CHAPTER 3
OPERATIONS CONCEPTS

CONTENTS

LIST OF EXHIBITS

1. INTRODUCTION

Chapter 3 of the *Transit Capacity and Quality of Service Manual* (TCQSM) presents the basic transit capacity, speed, and reliability concepts that form the basis for many of the computational methods found in later chapters:

Organization of Chapter 3.

- Section 2 defines transit capacity, speed, and reliability, and highlights the key factors influencing each. Later sections in this chapter focus in more detail on these factors and their specific effects on capacity and speed.
- Section 3 provides an overview of transit passenger demand patterns and the external factors (i.e., factors not under the control of a transit agency) that influence demand.
- Section 4 discusses dwell time's significant impact on transit capacity and speed and the factors that contribute to dwell time.
- Section 5 reviews the characteristics of transit operating environments (rights-of-way) that influence capacity, speed, and reliability.
- Section 6 covers factors related to transit stops and stations (e.g., fare collection, stop spacing, passenger service time) that affect capacity and speed.
- Section 7 is a list of the references that provided material used in the chapter.

HOW TO USE THIS CHAPTER

This chapter provides a basic set of capacity and quality of service definitions used throughout the TCQSM; all readers will ideally be familiar with Section 2 before applying the computational methods presented later in the manual (Chapters 5–10).

Although the TCQSM's scope does not include ridership estimation, changes in ridership demand can nevertheless affect transit speed and capacity by changing dwell time. Section 3 summarizes current research on external influences on ridership demand, including time-of-day demand patterns, land use density, demographic patterns, and travel demand management (TDM) programs. This material will be of interest to readers wanting to know more about the relative impacts of various external factors on ridership. (Ridership changes related to changes in quality of service are discussed in Chapter 4, Quality of Service Concepts.)

Sections 4–6 examine in detail the influence of various factors related to dwell time, operating environment, and stops and stations, respectively, on transit capacity and speed. These sections are recommended reading for those new to transit operations analysis. In addition, these sections provide a series of "illustrative exhibits" that depict the relative impact of these factors on capacity and speed. These exhibits will be useful to readers who want to quickly identify areas to consider prioritizing or studying in detail when speed or capacity improvements are desired.

Because exact values of speed and capacity are highly dependent on the specific conditions existing on a particular transit route or facility, these exhibits deliberately do not present specific capacity and speed values. Readers desiring such values can apply the speed and capacity methods presented by mode in Chapters 6–9.

While an effort has been made to select representative conditions when developing the illustrative exhibits, all relationships presented in the exhibits apply only to the set of assumptions used to create the exhibit (and listed with each exhibit). It is not expected that changing these assumptions will change the overall trends or relationships; however, it is not recommended that these exhibits be used as a substitute for calculations when an exact answer is required.

OTHER RESOURCES

Other TCQSM material related to this chapter includes:

- The "What's New" section of Chapter 1, User's Guide, which describes the changes made in this chapter from the 2nd Edition;
- Chapter 2, Mode and Service Concepts, which introduces the operating environments that are addressed in more detail in this chapter;
- The initial sections of Chapters 6 (Bus Transit Capacity), 8 (Rail Transit Capacity), and 9 (Ferry Transit Capacity), which provide mode-specific operations concepts that build upon this chapter's more broadly applicable material; and
- The manual's CD-ROM, which provides links to electronic versions of all of the TCRP reports referenced in this chapter.

2. CAPACITY, SPEED, AND RELIABILITY

OVERVIEW

Transit agencies may consider themselves fortunate when they have capacity problems—it indicates a strong demand for their service. However, for the majority of small and mid-size transit systems, capacity constraints are usually not an issue—sufficient demand exists to provide service only once or twice per hour on most routes and perhaps more frequently on the busiest routes. However, even smaller systems may experience capacity issues in downtown areas where a number of routes may converge.

Why, then, should transit agencies and transportation planners be concerned with transit capacity? There are a number of reasons:

Factors influencing capacity also influence speed and reliability.

Recovery time is time included in the schedule between vehicle runs to allow late-arriving vehicles to start their next runs on time.

- **Improving speed and reliability.** The same factors that influence transit capacity also influence speed and reliability. Faster, more reliable service is more attractive to passengers. Speed improvements reduce the time required for a transit vehicle to travel its route, while reliability improvements may allow reductions in the scheduled recovery time. In the best-case scenario for a transit operator, the combined reduction in running and recovery time would be greater than or equal to one headway. This result allows the route to be operated with one fewer bus or, alternatively, to be operated at a higher frequency than before at the same operating cost. More typically, the time saved postpones the need to add more service to maintain a particular headway, due to delays arising from traffic congestion. This result is nevertheless a positive outcome, as it results either in (*a*) costs postponed to future years or (*b*) the need to cut service postponed to future years, in situations where the budget cannot accommodate increased costs (*1*).
- **Managing passenger loads.** Capacity plays a role in determining how many buses, trains, or railcars are needed to provide a desired quality of service with respect to passenger loading.

Changing the fare collection method or vehicle type can have unanticipated impacts on running time and crowding that may entail additional costs to correct.

- **Forecasting the effects of changes** in fare collection procedures, vehicle types, or other agency decisions. Dwell time, the time a vehicle spends stopped to load and unload passengers, is often the key determinant of speed and capacity. Changes that impact passenger service times may create unanticipated impacts on running times, passenger loads, or vehicle bunching, which may entail additional costs to correct. Changes in vehicle types (e.g., switching from standard to articulated buses, or high-floor to low-floor buses) may also have dwell time and passenger capacity impacts.
- **Planning for the future.** Planning studies may suggest more than one possible mode or service type to meet a particular travel demand. Knowledge of the speed and capacity provided by each option is essential for making an informed decision. New light rail and bus rapid transit (BRT) systems are sometimes developed with built-in capacity constraints to help reduce initial costs. Knowing how much of a constraint will exist is important for comparing short-term savings with long-term costs.
- **Analyzing the operation of major bus streets** in large cities and the areas around transit centers in all sizes of communities. Small cities that operate a

small number of buses will often have all of the buses meet at a central location. Because delays in bus arrivals will often result in delays to the other bus departures (to avoid missing transfer connections), efficient bus access into and out of the transit center is important. Larger cities will often have a number of routes converge on a small number of downtown streets, and the TCQSM's capacity procedures can be used to analyze the operation of those streets.

- **Special event service.** Bus services are sometimes required to bring a portion of the demand for community festivals, county fairs, sporting events, and the like to the event site from remote parking areas. The procedures in this manual can be used to help size passenger waiting areas at the event site and to help determine the appropriateness of temporary transit preferential treatments (e.g., temporary bus lanes).
- **Transportation system management.** Transit vehicles can carry many more passengers than automobiles. As a result, an increase in transit vehicle capacity will increase the person capacity of a facility by more than a corresponding percentage increase in automobile vehicle capacity (*2*).

Readers who are familiar with the *Highway Capacity Manual* (*3*) will find that transit capacity is different than highway capacity: transit capacity deals with the movement of *both* people and vehicles; depends on the size of the transit vehicles and how often they operate; and reflects interactions between transit vehicles, passengers, and other travel modes. Transit capacity also depends on the transit agency's operating policies, which normally specify service frequencies, allowable passenger loading, and the type of vehicle used to carry passengers. Accordingly, the traditional concepts applied to highway capacity need to be adapted and broadened (*2*).

The remainder of this section introduces the basic capacity, speed, and reliability concepts common to all public transit modes. Subsequent sections discuss the impacts of specific factors on capacity, speed, and reliability. Chapters 6 through 10 apply these concepts to the development of mode- and facility-specific calculation procedures. Many of these concepts also relate to the quality of service perceived by transit passengers; these issues are discussed further in Chapters 4 and 5.

CAPACITY CONCEPTS

Public transit service focuses on moving people from one place to another. Consequently, transit capacity is focused more on the number of people that can be served in a given amount of time (*person capacity*) than on the number of transit vehicles served by a transit facility (*facility* or *line capacity*). However, determining vehicle capacity is often a necessary first step in determining person capacity.

Person Capacity

The number of people that can be served by a particular transit facility depends on a number of factors, some under the control of the transit operator and some not. At its most basic level, person capacity (persons per hour) is the product of facility capacity (vehicles per hour) and vehicle passenger capacity (persons per vehicle).

Person capacity defined.

The person capacity of a given transit route or facility is defined as follows:

> The maximum 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.

This definition is not absolute, and it is instructive to look at the meaning of specific pieces of the definition:

- *"A given location"*: Capacity is determined at a specific location, typically the segment of a route or facility that carries the most people, known as the maximum load segment. The number of boardings over the length of a route over the course of an hour may be considerably greater than the value of capacity, depending on how often passengers get on and off; capacity represents the maximum number of passengers that can be carried past a given location.
- *"Specified operating conditions"*: The number of people that can be carried depends on the number of vehicles operated and the size of those vehicles. It should be specified whether a reported capacity reflects scheduled capacity (how many people *can* be served under the current schedule), design capacity (how many people *could* be served with no limits on vehicle availability), or some other condition.
- *"Without unreasonable delay"*: Person capacity is maximized when a constant queue of passengers exists to fill all available passenger spaces each time a vehicle arrives, as happens with amusement park rides, for example. Achieving this theoretical capacity requires that some or all passengers be passed up by the first vehicle to arrive, and often by subsequent vehicles. Transit passengers generally dislike pass-ups, particularly when there is a long wait involved for the next vehicle, although they may tolerate it for special event service, when they know another vehicle will be along shortly. Consequently, person capacity for transit must allow some slack to accommodate potential surges in demand, when it is desired that virtually all passengers will be able to board the first vehicle that goes to their destination.
- *"Without…hazard or restriction"*: A key assumption in determining person capacity is the passenger capacity of each vehicle. Person capacity will be greatest when people are assumed to be packed in as tightly as possible (*crush loading*), but in practice, North Americans will not tolerate such conditions and will wait for another vehicle. Therefore, person capacity should be based on the maximum level of crowding that persons will normally tolerate. Similarly, many longer-distance transit services design for all passengers being seated, both for passenger comfort and (with freeway operations) liability reasons.
- *"With reasonable certainty"*: Capacity should reflect the number of people that can be carried on a sustained basis day after day, considering variations in passenger demand, traffic congestion, and other factors not under the control of the transit operator. More people than the design capacity may sometimes be carried, but not most or all of the time.

Vehicle Capacity

The vehicle capacity of a given transit route or facility is defined as follows:

Vehicle capacity defined.

> The maximum number of transit vehicles (buses, trains, vessels, etc.) that can pass a given location during a given time period at a specified level of reliability.

Different transit modes have historically referred to vehicle capacity by different names.

Vehicle capacity is known by different names in the modal capacity chapters of this manual (Chapters 6 through 9)—for example, bus capacity, line capacity, and vessel capacity—but all of these names relate back to the number of transit vehicles that can pass a point during a given period of time, typically 1 h. Ultimately, vehicle capacity depends on the minimum possible headway (time spacing) between individual transit vehicles. This minimum headway is dependent on control systems (e.g., traffic or train signals), passenger boarding and alighting demand at busy stops, the number of transit vehicles that can use a stop or station simultaneously, and, often, interactions with other vehicles (transit or non-transit).

An important part of the vehicle capacity definition is "at a specified level of reliability." Vehicle capacity is maximized when a route or line is operated at the minimum headway, so that the next vehicle is ready to arrive at a stop or station when the vehicle ahead of it pulls out (and, in the case of rail operations, is a safe distance down the line). However, this is an unstable form of operation. The moment that one vehicle's dwell time exceeds the value used to develop the minimum headway, all subsequent transit vehicles will be delayed until the end of the peak period, when headways increase again. The result is that the actual number of transit vehicles that can be reliably served will be less than the theoretical maximum capacity.

Operating margins.

The TCQSM uses the concept of an *operating margin* to allow the analyst to specify a desired level of reliability. The operating margin is added to the minimum headway as an allowance for longer-than-average dwell times. The sum of dwell time and operating margin represents the longest dwell time that can occur without one transit vehicle impeding the following transit vehicle. Although the value of capacity that is obtained will be lower when an operating margin is used, achieved speeds will be higher, as vehicles will not have to stop and wait for the preceding vehicle as often, and overall reliability will be better.

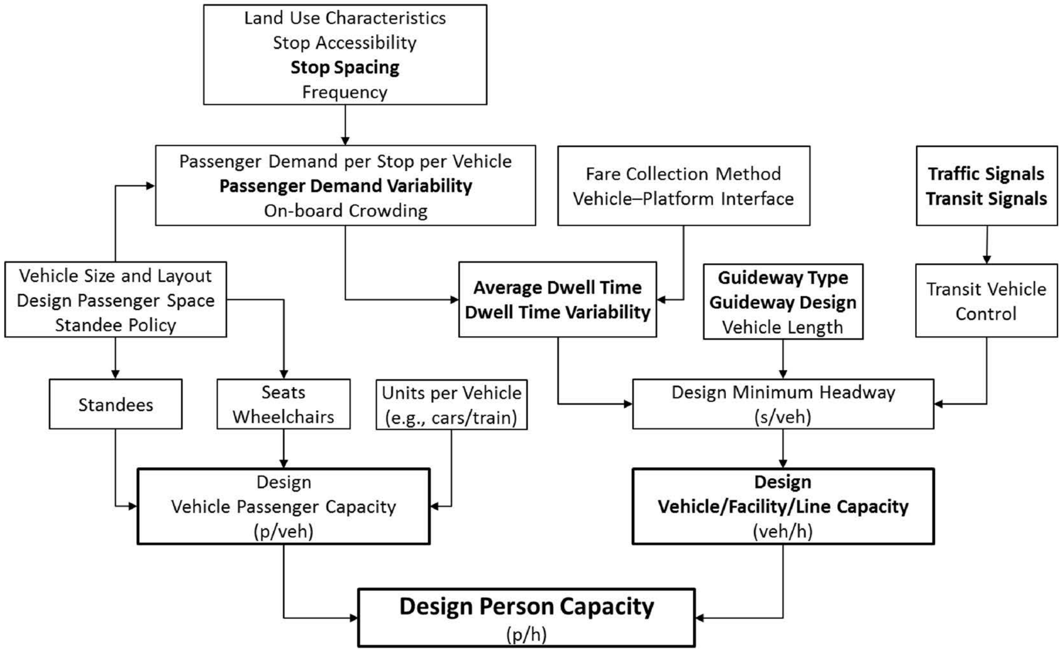
Factors Influencing Transit Capacity

Exhibit 3-1 lists the major factors that influence person capacity—the number of people that can consistently be transported past a given point. It can be seen that factors from every category in the list above are shown as influences in the exhibit. Some of these factors, shown in bold, also influence speed, reliability, or both.

Unless stated otherwise, all capacities given in the TCQSM are design capacities that can be regularly achieved. They are less than maximum (theoretical) capacities.

Exhibit 3-1 also shows person capacity as a *design* capacity. As explained further in Section 7, Capacity Concepts, all capacities given in the TCQSM are design capacities, unless stated otherwise. Design capacities are capacities that can be sustained day after day, accounting for small irregularities in service and variations in passenger demand and arrival patterns. Design capacities are less than the maximum (*theoretical*) capacities that could be achieved if service was 100% reliable, passenger demand never varied, passengers filled every available space on every trip, and so on.

Exhibit 3-1
Factors Influencing Person Capacity



Note: Inputs to design person capacity shown in bold also influence transit speed, reliability, or both.

Exhibit 3-1 shows that person capacity depends on both how many transit vehicles can pass by a point in an hour (*vehicle, facility,* or *line capacity*) and the number of passengers that can be carried on those vehicles (*passenger capacity*).

Factors influencing vehicle passenger capacity.

Passenger capacity is influenced by the number of units per vehicle (e.g., cars per train), the size of the vehicle, and how the space inside each transit vehicle is allocated between seats and standees. Agency policies or government regulations may determine whether standees are allowed and the number of wheelchair positions that must be provided. Agency policy will also determine a design space per standing passenger which, in turn, determines how many standees can be accommodated.

Factors influencing dwell time.

Vehicle size and layout also influence dwell time, because they affect the likelihood of a vehicle arriving at a stop already crowded with passengers, some of whom will need to make their way to and out of the door(s) before other passengers can board. The fare collection method, the height of the platform relative to the vehicle floor, the location of waiting passengers relative to boarding doors, and the number and width of boarding doors all influence the average boarding time per passenger. Finally, various land use, pedestrian infrastructure, and transit service characteristics influence the demand to use transit at a given stop or station. Thus, dwell time is the product of the number of boarding passengers at the critical (typically busiest) door multiplied by the time to serve each passenger, plus the time required to serve alighting passengers through the same door.

The minimum operable headway controls vehicle (bus facility, rail line, ferry vessel) capacity.

Dwell time, guideway characteristics (e.g., mixed traffic operation vs. exclusive guideway operation, platform lengths at stations), and traffic and transit signals influence the minimum headway that can be operated, which in turn controls vehicle capacity.

Other Capacity Considerations

The following considerations are also important (*2*):

1. Operations at vehicle capacity tend to strain transit systems, resulting in vehicle bunching, slower speeds, and passenger delays. These operations do not represent desirable operating conditions. Most North American transit systems operate at vehicle capacity for relatively short periods of time, if at all.
2. Person capacity relates closely to system performance and service quality in terms of speed, comfort, and service reliability. A single fixed number for capacity can often be misleading. The concept of *productive capacity*, the product of person capacity and speed, provides a useful measure of system performance that incorporates both the passenger (speed) and operator (capacity) points of view (*4*).
3. Capacities obtained by analytical methods or simulation must be checked against actual operating experience for reasonableness.

Illustrative Transit Capacities

Difficulty of Providing Representative Capacities

The capacity offered by a given mode can vary widely, depending on the circumstances.

It is difficult to provide representative transit capacities by mode, because of the range of factors that enter into the determination of capacity. For example, heavy rail person capacity can range from around 12,000 persons per hour per direction (p/h/dir) with short trains and a combination of train signaling and critical station dwell time that allows 25 trains per hour, to around 48,000 p/h/dir with long trains and the ability to operate 32 trains per hour. Both of these values assume maximum design load conditions—sufficient space to allow passengers to stand without touching while the vehicle is in motion. When trains are more tightly packed, higher capacities can be achieved, with a resulting poorer passenger quality of service.

Influence of stopping patterns on capacity.

Stopping patterns also play a role in determining capacity. For example, when buses operate non-stop on freeway managed lanes or on some grade-separated busways, a very high volume of buses can be served: for example, up to 735 bus/h/dir on the New Jersey approach to the Lincoln Tunnel (*5*) and 280 bus/h/dir on the busiest portions of Bogotá's TransMilenio BRT system (*6*). In these cases, the facility acts like a pipe, transporting buses to their ultimate destinations, and the capacity of the bus terminal(s) receiving the buses ultimately constrains the facility capacity. Rail corridors can be constructed with multiple tracks, allowing a variety of stopping patterns to be provided and increasing the number of trains that can be accommodated in the corridor.

To obtain an apples-to-apples comparison of the capacities achievable by different combinations of modes, rights-of-way, and stopping patterns, it is necessary to calculate the capacity of each combination using a common set of assumptions (e.g., passenger demand, design space per passenger, right-of-way type). The procedures given in Chapters 6–9 can be used to determine these capacities. The results should be reported for the maximum load segment. When not every transit service stops at every station, evaluating the vehicle capacity of individual stations may also be important to an analysis.

Passenger Traffic Density

As an illustration of the relative abilities of different modes to carry large numbers of passengers, the concept of *passenger traffic density* (passenger miles per directional route mile) is employed. Passenger traffic density measures how many passengers are carried on average over a given mile of a route. When applied to a facility's maximum load segment and peak hour, traffic density can directly express capacity in terms of the maximum number of passengers that can be carried through the maximum load segment during the peak hour.

When measured over longer distances and timeframes, passenger traffic density values are influenced not only by capacity (the greater the capacity, the more passengers that *can be* carried on a section of a route), but also by demand over the timeframe (the greater the demand, the more passengers that *are* carried) and by loading levels (the greater the average load, the more passengers on board in a given section of the route). The data available from the National Transit Database (NTD, *7*) usable for determining passenger traffic density are system-level by mode on weekdays. As a result, NTD-based passenger traffic density values reflect more than just capacity. They are nevertheless useful for comparing relative amounts of passenger service by mode, particularly at the higher end of the traffic density range for each mode.

Exhibit 3-2 shows the range of weekday passenger traffic densities and the median (50th-percentile) value by mode from all U.S. transit systems reporting to the NTD in 2010. Definitions of each mode and system size are provided with the exhibit. Note that the chart uses a logarithmic scale.

Several observations can be made about this exhibit:

- The modes with the highest passenger traffic densities typically provide the highest-capacity vehicles, the most frequent service, or both.
- There is considerable overlap in the passenger density ranges between modes, suggesting that more than one mode is often feasible from a capacity standpoint for accommodating a particular passenger demand.
- The ferry range includes New York's Staten Island Ferry as an outlier at the high end. This ferry serves a role closer to a subway line in terms of its passenger-carrying characteristics (almost 33,000 passenger-miles per route mile on an average weekday). The second-highest ferry system, Washington State Ferries, carried 2,170 passenger-miles per route mile on weekdays.
- The commuter bus mode has relatively high passenger densities because commuter buses tend to be highly loaded for most or all of their route and service can be operated frequently.
- Passenger traffic density values in the lower half of the ranges for each mode are more reflective of demand than of capacity.

BRT does not appear in the exhibit, as the NTD did not include it as a separate mode in 2010 and no independent source of passenger-mile data for BRT was available. Given the range of possible BRT operation (e.g., freeways, busways, on-street), a relatively large range of passenger traffic densities would be expected, likely in the range of large bus systems up to the upper end of the commuter bus range for mature systems.

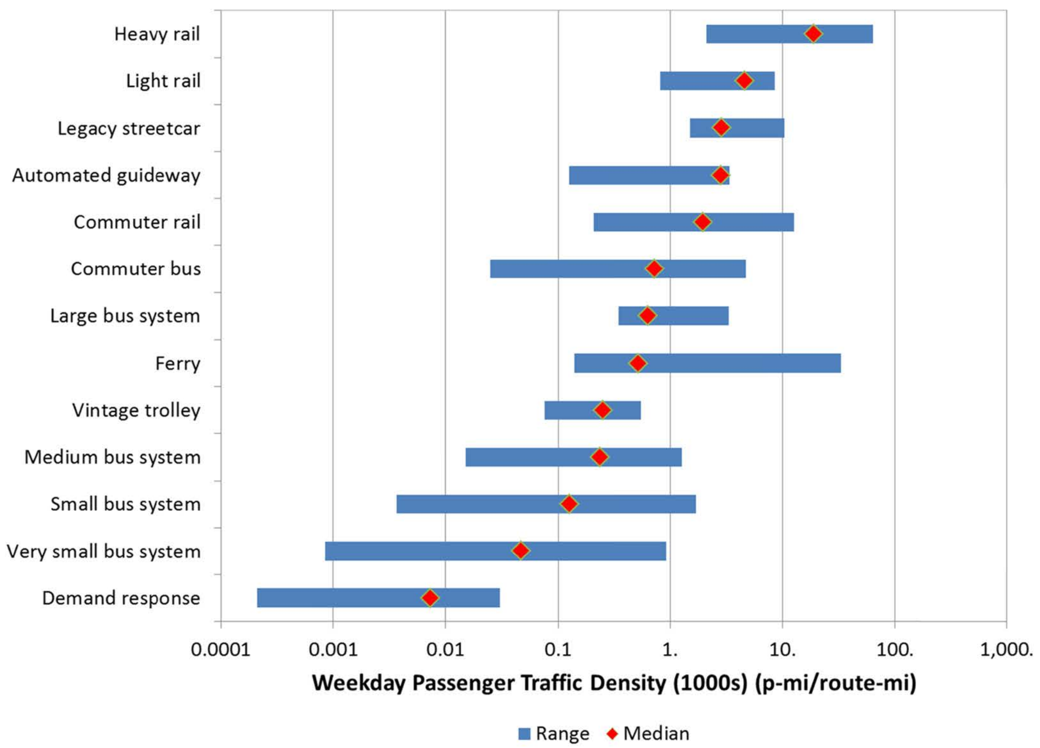


Exhibit 3-2
Average Weekday Passenger Traffic Densities (2010)

Source: Derived from NTD data (*7*).

Notes: Light rail = modern light rail systems built in the 1970s or later.
Legacy streetcar = light rail systems built before the 1970s.
Vintage trolley = non-legacy streetcar systems using historic or historic-looking vehicles.
Insufficient data available to separate modern streetcar from light rail.
Commuter bus = motorbus data from NTD reporters that primarily operate commuter bus service.
Large bus system = motorbus data from NTD reporters with >50 million annual boardings.
Medium bus system = motorbus data from NTD reporters with 10–50 million annual boardings.
Small bus system = motorbus data from NTD reporters with 1–10 million annual boardings.
Very small bus system = motorbus data from NTD reporters with <1 million annual boardings.
Bus rapid transit was not reported as a separate NTD mode in 2010 and thus is not shown.
Equivalent route miles for demand response calculated as (average passenger trip length [passenger miles per unlinked trip]) × (number of vehicles operated in maximum service) × 2.

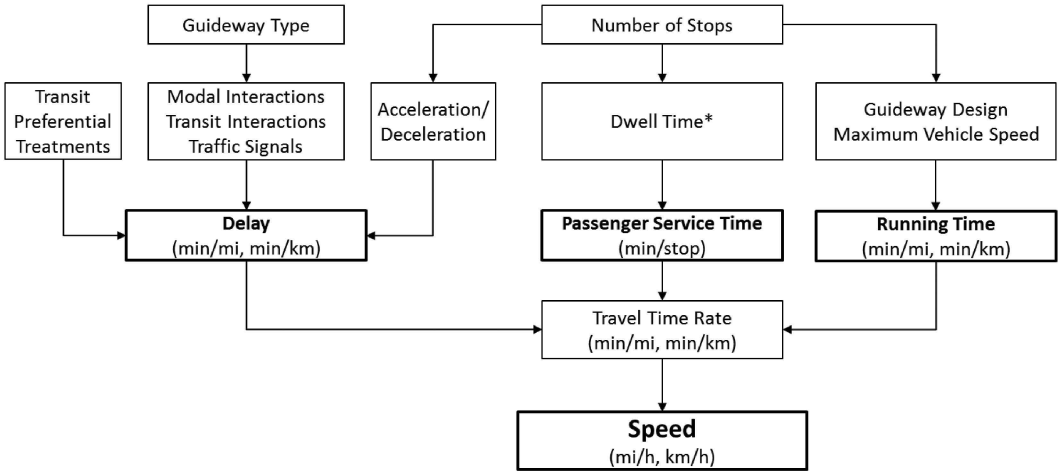
SPEED CONCEPTS

Speed is important to passengers, as it directly impacts the time required to make a trip. The more competitive that transit travel time is with competing modes, in particular the automobile, the more attractive transit service is to potential passengers. Attracting ridership is of course important to transit operators, but speed also impacts the cost of operating a route. The number of transit vehicles required to operate a service at a given frequency depends on the route's cycle time—the time required to make a round-trip on the route, plus driver layover time and any additional schedule recovery time required beyond layover time. The cycle time (in minutes) divided by the headway (in minutes per vehicle) gives the required number of vehicles to serve the route. If a route's cycle time can be reduced sufficiently to reduce the required number of vehicles, cost savings result. Alternatively, the saved vehicle can be used to increase frequency on this or another route, with no net change in operating costs.

Factors Influencing Transit Speed

Exhibit 3-3 shows the major factors that influence transit speed. As was the case with capacity, factors from nearly all of the categories listed at the start of this section contribute to transit speed (keeping in mind that a number of factors, not shown here, but shown in Exhibit 3-1, influence dwell time).

Exhibit 3-3
Factors Influencing Transit Speed



Note: *Factors influencing dwell time are shown in Exhibit 3-1.

Running time, passenger service time, and delay are the main components of transit speed.

Exhibit 3-3 shows that there are three main components of transit speed (shown in bold in the exhibit): *running time* (time spent at constant speed following acceleration), *passenger service time* (boarding and alighting time), and *delay* (external factors that impede transit vehicles). These times can be expressed as a travel time rate (time required to travel a given distance); the inverse of the travel time rate is speed.

The number of stops along a route influences transit speed in several ways.

Exhibit 3-3 also shows that the number of stops influences all three components of transit speed. The more frequently that transit vehicles stop, the more time they spend decelerating and accelerating, compared to time that could have been spent at running speed. More-frequent stops spreads passenger demand among stops, reducing the average boarding volume at any given stop and thus dwell time; however, acceleration and deceleration delays typically more than offset any dwell time benefits. Finally, when stops are frequent, transit vehicles may never reach the maximum speed they are capable of before they must begin decelerating again to the next stop.

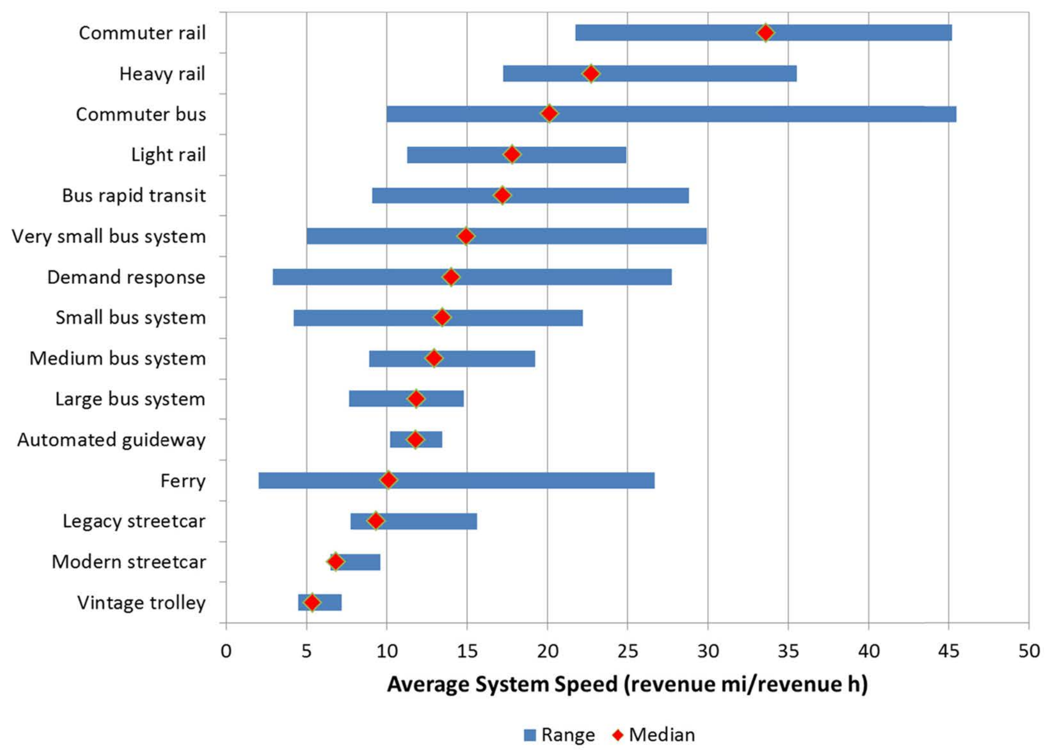
Factors influencing running time, passenger service time, and delay.

Running time is typically constrained by the guideway design (e.g., maximum allowed operating speed, vehicle passing provisions), the characteristics of the vehicles being operated (e.g., acceleration, maximum vehicle speed), and stopping frequency (constraining the achievable running speed). Passenger service time is directly related to the number of stops made to serve passengers and the average dwell time at each stop. Delay is primarily related to the type of guideway (e.g., mixed traffic operation vs. exclusive guideway), which determines how much transit vehicles are impeded by other modes (i.e., automobile, pedestrian, bicycle) that use or cross the guideway. The number of transit vehicles using a guideway relative to its capacity also influences delay (the closer a guideway is operated to its capacity, the more likely that transit vehicles will impede each other). Transit vehicles operating on roadways are also subject to traffic signal delays, which can be considerable. Transit preferential treatments can help offset some of mixed-traffic operation's negative impacts on transit speed.

Illustrative Transit Speeds

Exhibit 3-4 shows ranges of average system speeds (revenue miles per revenue hour) by mode in 2010, along with median speeds, based on all transit agencies reporting to the NTD (*7*). Exceptions are BRT, which is based on 2008 conditions and includes Canadian BRT data (*8*), and modern streetcar, which is based on mid-2012 operator data for the three lines in operation at the time. Average system speeds are based on all portions of all lines of a given mode operated by a given transit agency during all service hours. Actual operating speeds during peak hours, particularly in downtown locations, may be lower. Modes may be capable of higher average speeds than suggested by the U.S. operating data used to develop the exhibit. Nevertheless, the exhibit provides a reasonable comparison of relative differences in speed by mode.

Exhibit 3-4
Average System Speeds by Mode (2010)



Source: Derived from NTD data (*7*), Diaz and Hinebaugh (*8*), and modern streetcar operator data.

Notes: Light rail = light rail systems built in the 1970s or later.
Legacy streetcar = light rail systems built before the 1970s.
Modern streetcar = streetcar system using modern vehicles (2012 data).
Vintage trolley = non-legacy streetcar systems using historic or historic-looking vehicles.
Commuter bus = motorbus data from NTD reporters that primarily operate commuter bus service.
Large bus system = motorbus data from NTD reporters with >50 million annual boardings.
Medium bus system = motorbus data from NTD reporters with 10–50 million annual boardings.
Small bus system = motorbus data from NTD reporters with 1–10 million annual boardings.
Very small bus system = motorbus data from NTD reporters with <1 million annual boardings.
Bus rapid transit data reflect 2008 conditions and include Canadian systems.

A number of observations can be made about Exhibit 3-4:

- Higher speeds, regardless of mode, typically reflect long stop or station spacings and relatively high operating speeds.
- The modes with the highest median speeds also tend to operate in environments that provide some degree of separation from other traffic.
- A relatively wide range of speeds exists for most modes, reflecting differences in stop spacing and operating environment among different systems operating that mode (e.g., on-street vs. freeway operation for BRT).
- The larger the bus system in terms of annual boardings, the lower the average system speed, as larger systems tend to be found in larger cities with higher levels of traffic congestion.
- Ferry systems at the low end of the ferry speed range operate short crossings, where passenger service time and vessel docking time constitute a majority of the time spent in revenue service.

RELIABILITY CONCEPTS

As will be discussed in greater detail in Chapter 4, Quality of Service Concepts, reliability is important to passengers from the standpoints of arriving at one's destination on time and not having to wait too long at a stop or station for one's transit vehicle to arrive. From the operator's perspective, reliability impacts the schedule recovery component of cycle time (discussed above in the Speed Concepts subsection), and thus can be a contributor to increased operating costs when recovery time needs require that one or more extra vehicles be used to operate a route at a given frequency. Unreliable operations on frequent-service transit lines can result in vehicle bunching, with more passengers experiencing crowded onboard conditions.

Factors Influencing Transit Reliability

Exhibit 3-5 lists the major factors that influence transit reliability, divided into *internal* (under a transit agency's control) and *external* (not under a transit agency's control) factors. As can be seen from the exhibit, many different functions within a transit organization contribute to providing a reliable service for passengers. Most of these functions influence aspects of reliability under an agency's control; however, the capital projects function is responsible for projects that can help offset or even eliminate some external influences on reliability. Causes of and potential remedies for transit reliability issues are discussed in Chapter 4.

Exhibit 3-5 also shows that there are a number of interactions between the external and internal contributors to overall reliability. For example, although the scheduling and operations functions cannot control passenger and traffic demand variability, they can plan to control the effects of that variability. Passengers holding train doors open affect the reliability of that particular train and—if they jam the door mechanism in the process—also create a vehicle availability issue for the agency's maintenance and operations functions to address.

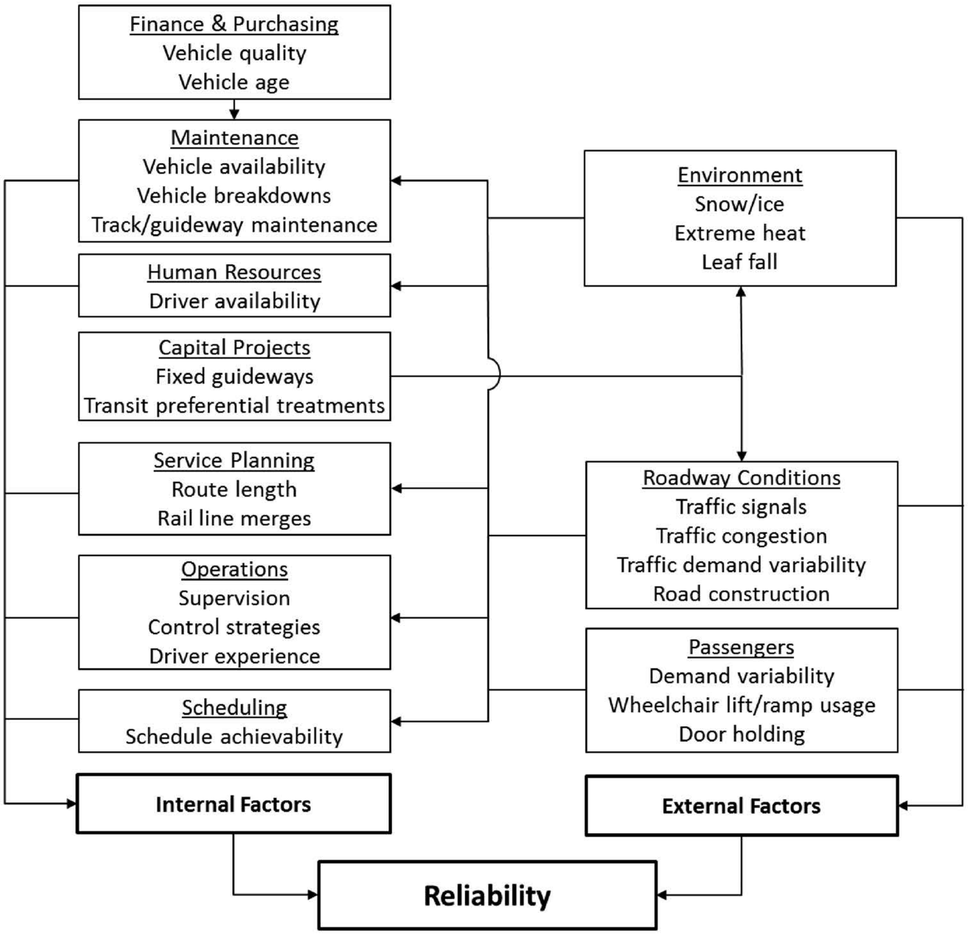


Exhibit 3-5
Factors Influencing Transit Reliability

3. PASSENGER DEMAND CHARACTERISTICS

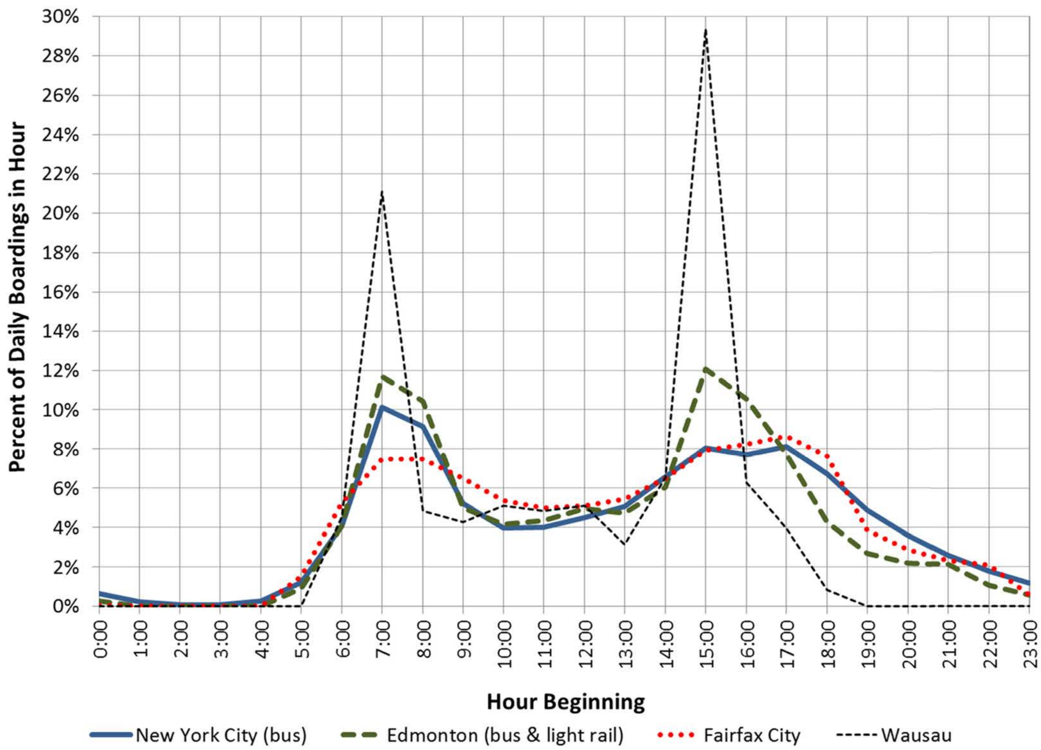
It is clear from the previous section that the demand to use transit, and variations in that demand, are important factors that influence transit capacity, speed, and reliability. As will be seen in Chapter 4, Quality of Service Concepts, demand also influences an transit operator's ability to provide a particular quality of service, as cost-effectiveness considerations enter into the decision-making process. Although the TCQSM is not a ridership forecasting manual, it is nevertheless useful to provide a high-level overview of some of the external factors that influence transit demand. Quality of service factors that influence ridership are discussed in Chapter 4.

TRANSIT PASSENGER DEMAND PATTERNS

Time-of-Day Demand Variation

Transit passenger demand has distinct peaking patterns, typically coinciding with peak commuting periods and—in many cases—school schedules. Exhibit 3-6 shows peaking patterns associated with four transit systems of various sizes: Wausau, Wisconsin (2011 population 39,000); Fairfax City, Virginia (suburban Washington, D.C., population 25,000); Edmonton, Alberta (bus and light rail service, population 812,000); and New York City (showing bus service only, population 8.2 million).

Exhibit 3-6
Illustrative Time-of-Day Variations in Transit Demand



Sources: Lu and Reddy (*9*), City of Edmonton (*10*), Connetics Transportation Group (*11*), and Urbitran Associates and Abrams-Cherwony & Associates (*12*).

Despite the wide range of population sizes and land use patterns represented by these locations, all share an a.m. peak that is highest in the 7:00–8:00 hour and (except for Wausau) an 8:00–9:00 hour that is nearly as high. All also share a midday period from 10:00 (and for all but Fairfax, 9:00) to 14:00 where hourly demands are relatively constant at around 4–5% of daily demand. Finally, all have a p.m. peak period that begins in the 15:00–16:00 hour and (except for Wausau) spreads out more than during the a.m. period.

There are also differences between the four agencies' demand patterns:

- Wausau has two very short, sharp peaks, corresponding to school start and end times, and relatively constant demand throughout the rest of its service day (which is shorter than that of the other systems). At the time the data were collected, peak demand was 5.75 times as high as off-peak demand, which required eight buses (most making just one a.m. and one p.m. trip) to supplement the nine regular buses (*12*).
- Fairfax City's off-peak demand, in contrast, is much closer to its peak demand and it has the most spread out peak periods. At the time the data were collected, the city operated two bus routes connecting a Metrorail rapid transit station to the George Mason University campus, circulating through the city along the way. Thus, its demand patterns reflect both commuting patterns into the center of the region, and student travel to and from the university. Peak demand is only 1.7 times off-peak demand, which allowed the same service levels to be provided throughout the day (*11*).
- Edmonton's peak demand is high relative to its off-peak periods, with peak demand 2.6 times as high as off-peak demand. This pattern requires that a significant amount of peak-period-only service be provided, much of which connects lower-density neighborhoods in the outer parts of the city to downtown, the University of Alberta, or light rail (which serves both activity centers). The p.m. peak is highest relatively early, with the greatest demand occurring during the 15:00–16:00 hour. (This pattern does not hold for every route; for example, light rail peaks an hour later and has a mini-peak at 21:00 when night classes end at the university.) (*10*)
- New York City, which is extremely dense, has relatively high midday demand relative to peak demand, with peak demand about twice as high as off-peak demand and a broad p.m. peak. This demand pattern requires extra service during peak periods, but proportionately less than required by Edmonton. Unlike the other examples, New York's demand is highest in the a.m. peak.

These demand patterns illustrate several important points about linkages between demand, land use patterns, service patterns and costs, and quality of service. Extra service added during the peak often costs more to provide, due to contractual needs to provide part-time drivers a minimum amount of work (not all of which may be possible to fill with revenue service) or to pay drivers working split shifts at a higher rate because of the inconvenience of the work schedule. Extra service also requires more vehicles to provide the service (added capital costs) and extra staff to maintain those vehicles. Transit service in very dense areas, or transit service that serves several different trip purposes (as in the Fairfax example) has less peaking, making it more feasible to provide good all-day service on those routes. Otherwise, service between

Drivers working split shifts work both peaks, with time off in between.

low-density residential areas and major activity centers may only be feasible during peak periods or at a very low frequency (hourly or worse) during off-peak periods (*13*).

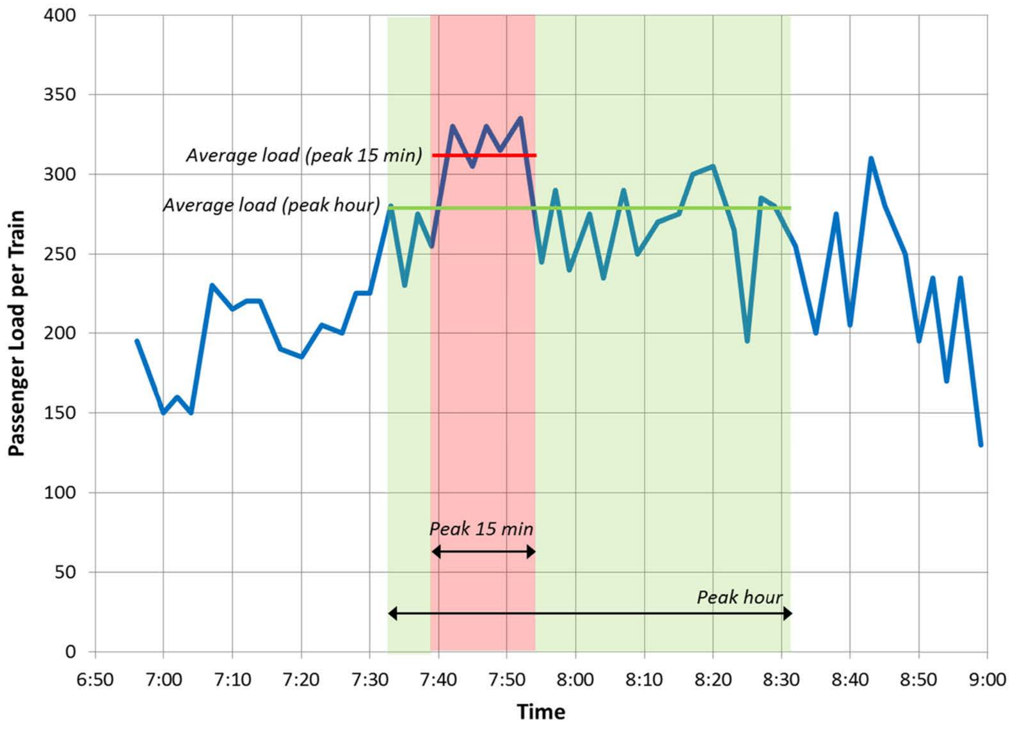
Peak-Hour Demand Variation

Passenger demand can also vary within the peak period. Some of this variation is attributable to people timing their trips to arrive at a destination (e.g., job, school) as close to the desired starting time as possible; other is due to day-to-day variations in people's activities that result in them taking different transit vehicles on different days. These variations have implications on the level of onboard crowding, as a service scheduled to accommodate average demand over the peak hour may experience overcrowded conditions during the peak of the peak.

The concept of a *peak hour factor* (PHF) is used to express this demand variation within the peak hour (or any other analysis hour). The PHF is defined as the demand during the hour divided by four times the demand during the peak 15 min of the hour. Thus a PHF of 1.00 indicates even demand in each 15 min period of the hour, while a PHF of 0.25 would indicate that all the demand occurs in one 15-min period. Typical transit PHFs range from 0.60 to 0.95 (*2, 14*).

Exhibit 3-7 shows actual train loading data for the a.m. peak period for one day at a peak load station on Vancouver's SkyTrain (*15*), with the peak hour and the peak 15 min indicated, along with the average passenger loads during those time periods. The PHF represented in the graph is 0.92, which is relatively high (i.e., relatively even loading by 15-min intervals) for transit service.

Exhibit 3-7
Illustrative Variation in Peak-Hour Demand



Source: Derived from *TCRP Report 13* (*15*).
Note: Vancouver, B.C., Broadway Station inbound, October 27, 1994.

Even though the average load throughout the peak hour, relative to the peak 15 min, is fairly even, it can be seen from the exhibit that there are considerable variations from one train to the next. Furthermore, the average load during the peak 15 min is 35 passengers per train higher than the average for the peak hour. If this agency had only peak-hour ridership totals to work with and had (hypothetically) a service standard of 300 passengers per train, it might appear to meet its standard based on the average peak hour load, while in actuality, peak 15-min loads would exceed the standard. In many cases, the proportional difference between peak-hour and peak-15-min demands will be much greater than shown in Exhibit 3-7.

Both Exhibit 3-6 and Exhibit 3-7 have illustrated the importance of being aware of demand patterns over both long and short periods of time. The use of automatic passenger counting (APC) equipment allows the collection of passenger demand data on a regular basis. *TCRP Report 113: Using Archived AVL-APC Data to Improve Transit Performance and Management* (*16*) provides guidance on collecting, archiving, and using APC data. *TCRP Report 135: Controlling System Costs: Basic and Advanced Scheduling Manuals and Contemporary Issues in Transit Scheduling* (*17*) describes the use of ridership data, in conjunction with transit agency loading standards and policy headways, when developing transit schedules.

DEMAND RELATED TO DEMOGRAPHICS

The *2009 National Household Transportation Survey* (NHTS, *18*) provides data on household travel patterns for all travel modes and trip purposes. The following are selected demographic factors that relate to transit use in the U.S. (*19*):

- *Gender.* Controlling for other factors that influence mode choice, males are 7% more likely to use transit for a given trip than females.
- *Age.* Compared to persons 16–24 years old, persons in the 25–44 and 45–64 age groups are about half as likely to use transit for a given trip (45–64 years olds are slightly less likely to use it than 25–44 year olds), and those 65 and older are one-fifth as likely to use it. (The NHTS did not ask about trips made by children.)
- *Employment.* Persons who are employed are 41% more likely to use transit for a given trip than those not in the workforce or unemployed.
- *Number of cars in household.* Compared to zero-car households, one-car households are 10% as likely, two-car households 3% as likely, and three-car households 2% as likely to use transit for a given trip.

DEMAND RELATED TO LAND USE

Land Use Densities Supporting Various Transit Service Modes and Levels

As indicated above, there are a number of factors that influence the ridership demand for a given transit line—for example, ease of access, demographic factors such as age and car ownership, cost and convenience of transit relative to competing modes—but the density of land uses along the line is a basic requirement. Simply put, the more people and the more jobs that are within easy access distance of transit service, the more potential customers there are to support high-quality service. Conversely, the more spread apart land uses are, the more difficult it is to develop a transit line that can connect the relatively sparse population and can also provide the necessary travel speed to compete with driving an automobile.

Any guidance on the minimum land use density that can support a particular frequency or mode of transit service must come with the caveat that the answer depends on how much one is willing to subsidize service. In the case of fixed-guideway transit service, the answer also depends on how much grade separation is desired or required, as that greatly affects the capital cost of constructing the guideway.

Existing guidance on the minimum density required to support a particular frequency of service ultimately derives from one mid-1970s study (*20*). This study developed rates of transit trip-making at different land use densities and estimated the number of transit vehicles required to provide service per square mile at different land use densities, with the assumption that transit vehicles can travel faster in areas with lower density (i.e., areas with less activity and congestion). Given a transit vehicle requirement for a given land use density, the average transit ridership generated at a given land use density, and mid-1970s values for average bus operating costs and fares, the subsidy required for any given combination of land use density and desired frequency can be determined. The determination of whether a particular service frequency could be supported at a given land use density was made on the basis of the service being self-supporting (i.e., zero subsidy or profitable).

Average U.S. bus operating costs in 2010 were approximately 7 times higher ($120 per revenue hour) than the values used in the study ($15 to $20), while average fares were only 2.3 times as high ($1.44 per linked trip versus $0.50 to $0.75), based on National Transit Database data (*7*) and a ratio of unlinked to linked trips of 1.5 (*21*). This change in costs relative to farebox revenue means that either the study's recommended minimum densities need to increase by a factor of 3 (7 / 2.3) to meet the original target of zero subsidy, or that a subsidy needs to be provided so that fares only cover 33% (2.3 / 7) of operating costs, assuming no change in transit trip-making characteristics. Since fares covered approximately 27% of bus operating costs on average in 2010 (i.e., a higher level of subsidy) (*7*), the general relationships between density and frequency still hold if a transit agency and its stakeholders are comfortable with the average U.S. bus subsidy level. A smaller farebox subsidy would require higher densities to support a given frequency, while a greater farebox subsidy would allow a given frequency to be offered at lower densities.

Exhibit 3-8 presents residential densities based on net acres. The "transit-supportive area" definition used in Chapter 5 is based on gross acres.

Exhibit 3-8 presents minimum land use densities that can support a given frequency for a selection of modes. The exhibit assumes a service span of 20 hours per weekday; a shorter weekday service span would allow more frequent weekday service, service at a lower density threshold, some weekend service, or some combination of these for the same overall operating cost. All frequencies are directional. All residential densities are given as *net acres*, which count only the land actually developed as residential use. *Gross acres,* which represent total land area, including that used for streets or not developed, can be approximated by multiplying net acres by a factor of 1.5.

Transit Service	Minimum Residential Density	CBD Commercial/Office Density
Local bus, 1 bus/h	4.5 dwelling units/net acre	5–8 million ft^2
Local bus, 2 bus/h	7 dwelling units/net acre	8–20 million ft^2
Local bus, 6 bus/h	15 dwelling units/net acre	20–50 million ft^2
Light rail, 5-min peak headway	9 dwelling units/net acre in 25–100 mi^2 corridor	35–50 million ft^2 (20 million ft^2 if 100% at-grade)
Rapid transit, 5-min peak headway	12 dwelling units/net acre in 100–150 mi^2 corridor	>50 million ft^2
Commuter rail, 20 trains/day	1–2 dwelling units/net acre	>100 million ft^2

Sources: Pushkarev and Zupan (*20*), Institute of Transportation Engineers (*22*), and Moore et al. (*23*).
Note: Assumes 20 h/weekday service span, 33% farebox recovery.

Exhibit 3-8
Minimum Land Densities Supporting Transit Service at Various Frequencies

At the time of writing, TCRP Project H-42, "An Exploration of Fixed-Guideway Transit Criteria Revisited", was developing updated guidance on the conditions that are needed to support fixed-guideway transit systems, including considerations of land use patterns (*24*).

Density and Transit Use Relationships

Density has a double effect on the demand for transit service: (*a*) persons are more likely to use transit when they live in dense areas and (*b*) there are simply more people within walking distance of transit service as density increases. Exhibit 3-9 illustrates this concept, with the likelihood of transit use based on NHTS data (*18*):

Household Density		Multiplicative Change Relative to Base Condition		
(HH/acre)	(HH/ha)	Households	Likelihood of Using Transit	Overall Transit Demand
2.35	5.8	1.0	1.0	1
4.7	11.6	2.0	2.0	4
10.9	26.9	4.7	5.9	28
26.6	65.7	11.7	15.9	186
46.9	115.9	20.0	24.0	480

Source: Calculated for the TCQSM 3rd Edition from 2009 National Household Travel Survey data (*18*).
Note: HH = households. Base condition is 2.35 HH/acre (5.8 HH/ha). Household densities based on the densities of the census block groups of survey respondents.

Exhibit 3-9
Illustrative Change in Transit Demand with Density

Thus, as household density increases from 2.35 households per acre to 4.7 households per acre, transit demand from a given area would be expected to double, because there are twice as many people living in the area. Furthermore, a person living in the higher-density area is twice as likely to use transit for a given trip as a person living in the lower-density area. The combined effect is that transit demand would be expected to be four times as high at a density of 4.7 households per acre than at 2.35 households per acre.

Concentrations of employment, especially in city centers, also influence ridership. In concentrated areas such as Manhattan's business districts and the Chicago Loop, transit is the main means of travel to and from the area. In smaller, less concentrated centers, transit's mode share is much less.

Transit-Oriented Development

Transit-oriented developments (TODs) can be good generators of transit trips because many of the density and demographic characteristics that are indicative of higher propensities of transit use are found there. In addition, the mix of uses frequently found in TODs can generate reverse-direction and off-peak transit trip making. TODs can be described as developments close to high quality transit service (5–8 min peak headways, 15-min or better off-peak headways), with higher densities (minimum 12 residential units or 50 jobs per acre), parking management programs, and good walking environments (*25*).

TOD residents are 2–5 times as likely to commute by transit and to make non-work trips by transit as non-TOD residents. They are twice as likely not to own a car as non-TOD residents and own half as many cars on average. There may also be an element of self-selection involved: persons who would like to avoid owning a car may choose to live in TODs because the walking environment, transit access, and mix of uses allows them to go about their lives without relying on a car (*25, 26*).

DEMAND RELATED TO TRANSPORTATION DEMAND MANAGEMENT STRATEGIES

Transportation demand management (TDM) programs seek to reduce automobile trip making through a variety of means:

- Incentives to use alternative modes (e.g., preferential carpool parking, transit pass subsidies);
- Flexible employee work schedules (e.g., compressed work weeks, flexible arrival and departure times) or locations (e.g., telecommuting);
- Support infrastructure (e.g., pedestrian-friendly environments, bicycle lockers, shower facilities);
- Support programs (e.g., guaranteed ride home, carpool matching, carsharing);
- Disincentives for driving (e.g., parking charges, reduced parking supply); and
- Marketing programs that raise awareness of transportation options.

Chapter 19, Employer and Institutional TDM Strategies, of *TCRP Report 95: Traveler Response to Transportation System Changes* (*27*) provides information, summarized below, on the relationships between transit availability, transit-focused TDM strategies, and vehicle trip reductions (VTRs). The Environmental Protection Agency's COMMUTER model (*28*) and the Florida DOT's TRIMMS model (*29*) are two tools that can be used to estimate the impact of a specific set of TDM strategies on transit usage. The *Online TDM Encyclopedia* (*30*) incorporates new research findings about TDM strategy effects as they are published.

The results presented below are primarily based on three studies from the 1990s of 82 exemplary TDM programs for which detailed data were available. Because these programs were originally selected for study as potential role models of successful TDM programs, the results from these programs tend to be better than those of typical programs. In addition, VTRs resulting from a TDM strategy do not correspond one-to-one with transit trip additions, as other travel modes (particularly carpooling and walking) can be substituted for some trips, while other trips could be combined or simply not made as a work-based trip. As a result, these results should be considered an upper bound on the potential VTR effect of a particular TDM strategy (*27*):

- When transit availability at a site was high (in terms of frequency and number of routes, although the criteria are not specifically stated in *TCRP Report 95*), VTRs were 14 percentage points higher than when transit availability was medium or low—in other words, the presence of good transit service was correlated with better overall TDM program results.
- Programs with transit subsidies had VTRs that were 8 percentage points higher than programs without subsidies, and programs combining transit subsidies with parking restrictions or parking fees had VTRs 16 percentage points higher than programs without subsidies.
- A California study (*31*) found an average 3 percentage point increase in transit mode share when a parking cash-out program was offered.
- The level of support given to a program by employers had minimal effect (VTRs up to 4 percentage points higher) when transit availability was high, but had more of an effect when transit availability was medium or low (VTRs 7–12 percentage points higher).
- Programs providing transportation services (e.g., shuttles to transit stations, vanpools) had VTRs 5 percentage points higher than programs without such services, in areas with high transit availability.
- Programs offering any kind of alternative work schedule had VTRs no different than those that did not when transit availability was high, but programs offering flexible work schedules had VTRs 7–8 percentage points higher than those that did not, when transit availability was medium or low.

4. DWELL TIME

DEFINITION

For the purposes of the TCQSM, *dwell time* is defined as the time spent at a stop or station serving passenger movements, including the time required to open and close the doors. Time spent at a stop for any other reason—for example, waiting for a traffic signal, waiting for another transit vehicle to move, or waiting for a late-arriving passenger—is considered delay and is not counted as part of dwell time.

DWELL TIME COMPONENTS

Dwell time is among the most important factors determining transit capacity and average speed. Dwell time at a given stop is directly related to the following factors:

- *Passenger boarding and alighting volumes.* The more people that must be served, the longer it takes to serve them.
- *Fare payment method.* Some fare payment methods require more time than others. Minimizing fare payment time is a key factor in reducing dwell time.
- *Vehicle type and size.* Passengers spend less time boarding and alighting when boarding is level or near-level, particularly for passengers bringing items with them, older and younger passengers, and passengers with disabilities. Multiple or wide doors that allow several people to board or alight simultaneously also help expedite passenger movement. However, if the fare payment method requires all passengers to use a single door or door channel, then having multiple door channels only expedites alighting passenger movements.
- *In-vehicle circulation.* Boarding and alighting occurs more slowly when standees are present. The amount of space between standees, as well as the aisle width, also influences how easily passengers circulate within the vehicle. Passengers who exit buses through the front door rather than the rear door(s) delay the start of passengers boarding.

Dwell time is indirectly related to stop spacing. Assuming walkable distances and environments between stops and therefore a fixed passenger boarding demand, more stops over a given distance will spread out passenger volumes over a greater number of stops, resulting in smaller average dwell times at each stop. However, the greater number of stops will tend to slow down overall transit speeds, despite the shorter dwell times, as acceleration and deceleration delay is incurred with each stop. In addition, buses and streetcars may incur additional traffic signal delay with each stop, when stopping causes these vehicles to fall out of the progression band provided by the street's traffic signal timing. As a result, consolidating stops can be a productive way to improve transit speeds, even though average dwell times increase, as long as accessible routes are available from a consolidated stop to the next closest stop and walking distances are not excessive.

DWELL TIME VARIABILITY

Dwell time variability—the variation in dwell times between successive vehicles using a stop or station—is an important factor influencing both transit reliability and capacity. Dwell time variability can arise from, among other reasons:

- Variations in passenger demand for a particular route over the course of 15 min, 30 min, or an hour;
- Variations in passenger demand between different routes sharing the same stop;
- Irregularities in maintaining the planned schedule or headway, which can result in more passengers accumulating when a transit vehicle runs late, causing it to fall farther behind schedule;
- Crowded conditions on board a vehicle, which causes passengers to board and alight more slowly than normal;
- Wheelchair and lift deployment, and bicycle rack usage; and
- Driver interactions with passengers (e.g., answering questions, fare disputes).

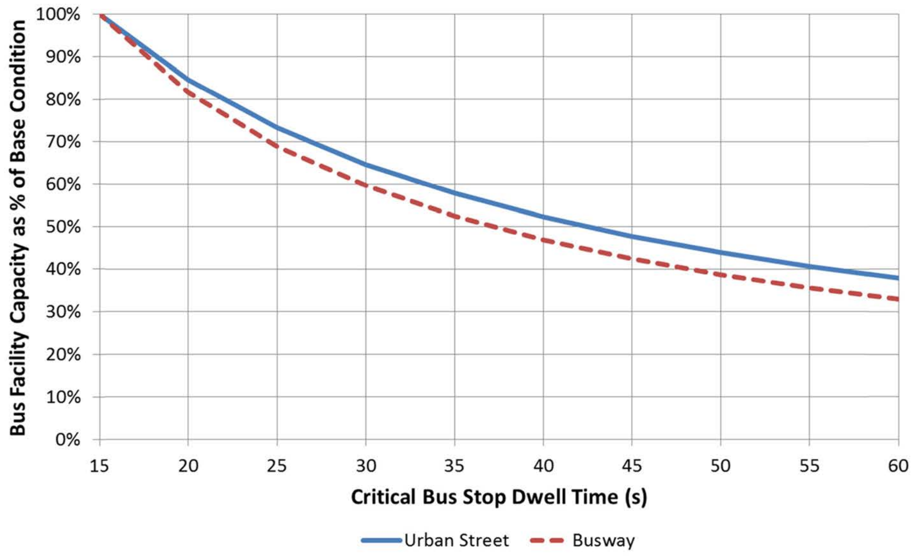
As was shown in Exhibit 3-1, dwell time variability influences the minimum headway between successive transit vehicles, which in turn controls the capacity of a transit facility. The TCQSM accounts for dwell time variability through the concept of an *operating margin,* additional time added to the minimum headway to account for longer-than-normal dwell times. The operating margin ensures that one transit vehicle does not delay following transit vehicles more than an analyst- or transit agency–specified percentage of time. The greater the dwell time variability, the greater the operating margin should be, with the result that the design capacity will be lower than it otherwise could be.

ILLUSTRATIVE IMPACTS OF DWELL TIME ON CAPACITY

Exhibit 3-10 illustrates how bus facility capacity (and by extension, person capacity) is influenced by dwell time at the critical bus stop along the facility (typically, the bus stop with the longest dwell time). It can be seen that capacity decreases as dwell time increases, with the effect strongest at lower dwell times. The capacity that can be achieved with a critical dwell time of 60 s is 50% that provided by a 30-s dwell time and approximately 75% that provided by a 45-s dwell time, for the conditions stated in the exhibit. Similarly, reducing dwell time from 30 s to 25 s improves the critical stop's capacity by (73% / 65%) or 12%, for the given conditions. Capacity drops somewhat more rapidly with increasing dwell time for busways than for urban streets, as there are fewer other things besides dwell time that influence the capacity of busway stations.

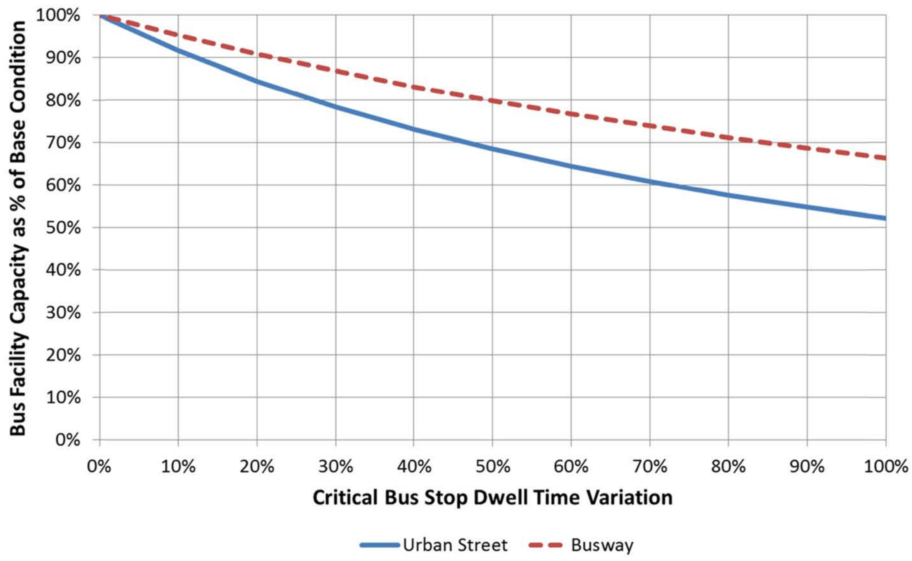
Exhibit 3-11 illustrates the impact of dwell time variability (standard deviation of dwell time divided by average dwell time) on bus facility capacity. By comparing the slopes of the lines to those in Exhibit 3-10, it can be seen that dwell time variability has less of an effect on capacity than dwell time itself (e.g., a 10% increase in the coefficient in variation reduces capacity less than a 10% increase in dwell time does). Nevertheless, the typical dwell time variability value of 60% for buses produces one-quarter to one-third lower capacity for the stated conditions than if bus dwell times were exactly the same (0% variability).

Exhibit 3-10
Illustrative Impact of Dwell Time on Bus Facility Capacity



Source: Calculated using TCQSM methods.
Note: Base condition assumes 15-s average dwell time, no traffic signals (busway) or 40% traffic signal green time for the bus' direction of travel (urban street), 10-s clearance time, and 60% dwell time variability. See Chapter 6, Bus Transit Capacity, for explanations of these parameters.

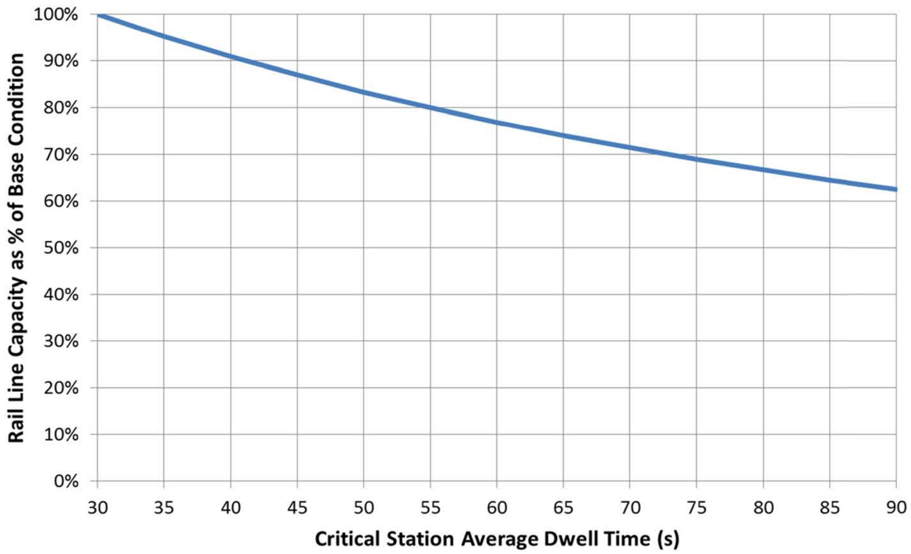
Exhibit 3-11
Illustrative Impact of Bus Dwell Time Variability on Capacity



Source: Calculated using TCQSM methods.
Note: Base condition assumes 30-s average dwell time, no traffic signals (busway) or 40% traffic signal green time for the bus' direction of travel (urban street), 10-s clearance time, and 0% dwell time variability (i.e., all buses dwell exactly 30 s). See Chapter 6, Bus Transit Capacity, for explanations of these parameters.

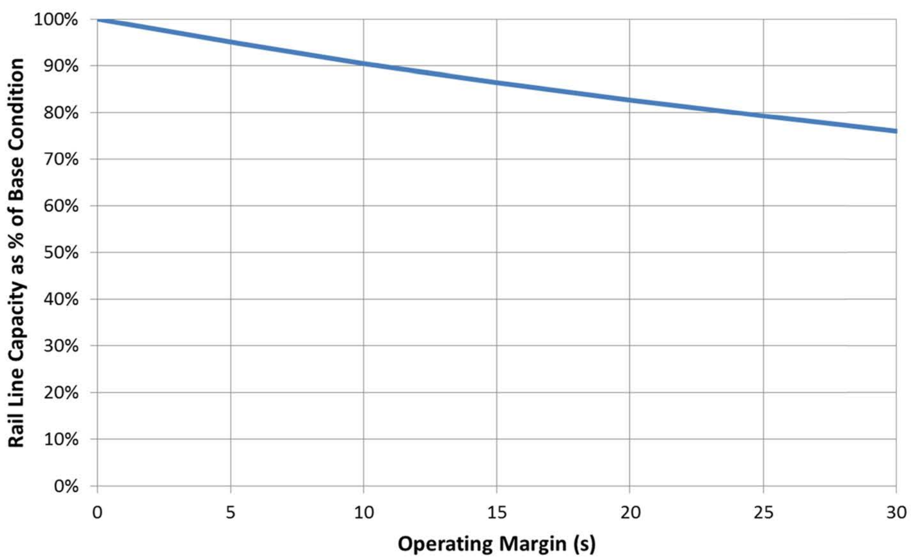
Exhibit 3-12 shows the impact of increasing dwell time on rail line capacity. In comparison to bus facility capacity, increases in dwell time have a smaller proportional impact on capacity, as other factors (in particular, the minimum train separation imposed by the train control system) also contribute significantly to the minimum train headway. Exhibit 3-13 shows the impact of operating margin (an allowance for longer-than-average dwells and other irregularities) on capacity. In the typical range of 15–25 s recommended in Chapter 8, Rail Transit Capacity, for operating margin, line capacity is 14–21% lower for the stated conditions than if dwell times were exactly the same and service was otherwise perfectly reliable.

Exhibit 3-12
Illustrative Impact of Dwell Time on Rail Line Capacity



Source: Calculated using TCQSM methods.
Note: Base condition assumes 30-s average dwell time, 20-s operating margin, and 50-s minimum train separation time. See Chapter 8, Rail Transit Capacity, for explanations of these parameters.

Exhibit 3-13
Illustrative Impact of Operating Margin on Rail Line Capacity

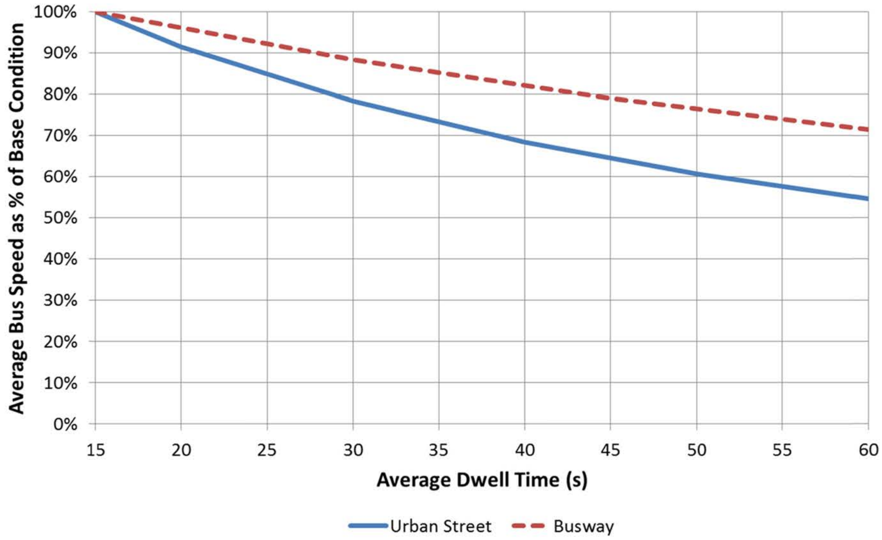


Source: Calculated using TCQSM methods.
Note: Base condition assumes 45-s average dwell time, 0-s operating margin, and 50-s minimum train separation time. See Chapter 8, Rail Transit Capacity, for explanations of these parameters.

ILLUSTRATIVE IMPACTS OF DWELL TIME ON SPEED

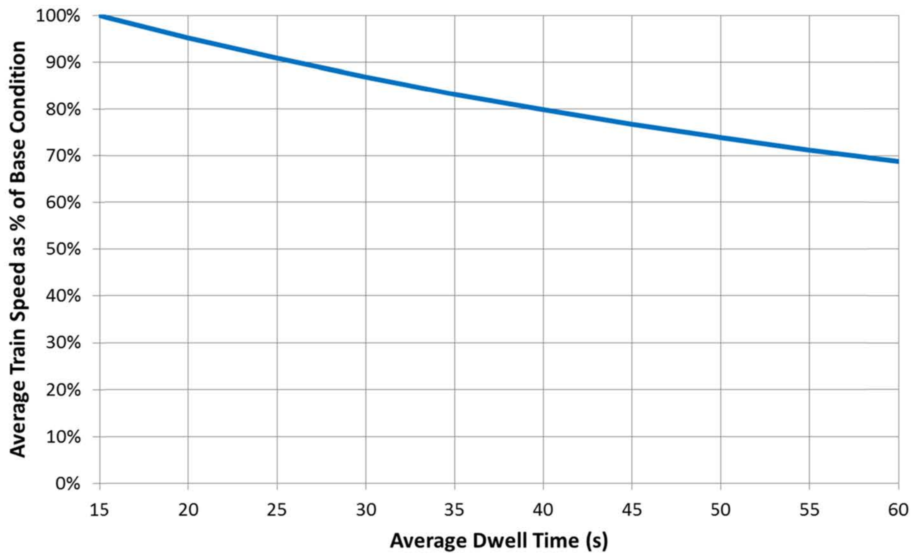
Exhibit 3-14 and Exhibit 3-15 illustrate the effects of increasing dwell time on bus and rail speeds, respectively, for the stated conditions. Dwell time has a smaller impact on busway speed than for urban street speeds due to the longer stop spacing typically found on busways.

Exhibit 3-14
Illustrative Impact of Dwell Time on Average Bus Speed



Source: Calculated using TCQSM methods.
Note: Base condition assumes 15-s average dwell time, 1 stop/mi (busway) or 8 stops/mi (urban street), and mixed traffic operation (urban street). See Chapter 6, Bus Transit Capacity, for explanations of these parameters.

Exhibit 3-15
Illustrative Impact of Dwell Time on Average Train Speed



Source: Calculated using TCQSM methods.
Note: Base condition assumes 15-s average dwell time, 1 stop/mi, and 55 mi/h maximum train speed.

5. OPERATING ENVIRONMENT

Chapter 2, Mode and Service Concepts, introduced four main types of operating environments for transit vehicles. In order of increasing speed, capacity, and reliability, these are:

- *Mixed traffic*—shared lane operation with general traffic;
- *Semi-exclusive*—a lane partially reserved for transit use, but also available for other use at certain times or in certain locations;
- *Exclusive*—a lane, portion of a roadway (e.g., the median), or right-of-way reserved for transit use at all times, but still subject to some external traffic interference (e.g., intersections, grade crossings); and
- *Grade-separated*—a facility dedicated to the exclusive use of transit vehicles, without at-grade crossings.

This section discusses how these different operating environments affect transit speed, capacity, and reliability.

GUIDEWAY TYPE AND DESIGN

The more exclusive the right-of-way, the less interaction that occurs between transit vehicles and other transportation modes (e.g., automobiles, pedestrians, bicycles). This interaction can take the form of *traffic control* that regulates when transit vehicles can move; *traffic delays* that temporarily impede transit vehicles; and *speed restrictions* that prevent transit vehicles from moving as fast as they otherwise could.

Traffic control (e.g., traffic signals, STOP signs) influences capacity by restricting the time available for transit vehicles to pass through an intersection over the course of an hour. It affects speed as a result of the delay that transit vehicles incur while other traffic movements are being served. Train control systems impose a minimum safe separation distance between trains that directly influences minimum headways and thus capacity; this minimum safe separation distance increases as operating speeds increase.

Traffic signals can also be a source of travel time unreliability. Because of the relatively long delays that can be imposed by traffic signals, both schedule and headway reliability can be affected when some buses are able to make it through a signal on green, but other buses miss the green and are delayed a minute or two.

Traffic delay (e.g., delay waiting for a vehicle in front to make a turn or to park) influences capacity at signalized intersections by cutting into the amount of green time that transit vehicles can actually use to pass through an intersection. It influences speed both through the actual delay incurred and through the deceleration/acceleration delays that occur each time a transit vehicle has to stop or slow instead of proceeding at speed. The degree to which traffic delays cause transit vehicles to miss green lights they would have otherwise made affects transit speed and reliability.

Speed restrictions can take the form of posted speeds on roadways that transit vehicles must observe, policy speeds imposed by the transit agency for safety reasons at particular locations, and guideway design elements (e.g., curves, grades) that slow down transit vehicles. Speed restrictions generally do not affect capacity, except that rail line capacity can be constrained when a sharp curve, downgrade, or policy speed restriction occurs just before a station, causing trains to enter the station more slowly or to begin to decelerate sooner than they would have otherwise.

Exhibit 3-16 summarizes the magnitudes of the traffic interactions associated with each guideway type.

Exhibit 3-16 Impacts of Other Modes on Transit Speed and Capacity

Guideway Type	Traffic Control	Traffic Delay	Speed Restrictions
Mixed traffic	Transit vehicles regulated by traffic signals [a]	Full exposure to potential traffic delays	Transit vehicle speeds regulated by roadway posted speed
Semi-exclusive	Transit vehicles regulated by traffic signals [a]	Partial exposure to potential traffic delays (typically right turns)	Transit vehicle speeds regulated by roadway posted speed
Exclusive (median)	Transit vehicles regulated by traffic signals [b]	Non-transit traffic prohibited on guideway, pedestrian crossing points may be provided	Transit vehicle speeds regulated by roadway posted speed
Exclusive (off-street)	Buses regulated by traffic signals at street crossings; [c] rail provided with gated crossings, train control signals	Non-transit traffic prohibited on guideway, pedestrian crossing points may be provided	Transit vehicle speeds constrained by vehicle performance and guideway design [c]
Grade-separated	No signal control for busways (unless shared with light rail); train control signals for rail lines	Non-transit traffic prohibited on guideway [d]	Transit vehicle speeds constrained by vehicle performance and guideway design [d]

Notes: (a) Transit signal priority may provide some benefit.
(b) Transit vehicles may be provided with signal priority (less feasible with high volumes of transit vehicles). Light rail may be allowed to preempt traffic signals.
(c) Bus signal priority or preemption may be provided. Bus speed restrictions typically imposed at signalized roadway crossings, due to safety issues with cross traffic not observing the traffic signals (*8*).
(d) Some busways allow pedestrian crossings at stations, in conjunction with bus speed restrictions for buses not stopping at the station.

TRAFFIC AND TRANSIT VEHICLE EFFECTS

The other transportation modes sharing or crossing a transit guideway affect transit operations and vice versa. Exhibit 3-17 lists some of the main interactions between transit vehicles and other transportation modes.

Transit vehicles can also impede each other. Bus speeds begin to decline when approximately half of a bus facility's capacity is used, as buses begin to interfere with other buses (e.g., blocking access into or out of bus stops, passing maneuvers). Trains operating under a train control system (as opposed to line-of-sight operation on a street) can interfere with each other. For example, if one train's dwell time at a station exceeds the average dwell time plus the operating margin, and the next train is following at the minimum headway, the following train will have to slow or stop until the leading train moves a safe distance down the line. Similarly, when one train arrives at a merge or crossing of two lines later than scheduled, the next train on the other line may be delayed.

When buses and light rail share a guideway, operating rules typically favor light rail service, potentially causing delays to buses on, or arriving at, the guideway at the same time.

Exhibit 3-17
Interactions of Transit with Other Modes

Interaction	Motorized Vehicles	Bicyclists	Pedestrians
Other modes on transit	• Traffic congestion delays transit vehicles operating in mixed traffic • Traffic may delay buses re-entering roadway from bus stops • Day-to-day variation in traffic volumes and delays affects transit travel time and reliability	• May delay buses sharing a lane with bicycles • Bicyclists delay buses re-entering roadway from bus stops • Bicycle environment quality influences ability of transit passengers to bike to transit service	• Traffic signal timing constrained by need to serve pedestrians crossing streets • May directly (crossing street) or indirectly (crossing parallel to street, with turning traffic yielding) delay buses • Pedestrian environment quality influences transit passenger ability to walk to transit service
Transit on other modes	• Buses are equivalent to 2 cars in terms of their effect on roadway capacity • Transit vehicles stopped in travel lane at bus stops reduce available roadway capacity and create delay • Transit signal priority reallocates green time, with potential capacity and delay impacts (both positive and negative)	• Heavy vehicle volume and speed in curb lane (including transit vehicles) negatively impacts bicycle quality of service • Stopped transit vehicles may delay bicyclists or force them to shift lanes • Bicyclists and buses have similar average speeds, creating leapfrog passing patterns when sharing lanes • Bicyclists can use transit to greatly extend the range of a bicycle trip, when bicycles can be brought aboard transit vehicles	• Traffic volume in curb lane (including transit vehicles) negatively impacts pedestrian quality of service • Waiting passengers may block pedestrian flow on sidewalk • Alighting passengers may create cross-flows that disturb pedestrian flow on sidewalk

Source: Derived from *Highway Capacity Manual 2010* (*3*).

ILLUSTRATIVE IMPACTS OF OPERATING ENVIRONMENT ON CAPACITY

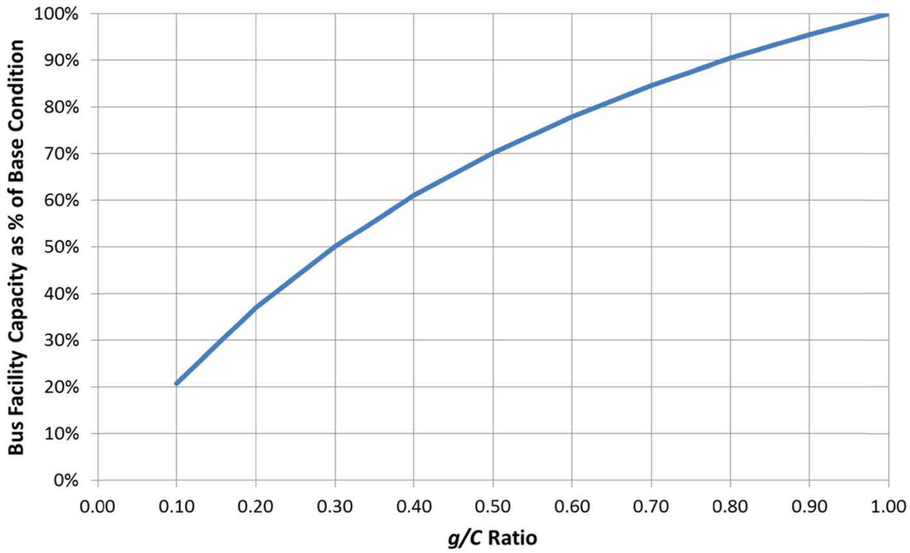
Traffic Control

Exhibit 3-18 demonstrates how bus facility capacity decreases as the amount of green time provided for bus movements at a bus stop decreases. This effect is measured by the *g/C ratio,* the amount of effective green time provided by the traffic signal for the bus' direction of travel g, divided by the traffic signal cycle length C. Illustrative g/C ratios are as follows:

- Through movement at an intersection of two roadways with similar volumes: 0.45 with no protected left-turn phasing (i.e., left-turn arrow) or 0.40 with protected left-turn phasing (*32*).
- Through movement on a major roadway intersecting a minor roadway: 0.50 to 0.70, depending on relative traffic volumes and use of protected left-turns (*33*).
- Through movement on a minor roadway intersecting a major roadway: 0.20 to 0.30, depending on relative traffic volumes and use of protected left-turns (*33*).
- Protected left-turn movement: 0.10.

The g/C ratio is 1.00 for bus stops not located in the vicinity of a traffic signal.

Exhibit 3-18
Illustrative Impact of Traffic Signalization on Bus Facility Capacity



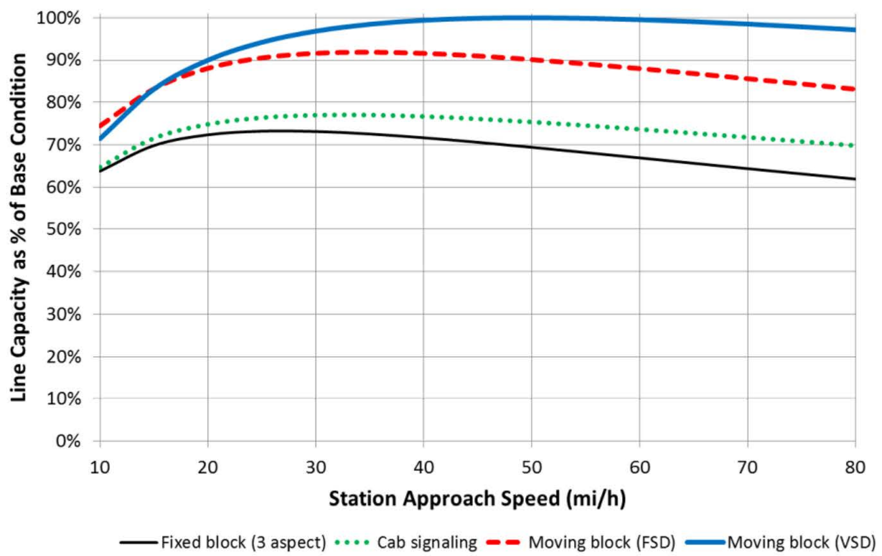
Source: Calculated using TCQSM methods.
Note: Base condition assumes 30-s average dwell time, 10-s clearance time, 60% dwell time variability, and no traffic signal (g/C = 1.00). See Chapter 6, Bus Transit Capacity, for explanations of these parameters.

Exhibit 3-19 shows the impacts of the train signaling system and station approach speed on line capacity. Chapter 8, Rail Transit Capacity, provides descriptions of the various train signaling systems; the systems that provide greater capacity know each train's position more precisely and thus allow trains to operate closer together. It can be seen in the exhibit that each signaling system has an optimal station approach speed that maximizes a given signaling system's capacity. However, the optimal speed from a capacity standpoint is not necessary optimal from a passenger travel time (quality of service) perspective.

Traffic Delay

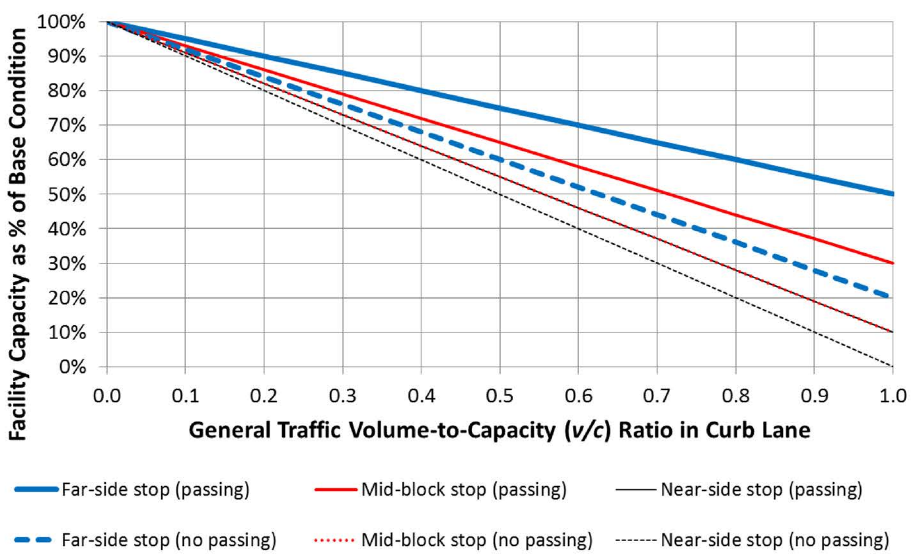
Exhibit 3-20 depicts how bus and streetcar capacity declines when operating in mixed traffic or semi-exclusive guideways (e.g., transit lanes allowing right turns), as the volume of non-transit movements using the guideway increases relative to the guideway's capacity for serving those movements. It can be seen that far-side stops provide greater capacity than mid-block or near-side stops for a given general traffic volume-to-capacity (v/c) ratio, and that having the ability to move around (pass) stopped traffic also results in higher capacity for a given v/c ratio than being forced to remain in the curb lane. Streetcars do not have the ability to leave their lane, while buses may be able to do so if more than one lane is provided for their direction of travel and traffic volumes in that lane permit buses to change lanes.

Exhibit 3-19
Illustrative Impact of Train Signaling System and Station Approach Speed on Line Capacity



Source: Calculated using TCQSM methods.
Note: FSD = fixed safety distance, VSD = variable safety distance.
Base condition assumes moving block signals with variable safety distances, 45-s average dwell time, and 20-s operating margin, and no grade entering station. See Chapter 8, Rail Transit Capacity, for explanations of these parameters.

Exhibit 3-20
Illustrative Impact of Curb Lane Traffic Congestion on Bus and Streetcar Capacity



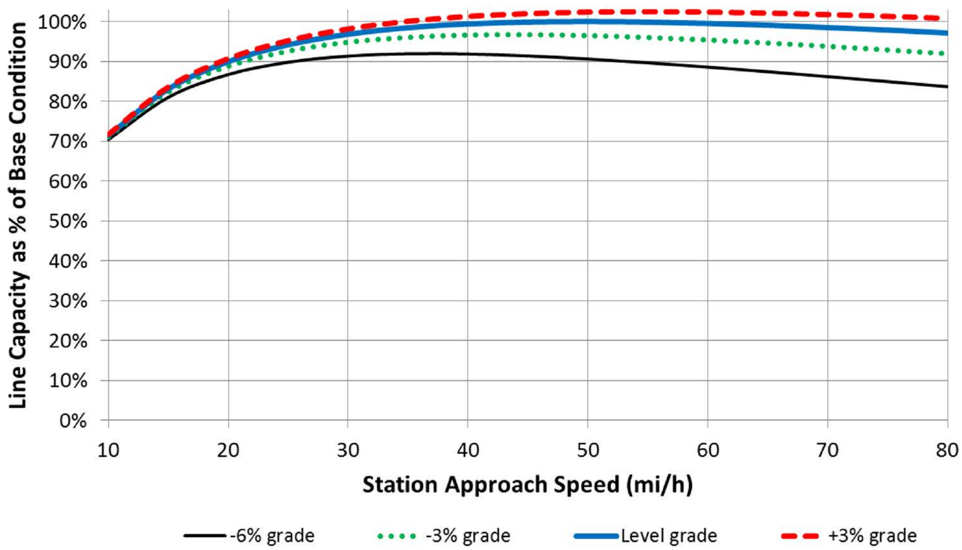
Source: Calculated using TCQSM methods.
Notes: Base condition assumes that only transit vehicles are allowed to use the curb lane.
"Passing" indicates ability of buses to leave the curb lane to pass stopped vehicles.
"Mid-block (no passing)" and "Near side (passing)" have the same characteristics.

Capacities at or near 0% of base conditions are more theoretical than practical, as one or two vehicles (*sneakers*) will typically complete their turning movement at the end of the green signal phase, allowing the vehicles behind them to move forward. Nevertheless, high *v*/*c* ratios in the curb lane are undesirable for transit operations, as they result in low capacities, low speeds, and poor reliability. Capacities are highest when only transit vehicles are allowed to use the curb lane (general traffic v/c = 0).

Speed Restrictions

Exhibit 3-21 shows the impact of station approach grade on rail line capacity at various station approach speeds. Trains take longer to decelerate from line speed when going downhill into a station, as gravity is working against them; this extra time adds to the required safe separation time between trains and thus decreases capacity. Gravity works with trains when deceleration occurs uphill into a station, resulting in a small decrease in the minimum headway and a corresponding small increase in capacity. However, this capacity effect is more theoretical than practical, as the total combined deceleration rate from the train's braking system and gravity should not exceed the maximum deceleration rate set for passenger comfort and safety reasons. Nevertheless, rapid transit systems—particularly underground systems—are often designed with uphill grades into stations and downhill grades out of stations as an energy conservation measure.

Exhibit 3-21
Illustrative Impact of Station Approach Grade and Speed on Line Capacity



Source: Calculated using TCQSM methods.
Note: Base condition assumes moving block signals with variable safety distances, 45-s average dwell time, 20-s operating margin, and level grade entering station. See Chapter 8, Rail Transit Capacity, for explanations of these parameters.

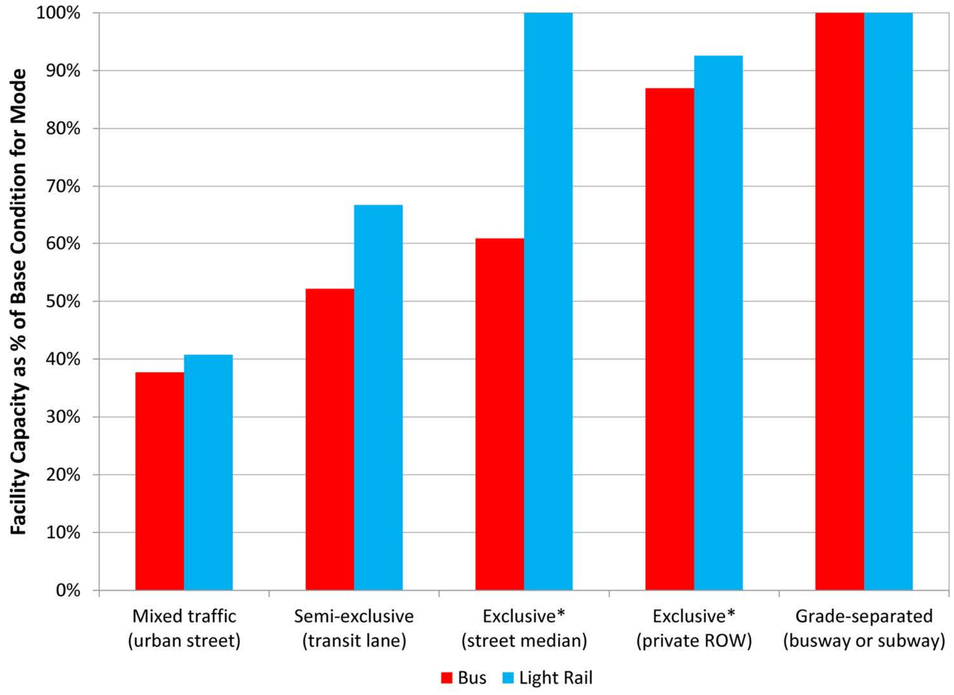
Overall Impact of Operating Environment on Capacity

Exhibit 3-22 illustrates the overall impact of transit vehicle control, traffic delay, and speed restrictions on the capacity of the bus and light rail modes. These modes are selected as they are ones most capable of operating in any environment. *All percentages shown in the exhibit are relative to the base condition for a particular mode*, expressed in vehicles per hour. Typical light rail line capacities (trains per hour) will be lower than bus facility capacities (buses per hour) because of the need to provide time separation between trains for safety reasons. However, in terms of person capacity (persons per hour), either mode is capable of providing the greater capacity, depending on the particular circumstances.

The exhibit shows that both modes are generally sensitive to the increased traffic control and traffic delay effects of less-exclusive operating environments, but there are a few differences. Bus operations at or near capacity in a street median, typically involving high volumes of buses, generally do not allow transit signal priority or preemption to be employed, as it would be too disruptive to cross-street traffic and pedestrian operations. In contrast, the number of light rail trains at capacity is much smaller, and can be often be accommodated with preemption or a traffic signal timing plan designed to progress light rail vehicles.

In an exclusive right-of-way environment, light rail trains may activate railroad crossing gates or preempt traffic signals near a station exit when passenger movements have ended. The extra time that a train spends in a station waiting for the gates to lower or the preemption sequence to complete results in a slightly lower line capacity when this occurs at a station with a long dwell time. When transit operates in the street median, stations may be located on the far-side of the intersection, avoiding the need for preempting traffic signals on exit. The need to serve very high cross-street traffic volumes may constrain the ability of exclusive operating environments to provide their maximum possible capacity.

Exhibit 3-22
Illustrative Impact of Operating Environment on Facility Capacity



Source: Calculated using TCQSM methods.

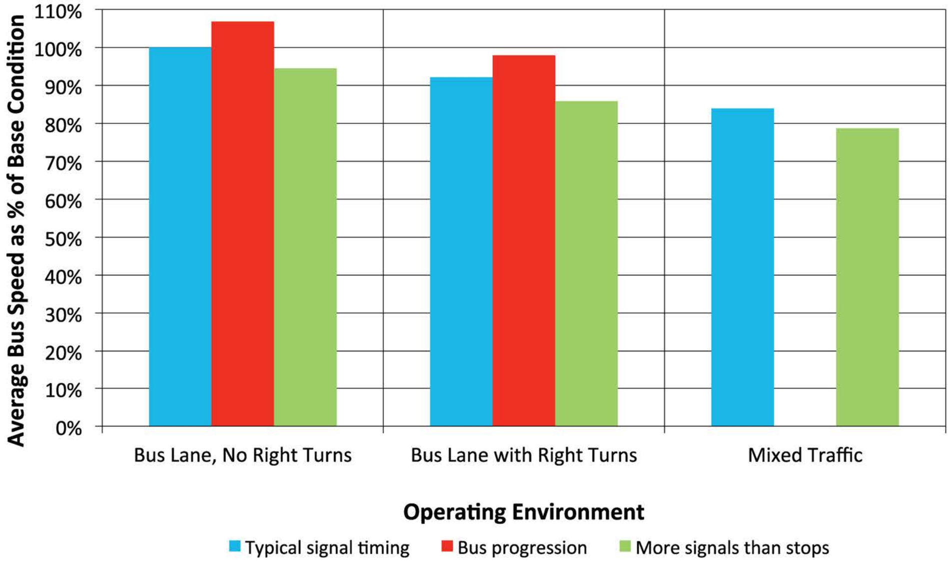
Note: *Capacity may be lower when very high cross-street volumes must be accommodated.
Percentages calculated relative to the base condition for a given mode. Base condition for bus assumes grade separation, 30-s dwell time, no traffic signals, 10-s clearance time, and 60% dwell time variation (see Chapter 6, Bus Transit Capacity, for explanations of these terms). Base condition for light rail assumes 3-aspect train signals, 45-s dwell time, and 20-s operating margin (see Chapter 8, Rail Transit Capacity, for explanations of these terms). Exclusive light rail ROW assumes far-side stations when operating in street medians and a grade crossing on the exit to the critical station for private ROW. Semi-exclusive assumes 100-s signal cycle, g/C = 0.40, and (bus only) v/c = 0.25. Mixed traffic assumes g/C = 0.40 and v/c = 0.75 for both modes.
ROW = right-of-way.

ILLUSTRATIVE IMPACTS OF OPERATING ENVIRONMENT ON SPEED

Traffic Control

Exhibit 3-23 depicts the impact of traffic signals on bus speeds in semi-exclusive and mixed traffic environments. (Although calculated specifically for buses, streetcar operation would be similar.) The exhibit shows that timing signals to progress buses rather than motor vehicles provides the greater speeds, while operating on a street where signalized intersections are more frequent than bus stops results in lower speeds, compared to the base condition. In addition, the greater the opportunity for interactions with general traffic, the lower the overall speed. Light rail is usually provided with traffic signal preemption or signal timing to progress trains and thus is not delayed by traffic signals, except in unusual circumstances.

Exhibit 3-23
Illustrative Impacts of Traffic Signals on Bus Speeds



Source: Calculated using TCQSM methods.
Note: Base condition assumes 30-s average dwell time, 8 stops/mi, central business district location, and an exclusive bus lane not allowing general traffic right turns. See Chapter 6, Bus Transit Capacity, for explanations of these parameters.

Transit Vehicle Interference

As the volume of buses on an urban street increases, the probability increases that one bus will delay another bus, either by blocking access into or out of a bus stop or by requiring passing maneuvers. These delays result in lower overall speeds. Exhibit 3-24 shows that until scheduled bus (or streetcar) volumes reach about half of the facility's maximum capacity (i.e., capacity without regard for reliability), these delays are negligible. When 50% of a facility's maximum capacity is in use, speeds begin to decline, and when all of a facility's capacity is used, speeds are approximately one-half what they would be without bus interference.

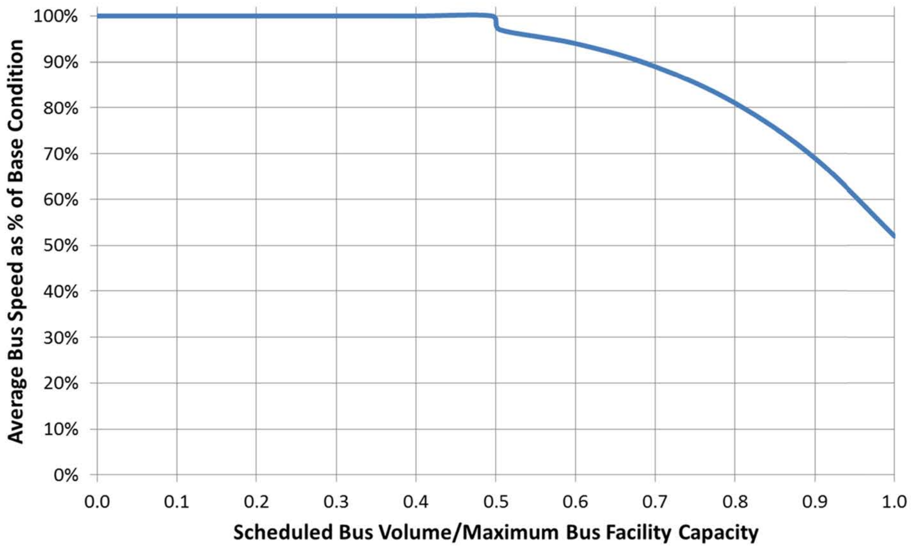


Exhibit 3-24
Illustrative Impact of Bus Congestion on Bus Speeds

Source: Calculated using TCQSM methods.
Note: Base condition assumes less than half the facility's maximum capacity in use.

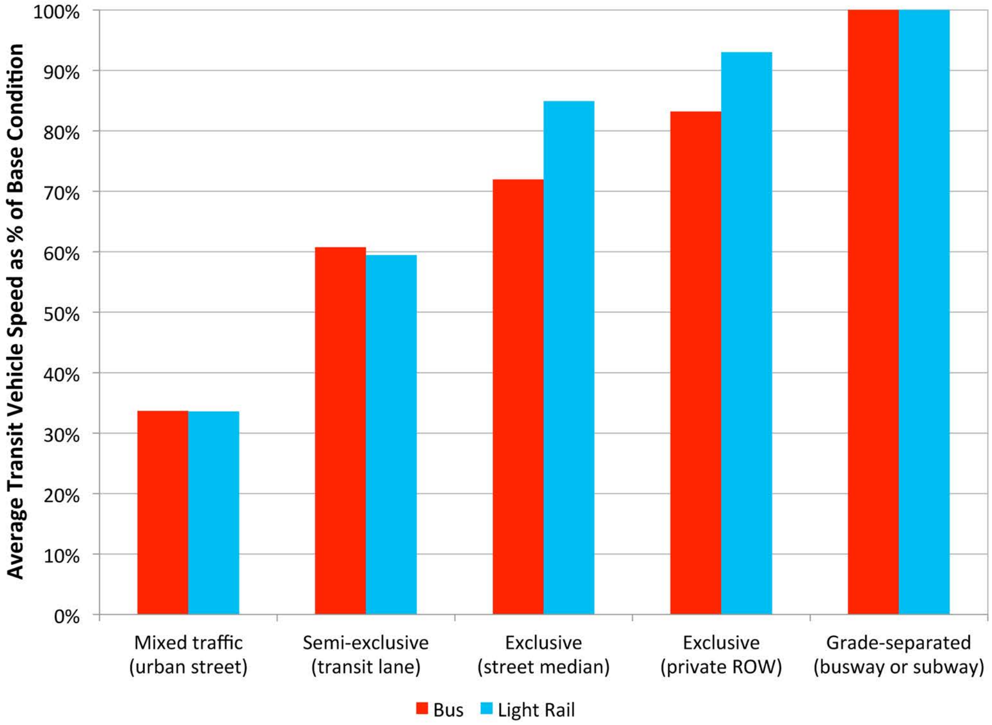
Because light rail trains are normally separated from each other by a train control system, interference effects typically occur at capacity, when one train's dwell time exceeds the scheduled dwell time plus operating margin, causing delays to the following trains. Capacity conditions can occur either because of normal scheduling or because of a disruption to service (e.g., track blockage) that causes a queue of trains to build up.

Overall Impact of Operating Environment on Speed

Exhibit 3-25 illustrates the overall impact of transit vehicle control, traffic delay, and speed restrictions on the average speed of the bus and light rail modes. *All percentages shown in the exhibit are relative to the base condition for a particular mode*, expressed in miles per hour.

As with the capacity relationships previously illustrated in Exhibit 3-22, this exhibit shows that both modes are sensitive to the increased traffic control, traffic delay, and speed restrictions associated with less-exclusive operating environments. Buses are more likely to be delayed at traffic signals than light rail in exclusive right-of-way types, but light rail may experience extra holding time in stations on private right-of-way while waiting for railroad crossing gates to be activated at a crossing near the station exit. Light rail speeds in street medians are typically restricted by policy to be no more than the posted speed for the street.

Exhibit 3-25
Illustrative Impact of Operating Environment on Average Transit Speed



Source: Calculated using TCQSM methods.
Note: Base condition assumes 30-s average dwell time, 2 stops/mi, and a grade-separated environment. Light rail values assume 55 mi/h maximum speed in private right-of-way (ROW) and grade-separated environments, 35 mi/h in street medians, and 20 mi/h otherwise.

IMPACT OF OPERATING ENVIRONMENT ON RELIABILITY

Reliability is discussed in more detail in Chapter 4, Quality of Service Concepts.

With grade-separated facilities, the potential sources of schedule unreliability are generally limited to (*a*) things under the transit agency's control, such as schedule achievability, vehicle maintenance, and route length and number of stops, and (*b*) variations in passenger demand, including randomness in the use of wheelchair lifts and ramps. The introduction of at-grade crossings introduces potential conflicts with other travel modes. On-street facilities introduce traffic signals (potential randomness in whether a transit vehicle receives a red or green signal when approaching an intersection), the potential for road construction, and the potential for unauthorized use of the facility (e.g., stopped or parked vehicles). Semi-exclusive facilities have greater potential for unauthorized usage, introduce potentially variable right-turning traffic delays, and introduce the potential for parking maneuvers. Finally, mixed-traffic operations introduces potential travel time variability due to traffic congestion and variability in traffic volumes from one hour or day to the next.

6. STOP AND STATION CHARACTERISTICS

VEHICLE–PLATFORM INTERFACE

Factors involving the vehicle–platform interface that affect transit speed and capacity include:

- Height differential between the vehicle floor and the platform,
- Platform position relative to the guideway, and
- Number of transit vehicles that can stop simultaneously.

The elevation difference between the vehicle floor and the platform influences how quickly passengers can board and alight. In addition, if the horizontal or vertical separation between vehicle floor and platform exceeds ADA standards, a bridgeplate, wheelchair lift, or similar device must be employed to provide access to passengers with disabilities. These devices take time to deploy and stow again after use, which affects dwell time. They can also potentially affect reliability when dwell times are significantly extended when these devices are used.

Stops and stations can be *on-line,* where the transit vehicle stops in the guideway (e.g., the travel lane on a street, the mainline tracks on a rail line) to serve passenger movements, or they can be *off-line,* where the transit vehicle stops out of the guideway (e.g., in a bus pull-out, in the parking lane, on a passing siding at a station) to serve passengers. In a mixed-traffic environment, on-line stops allow transit vehicles to proceed again as soon as passenger movements are finished, traffic control permitting, with no delay waiting for a gap in traffic to re-enter the street. Otherwise, when the guideway provides only one lane or track per direction of travel, off-line stops allow transit vehicles to pass each other at stations. This arrangement allows a mix of all-stop and limited-stop services to share the guideway, allowing higher speeds for the limited-stop services and often resulting in a greater vehicle throughput (capacity) on the guideway.

There are also safety and traffic operations considerations when deciding between on-line and off-line stops in mixed-traffic environments; these are discussed in Chapter 6, Bus Transit Capacity.

The number of transit vehicles that can stop simultaneously at a stop or station directly affects the facility capacity. This is primarily a consideration for bus transit, but short streetcars and light rail vehicles operating under line-of-sight control are also capable of sharing long platforms. The number of stopping positions provided, and their design (allowing independent movement in and out of each position, or not) determines capacity. Speed is indirectly affected, because (as was seen in Section 5), average bus speed is related to the amount of capacity in use; thus, increasing capacity without scheduling more vehicles to use it will decrease the number of interactions between vehicles and will improve speeds when more than half the facility's maximum capacity was in use prior to the increase in capacity.

VEHICLE CHARACTERISTICS

As was discussed in Section 4, the number of doors available for passenger use and their width influences how many passengers can simultaneously board or alight a transit vehicle, which in turn affects dwell time. However, even when several doors are provided, onboard fare collection needs may restrict boarding passengers to using the front door. In addition, the seating arrangement inside the bus (e.g., seats facing forward vs. seats facing the aisle, number of seats per row) influences the width of the aisle and thus the ease with which passengers can circulate to and from the doors when standees are present.

FARE COLLECTION

With proof-of-payment fare collection, passengers purchase their fare prior to boarding and can be asked to show proof-of-payment during their trip, with a potential fine if they are traveling without a valid fare.

Fare collection affects dwell time in several ways. First, when fares are collected on board, each fare collection method has a passenger service time associated with it—some methods are faster than others. Second, the fare collection policy may require all passengers with pre-paid fares (e.g., passes) or smart cards to interact with the driver, or the policy may allow these passengers to board any door, with smart card holders tagging their cards at one of the rear doors. Finally, when fares are collected off-board (e.g., using faregates or proof-of-payment fare collection), passengers can use any door to board. Although proof-of-payment fare collection can significantly reduce dwell times (thus providing improved speeds and potential operating cost savings), and the cost of additional fare inspectors can be more than the additional fare revenue or fines collected, there has always been a tension between the operating efficiencies that the method provides and political and public perceptions that some people cheat the system by not paying their fare (and potentially are the source of more serious crimes).

STOP SPACING

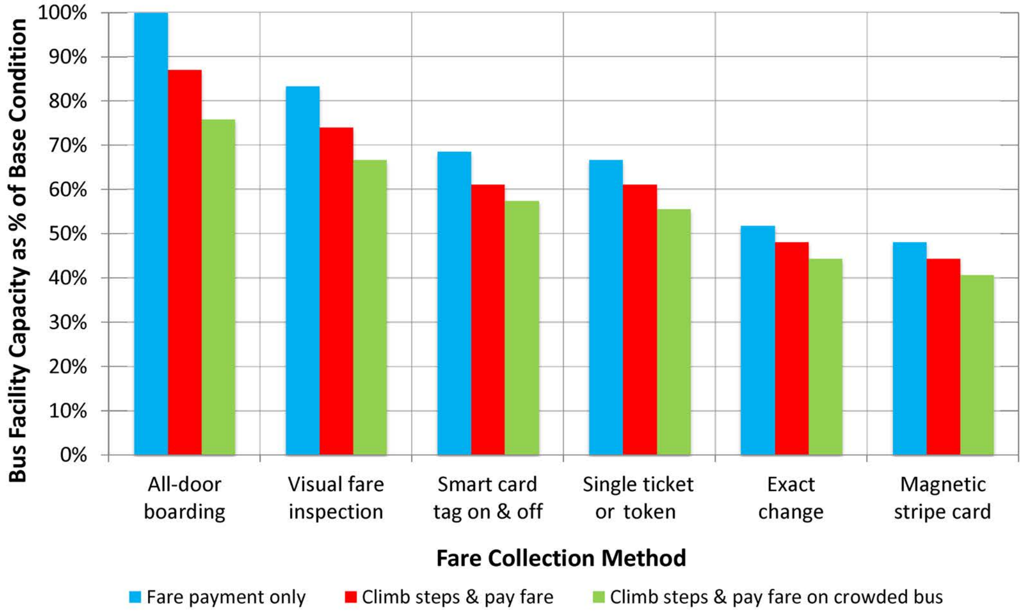
As was discussed in Sections 3 and 4, the more frequently that transit vehicles stop, the more time that is lost in decelerating and accelerating. In addition, when transit vehicles operate on street, each stop carries the risk that the vehicle will fall out of the progression band provided by the street's signal timing and will be further delayed at the next traffic light. Finally, when stops are too close together, a transit vehicle becomes incapable of reaching its maximum allowed speed before it has to decelerate again for the next stop.

ILLUSTRATIVE IMPACTS OF STOPS AND STATIONS ON CAPACITY

Passenger Service Time

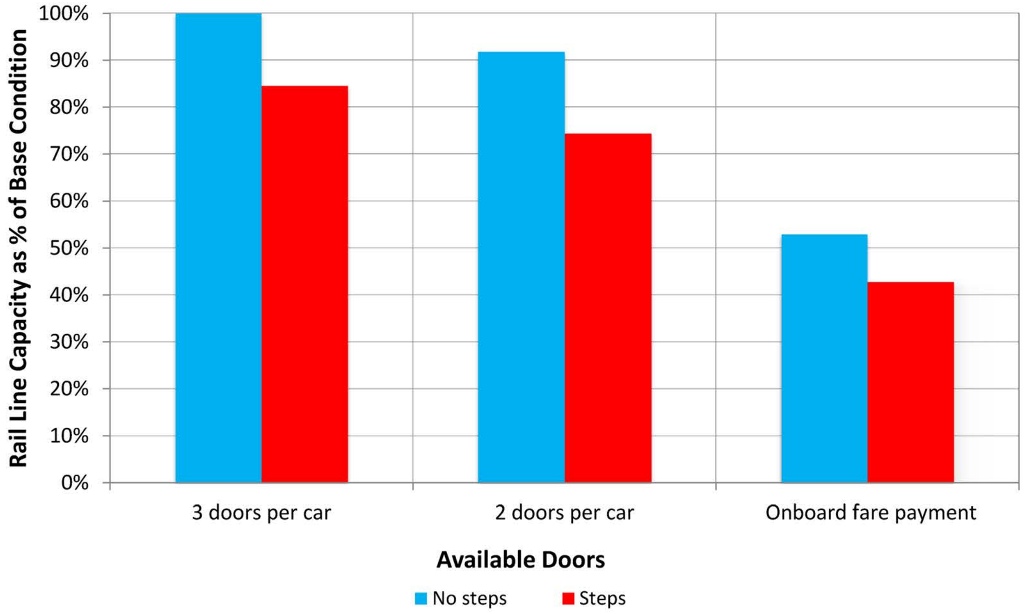
Exhibit 3-26 and Exhibit 3-27 show the impact of fare collection method, level vs. non-level boarding, and bus crowding (collectively, passenger service time) on bus facility and light rail line capacity, respectively. Exhibit 3-26 shows that there are clear impacts on bus capacity with different fare collection methods, and that climbing steps or entering a crowded bus increases passenger service time and thus reduces capacity. The impacts of steps and crowding are more severe when fare collection times are low, as other factors play more of a role in determining overall capacity at higher dwell times. Exhibit 3-27 shows that passenger service times decrease and capacity increases as more door channels are available to serve passengers. A rail system that requires passengers to enter through the front door to pay fares cannot come close to the maximum capacity it is otherwise capable of providing.

Exhibit 3-26
Illustrative Impact of Bus Passenger Service Time on Capacity



Source: Calculated using TCQSM methods, including default fare collection times from Chapter 6, Bus Transit Capacity.
Note: Base condition assumes 10 passengers boarding and 4 passengers alighting at the critical stop, level boarding, no standees, all-door boarding, 60% dwell time variation, 10-s clearance time, and 0.40 *g/C* ratio. See Chapter 6, Bus Transit Capacity, for explanations of these parameters.

Exhibit 3-27
Illustrative Impact of Floor Height and Door Availability on Light Rail Line Capacity

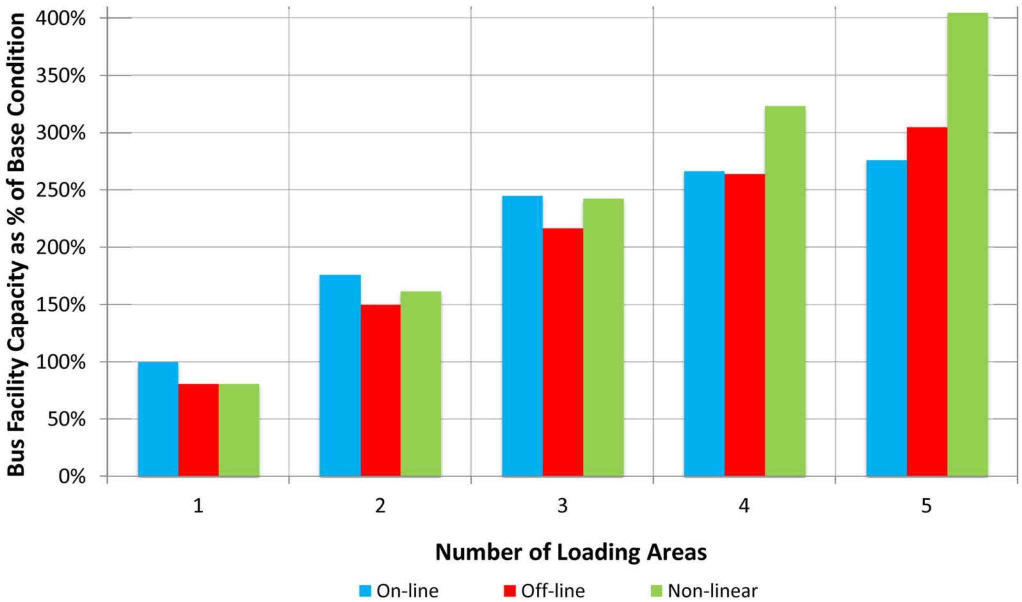


Source: Calculated using TCQSM methods.
Note: Base condition assumes 2-car light rail train with an average of 20 passengers boarding and 20 passengers alighting at the critical stop, level boarding, 20-s operating margin, and 50-s safe train separation time. See Chapter 8, Rail Transit Capacity, for explanations of these parameters.

Type and Number of Loading Areas

Exhibit 3-28 illustrates how bus facility capacity increases as the number of loading areas provided at the critical stop increase. With 1–3 loading areas, for the conditions used to develop the exhibit, on-line stops provide the greatest capacity, as buses are not delayed by other traffic when they are ready to continue after serving passengers. With 4–5 loading areas, off-line loading areas provide as much or more capacity as on-line loading areas, as the ability of buses to access unoccupied loading areas at the front of the stop overcomes the disadvantage of having to yielding to street traffic on departure. The incremental benefit of a fourth or fifth loading area is relatively low for either on-line or off-line loading area designs, compared to adding a second or third. Non-linear loading areas can be independently accessed by buses and thus add the same increment of capacity with each additional loading area. However, because of the extra curb space required to develop non-linear loading areas, they are more often used at off-street bus stops than at on-street stops.

Exhibit 3-28
Illustrative Impact of Number and Type of Loading Areas on Bus Facility Capacity



Source: Calculated using TCQSM methods.
Note: Base condition for the critical stop assumes 1 on-line loading area, 30-s average dwell time, 60% dwell time variability, 10-s clearance time, and 0.4 *g/C* ratio. Off-line and non-linear loading areas assume 18-s clearance time. See Chapter 6, Bus Transit Capacity, for explanations of these parameters.

ILLUSTRATIVE IMPACTS OF STOPS AND STATIONS ON SPEED

Fare Collection

Exhibit 3-29 shows the impact of fare collection method on average bus speeds for busways, arterial streets outside central business districts (CBDs), and mixed-traffic operation within a CBD. The base condition is exact change fare payment and a bus facility consisting of a non-CBD arterial street. For the conditions used to develop the exhibit, it can be seen that visual inspection of pre-paid fares and all-door boarding both result in average speeds 20% or more higher than with exact-change fare collection. However, the type of operating environment has a greater impact on speed than the choice of fare collection method.

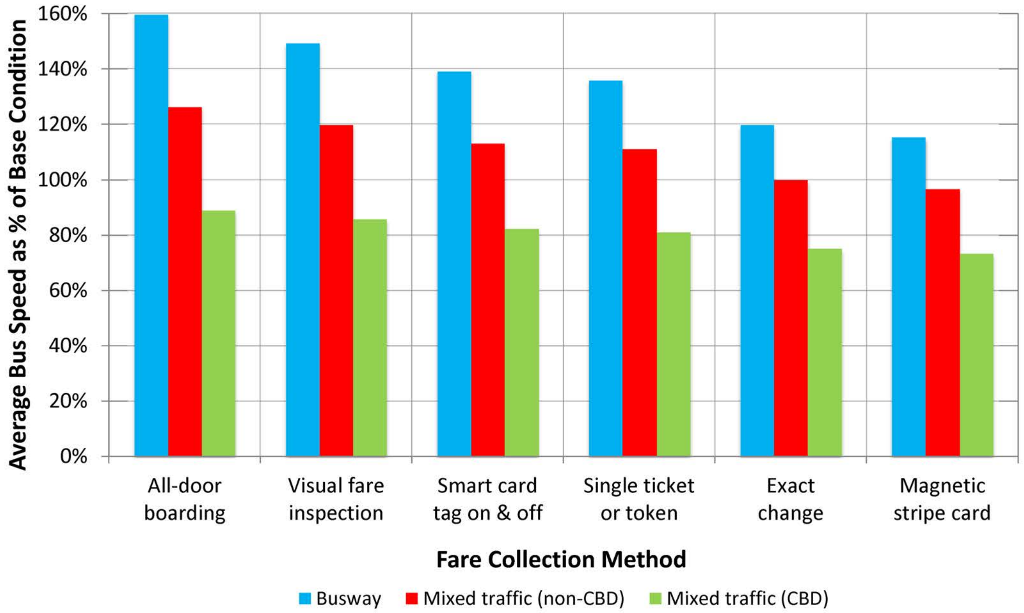


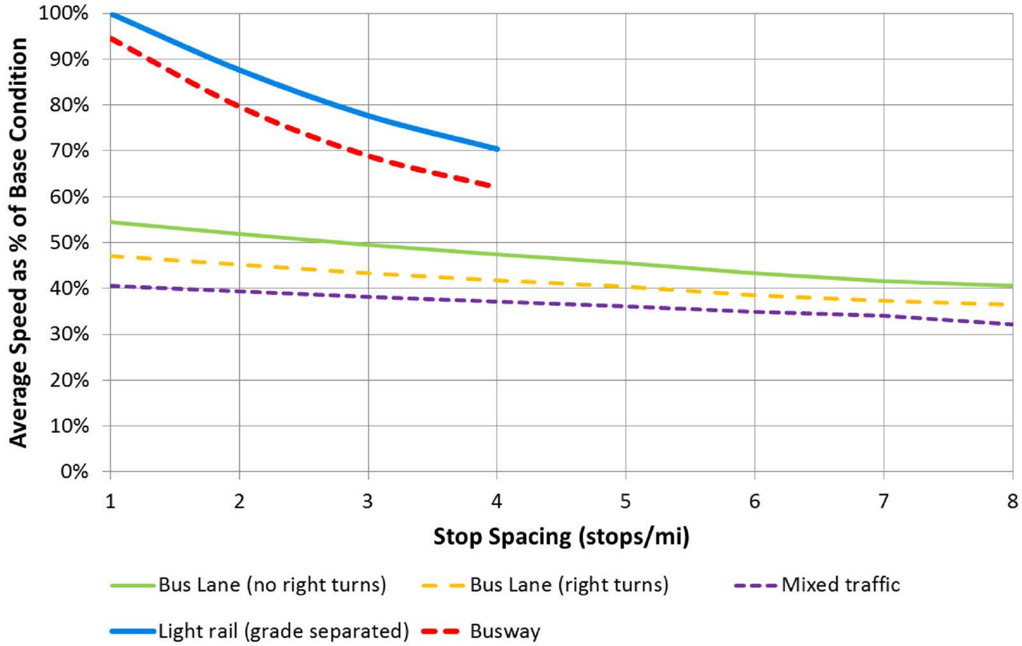
Exhibit 3-29
Illustrative Impact of Fare Collection on Average Bus Speed by Facility Type

Source: Calculated using TCQSM methods.
Note: Base condition assumes 32-s dwell time, exact change fare payment, non-CBD mixed traffic operation, level boarding, no standees, 35 mi/h maximum speed, and 4 stops/mi. See Chapter 6, Bus Transit Capacity, for explanations of these parameters.

Stop Spacing

Exhibit 3-30 illustrates the impact of stop spacing on average transit speeds for different types of transit facilities. For the purpose of this exhibit, passenger demand is assumed to be unaffected by stop spacing; thus the average passenger service time at 1 stop/mi is assumed to be eight times the average passenger service time per stop at 8 stops/mi. Therefore, differences in speeds for a given facility type are due solely to deceleration and acceleration delays. Differences in speeds between facility types are due to differences in operating environment and, in the case of grade-separated light rail vs. busway, differences in vehicle acceleration characteristics (light rail vehicles can accelerate more quickly than buses and thus spend more time at their running speed). It can be seen from the exhibit that stop spacing impacts speed more severely when running speeds are high (e.g., on grade-separated facilities), as more time is spent decelerating and accelerating than at lower speeds.

Exhibit 3-30
Illustrative Impact of Stop Spacing on Average Transit Speed



Source: Calculated using TCQSM methods.
Note: Base condition assumes grade-separated light rail and 1 stop/mi. Assumed dwell time is 15 s at 8 stops/mi (10-s passenger service time and 5-s door opening and closing time), with the passenger service time component increasing proportionately as the number of stops decreases (e.g., 25-s dwell time at 4 stops/mi). Assumed running speed is 55 mi/h for light rail and busway and 25 mi/h otherwise.

7. REFERENCES

Links to the TCRP reports listed here can be found on the accompanying CD-ROM.

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