, $f_{bb}$, is 0.84.
- ✓ The heavy vehicle saturation flow adjustment factor, $f_{HV}$, is 0.971.
- ✓ The area saturation flow adjustment factor is 0.90 for a CBD.
- ✓ The bus stop location factor, $f_l$, is 0.90 (Type 2 lane, near-side stop), from Exhibit 2-48.
- ✓ For on-line stops, assume a 10-second clearance time.
- ✓ $Z_a$ = 1.44 for 7.5% failure rate, from Exhibit 2-15.
- ✓ Assume 60% coefficient of variation of dwell times.
- ✓ For two linear on-line berths, the number of effective berths, $N_{EB}$, is 1.85, from Exhibit 2-17.

***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 must be found first, which will then be modified by the number of effective loading areas at each stop and the mixed traffic adjustment factor from Equation 2-18.

***Steps***

1. Calculate the right-turn saturation adjustment factor for each stop, using the procedures from the *Highway Capacity Manual.* The factor is related to the pedestrian volume and the proportion of right turns from the lane. The right-turn lane volume used is the sum of the through auto volumes, right-turn auto volumes, and bus volumes in the lane.

For stop #1:

$$f_{RT} = 1.0 - P_{RT}\left[0.15 + (PEDS/2100)\right]$$

$$f_{RT} = 1.0 - \left(\frac{350}{440}\right)\left[0.15 + (100/2100)\right]$$

$$f_{RT} = 0.843$$

2. Calculate the right-turn lane capacity.

For stop #1:

$$c = v_0 (g/c) f_{bb} f_{HV} f_a f_{RT}$$
$$c = (1900 \text{ vph})(0.45)(0.84)(0.971)(0.90)(0.843)$$
$$c = 529 \text{ vph}$$

3. Calculate the mixed traffic interference factor from Equation 2-18.

For stop #1:

$$f_m = 1 - f_l \left( \frac{v}{c} \right)$$
$$f_m = 1 - 0.90 \left( \frac{440}{529} \right)$$
$$f_m = 0.25$$

4. Calculate the loading area vehicle capacity from Equation 2-4.

For stop #1:

$$B_{bb} = \frac{3{,}600(g/C)}{t_c + (g/C)t_d + Z_a c_v t_d}$$
$$B_{bb} = \frac{3{,}600(0.45)}{10 + (0.45)(30) + (1.44)(0.60)(30)}$$
$$B_{bb} = 33 \text{ bus/h}$$

5. Calculate the curb lane's bus vehicle capacity at this bus stop from Equation 2-19.

For stop #1:

$$B = B_{bb} N_{eb} f_m$$
$$B = (33 \text{ bus/h})(1.85)(0.25)$$
$$B = 15 \text{ bus/h}$$

Summary table for all stops:

| Stop # | $P_{RT}$ | $f_{RT}$ | $c$ | $v$ | $f_m$ | $B_{bb}$ | $B$ |
|---|---|---|---|---|---|---|---|
| 1 | 0.795 | 0.843 | 529 | 440 | 0.25 | 33 | 15 |
| 2 | 0.588 | 0.828 | 519 | 340 | 0.41 | 29 | 22 |
| 3 | 0.417 | 0.838 | 525 | 240 | 0.59 | 26 | 28 |
| 4 | 0.769 | 0.811 | 509 | 390 | 0.31 | 45 | 26 |

***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 curb lane bus vehicle capacity is 15 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 failure rate that is allowed; however, this decreases schedule and headway reliability and should be avoided when possible. 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 5

***The Situation*** The CBD street from Example Problem 4. Having determined that a mixed traffic lane with near-side stops will not work, the transit operator would like to try 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 Example Problem 4, except that stops are now far-side.

***Outline of Solution***

As in Example Problem 4, 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.

Summary table for all stops:

| Stop # | $P_{RT}$ | $f_{RT}$ | $c$ | $v$ | $f_m$ | $B_{bb}$ | $B$ |
|---|---|---|---|---|---|---|---|
| 1 | 0.795 | 0.843 | 529 | 440 | 0.58 | 33 | 35 |
| 2 | 0.588 | 0.828 | 519 | 340 | 0.67 | 29 | 36 |
| 3 | 0.417 | 0.838 | 525 | 240 | 0.77 | 26 | 37 |
| 4 | 0.769 | 0.811 | 509 | 390 | 0.62 | 45 | 52 |

***The Results*** Bus lane vehicle capacity improves substantially as a result of using far-side stops, but is still below the value of 40 buses per hour that is required. 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 6

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

***The Situation*** The CBD street from Example Problems 4 and 5. 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 Example Problem 5.

Half of the buses will use “A”-pattern stops, which are the same ones used in Problem 4. 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.

***Comments***

Random bus arrivals are assumed.

Automobile volumes in the left two lanes are assumed to be evenly distributed.

Adjustment factor *K* for random arrivals, from Equation 2-10, 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 will need to be 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.

***Steps***

1. Calculate the adjacent lane capacity.

At stop #1:

$$v = (1200 - 350 - 50)/2 = 400 \text{ vph}$$

$$c = v_0 (g/C) f_{HV} f_a$$

$$c = (1900 \text{ vph})(0.45)(0.971)(0.90)$$

$$c = 747 \text{ vph}$$

2. Calculate the adjacent lane impedance factor, from Equation 2-11.

At stop #1:

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

$$a = 1 - 0.8\left(\frac{400}{747}\right)^3$$

$$a = 0.88$$

3. Calculate the skip-stop adjustment factor from Equation 2-10.

$$f_k = \frac{1 + Ka(N_s - 1)}{N_s}$$

$$f_k = \frac{1 + (0.5)(0.88)(2-1)}{2}$$

$$f_k = 0.72$$

4. The “A” pattern bus lane capacity, from Example Problem 2 is 35 buses per hour. The “B” pattern is assumed to be the same. Calculate the total bus vehicle capacity of the street, using Equation 2-13.

$$B = f_k\,(B_1 + B_2 + \ldots + B_n)$$
$$B = (0.72)(35 + 35)$$
$$B = 50 \text{ bus/h}$$

***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 7

*Bus person capacity.*

***The Situation*** The CBD street from Example Problems 4-6.

***The Question*** How many people can be carried at the street's maximum load point?

***The Facts***

- ✓ Same assumptions as Example Problem 6.
- ✓ 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.
- ✓ The remaining local buses allow standees.

***Comments***

- ✓ Assume maximum schedule loads for the local buses, equivalent to a load factor of 1.50 for standard buses.
- ✓ The peak hour factor is 0.75.

***Outline of Solution***

The person capacity at the street's maximum load point is equal to the street's bus vehicle capacity times the allowed passenger load per bus times the peak hour factor. From Example Problem 6, the street's bus vehicle capacity is 50 buses per hour.

***Steps***

1. Calculate the street's bus person capacity at its maximum load point, under the proposed operation.

$$P = [(10*43) + (30*43*1.50)]*0.75$$
$$P = 1{,}770 \text{ people}$$

2. Calculate the street's maximum bus person capacity at its maximum load point.

$$P = [(10*43) + (40*43*1.50)]*0.75$$
$$P = 2{,}250 \text{ people}$$

***The Results*** Under the proposed operation, the street can carry about 1,770 people per hour in buses at its maximum load point. If the street's bus vehicle capacity of 50 buses per hour were to be scheduled, the street's person capacity would be about 2,250 people at the maximum load point.

*Implementing an exclusive bus lane on a CBD street.*

## Example Problem 8

***The Situation***

A transit operator currently operates 40 buses in mixed traffic on a three-lane one-way CBD street (Example Problems 4-6). The transit operator would like to accommodate future growth in bus volumes and to maintain schedules as city streets become more congested, and therefore has proposed that one lane of the street be converted to exclusive bus use, with right turns prohibited from the lane. The city traffic engineer is concerned about the additional delay that will be experienced by motorists if the lane is implemented.

***The Question***

Will the proposed exclusive bus lane increase or decrease overall person delay?

***The Facts***

- ✓ Same assumptions as Example Problem 6.
- ✓ Pre-timed signals, 60-second cycle, $g/C$ = 0.45, arrival type 5, 40 km/h (25 mph) free-flow speed.
- ✓ 1200 automobiles and 40 buses per hour use the street.
- ✓ No on-street parking, no grades, 3.6-m (12-ft) travel lanes, arterial class IV.
- ✓ Far-side, on-line stops located every two blocks, with a two-block skip-stop operation in use.
- ✓ No right turns will be allowed across the bus lane.
- ✓ Buses will be able to use the adjacent mixed traffic lane to pass other buses in the exclusive bus lane (i.e., the lane will be a Type 2 exclusive bus lane).
- ✓ Blocks are 135 m (440 ft) long, with signalized intersections at the end of each block.
- ✓ 10 buses per hour will be express buses, with no standees allowed by policy; the remaining buses will be local buses on which standees will be allowed. The buses in use have 43 seats.
- ✓ Average vehicle occupancies are 1.2 for automobiles, 40 for express buses, and 50 for local buses.
- ✓ Buses arrive randomly. Half of the buses will use “A”-pattern skip stops; the other half will use “B”-pattern skip stops in the alternate blocks. The critical “B”-pattern stop has the same characteristics as the critical “A”-pattern stop.
- ✓ Under the exclusive bus lane scenario, the automobiles currently making right turns from this street will have to divert to a parallel street to make their turns, incurring an extra 60 seconds of delay each. Added delay to vehicles on these parallel streets, as well as the reduced delay to other vehicles that take their place on the bus street is neglected.

***Comments***

- ✓ The base saturation flow rate, $v_0$, is 1900 pv/hg/ln.
- ✓ Traffic volumes in the left two lanes are assumed to be evenly distributed.
- ✓ Assuming bus use of the mixed traffic lane to pass other buses, the heavy vehicle saturation flow adjustment factor, $f_{HV}$, is 0.968.
- ✓ The area saturation flow adjustment factor is 0.90 for a CBD.
- ✓ The bus stop location factor, $f_l$, is 0.50 for a Type 2 exclusive bus lane, from Exhibit 2-48.
- ✓ For pre-timed signals, the actuated control adjustment factor, $k$, is 0.50.
- ✓ For on-line stops, assume a 10-second clearance time.
- ✓ $Z_a$ = 1.44 for a 7.5% bus stop failure rate, from Exhibit 2-15.
- ✓ Assume a 60% coefficient of variation of dwell times.
- ✓ The adjustment factor $K$ for random bus arrivals, from Equation 2-10, is 0.50.
- ✓ For two linear on-line berths, the number of effective berths, $N_{EB}$, is 1.85, from Exhibit 2-17.
- ✓ From Example Problem 6, the capacity of the lane adjacent to the bus lane is 747 vph.
- ✓ Average bus speeds under the mixed traffic operation described in Example Problem 6 are 7.5 km/h (4.7 mph).

***Outline of Solution***

All of the input parameters are known. Travel speeds will be calculated for passenger vehicles and buses with and without the exclusive bus lane, using methodologies from the *Highway Capacity Manual 2000*. These speeds will be converted to travel times over the length of the 1080-meter (3520-foot) analysis section. Using the vehicle occupancies given above, the travel time difference by mode between the two scenarios will be calculated and from this, the net change in person trip times will be calculated.

***Steps***

*(a) Determine Transit Travel Times*

1. Calculate the critical bus stop capacity under the exclusive bus lane scenario, using Equation 2-5. With right turns prohibited, the critical stop is the one with the highest dwell time, stop #3.

$$B_s = B_{bb} N_{eb}$$

$$B_{bb} = \frac{3{,}600(g/C)}{t_c + (g/C)t_d + Z_a c_v t_d}$$

$$B_{bb} = \frac{3{,}600(0.45)}{10 + (0.45)(40) + (1.44)(0.60)(40)}$$

$$B_{bb} = 26 \text{ bus/h}$$

$$B_s = (26)(1.85)$$

$$B_s = 48 \text{ bus/h}$$

2. Calculate the skip-stop capacity adjustment factor from Equation 2-10. Half of the automobiles are assumed to use the lane adjacent to the exclusive bus lane.

$$f_k = \frac{1 + Ka(N_s - 1)}{N_s}$$

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

$$a = 1 - 0.8\left(\frac{600}{747}\right)^3$$

$$a = 0.59$$

$$f_k = \frac{1 + (0.50)(0.59)(2 - 1)}{2}$$

$$f_k = 0.65$$

3. Calculate the bus vehicle capacity of the exclusive bus lane, using Equation 2-13.

$$B = f_k (B_1 + B_2 + \ldots + B_n)$$

$$B = 0.65(48 + 48)$$

$$B = 62 \text{ bus/h}$$

4. Identify the base bus speed, using Exhibit 2-53. Because the capacity analysis accounts for right-turn delays (or the lack of delays in this case), the dual/contraflow column is used. The average dwell time for the four stops is 31.25 seconds, so interpolate between the 30-second and 40-second values.

$$V_0 = 12.7 \text{ km/h}$$

5. Calculate the skip-stop speed adjustment factor using Equation 2-17.

$$f_s = 1 - \left(\frac{d_1}{d_2}\right)\left(\frac{v}{c}\right)^2\left(\frac{v_b}{c_b}\right)$$

$$f_s = 1 - \left(\frac{135}{270}\right)\left(\frac{600}{747}\right)^2\left(\frac{40}{62}\right)$$

$$f_s = 0.79$$

6. Calculate the bus-bus interference factor, interpolating from Exhibit 2-55.

$$f_b = 0.92$$

7. Calculate the bus travel speed, from Equation 2-16.

$$V_t = V_0 f_s f_b$$

$$V_t = (12.7 \text{ km/h})(0.79)(0.92)$$

$$V_t = 9.2 \text{ km/h}$$

8. Calculate the time to travel the 1080-meter analysis section with and without the exclusive bus lane.

Without:
$t$ = (1.08 km)/(7.5 km/h) = 0.14 hr
$t$ = 8.6 min

With:
$t$ = (1.08 km)/(9.2 km/h) = 0.12 hr
$t$ = 7.0 min

9. Calculate the change in person-minutes of travel time for transit passengers.

$\Delta t$ = [(10*40) + (30*50)] * (8.6-7.0)
$\Delta t$ = 3040 person-minute decrease

*(b) Determine Automobile Travel Times*

10. Using the procedures provided in the *Highway Capacity Manual 2000,* calculate the average travel speeds for automobiles on the street without the exclusive bus lane (there are several steps to this process, which are not shown here).

$$S_A = 17.2 \text{ km/h}$$

11. Repeat Steps 10 for the exclusive bus lane scenario.

$$S_A = 15.8 \text{ km/h}$$

12. Calculate the time to travel the 1080-meter analysis section with and without the exclusive bus lane.

Without:
$t$ = (1.08 km)/(17.2 km/h) = 0.063 hr
$t$ = 3.8 min

With:
$t$ = (1.08 km)/(15.8 km/h) = 0.068 hr
$t$ = 4.1 min

13. Calculate the change in person-minutes of travel time for automobile passengers, including the added delay to the 950 diverted right-turning vehicles.

$\Delta t$ = (1200*1.2)(4.1-3.8)+(950)(1)
$\Delta t$ = 1380 person-minute increase

***The Results***

The proposed exclusive arterial street bus lane will reduce peak-hour person delay by 1660 person-minutes. Buses will be able to traverse the section 1.6 minutes faster than before, through automobiles will be slowed by only 0.3 minutes, and diverted right-turning vehicles will be slowed by 1.0 minute.

## Example Problem 9

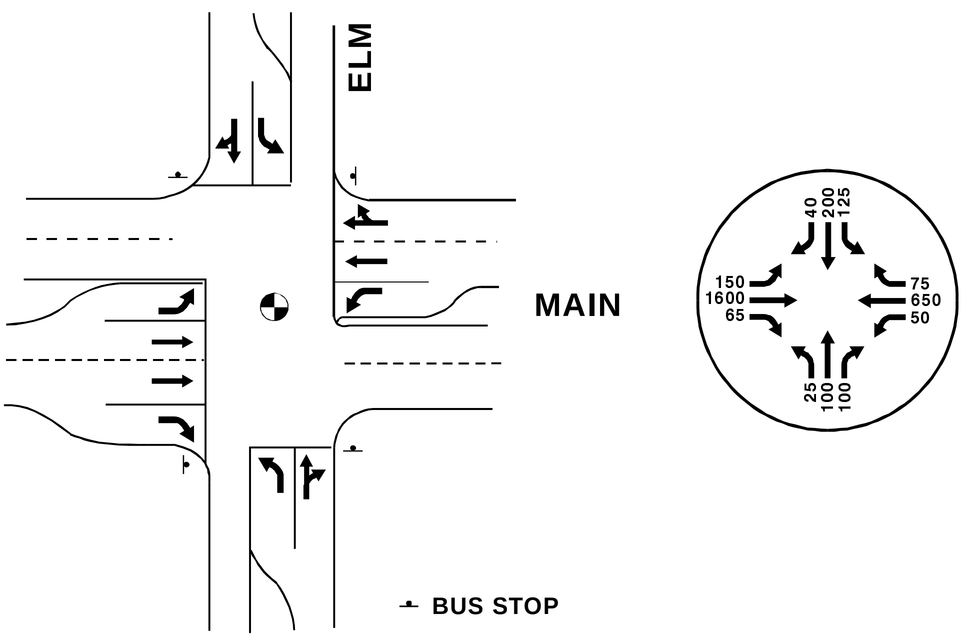
*Implementing a queue jump at a traffic signal.*

***The Situation*** A transit operator would like to implement queue-jump signal priority at a signalized intersection on a city arterial street. The city traffic engineer is concerned about how automobile traffic will be affected.

***The Question*** Compare the change in person delay as a result of the signal priority measure.

***The Facts***

- ✓ Buses arrive at a near-side stop located in a right-turn lane during the green signal phase for Main Street. Boarding and discharging passengers is completed before the end of the red signal phase for Main Street. The proposed queue jump will give eastbound peak-direction buses a green indication for three seconds in advance of other traffic moving in the peak direction, allowing these buses to merge back into the travel lane ahead of the other vehicles stopped at the signal. A detector at the bus stop is used to provide a queue jump signal phase only when a bus occupies the stop. The three seconds is taken from the green time for the peak direction of travel.
- ✓ Lane configurations and traffic volumes are given in the figure below. The queue jump operates on the eastbound direction on Main Street.




- ✓ The traffic signal cycle length is 90 seconds. Protected left-turn phasing is provided on Main Street and permitted left-turn phasing is provided on Elm Street.
- ✓ The peak hour factor is 0.94.
- ✓ Buses operate at 10-minute headways on Main Street and at 30-minute headways on Elm Street.
- ✓ Average passenger vehicle occupancy is 1.2, average bus occupancy on Main Street is 40 in the peak direction and 20 in the off-peak direction, and average bus occupancy on Elm Street is 25 in the peak direction and 10 in the off-peak direction.

***Comments***

- ✓ Bus re-entry delay cannot be calculated from Exhibit 2-14 in this case because the re-entry delay is caused by waiting for a queue to clear at a signalized intersection, rather than waiting for a gap in a traffic stream of randomly arriving vehicles. Field measurements indicate that it takes 18 seconds on average for the queue to clear before buses are able to re-enter the street. The proposed queue jump would eliminate this delay.
- ✓ A capacity analysis using the *Highway Capacity Manual* finds that the intersection's volume-to-capacity ratio is sufficiently low that the added three seconds of delay to peak-direction traffic during a queue jump should not cause cycle failures (i.e., all queued peak-direction traffic will clear the intersection on the next green signal).

***Outline of Solution***

All of the input parameters are known. Because the queue jump only takes green time away from through traffic in one direction, it is not necessary to calculate delays for all movements. Rather, the average delay for peak-direction automobile traffic is 3 seconds longer for those cycles when the queue jump is used. The added delay to persons in automobiles during the queue jump cycles will be compared to the delay savings experienced by persons in peak-direction buses. All other persons in all other vehicles at the intersection experience no net change in person-delay.

***Steps***

1. Calculate the delay savings to persons on peak-direction buses.

$$\Delta t = (18\text{ s})(6\text{ bus/h})(40\text{ p/bus})$$
$$\Delta t = 4320\text{ person-seconds}$$
$$\Delta t \approx 72\text{ person-minute decrease}$$

2. The average number of peak-direction automobiles traveling through the intersection during a cycle in which a queue jump occurs is (1600/40) or about 40 veh/cycle. Calculate the added delay to the occupants of these vehicles.

$$\Delta t = (3\text{ s})(6\text{ cycle/h})(40\text{ veh/cycle})(1.2\text{ p/veh})$$
$$\Delta t = 864\text{ person-seconds}$$
$$\Delta t \approx 15\text{ person-minute increase}$$

***The Results***

The proposed queue jump will decrease person-delay by approximately 57 person-minutes during the peak hour. The proposed queue jump should be viewed favorably.

# APPENDIX A. DWELL TIME DATA COLLECTION PROCEDURE

## INTRODUCTION

As discussed in Chapter 1, passenger service times (and dwell times) can vary greatly depending on many factors. For example, passenger service times reported in the literature range from 1 to 10 seconds per passenger.[R1,R8,R21,R25] For this reason, it is recommended that field data be collected to develop procedures for estimating passenger service times and dwell times for a given system.

Although the passenger service time of a transit vehicle may be affected by many factors, most of these factors are constant for a given system. For this reason, the principal determinants of service time typically include aspects of passenger demand. Therefore, for a given transit system with constant operating characteristics (i.e., fare collection system, number and width of doors, number of steps to board/alight, etc.), the major factors affecting service time will include:

- number of passengers boarding;
- number of passengers alighting; and
- number of passengers on board.

The following are methodologies to measure passenger service times and dwell times for buses and light rail transit (LRT) in the field.

## PASSENGER SERVICE TIMES

Passenger loadings at most stops are small, typically one or two per stop. In these situations, dwells are relatively independent of passenger service times, and it is not possible to collect statistically useful data. To determine passenger service times for use in evaluating the differences between systems (such as single and dual stream doors, high- and low-floor buses, or alternate fare collection systems), data collection should be done only at high-volume stops. These stops are typically downtown or at major transfer points. The data collection effort will require one or two persons, depending on the volume of passengers.

Following are steps that may be used to collect field data for estimating passenger service times. An example of a data collection sheet is shown in Exhibit 2-64.

1. From a position at the transit stop under study, record the identification number and run number for each arriving vehicle.
2. Record the time that the vehicle comes to a complete stop.
3. Record the time that the doors have fully opened.
4. Count and record the number of passengers alighting and the number of passengers boarding.
5. Record the time that the major passenger flows end. (Note: This is somewhat subjective but essential to correlate flows per unit of time. The time for stragglers to board or exit should not be included.)
6. When passenger flows stop, count the number of passengers remaining on board. (Note: If the seating capacity of the transit vehicle is known, the number of passengers on board may be estimated by counting the number of vacant seats or the number of standees).
7. Record time when doors have fully closed.
8. Record time when vehicle starts to move. (Note: Leave time should exclude

waits at timepoints or at signalized intersections where dwell is extended for cycle.)

9. Note any special circumstances. In particular, any wheelchair movement times should be noted.

Passenger service time for each arrival is computed by taking the difference between the time that the door opens and the main flow stops. Service time per passenger is computed by dividing the number of passengers boarding by the total service time.

Exhibit 2-64
Sample Passenger Service Time Data Collection Sheet

**Passenger Service Time Data Sheet** #____

**Date ________ Time ________**
**Route _______ Location ______ Direction ________**

| Bus Run Number | Arrival Time | Doors Open | Main Flow Stops | Doors Closed | Bus Leaves | Passengers. Boarding | | Passengers. Alighting | | Psgrs. Departing On Board | Notes |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Front | Rear | Front | Rear | | |
| | | | | | | | | | | | |
| | | | | | | | | | | | |
| | | | | | | | | | | | |
| | | | | | | | | | | | |
| | | | | | | | | | | | |

## DWELL TIMES

The procedure for determining dwell times is similar to that for estimating passenger service times, except dwell times are best determined with ride checks. With ride checks, the observer rides the transit vehicle over the entire route for several runs at different times of day. A single observer can usually monitor both doorways on a 12-meter (40-foot) bus. While it is more difficult for a single observer to handle articulated buses that have three doorways, it is possible with an experienced checker. For light rail transit vehicles, at least one observer per car will be required. Automated equipment can also monitor dwell times, possibly in conjunction with automatic passenger counting equipment.

Usually a given route will have similar equipment. Where equipment types, single door/double doors, rigid/articulated, high floor/low-floor are intermixed, separate data sets should be obtained for each type of equipment. Following are steps that may be used to collect the necessary field data to develop a procedure for estimating dwell time for buses or LRT.

A sample data collection sheet is shown in Exhibit 2-65. This sheet can be adapted to also record traffic and intersection delays. Where passenger service times are not needed, door open, flow stop and door close columns can be omitted. Following are steps that may be used to collect field data for estimating passenger service times

1. From a position on the transit vehicle, record the stop number or name at each stop.

2. Record the time that the vehicle comes to a complete stop.

3. Record the time that the doors have fully opened.

4. Count and record the number of passengers alighting and the number of passengers boarding.

5. Record the time that the major passenger flows end.

6. When passenger flows stop, count the number of passengers remaining on board. (Note: If the seating capacity of the transit vehicle is known, the number of passengers on board may be estimated by counting the number of vacant seats or the number of standees).

7. Record time when doors have fully closed.

8. Record time when vehicle starts to move. (Note: Waits at timepoints or at signalized intersections where dwell is extended for cycle should be noted but *not* included in the dwell time. Delays at bus stops when a driver is responding to a passenger information request are everyday events and *should* be included in the calculation of dwell time. Time lost dealing with fare disputes, lost property or other events should *not* be included.)

9. Note any special circumstances. In particular, any wheelchair movement times should be noted. Whether this is included in the mean dwell time depends on the system. Dwell times due to infrequent wheelchair movements are often not built into the schedule but rely on the recovery time allowance at the end of each run.

The observer must use judgment in certain cases. At near-side stops before signalized intersections the driver may wait with doors open as a courtesy to any late-arriving passengers. The doors will be closed prior to a green light. This additional waiting time should *not* be counted as dwell time but as intersection delay time.

Exhibit 2-65
Sample Dwell Time Data Collection Sheet

**Dwell Time Data Sheet** #____

**Date ____ Time ____ Bus No. _____ Bus Type_______**
**Route ___ Run No. ___ Direction _____**

| Stop # / Name | Arrival Time | Doors Open | Main Flow Stops | Doors Closed | Bus Leaves | Passengers. Boarding | | Passengers. Alighting | | Psgrs. Departing On Board | Notes |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Front | Rear | Front | Rear | | |
| | | | | | | | | | | | |
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# APPENDIX B. EXHIBITS IN U.S. CUSTOMARY UNITS

Exhibit 2-23a
Characteristics of Bus Transit Vehicles—United States and Canada

| Bus Type | Length (ft) | Width (ft) | Typical Capacity Seats | Standees | Total |
|---|---|---|---|---|---|
| Small Bus/Minibus | 18-30 | 6.5-8.0 | 8-30 | 0-10 | 8-40 |
| Transit Bus | 35 | 8.0-8.5 | 30-35 | 20-30 | 50-60 |
| | 40 | 8.5 | 35-50 | 30-40 | 65-75 |
| (low floor) | 40 | 8.0 | 30-40 | 25-40 | 55-70 |
| (articulated) | 60 | 8.0-8.5 | 65 | 55 | 120 |

NOTE: In any transit vehicle, the total passenger capacity can be increased by removing seats and by making more standing room available; however, this lowers the passengers' quality of service.

Exhibit 2-44a
Estimated Average Speeds of Buses Operating in Freeway HOV Lanes (mph)

| Stop Spacing (mi) | Dwell Time (s) 15 | 30 | 45 | 60 |
|---|---|---|---|---|
| **50 mph Running Speed** | | | | |
| 1.0 | 34.2 | 29.9 | 26.6 | 23.9 |
| 1.5 | 38.2 | 34.5 | 31.5 | 29.0 |
| 2.0 | 40.6 | 37.4 | 34.7 | 32.4 |
| 2.5 | 42.2 | 39.4 | 37.0 | 34.8 |
| 3.0 | 43.3 | 40.9 | 38.7 | 36.7 |
| **55 mph Running Speed** | | | | |
| 1.0 | 35.8 | 31.1 | 27.6 | 24.7 |
| 1.5 | 40.5 | 36.4 | 33.0 | 30.3 |
| 2.0 | 43.3 | 39.8 | 36.7 | 34.1 |
| 2.5 | 45.3 | 42.1 | 39.3 | 36.9 |
| 3.0 | 46.6 | 43.8 | 41.3 | 39.0 |
| **60 mph Running Speed** | | | | |
| 1.0 | 37.1 | 32.1 | 28.3 | 25.3 |
| 1.5 | 42.5 | 38.0 | 34.4 | 31.4 |
| 2.0 | 45.8 | 41.8 | 38.5 | 35.6 |
| 2.5 | 48.1 | 44.5 | 41.5 | 38.8 |
| 3.0 | 49.8 | 46.5 | 43.7 | 41.2 |

NOTE: Assumes constant 4 $ft/s^2$ acceleration/deceleration rate.

Exhibit 2-53a
Estimated Bus Speeds, $V_0$ (mph)—Exclusive Arterial Street Bus Lanes[(R29)]

| Stops/ mi | Without Traffic Delays [a] | Single Normal Flow Bus Lanes [b] | | | Dual/Contraflow Bus Lanes [c] |
|---|---|---|---|---|---|
| | | CBD | Central City | Suburbs | |
| | Delay: 0 min/mi | Delay: 2.0 min/mi | Delay: 0.6 min/mi | Delay: 0.5 min/mi | Delay: 1.2 min/mi |
| **10-second dwell time** | | | | | |
| 2 | 25.0 | 13.6 | 20.0 | 20.7 | 16.3 |
| 4 | 18.3 | 11.4 | 15.5 | 15.9 | 13.4 |
| 6 | 14.3 | 9.7 | 12.5 | 12.8 | 10.9 |
| 8 | 11.3 | 8.2 | 10.1 | 10.3 | 9.2 |
| 10 | 8.6 | 6.7 | 7.8 | 8.0 | 7.3 |
| **20-second dwell time** | | | | | |
| 2 | 22.0 | 12.7 | 18.0 | 18.6 | 15.3 |
| 4 | 15.3 | 10.1 | 13.2 | 13.5 | 11.7 |
| 6 | 11.5 | 8.3 | 10.3 | 10.5 | 9.2 |
| 8 | 9.0 | 6.9 | 8.3 | 8.4 | 7.6 |
| 10 | 6.9 | 5.6 | 6.5 | 6.5 | 6.1 |
| **30-second dwell time** | | | | | |
| 2 | 19.5 | 11.8 | 16.3 | 16.8 | 14.0 |
| 4 | 13.0 | 10.7 | 11.5 | 11.8 | 10.3 |
| 6 | 9.7 | 7.3 | 8.8 | 9.0 | 8.0 |
| 8 | 7.5 | 6.0 | 7.0 | 7.0 | 6.5 |
| 10 | 5.8 | 4.9 | 5.5 | 5.5 | 5.2 |
| **40-second dwell time** | | | | | |
| 2 | 17.6 | 11.1 | 15.0 | 15.4 | 13.0 |
| 4 | 11.4 | 8.3 | 10.2 | 10.4 | 9.3 |
| 6 | 8.3 | 6.5 | 7.7 | 7.8 | 7.1 |
| 8 | 6.4 | 5.3 | 6.0 | 6.1 | 5.7 |
| 10 | 5.0 | 4.3 | 4.8 | 4.8 | 4.5 |
| **50-second dwell time** | | | | | |
| 2 | 16.0 | 10.5 | 13.8 | 14.2 | 12.1 |
| 4 | 10.1 | 7.6 | 9.2 | 9.3 | 8.4 |
| 6 | 7.3 | 5.9 | 6.8 | 6.9 | 6.3 |
| 8 | 5.6 | 4.7 | 5.3 | 5.4 | 5.1 |
| 10 | 4.4 | 3.8 | 4.2 | 4.2 | 4.0 |
| **60-second dwell time** | | | | | |
| 2 | 14.7 | 9.9 | 12.8 | 13.1 | 11.4 |
| 4 | 9.1 | 7.0 | 8.4 | 8.5 | 7.7 |
| 6 | 6.5 | 5.4 | 6.1 | 6.2 | 5.7 |
| 8 | 5.0 | 4.3 | 4.8 | 4.8 | 4.5 |
| 10 | 3.9 | 3.5 | 3.8 | 3.8 | 3.6 |

NOTE: Data based on field measurements. Traffic delays shown reflect peak conditions. Dwell times are average dwell times.
[a] Without traffic or control delays.
[b] Includes signal and right-turn delays.
[c] Includes control delay. This column should also be used for single normal-flow bus lanes where the capacity analysis includes deductions for right-turn interferences.

Exhibit 2-60a
Estimated Bus Speeds, $V_0$ (mph)—Mixed Traffic[R29]

| Stops/ mi | CBD Delay: 3.0 min/mi | Central City Delay: 0.9 min/mi | Suburbs Delay: 0.7 min/mi |
|---|---|---|---|
| **10-second dwell time** | | | |
| 2 | 11.1 | 18.2 | 19.4 |
| 4 | 9.6 | 14.4 | 15.1 |
| 6 | 8.4 | 11.8 | 12.3 |
| 8 | 7.2 | 9.6 | 10.0 |
| 10 | 6.0 | 7.6 | 7.8 |
| **20-second dwell time** | | | |
| 2 | 10.5 | 16.5 | 17.5 |
| 4 | 8.8 | 12.4 | 13.0 |
| 6 | 7.3 | 9.8 | 10.1 |
| 8 | 6.0 | 7.9 | 8.1 |
| 10 | 5.1 | 6.3 | 6.4 |
| **30-second dwell time** | | | |
| 2 | 9.9 | 15.1 | 15.9 |
| 4 | 7.9 | 10.9 | 11.3 |
| 6 | 6.5 | 8.4 | 8.7 |
| 8 | 5.5 | 6.7 | 6.9 |
| 10 | 4.5 | 5.3 | 5.4 |
| **40-second dwell time** | | | |
| 2 | 9.4 | 14.0 | 14.6 |
| 4 | 7.3 | 9.7 | 10.1 |
| 6 | 5.9 | 7.4 | 7.6 |
| 8 | 4.9 | 5.9 | 6.0 |
| 10 | 4.0 | 4.7 | 4.7 |
| **50-second dwell time** | | | |
| 2 | 8.9 | 12.9 | 13.5 |
| 4 | 6.7 | 8.8 | 9.1 |
| 6 | 5.4 | 6.6 | 6.7 |
| 8 | 4.4 | 5.2 | 5.3 |
| 10 | 3.6 | 4.1 | 4.2 |
| **60-second dwell time** | | | |
| 2 | 8.5 | 12.1 | 12.6 |
| 4 | 6.3 | 8.0 | 8.2 |
| 6 | 5.0 | 5.9 | 6.0 |
| 8 | 4.0 | 4.7 | 4.7 |
| 10 | 3.3 | 3.7 | 3.7 |

NOTE: Data based on field measurements. Traffic delays shown reflect peak conditions. Dwell times are average dwell times.

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