PART 3
RAIL TRANSIT CAPACITY

CONTENTS

LIST OF EXHIBITS

1. RAIL CAPACITY BASICS

INTRODUCTION

Part 3, has been condensed from TCRP Report 13, Rail Transit Capacity$^{(R7)}$

This chapter develops an initial framework to analyze and determine the capacity of rail transit modes in North America. Throughout Part 3 capacity analysis is sub-divided into two methods. The first, called the *simple method*, is an easy-to-use procedure for calculating capacity. The second, called the *complete method*, adds more variables and is aimed at the experienced user who wishes to review rail transit capacity in alternate scenarios—for example: changes in seating arrangements or other aspects of interior car design, light rail with high or low loading, with single track sections, with or without traffic signal pre-emption, etc.

The procedures in both methods include the rail transit operations variables that affect capacity. The procedures compensate for the differences between *design* capacity, and *achievable* capacity—the actual sustainable peak hour capacity.

Exhibits appearing in Appendix A are indicated by a marginal note such as this.

Chapter 11 presents example problems that demonstrate how to apply the capacity procedures presented in Part 3. Appendix A provides substitute exhibits in U.S. customary units for Part 3 exhibits that use metric units.

GROUPING

For capacity analysis, heavy rail, light rail, commuter rail, and automated guideway transit are grouped into unique categories based on alignment, equipment, train control, and operating practices.

Fully segregated, electric multiple unit rail.

The first category is fully segregated, signaled, double track right-of-way, operated by electrically propelled multiple-unit trains. This is the largest category encompassing all rail rapid transit[1], including automated routes[2], several light rail sections (for example, the Market Street subway in San Francisco), and several commuter rail lines. This category is termed *Grade-Separated Rail*.

Light rail without full segregation.

The second category is light rail without fully segregated tracks, divided into on-street operations and right-of-way with grade crossings. Streetcar-only operations (Toronto and New Orleans) form a subset of the on-street section.

Commuter rail without full segregation.

The third category is commuter rail other than services in category one.

Automated guideway transit.

The fourth category includes automated guideway transit routes that are intended to serve a single major activity center. Although most automated guideway transit is a sub-set of the main category, *Grade-Separated Rail*, with very short trains, the use of off-line stations—on certain systems—is unique to this mode and requires separate examination. Off-line stations can also increase the capacity of more conventional rail transit as discussed in Chapter 5, *Operating Issues*.

Each of these categories is provided with its own section with procedures for determining capacity: Chapter 6, *Grade-Separated Rail Capacity*, Chapter 7, *Light Rail Capacity*, Chapter 8, *Commuter Rail Capacity*, and Chapter 9, *Automated Guideway Transit Capacity*.

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[1] The minor exceptions where there are grade crossings on rail rapid transit (CTA) will be discounted. Routes with more than two tracks will be discussed relative to express, local, and skip-stop service. However, it is not intended to otherwise develop unique capacity calculations for multiple track routes.

[2] The Morgantown automated guideway transit, the only North American example of AGT with off-line stations, is not classed as a public operation by APTA.

THE BASICS

Many rail transit capacity calculations add constants, multipliers, reductive factors, or other methods to correlate theory with practice. In this manual emphasis has been placed on reducing the number of qualifications and quantifying, describing and explaining adjustments between theory and practice in determining rail transit capacity.

This manual uses two definitions of capacity.

Design Capacity
The maximum number of passengers past a single point in an hour, in one direction on a single track.

Design capacity is similar to, or the same as, *maximum capacity*, *theoretical capacity,* or *theoretical maximum capacity*—expressions used in other work. It makes no allowance for whether those spaces going by each hour will be used— they would be fully used only if passengers uniformly filled the trains throughout the peak hour. This does not occur and a more practical definition is required. Achievable capacity takes into account that demand fluctuates over the peak hour and that not all trains—or all cars of a train—are equally and uniformly full of passengers.

Achievable Capacity
The maximum number of passengers that can be carried in an hour in one direction on a single track allowing for the diversity of demand.

Achievable capacity (sometimes called practical capacity) refers to capacity in one direction on a single track. This is necessary as most trunk routes in New York[3] have three or four tracks while the Broad Street subway in Philadelphia and the North Side elevated in Chicago have four tracks. The capacity of four track lines is not a simple multiple of two single tracks and varies widely with operating practices such as the merging and dividing of local and express services and trains holding at stations for local-express transfers. The result is that four tracks rarely increase capacity by more than 50% over a double track line—and often less. A third express track does not necessarily increase capacity at all when restricted to the same station *close-in* limitations at stations with two platform faces.

Design capacity has two factors, *line capacity* and *train capacity,* and can be expressed as:

$$C_D = C_L \times C_T$$

Equation 3-1

where:
C_D = design capacity (p/h);
C_L = line capacity (trains/h); and
C_T = train capacity (p/train).

In expanded form, design capacity is given by Equation 3-2:

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[3] All but two New York three- and four-track trunks merge or split into double-track sections, tunnels, or bridges, crossing the Harlem and East Rivers, often with one crossing used for local trains and a second used for express services. The Concourse line used by the C and D trains, and the Seventh Avenue – Broadway line used by the 1 and 9 trains are the only three-track river crossings. The Manhattan Bridge carries four tracks but only two are in service.

$$C_D = \frac{3600}{\left(t_S + t_d\right)} \times P_C \times N_C$$

Equation 3-2

where:

C_D = design capacity (p/h);
t_s = minimum train separation (s);
t_d = dwell time at the controlling station (s);
P_C = total passengers per car; and
N_C = number of cars per train.

In turn, the achievable capacity can be expressed as:

$$C_A = C_D \times PHF$$

Equation 3-3

where:

C_A = achievable capacity (p/h);
C_D = design capacity (p/h);
PHF = peak hour factor.

Minimum headway and close-in time.

The first expression in Equation 3-2 determines the number of trains per hour and is the inverse of the closest or minimum headway. It determines train throughput at the controlling station—usually the maximum load point station. In rare cases speed restrictions or heavy mixed passenger flows may dictate that other than the maximum load point station controls train throughput. The relevant minimum train separation in seconds is the minimum time from when a train starts to leave the most restrictive station, usually the maximum load point station, until the following train can berth at that station. This is referred to as the "close-in" time and is based on *non-interference* with the following train, i.e., no speed restrictions or stops. In a small number of cases the critical governor of headway is a junction or a terminal maneuver.

Controlling dwells.

Controlling dwell is based on actual station dwell time adjusted to a controlling value over the peak hour. The controlling dwell may contain an operating margin or a margin can be added separately to the denominator of the expression. Chapter 3, *Station Dwell Times*, develops the methodology and analysis of dwells. Chapter 5, *Operating Issues*, discusses and develops operating margins.

DESIGN VERSUS ACHIEVABLE CAPACITY

This manual provides guidelines and methods that can be used for real-world evaluation of rail transit capacities. The difference between *design* and *achievable* capacity is an important consideration.

Design capacity, in passengers per hour per direction (pphpd), is calculated using the following factors:

- number of seats per car,
- number of standees per car (= standing area x standee density),
- number of cars per train, and
- train headway (minimum headway determined by a combination of the signaling system, station dwell, and terminus constraints).

Capacity reduction from real world factors.

This approach does not incorporate factors that reduce the *actual* number of regular riders that the system can sustain.

- Standing densities vary; people will crowd in more tightly in some situations than in others.
- In a multi-car train; some cars carry more passengers on average than others.
- Many factors reduce train performance (propulsion faults or differences, door problems, operator variation), which may not only increase the sustainable average headway, but will increase the variation in headway, and consequently the passenger load waiting for that train.
- Minimum headway, by definition, leaves no margin for schedule recovery from even minor delays, leaving the system susceptible to more variation in service.
- Passenger demand is unevenly distributed within the peak period; there may be predictable "waves" of demand, corresponding to specific work start and finish times. The capacity rate requirement for the peak 10 to 15 minutes may have to be higher than the average for the peak one or two hours.
- There is day-to-day fluctuation in demand. Some may be associated with the day of the week (peaks have become lighter on Mondays and Fridays as more people move into shorter or flexible work weeks), seasonally (lighter in the summer and at Christmas time), weather and special events.
- Passengers are resilient to a degree, and will tolerate overcrowding or delay on occasion. This permits systems at capacity to accommodate special events or recover from service delays.

Achievable capacity approximated using peak hour factors.

Achievable capacity is the product of the *design* (maximum) capacity and a series of "reality" factors, which adjust the ideal capacity. These factors are not absolutes as they reflect human perception and behavior, as well as site-specific differences (expectations, cultural attitudes and the transportation alternatives). This manual has derived these factors from observation of existing U.S. and Canadian rail rapid transit operations to create a single *diversity* or *peak hour factor*. Chapter 4, *Passenger Loading Levels*, details existing peak hour factors and recommends factors for new systems.

Service Headway

Design (minimum) train operating headway is a function of:

- signaling system type and characteristics, including block lengths and separation;
- operating speed at station approaches and exits or other bottlenecks such as junctions; and
- train length and station dwells.

Chapter 2, *Train Control and Signaling*, compares signaling and train control systems.

Additional factors affecting achievable headway.

Achievable headway must account for additional factors that can affect the separation of individual trains. These include differences in operator and rolling stock performance, external factors, such as grade crossings, that can impose delays, and the need for schedule recovery time.

Station dwell effects on productivity and service attractiveness.

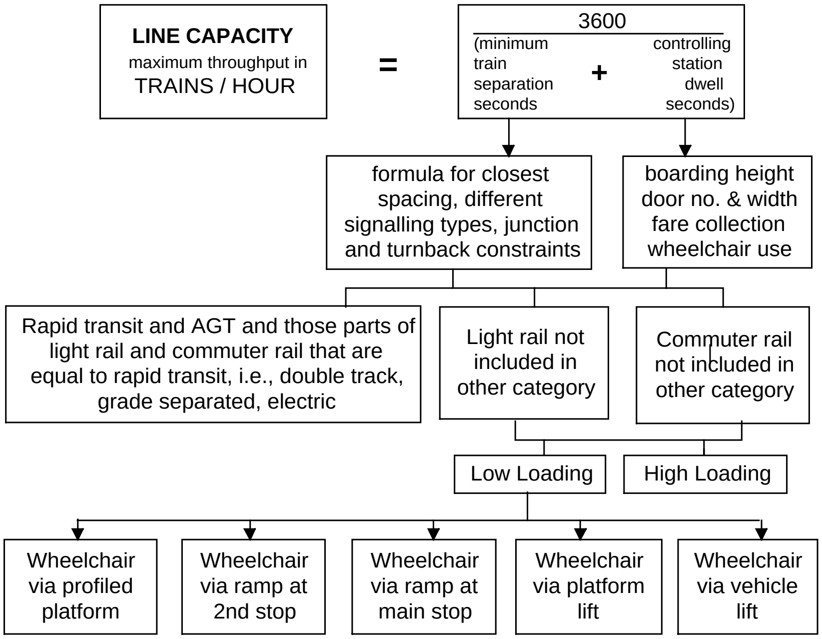
Station dwells combine with minimum operating headway to create a constraining headway bottleneck in the system. Typically this is a concern on fully segregated systems that are operating long trains on close headways. Busy stations, especially major passenger interchanges, can produce block occupancy times that limit the entire system.

Line Capacity

Line capacity definition.

Line capacity is the maximum number of trains that can be operated over a line in a peak hour.

Exhibit 3-1
Line Capacity Flowchart



(Not all wheelchair options apply to commuter rail)

Line capacity is determined by the train control system and station dwell times.

As shown in Exhibit 3-1, throughput of the train control system and dwell time at stations are the two major factors in determining line capacity.

Both factors can be sub-divided into the three categories based on alignment, equipment, train control, and operating practices. In turn, light rail and commuter rail lines must be divided by high or low loading and by the method of handling wheelchairs.

Train Control Throughput

The number of trains per hour that is theoretically possible is dependent on the particular signaling systems including:

- conventional block signaling;
- block signaling with short blocks, overlapping blocks, or *ghost* overlays to decrease headways; and
- communication or transmission based signaling systems with moving blocks.

Chapter 2**,** *Train Control and Signaling*, describes different signaling systems and develops empirical methods to estimate their throughput. More precise throughput determination requires the use of computer simulations.

Commuter Rail Throughput

Specific factors affecting throughput of commuter rail trains.

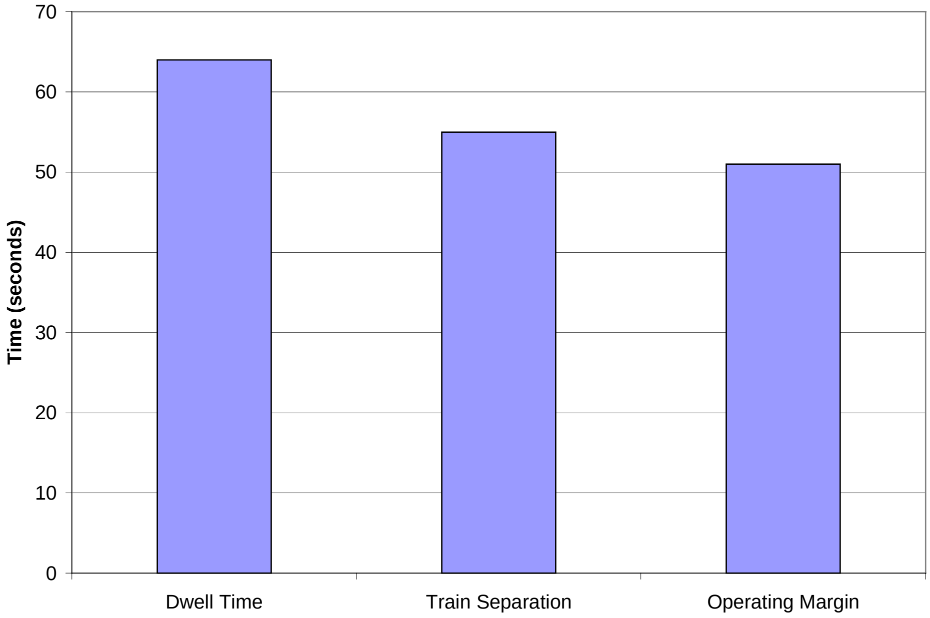
Certain line capacity issues are specific to commuter rail operation. Commuter rail signaling generally is of standard railroad operation and must accommodate trains of different lengths and speeds. Contract operations may set limits on the number of trains per hour. See Chapter 8 for specifics.

Station Dwells

Operational allowances and controlling dwell times.

Station dwells and train control system minimum separation are the two major factors in determining line capacity. In many circumstances dwells are the dominant factor. The third factor in headway is any operational allowance or margin. In some cases this margin can be added to the dwell time to create a *controlling dwell* time. An example of these headway components is shown in Exhibit 3-2 based on data from an at-capacity line in New York.

Exhibit 3-2
Average Rail Transit Headway Components in Seconds



The three main components of dwell times are:

- passenger flow time;
- door open time after flow ceases; and
- waiting to depart time after doors close.

These components vary widely from system to system. The methodology to determine dwell times is contained in Chapter 3, *Station Dwell Times*, and their associated operating margins in Chapter 5, *Operating Issues*.

Commuter Rail Dwells

Commuter rail dwells are often relatively independent of passenger flows.

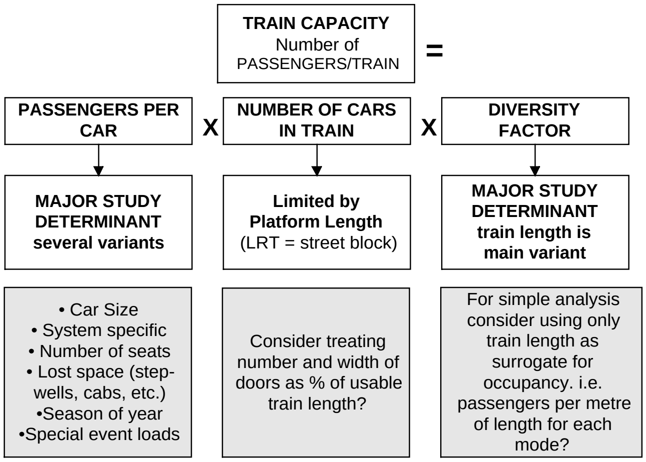
Dwells on many commuter rail lines are set by schedule or policy and can be relatively independent of passenger flows, although the schedule may be based on anticipated passenger flow times. As a result, passenger flow times on commuter rail can have a lesser effect on capacity than occurs on other modes.

TRAIN/CAR CAPACITY

Introduction

Train capacity is the product of passengers per car and the number of cars, adjusted to achievable capacity using a diversity factor to compensate for uneven car loadings over multiple-car trains (See Exhibit 3-3).

Exhibit 3-3
Train Capacity Flow Chart



Loading levels for the calculation of car capacity.

Car capacity is often quoted at the crush loading level, but such loading levels are rarely achieved in practice in the U.S. and Canada, but represent the load for which a car's structure, propulsion, and braking systems are designed.

Pass-ups define achievable car capacity.

The only true means of measuring achievable car capacity is on those systems where pass-ups occur. That is where passengers wait for the next train rather than crowd onto the one in their station. Determining full car capacity and pass-up capacity depends on interior arrangements, type of system, old or new, and time of peak loading.

Car Capacity

There are two approaches to the calculation and evaluation of car capacity—design-specific, and a generic average based on car length.

Design-Specific Capacity

If a specific car design has already been chosen, capacity calculation is relatively straightforward. Space used for seats, cabs, wheelchair, stroller or bicycle positions, baggage racks, stepwells, and other equipment is deducted from the interior floor area and the remaining, "standing" space assigned an appropriate standing density.

Train Length Alternative

This alternative offers the simplest method of establishing capacity per unit of car length based on policy decisions of seating type and quantity, and standing density. This method is developed and charts provided to determine capacity in Chapter 4, *Passenger Loading Levels.*

Train Capacity

Design train capacity is simply the product of car capacity and the number of cars per train. The number of cars is limited by platform length, or, for light rail with on-street operation, by the shortest city block length.

Loading variation within a train affects system capacity.

Achievable capacity is affected by variations in loading along the train—train loading diversity. Existing loading diversities are tabulated in Chapter 4, *Passenger Loading Levels*, and levels are recommended for use in calculating achievable capacity.

Station Constraints

In rare cases station capacity constraints can reduce achievable capacity by limiting the flow of passengers to the platform and trains. Although this manual is concerned with supply rather than demand, a section of Chapter 5, *Operating Issues*, discusses these factors.

2. TRAIN CONTROL AND SIGNALING

INTRODUCTION

The role of signaling is to safely separate trains from each other and protect specific paths through interlockings at junctions and crossovers. Additional functions include automatic train stops should a train run through a stop signal, and speed control to protect approaches to junctions, sharp curves, and approaches to terminal stations where tracks end at a solid wall.

Functions of signaling.

Rail transit signaling maintains high levels of safety based on brick wall stops and fail-safe principles ensuring that no single failure—and often multiple failure—should allow an unsafe event. The rigor with which fail-safe principles have been applied to rail transit has resulted in an exceptional safety record. However, the safety principles do not protect against all possibilities including possible human errors. An increasing inability to control the human element—responsible for three-quarters of rail transit accidents or incidents—has resulted in new train control systems using automation to reduce or remove the possibility of human error.

Signaling technology is very conservative.

Signaling cannot protect from every eventuality.

Automatic train control adds further features to the train protection of basic signaling, including automatic driving and train supervision that regulates service.

This chapter describes and compares the separation capabilities of various rail transit train control systems. It is applicable to the main rail transit grouping of electrically propelled, multiple-unit, grade separated systems.

Automatic train control.

All urban rail transit train control systems are based on dividing the track into blocks and ensuring that trains are separated by a suitable and safe number of blocks. Train control systems are then broken down into fixed-block and moving-block signaling systems.

FIXED-BLOCK SYSTEMS

In a fixed-block system, trains are detected by the wheels and axles of a train shorting a low-voltage current inserted into the rails. The rails are electrically divided into blocks. The blocks will be short where trains must be close together, for example in a station approach, and can be longer between stations where trains operate at speed.

The signaling system only knows the position of a train by the simple measure of block occupancy. It does not know the position of the train within the block; it may have only a fraction of the train, front or rear, within the block. At block boundaries, the train will occupy two blocks simultaneously for a short time.

Track circuits.

Fixed block systems provide a coarse indication of train location.

In the simplest two-aspect block system, the signals display only stop (red) or go (green). A minimum of two empty blocks must separate trains and these blocks must be long enough for the braking distance plus a safety distance. The simplest system can accommodate a throughput approaching 24 trains per hour. This does not provide sufficient capacity for some high volume rail lines. Higher capacity can be obtained from combinations of additional signal aspects (three is typical), shorter block lengths, and overlay systems that electronically divide blocks into yet shorter “phantom” sections—for trains equipped for this overlay.

A minimum of two empty blocks is required between trains for a two aspect system.

In this way conventional train control systems can support a throughput of up to 30 trains per hour with typical train length, performance, station dwells, and operating margins. Overlay systems can increase this throughput by 10 to 15%. A notable exception to this is in Russia where conventional signaling routinely handles 40 metro trains per hour. This is achieved by tightly controlling station dwells to a maximum of 25 seconds and rigorous adherence to schedule using digital clocks in each station to display the seconds from the departure of the previous train. New Moscow metro lines are being designed for 44 and 48 trains per hour—by far the closest train spacing on any rail system —irrespective of technology.

Requiring a driver to control a train's speed and commence braking according to multiple aspect color light signaling requires considerable precision to maximize throughput. Cab signaling provides assistance in this regard and reduces capital and maintenance costs.

CAB SIGNALING

Cab signaling sets authorized, safe train speeds.

Cab signaling uses codes inserted into each track circuit and detected by an antenna on each train. The code specifies the maximum allowable speed for the block occupied, and may be termed the *reference* or *authorized* speed. This speed is displayed in the driver's cab—often so that the authorized speed and actual speed can be seen together.

The authorized speed can change while a train is in a block, as the train ahead proceeds, allowing drivers to adjust train speed close to the optimum with less concern about overrunning a trip stop. Problems with signal visibility on curves and in inclement weather are reduced or eliminated. Cab signaling avoids much of the capital and maintenance costs of multiple-aspect color light signals, although it is prudent and usual to leave signals at interlockings and occasionally on the final approach to and exit from each station.

Reducing the number of color light signals makes it economically feasible to increase the number of aspects and it is typical, although not universal, to have the equivalent of five aspects on a cab signaling system. A typical selection of *reference* speeds would be 80, 70, 50, 35, and 0 km/h (50, 43, 31, 22, and 0 mph).

MOVING-BLOCK SIGNALING SYSTEMS

Moving block signaling is based on the use of target points.

Moving-block signaling systems are also called transmission-based or communication-based signaling systems. A moving-block signaling system can be compared to a fixed block system with very small blocks and a large number of aspects. However a moving-block signaling system has neither blocks nor aspects. The system is based on a continuous or frequent calculation of the clear (safe) distance ahead of each train and then relaying the appropriate speed, braking or acceleration rate to each train.

This requires a continuous or frequent two-way communication with each train, and a precise knowledge of a train's location, speed and length; and fixed details of the line—curves, grades, interlockings, and stations. Based on this information, a computer can calculate the next stopping point of each train—often referred to as the target point—and command the train to brake, accelerate, or coast accordingly. The target point will be based on the normal braking distance for that train plus a safety distance.

The safety distance is the maximum distance a train can travel after it has failed to act on a brake command before automatic override (or overspeed) systems implement emergency braking.

Without track circuits to determine block occupancy, a moving-block signaling system must have an independent method to accurately locate the position of the front of a train, then use look-up tables to calculate its end position from the length associated with that particular train's identification. The first moving block systems used a wire laid alongside or between the running rails periodically transposed from side-to-side. The wire transmits signals to and from antennas on the train while counting the transpositions determines location.

The use of exposed wayside wires is a maintenance problem and refinements use inert transponders located periodically along the track. These are interrogated by a radio signal from each train and return a discrete location code. Positioning between transponders relies on the use of a tachometer. Communications to and from the train are then radio based with protocols to ensure safety, reliability, and that messages are received by and only by the train they are intended for.

Communication can be made secure.

The computers that calculate and control a moving-block signaling system can be located on each train, at a central control office, dispersed along the wayside, or a combination of these. The most common arrangement is a combination of on-board and central control office locations.

Safety Issues

Safety on rail transit is a relative matter. It encompasses all aspects of design, maintenance, and operations. In fixed-block signaling, electrical interlockings, switch, and signal setting are controlled by relay logic. A rigorous discipline has been built around this long established technology which the use of processor-based controls is now infiltrating.

A moving-block signaling system is inherently processor controlled. Processor-based train control systems intrinsically cannot meet the fail-safe conventions of traditional signaling. Computers, microprocessors, and solid-state components have multiple failure opportunities and cannot be analyzed and tested in the same way as conventional equipment.

Instead, an equivalent level of safety is provided based on statistical failure modes of the equipment. Failure analysis is not an exact science. Although not all failure modes can be determined, the statistical probability of an unsafe event[4] can be predicted.

HYBRID SYSTEMS

Hybrid systems can allow equipment not equipped for moving block operation to operate on lines signaled with moving blocks.

There are times when an urban rail transit system shares tracks with other services, such as long distance trains, whose equipment is impractical or uneconomic to equip with the moving-block signaling system. Hybrid or overlay systems are available that allow use by unequipped trains—with longer separation—while still obtaining the close headway of the moving-block system for the urban or short distance trains.

AUTOMATIC TRAIN OPERATION

Automated train operation systems often also provide for manual operation.

Automatic acceleration has long been a feature of rail transit, where relays, and more recently microprocessors, control the rate of acceleration smoothly from the initial start to maximum speed. Linking this feature to on-board commands from the signaling system provides automatic train operation.

The acceptance of driverless trains in transit service has been slow.

The driver or attendant’s role is typically limited to closing the doors, pressing a train start button and observing the line ahead, with limited manual operating capabilities to deal with certain failures. Dispensing entirely with a driver or attendant is controversial but has demonstrated its economy and safety on numerous Automated Guideway Transit (AGT) systems, and on rail transit systems in Europe and Vancouver, B.C.

Automated train operation may provide a 2% to 4% capacity increase.

Automatic train operation (ATO), with or without attendants or drivers, allows a train to more closely follow the optimum speed envelope and commence braking for the final station approach at the last possible moment. This reduces station-to-station travel times, and more importantly from the point of capacity, it minimizes the critical station close-in time—the time from when one train starts to leave a station until the following train is berthed in that station. This can increase total line capacity by 2 to 4%.

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[4] An unsafe event may be referred to as a wrong-side failure.

AUTOMATIC TRAIN SUPERVISION

Automatic Train Supervision (ATS) is generally not a safety critical aspect of the train control system. At its simplest it does little more than display the location of trains on a mimic board or video screen in the central control or dispatcher's office. Increasing levels of functionality are available.

Corrective measures to correct late running trains.

In more advanced systems where there is automatic train operation, computer algorithms are used to attempt to automatically correct lateness. These are rare in North America and are generally associated with the newer moving-block signaling systems.

Predictive control.

A further level of ATS strategies is possible—predictive control where a computer looks ahead to possible conflicts, for example a merge of two branches at a junction. The computer can then adjust terminal departures, dwell times, and train performance to ensure that trains merge evenly without holds.

The non-vital ATS system can also be the host for other features such as on-board system diagnostics and the control of station and on-board information through visual and audio messages, including those required by the Americans with Disabilities Act (ADA).

FIXED-BLOCK THROUGHPUT

Determining the throughput of any rail transit train control system relies on the repetitive nature of rail transit operation. In normal operation trains follow each other at regular intervals traveling at the same speed over the same section of track. All modern heavy rail rolling stock has comparable performance.

Stations are the principal limitation on the maximum train throughput. In a well-designed and operated system, junction or turnback constrictions or bottlenecks should not occur. A flat junction can theoretically handle trains with a consolidated headway approaching two minutes. However, delays may occur and systems designed for such close headways will invariably incorporate grade-separated (flying) junctions. Moving-block signaling systems provide even greater throughput at flat junctions.

A two-track terminal station with either a forward or rear scissors cross-over can also support headways below two minutes. In this chapter, the limitations on headway will be calculated for all three possible bottlenecks: station stops, junctions, and turnbacks.

Station Close-In Time

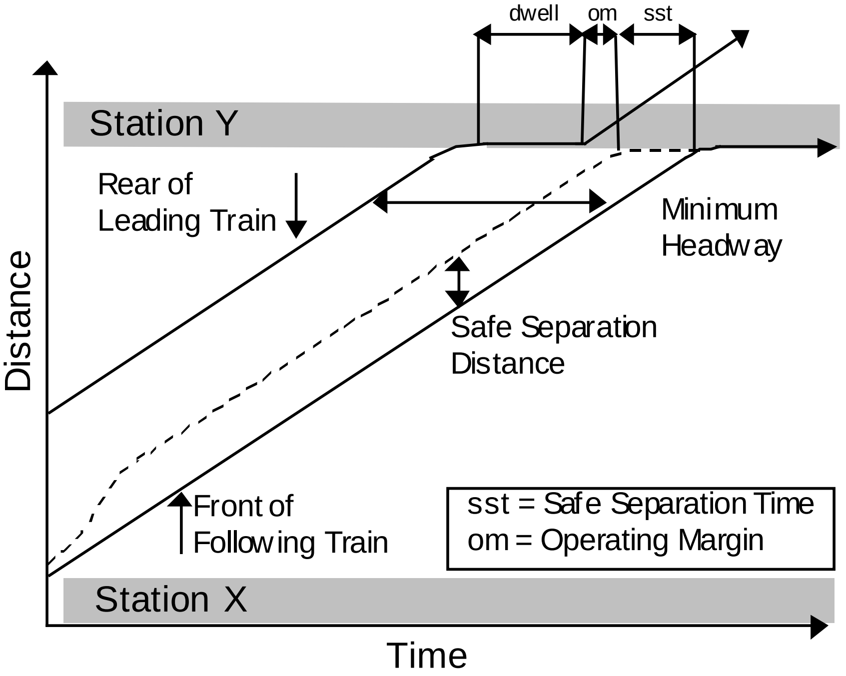
The close-in time is the main constraining factor on rail transit lines.

The time between a train pulling out of a station and the next train entering—referred to as *close-in*—is the main constraining factor on rail transit lines. This time, also known as the *safe separation time*, is primarily a function of the train control system, train length, approach speed, and vehicle performance. Close-in time, when added to the dwell time and an operating margin, determines the minimum possible headway achievable without regular schedule adherence impacts—referred to as the *non-interference headway*. Exhibit 3-4 shows a distance-time station stop diagram.

Computer simulations often provide the basis for accurate estimations of capacity.

The best method to determine the close-in time is from the specifications of the system being considered, from existing experience of operating at or close to capacity or from a computer simulation model. Such models can provide an accurate indication of the critical headway limitation—whether a station close-in maneuver, at a junction or at a turnback. If a model or actual operating data are not available then minimum headway can be calculated from Equation 3-4. The derivation of this equation and additional information on line versus station headways is available in TCRP Report 13.(R7)

Exhibit 3-4
Distance-Time Plot of Two Consecutive Trains
(acceleration and braking curves omitted for clarity)



$$H(s)=\sqrt{\frac{2(L+D)}{a_s}}+\frac{L}{v_a}+\left(\frac{100}{K}+B\right)\left(\frac{v_a}{2d_s}\right)+\frac{a_s t_{os}^2}{2v_a}\left(1-\frac{v_a}{v_{\max}}\right)+t_{os}+t_{jl}+t_{br}+t_d+t_{om}$$

Equation 3-4

where: *[typical values shown in square brackets]*

$H(s)$ = station headway (s);

L = length of the longest train; *[200 m or 660 feet]*

D = distance from front of stopped train to start of station exit block; *[10 m or 33 feet]*

v_a = station approach speed (m/s);

v_{max} = maximum line speed (m/s);

K = braking safety factor—worst case service braking is K% of specified normal rate—typically 75%; *[75]*

B = separation safety factor—equivalent to number of braking distances plus a margin, (surrogate for blocks) that separate trains; *[see text]*

t_{os} = time for overspeed governor to operate; *[3 s]*

t_{jl} = time lost to braking jerk limitation; *[0.5 s]*

t_{br} = operator and brake system reaction time; *[1.5 s]*

t_d = dwell time; *[45 s, see also Chapter 2]*

t_{om} = operating margin; *[20 s, see also Chapter 4]*

a_s = initial service acceleration rate; *[1.3 m/s^2 or 4.3 ft/s^2]* and

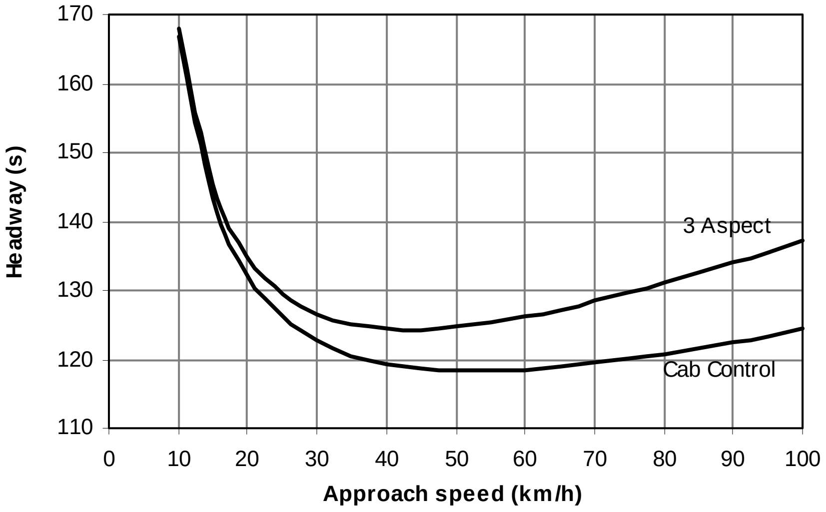
d_s = service deceleration rate. *[1.3 m/s^2 or 4.3 ft/s^2]*

The suggested 45 seconds dwell is higher than the 20-30 seconds often used in simulation programs.

Using these typical values, Equation 3-4 produces the results of Exhibit 3-5 where $B = 2.4$ for three-aspect signaling and $B = 1.2$ for multiple command speed cab controls.

An alternative version of this figure in U.S. customary units appears in Appendix A.

Exhibit 3-5
Station Headway for Lines at Capacity



Optimum approach speeds.

Exhibit 3-5 shows that the optimum approach speed for three-aspect signaling is 47 km/h (29 mph) and for multiple command speed cab controls 52 km/h (32 mph). If special work (interlockings) or curves restrict approach speeds below these values then the lower values must be calculated and used. Typical speed limits for switches and curves are shown in Exhibit 3-6. Determine any such station approach speed restrictions and their distance from the station stopping point. Then compare this speed restriction with the normal approach speed at that distance from the station as shown in Exhibit 3-7. The most restrictive approach speed must then be entered in Equation 3-4.

Switches (turnouts) and curves impose speed restrictions.

The vertical bars show the AREA recommended speed limit range for lateral and equilateral level turnouts of size #6, #8 and #10. Note that many operators have their own speed limits for turnouts that may differ from those shown. Transition spirals are not taken into account.

An alternative version of this figure in U.S. customary units appears in Appendix A.

Exhibit 3-6
Speed Limits on Curves and Switches

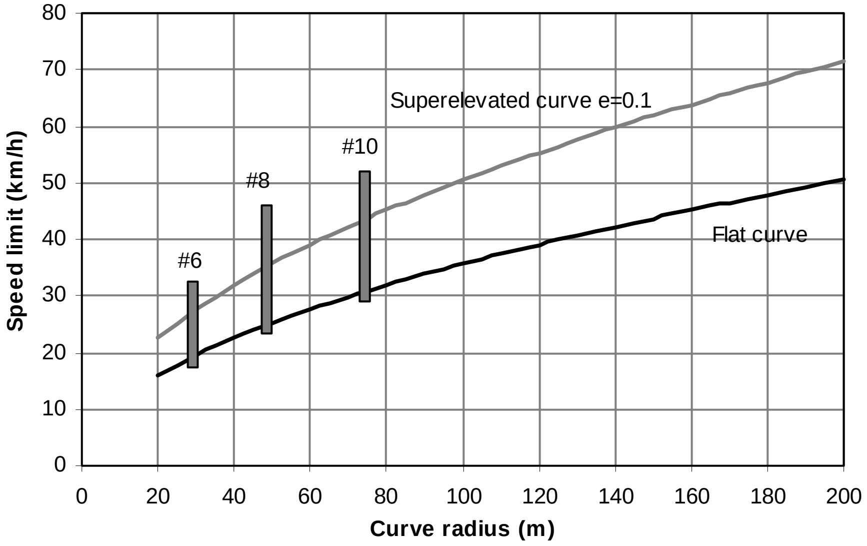
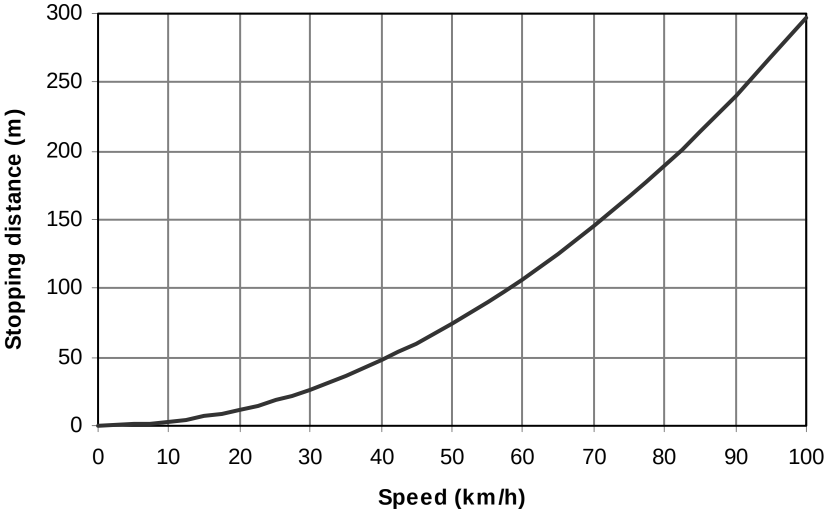


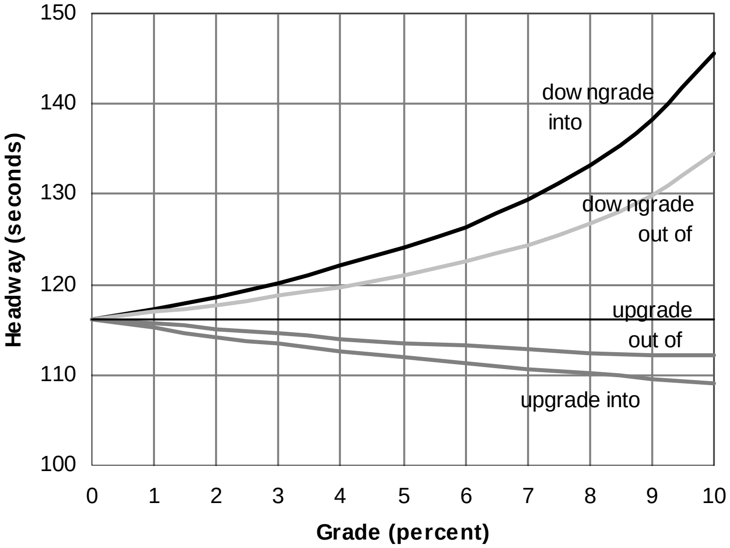
Exhibit 3-7
Distance-Speed Chart



An alternative version of this figure in U.S. customary units appears in Appendix A.

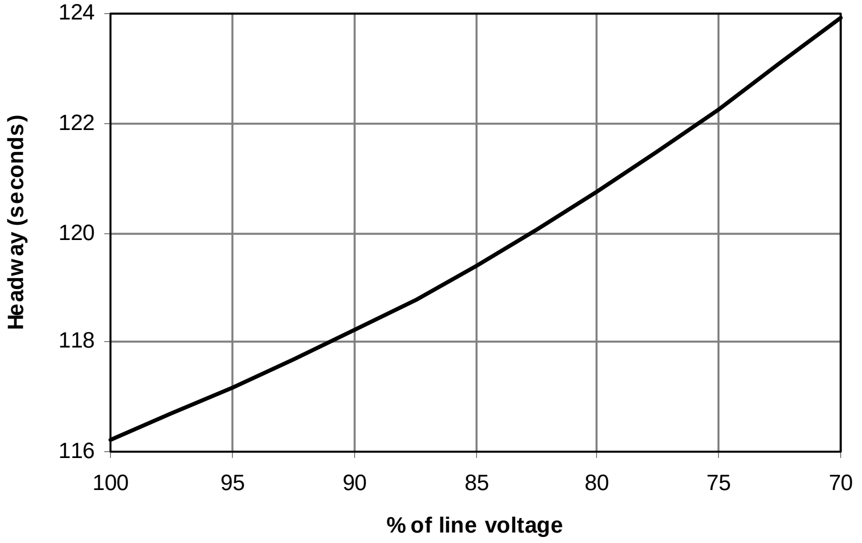
Two other factors affect minimum headways. Grades into or out of a station will change the acceleration and braking rates. Line voltage will drop below the nominal value on heavily used systems and reduce train performance. The results of grades and voltage drops are shown in Exhibit 3-8 and Exhibit 3-9 respectively. The calculations of these effects are complex and best left to a computer simulation. If a simulation model is not available then the approximate headway changes can be read from Exhibit 3-8 and Exhibit 3-9 and the calculation from Equation 3-4 adjusted by the number of seconds.

Exhibit 3-8
Effect of Grade on Station Headway



NOTE: cab signals, dwell = 45 seconds, operating margin = 20 seconds

Exhibit 3-9
Headway Changes with Voltage



Moving-Block Throughput

Moving block train separation safety distances can be fixed or variable.

Moving-block signaling systems replace separation by fixed blocks with a moving block based on the braking distance to a target point plus a safety separation distance. The safety separation distance can be fixed for a given system and type of rolling stock or can be continually adjusted with speed and grades.

Equation 3-5 determines the station headway for a moving-block signaling system with fixed safety separation. Note that the time for the overspeed governor to operate is incorporated into the safety distance and so does not appear in the equation.

$$H(s) = \frac{L + S_{mb}}{v_a} + \frac{100}{K}\left(\frac{v_a}{2d_s}\right) + t_{jl} + t_{br} + t_d + t_{om}$$

Equation 3-5

where: *[typical values shown in square brackets]*

$H(s)$ = station headway (s);
L = length of the longest train; *[200 m or 660 feet]*
v_a = station approach speed (m/s)
K = braking safety factor *[75]*
t_{jl} = time lost to braking jerk limitation (s); *[0.5 s]*
t_{br} = operator and brake system reaction time (s); *[1.5 s]*
t_d = dwell time (s); *[45 s, see also Chapter 2]*
t_{om} = operating margin (s); *[20 s, see also Chapter 4]*
d_s = service deceleration rate; *[1.3 m/s^2 or 4.3 ft/s^2]* and
S_{mb} = moving-block safety distance *[50 m or 165 feet]*

Equation 3-6 determines the station headway for a moving-block signaling system with a variable safety separation.

$$H(s) = \frac{L + P_e}{v_a} + \left(\frac{100}{K} + B\right)\left(\frac{v_a}{2d_s(1 + 0.1G)}\right) + \frac{a_s(1 - 0.1G)t_{os}^2}{2v_a}\left(1 - \frac{v_a}{v_{max}}\right) + t_{os} + t_{jl} + t_{br} + t_d + t_{om}$$

Equation 3-6

where:

P_e = positioning error; *[6.25 m or 20 ft]*

B = separation safety factor—equivalent to number of braking distances; *[1.0]*

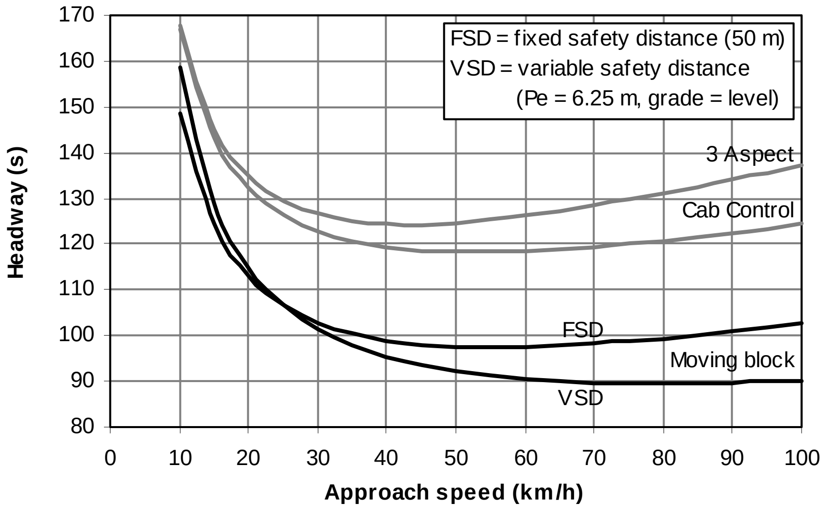
G = grade percentage into station; and

t_{os} = time for overspeed governor to operate (s). *[3 s]*

Equation 3-6 adjusts the safety separation entering a station due to any grade. A downgrade will increase the braking distance and so require a longer safety separation—and vice versa. For simplification the acceleration due to gravity, 9.807m/s^2, is rounded up to 10.0 m/s^2 (33 ft/s^2).

The results of Equation 3-5 and Equation 3-6 are shown in Exhibit 3-10. The resultant minimum headway of 97 seconds occurs at an approach speed of 56 km/h (35 mph). The respective curves for a conventional three-aspect signaling system and a cab control system are included for comparison. As would be expected, a moving block system with a speed variable safety distance shows the lowest overall headway. The difference between the two methods of determining the safety distance represents an eight second difference in the minimum headway. Voltage fluctuations have little effect on moving-block headways as the time to clear the platform is not a component in calculating the moving-block signaling system headway.

Exhibit 3-10
Moving Block Headways with 45-Second Dwell and 20-Second Operating Margin Compared with Conventional Fixed Block Systems



Clear capacity increases with a moving-block signaling system.

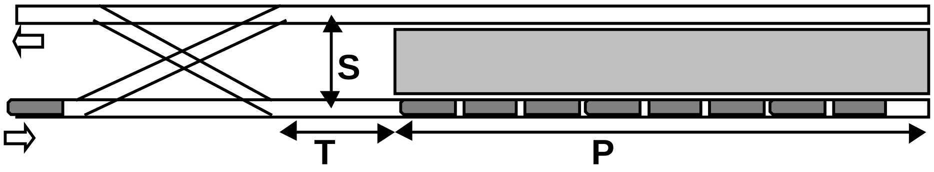
An alternative version of this exhibit appears in Appendix A.

TURN-BACK THROUGHPUT

Turn-backs should not be a constraint on capacity.

Correctly designed and operated turn-backs should not be a constraint on capacity. A typical terminal station arrangement with the preferred[5] center (island) platform is shown in Exhibit 3-11.

Exhibit 3-11
Terminal Station Track Layout



The worst case is based on the arriving train (lower left) being held at the cross-over approach signal while a train departs. It must, moving from a stop, traverse the cross-over and be fully berthed in the station before the next exiting train (lower right) can leave. The exiting train must then clear the cross-over and the interlocking switches must be reset before another train can enter the station. The minimum time for a train to unload and load passengers and for the driver to change ends, inspect the train and check train integrity and braking, allowing for the two berths, is shown in Equation 3-7.

$$t_l \le 2\left(H - t_s - \sqrt{\frac{2(P+T+CS)}{a_s+d_s}} - \sqrt{\frac{(P+T+CS)}{2a_s}} \right)$$

Equation 3-7

where: *[typical values shown in square brackets]*

t_l = terminal layover time (s);
H = train headway; *[120 seconds]*
t_s = switch throw and lock time; *[6 seconds]*
P = platform length; *[200 meters or 660 feet]*
T = distance from cross-over to platform *[20 meters or 65 feet]*
S = track separation = platform width + 1.6 m (5.25 feet) *[10 meters or 33 feet]*
C = switch angle factor:
—5.77 for #6 switch,
—6.41 for #8 switch, and
—9.62 for #10 switch.
a_s = initial service acceleration rate *[1.3 m/s^2 or 4.3 ft/s^2]*
d_s = service deceleration rate*[1.3 m/s^2 or 4.3 ft/s^2]*

A typical terminal layover time can then be calculated using the typical parameters in the square brackets above, including a headway of 120 seconds. The terminal time t_t is less than or equal to 175 seconds per track. This would increase by 9 seconds if the incoming train did not stop before traversing the cross-over. While this is not a generous amount of time, particularly to contain a schedule recovery allowance, many systems maintain such close headways with minimal delays.

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[5] While side platforms reduce the track to track centers and so reduce the maneuver time, they require passengers to be directed to the correct platform for the next departing train. This is inherently undesirable and becomes more so when a train cannot depart due to a defect or incident and passengers must be redirected to the other platform.

This analysis assumes that any speed restrictions in the terminal approach and exit are below the speed a train would reach in the calculated movements—approximately 21 km/h (34 mph) on a stop-to-stop approach, and 29 km/h (47 mph) as the end of the train leaves the interlocking on exit. Normally there would be no restrictions so low but following London Transport's Moorgate disaster—when a fully loaded train accelerated into the wall at the end of a terminal station—some systems have imposed low entry speeds, occasionally enforced with speed control signaling.

This maximum permitted terminal time can be calculated for the specific system and terminal parameters. Where the time is insufficient there are numerous corrective possibilities. These include moving the cross-over as close to the platform as possible; however, note that structures can restrict the cross-over location in subways.

Dual faced platforms and loops can reduce dwell times.

If passenger dwell is a limiting factor then this can be reduced with the use of dual faced platforms. At terminals with exceptionally heavy passenger loading, multiple-track layouts may be needed. An unusual alternative, used at SEPTA's 69th Street and PATH's World Trade Center termini, are loops—with the exception of several examples in Paris, these are rare luxuries for heavy rail transit.

Crew turnaround time can be expedited with set-back crewing. At a leisurely walking pace of 1 m/s (3 ft/s) it would take 200 seconds for a driver to walk the length of a 200-m (660-ft) train, more if the driver were expected to check the interior of each car for left objects or passengers. Obviously this could not be accommodated reliably in a 175-second terminal layover time.

Allowances should be made to prevent common delays from disrupting terminal operations.

Terminal arrangements should accommodate some common delays. An example would be the typical problems of a train held in a terminal for a door sticking problem, waiting for police to remove an intoxicated passenger, or for a cleaning crew to perform minor cleaning. Alternately one track may be pre-empted to store a bad order train. On these occasions the terminal is temporarily restricted to a single track and the maximum terminal layover time is reduced to 61 seconds with the above parameters (70 seconds without an approach stop). This may be sufficient for the passenger dwell but cannot accommodate changing ends on a long train and totally eliminates any schedule recovery allowance.

More expensive ways to improve turn-backs include extending tracks beyond the station and providing crossovers at both ends of the station. This permits a storage track or tracks for spare and disabled trains—a useful, if not essential, failure management facility. With crossovers at both ends of the station, on-time trains can turn-back beyond the station with late trains turning in front of the station—providing a valuable recovery time of some 90 seconds at the price of additional equipment to serve a given passenger demand.

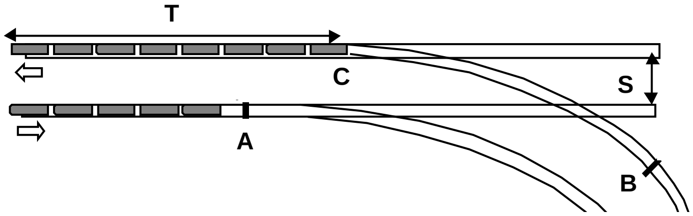
JUNCTION THROUGHPUT

Junctions should not constrain capacity.

Correctly designed junctions should not be a constraint on capacity. Where a system is expected to operate at close headways, high use junctions will invariably be grade separated. At such *flying junctions*, the merging and diverging movements can all be made without conflict and the only impact on capacity is the addition of the switch throw and lock times, typically 3 to 6 seconds. Speed limits, imposed in accordance with the radius of curvature and any superelevation, may reduce the schedule speed but should not raise the minimum headway—unless there is a tight curve close to a headway limiting station.

The capacity of a flat junction can be calculated in a similar manner to the terminal station approach. The junction arrangement is shown in Exhibit 3-12.

Exhibit 3-12
Flat Junction Track Layout



The worst case is based on a train (lower left) held at signal "A" while a train of length T moves from signal "B" to clear the interlocking at "C." The minimum operable headway is the line headway of train "A" plus the time required for the conflicting train to clear the interlocking plus the extra time for train "A" to brake to a stop and accelerate back to line speed. Ignoring specific block locations and transition spirals, this can be expressed approximately as:

$$H(j) = H(l) + \sqrt{\frac{2(T + 2CS)}{a_s}} + \frac{v_l}{a_s + d_s} + t_s + t_{om}$$

Equation 3-8

where: *[typical values shown in square brackets]*

H(j) = limiting headway at junction (s);
H(l) = line headway; *[32 seconds]*
T = train length; *[200 meters or 655 feet]*
S = track separation; *[10 meters or 33 feet]*
C = switch angle factor:
—5.77 for #6 switch,
—6.41 for #8 switch, and
—9.62 for #10 switch;
a_s = initial service acceleration rate; *[1.3 m/s^2 or 4.3 ft/s^2]*
d_s = service deceleration rate; *[1.3 m/s^2 or 4.3 ft/s^2]*
v_l = line speed; *[100 km/h = 27.8 m/s or 60 mph = 91 ft/s]*
t_s = switch throw and lock time; *[6 seconds]* and
t_{om} = operating margin time (s).

The limiting headway at the junction can then be calculated using the typical parameters in the square brackets above, resulting in a junction limiting headway of 102 seconds plus an operating margin. While in theory this should allow a 120 second headway with a flat junction, it does not leave a significant operating margin and there is a probability of interference headways. General guidance in rail transit design is that junctions should be grade separated for headways below 150 to 180 seconds.

Advantage of sophisticated supervision to reduce junction conflicts.

An exception is with a moving-block signaling system incorporating an automatic train supervision system with the capability to look forward—and so adjust train performance and station dwells to avoid conflicts at the junction, i.e., trains will not have to stop or slow down at the junction—other than for the interlocking's track design speed limit. In this case, the junction interference headway drops to 63 seconds, allowing 120-second, or slightly lower, headways to be sustained on a flat junction—a potentially significant cost saving associated with a moving-block signaling system.

SUMMARY

Results match actual field experience.

Using as few approximations as possible, the minimum headway can be calculated for a range of train control systems with a wide number of variables. The results are summarized in Exhibit 3-13. These concur with field data and, although a reliable guide, are not a substitute for a full and careful simulation of the train control system in conjunction with a multiple-train performance simulation.

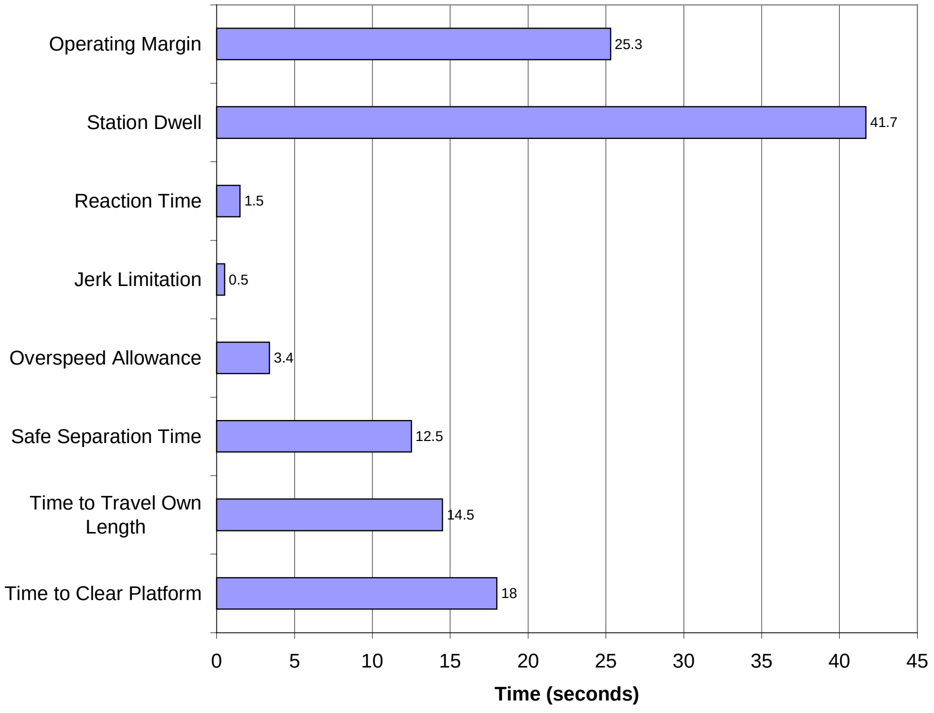
Exhibit 3-13
Headway Result Summary in Seconds with 200-m (660-ft) train

Station dwell (s)	**0**	**30**	**45**
Operating margin (s)	**0**	**15**	**25**
Three-aspect system	57	102	122
Cab controls	51	96	116
Moving Block — variable safety distance	32	77	102

The components of headway for a cab signaling system with typical heavy rail parameters are shown in Exhibit 3-14 with a station dwell of 45 seconds and an operating margin of 25 seconds. The components are shown in the order of Equation 3-4 with terms running from the bottom upwards. Dwell is the dominant component. The next chapter deals with dwells while approaches to reduce dwell and thus increase capacity are addressed in Chapter 10.

The components of headway for the above mid-range cab-control data are shown in the headway components, note the importance of station dwell.

Exhibit 3-14
Headway Components for Cab Control Signaling with a 120-Second Headway



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3. STATION DWELL TIMES

INTRODUCTION

Station dwell times are a major component of headway.

Station dwell times are the major component of headways at close frequencies as shown in Exhibit 3-14—based on a heavy rail system at capacity, operating 180-meter-long trains with a cab-control signaling system. The best achievable headways under these circumstances are in the range of 110 to 125 seconds.[6]

Controlling dwells.

Controlling station dwell time is the combination of dwell time and a *reasonable* operating margin—the dwell time during a normal peak hour that controls the minimum regular headway. Controlling dwell takes into account routine perturbations in operations—but not major or irregular disruptions. The sum of controlling dwell and the train control system's *minimum train separation time* produces the maximum train throughput without headway interference. In this chapter the components of dwell time will be examined and procedures provided to determine dwell times.

Dwell Time Components

Peak period dwell times on four selected systems.

Regularity of fully automated systems.

Dwell time is comprised of the time passenger flow occurs, a further time before the doors are closed, and then a time while waiting to depart with the doors closed. Exhibit 3-15 shows these dwell components for the peak-period of four selected rail transit stations. Each of the rail transit systems serving the particular stations has a different operating philosophy. BART in the San Francisco Bay Area is automatically driven with door closure and departure performed manually, the latter subject to override by the automatic train control. NYCTA in New York and the TTC in Toronto are entirely manual, subject only to a permissive departure signal. The TTC has a safety delay between door closure and train departure. BC Transit's SkyTrain in Vancouver, B.C. is an entirely automatic system with unattended cars; door closing and departure times are pre-programmed. This is evident from the exhibit which shows two services, including a short turn service with shorter dwells that ends about half way down. All data represent the heaviest used doorway(s) on the train.

There is great variance in dwell times between doors of a train and between stations in a system—the data shown is from doors with the heaviest flow at the busiest station.

Dwell reductions made possible by automation are often offset by slack operating procedures.

The proportion of dwell time productively used for passenger movements ranges from 31 to 64% of the total dwell time. This presents a challenge in determining dwell times from the passenger volumes. Dwells also vary depending on the operating practices of each system. Several North American light rail and heavy rail systems are notably more expeditious at station dwells than their counterparts, contributing to a faster—and so more economic and attractive—operation. Ironically, several automatically driven systems have sluggish station dwells in which expensive equipment and staff sit and wait—long after all passenger movement has ended. The high-capacity rail systems in Europe and Asia, particularly those of Russia and Japan, are noted for their efficient management and control of station dwells.

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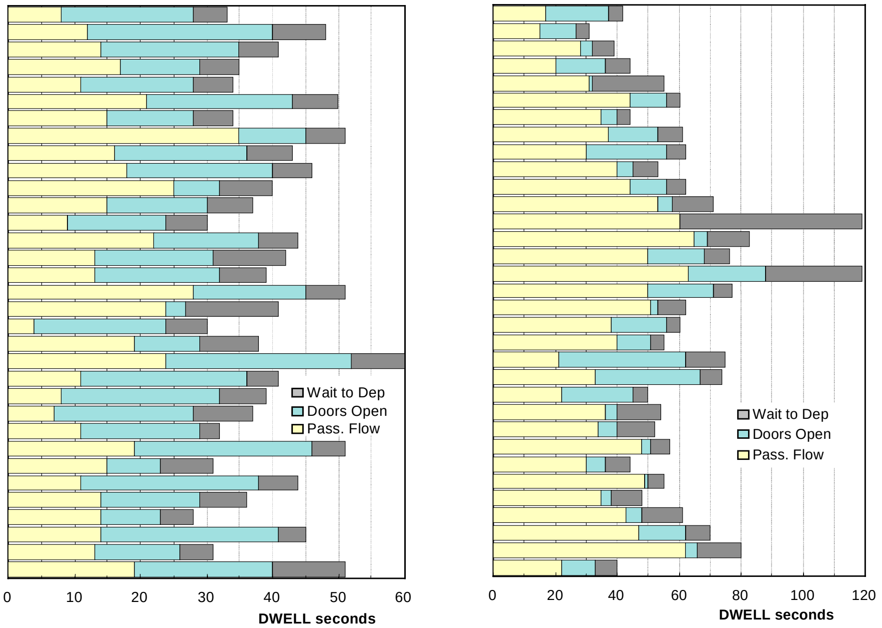
[6] Some Russian systems using multiple aspect cab-control signaling systems operate at headways down to 90 seconds by strict control of station dwell times—on occasion, closing doors before all passenger movements are complete. This is probably not an acceptable practice in North America.

Note that the scale of the Grand Central Station chart is twice that of the other charts in this series.

Exhibit 3-15
Dwell Time Components of Four Rail Transit Stations



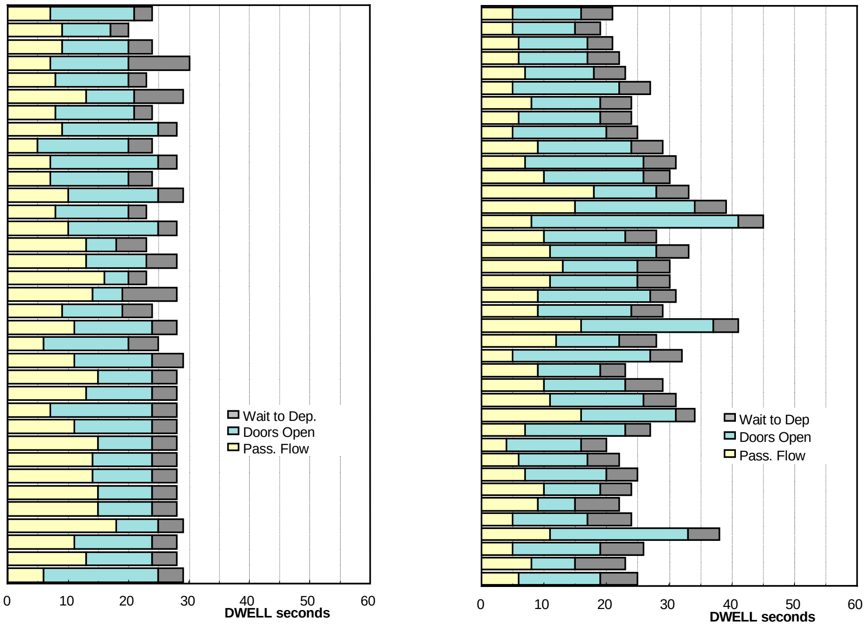
BART Montgomery Station (San Francisco)

Average headway: 153 seconds
Number of passengers observed: 586
Flow time averages 38% of total dwell

NYCT Grand Central Station (New York)

Average headway: 160 seconds
Number of passengers observed: 1,143
Flow time averages 64% of total dwell

These four charts are representative of 61 data sets of door flows collected in early 1995 for the TCRP Rail Capacity study.$^{(R7)}$ *Data are from systems operated at, or close to, the capacity of their respective train control systems. The data represent the movement of 25 154-passenger trains over 56 peak periods, two base (inter-peak), and three special event times, at 27 locations on 10 systems. Each bar represents an observation of an individual train.*



BC Transit SkyTrain Burrard Station (Vancouver)

Average headway: 153 seconds
Number of passengers observed: 586
Flow time averages 38% of total dwell

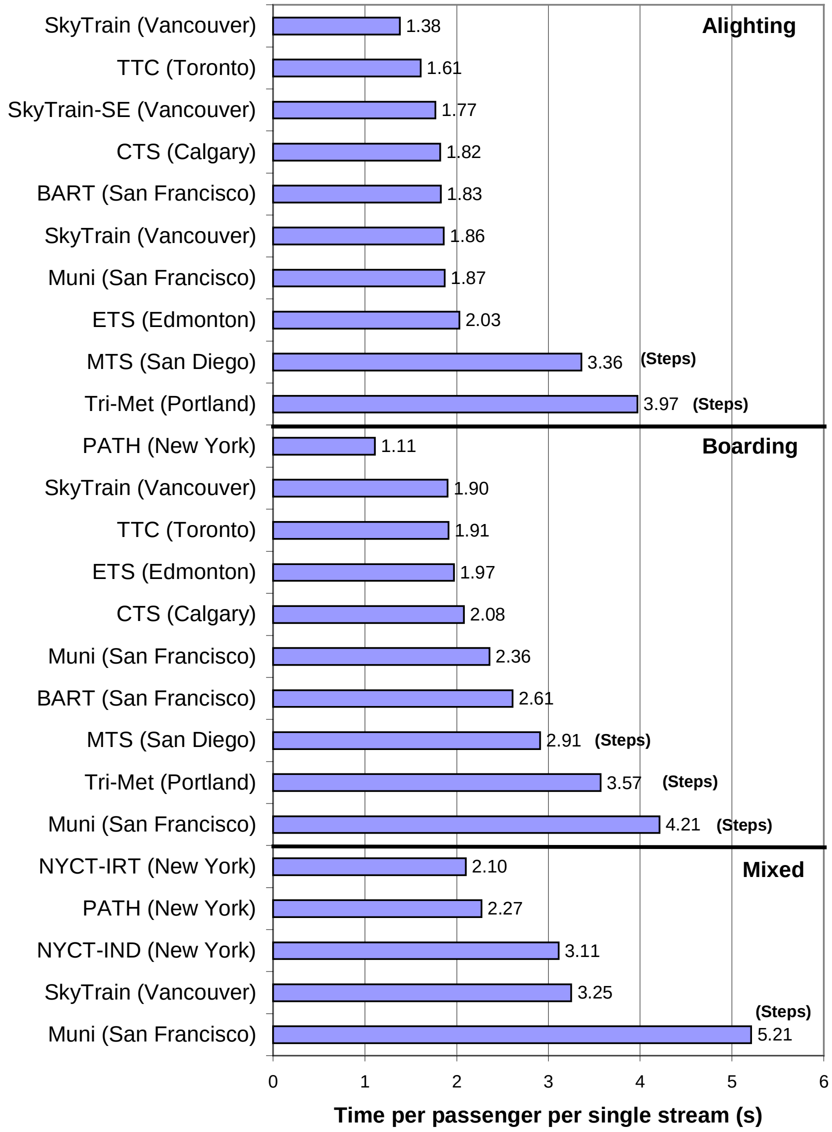
TTC King Station, Southbound (Toronto)

Average headway: 160 seconds
Number of passengers observed: 1,143
Flow time averages 64% of total dwell

Doorway Flow Rates

Flow time is the time in seconds for a single entering or exiting passenger to cross the threshold of the rail transit car doorway, per single stream of doorway width. Extensive rail transit door flow rate data collection took place in 1995 for the TCRP Project A-8, Rail Transit Capacity. Data were collected from a representative set of high-use systems and categorized by the type of entry—level entry being the most common, then light rail with door stairwells, with and without fare collection at the entrance. The data sets were then partitioned into mainly boarding, mainly alighting, and mixed flows. The results are summarized in Exhibit 3-16.

Exhibit 3-16
Selection of Rail Transit Door Flow Times

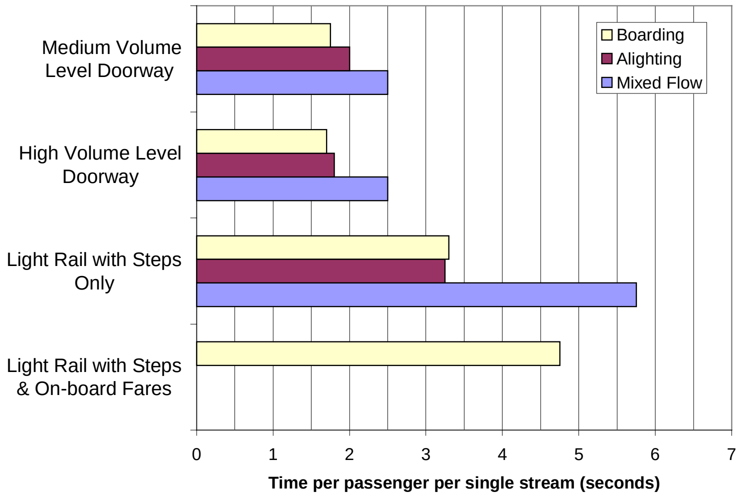


NOTE: Level boarding, except up or down steps where indicated.

Passengers ascend steps into a light rail vehicle faster than they descend them on exit.

An interesting result is that passengers enter high-floor light rail vehicles faster from street level than they exit. The overall fastest flow rate, 1.11 seconds per passenger per single stream, was observed on PATH when passengers were boarding empty trains at the Journal Square station in Newark in the morning peak. These flow data are consolidated and summarized by type of flow in Exhibit 3-17.

Exhibit 3-17
Summary of Rail Transit Average Door Flow Times



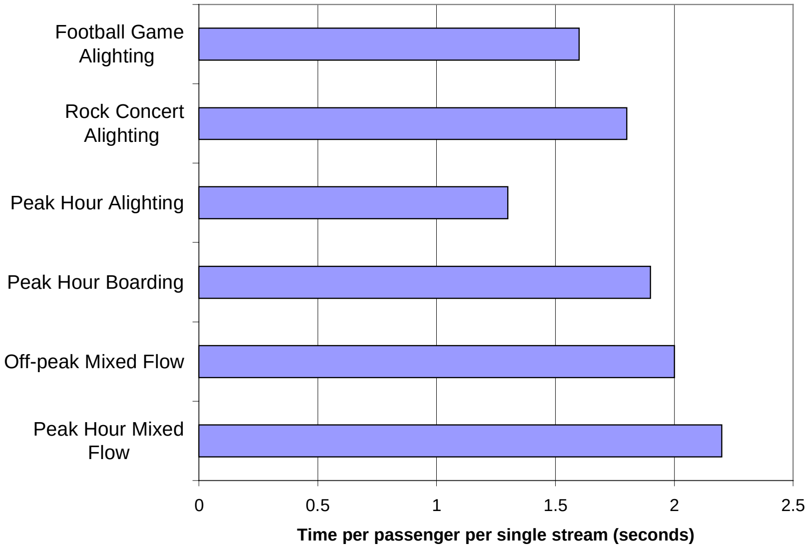
Doorway steps double boarding and alighting times.

The results show that, in these averages, there is little difference between the high-volume—older East Coast heavy rail transit—systems and the medium-volume systems—newer light rail and heavy rail transit. Doorway steps approximately double times for all three categories: mixed flow, boarding, and alighting. Light rail boarding up steps, with exact fare collection, adds an average of almost exactly one second per passenger.

While most of the field data collection on doorway flow rates was done during peak-periods, off-peak and special event flows were observed on BC Transit's SkyTrain and compared to peak period flows, as summarized in Exhibit 3-18.

Special event passenger rates were found to be slower than weekday peak rates.

Exhibit 3-18
BC Transit SkyTrain Door Flow Rate Comparisons



Special event flows were observed before a football game, before a rock concert, and on a busy suburban station in the early afternoon base period. The resultant data are contrary to the supposition that special event crowds move faster and that off-peak flows are slower than in the peak hour. BC Transit has also measured car occupancy differences between normal peak hour operation and after service delays. In the ensuing pressure to travel after a delay, standing density almost doubled from a mean of 2.8 passengers per m^2 to 5 passengers per m^2 (3.8 to 2.2 ft^2/p).

Effect of Door Width on Passenger Flow Times

Extensive doorway flow data has failed to show any meaningful relationship between door width and flow rate, within the 1.14 to 1.37 m (3.75 to 4.5 ft) range of door widths observed, all double-stream doors are essentially equal. Double-stream doors frequently revert to single stream flows and very occasionally three passengers will move through the doorway simultaneously.

Door widths on observed systems seemed to have little effect on flow rates.

At some width below this range, a doorway will be essentially single stream. At widths above those surveyed, a doorway will routinely handle triple streams. There are no single- or triple-stream doors on any modern North American rail transit vehicle, although they exist on AGT systems and in other countries. JR East in Tokyo is experimenting with a quadruple-stream doorway—shown in Exhibit 3-19. Wide doors have been a characteristic of the ADtranz C100 automated guideway transit used in many airports and on Miami's MetroMover. This four-stream 2.4 m (8 ft) door is shown below.

All observed doors were essentially double-stream.

Exhibit 3-19
Quadruple-Stream Doorways

Tokyo Miami

Estimating Dwell Times

There are three methods to estimate station dwell times. The first translates station passenger volumes and doorway flow rates into doorway flow times and then into dwell times. This involves complex mathematics involving logarithmic transforms and depends on knowledge of station passenger movements, which are often not readily available. Use of this method is limited and reference should be made to Chapter 4 of TCRP Report 13, *Rail Transit Capacity*.(R7)

Relating passenger volumes, and flow rates and times, to dwell times.

The second method is the traditional *Mean Plus Two Standard Deviations*. It provides a prediction interval for a new train as opposed to one for the mean of all trains. Since it is maximum capacity that is the ultimate objective, only the upper limit is of interest. This is of value for stations on existing systems where data can be collected at busy stations to allow the mean and standard deviation to be calculated.

Both one and two standard deviations have been used in other work. In either case it is necessary to ensure that the calculated controlling dwell time contains a sufficient allowance or margin to compensate for minor irregularities in operation. With the addition of one standard deviation, some additional allowance for operational irregularities is necessary. With the addition of two standard deviations, the need for any additional allowance is minor or unnecessary.

In many situations, particularly new systems, insufficient data is available to estimate the dwell standard deviation over a one-hour or even a 15-minute peak period. In these cases, or as an alternate approach in situations where data is available, an operational allowance or margin can be added to the estimated dwell time due to a specific volume of passenger movements. The results on controlling dwell times of adding 15 and 20 second operating margins on existing systems are shown in Exhibit 3-20.

Exhibit 3-20
Controlling Dwell Data Limits (seconds)

System & City	Mean	SD	# of samples	Upper Limit (Mean+SD) One SD	Upper Limit (Mean+SD) Two SD	Operational margin (s) +15	Operational margin (s) +20
BART (San Francisco)	46.3	12.0	290	58.3	70.2	61.3	66.3
CTS (Calgary)	35.7	15.7	91	51.5	67.0	50.7	55.7
ETS (Edmonton)	24.7	8.8	18	33.6	42.3	39.7	44.7
NYCT (New York)	30.7	20.9	380	51.6	72.6	45.7	50.7
PATH (New Jersey)	51.3	23.0	252	64.3	97.3	66.3	71.3
Tri-Met (Portland)	32.0	19.4	118	51.4	70.8	47.0	52.0
MTS (San Diego)	51.1	17.9	34	69.1	86.8	66.1	71.1
Muni (San Francisco)	50.4	21.8	75	72.2	93.9	65.4	70.4
TTC (Toronto)	36.6	23.2	322	59.8	83.0	51.6	56.6
SkyTrain (Vancouver)	30.7	7.2	82	37.9	45.1	45.7	50.7

SD: standard deviation

The third method is often the most practical, involving selection of dwell times and operational allowances from comparable existing systems. Chapter 5, *Operating Issues*, discusses the need for, and approaches to, estimating a reasonable operating margin and provides additional examples of existing controlling dwells.

4. PASSENGER LOADING LEVELS

INTRODUCTION

Establishing the loading level of rail transit is the final step in determining capacity. After the maximum train throughput has been calculated from the inverse of the sum of signaling separation time, dwell time, and operating margin, capacity is then based only on train length and loading level.

The existing loading levels on North American rail transit vary from the relaxed seating on many commuter rail lines to the denser loadings experienced on older subway and light rail systems. These loadings offer levels of passenger comfort that are inappropriate for new systems intended to compete with the automobile.

Loading levels vary widely by transit mode and system.

The next section reviews existing rail transit loading standards. The remainder of the chapter determines a range of loading standards that can be applied in specific circumstances for each mode.

LOADING STANDARDS

Most rail transit systems have loading standards for the peak-hour, peak-point location with more relaxed standards away from entry into the city center and for off-peak times. Exhibit 3-21 shows loading standards over the peak 15 minutes for selected heavy rail systems.

Mexico City's Metro is an exception and experiences loading that can exceed 8 passengers/m^2 (1.8 ft^2/p).

Exhibit 3-21
Passenger Space on Selected North American Heavy Rail Systems (R5)

System (City)	Passenger Space (based on Gross Floor Space) (p/m^2)	(ft^2/p)
NYCT (New York)	2.6 into CBD	4.0 into CBD
CTA (Chicago)	1.5 into CBD	7.0 into CBD
SEPTA (Philadelphia)	1.3 into CBD	8.0 into CBD
MBTA (Boston)	2.0 into CBD	5.0 into CBD
BART (San Francisco)	1.2-1.9	9.0-5.75
WMATA (Washington)	0.9-2.0	12.0-5.0
MARTA (Atlanta)	1.4-1.6	7.5-6.75
TTC (Toronto)	1.8-2.4	6.0-4.5
STCUM (Montréal)	2.6-3.2	4.0-3.4

It is customary to express passenger space requirements in passengers per square meter in metric and in square feet per passenger in U.S. customary units, even though this results in a reciprocal relationship.

Care should be taken in comparing and applying the service standards with hourly average loadings. Service standards are usually based on the peak within the peak—15 minutes or less. The difference between 15 minute and peak hour flows can be represented by a peak hour factor.

Service standards are usually based on peak within the peak loads.

The peak hour factor for New York subway's trunk routes averages 0.817. Outside New York the peak-within-the-peak period tends to be more pronounced and the peak hour diversity factor is lower. In part this is due to the long-established Manhattan program to stagger work hours and the natural tendency of passengers to avoid the most crowded period—particularly on lines that are close to capacity.

Peak hour diversity is lower in New York than most other cities.

In addition to standards or policies for the maximum loading on peak-within-the-peak period trains and for standards based on minimum *policy* headways, at off-peak times some operators specify a maximum standing time. This is more often a goal rather than a specific standard—20 minutes is typical.

Maximum standing time policies.

Loading levels for commuter rail are unique and uniform. Although standing passengers may be accepted for short inner-city stretches or during times of service irregularities, the policy is to provide a seat for all passengers. Capacity is usually cited at 90 to 95% of the number of seats on the train.

SPACE REQUIREMENTS

Passenger standing density.

The Batelle Institute(R4) recommends comfort levels for public transport vehicles and provides details of the projected body space of passengers in various situations. The most useful of these for rail transit capacity are shown in Exhibit 3-22 for males:

Gross vehicle floor area.

- Comfortable: 2-3 passengers per m^2 (5.4 to 3.6 ft^2/p),
- Uncomfortable: 5 passengers per m^2 (2.2 ft^2/p), and
- Unacceptable: >8 passengers per m^2 (1.3 ft^2/p).

Exhibit 3-22
Male Passenger Space Requirements(R4)

Suggested minimum space.

Situation	Projected Area (m^2)	Projected Area (ft^2)
Standing	0.13-0.16	1.4-1.7
Standing with briefcase	0.25-0.30	2.7-3.2
Holding on to stanchion	0.26	2.8
Minimum seated space	0.24-0.30	2.6-3.2
Tight double seat	0.36 per person	3.9 per person
Comfortable seating	0.54 per person	5.8 per person

Pushkarev et al.(R8) suggest *gross vehicle floor area* as a readily available measure of car occupancy, recommending the following standards:

- Adequate: 0.5 m^2 (5.4 ft^2) provides comfortable capacity per passenger space.
- Tolerable with difficulty: 0.35 m^2 (3.8 ft^2) is the lower limit in North America with "some touching."
- Totally intolerable: 0.2 m^2 (2.2 ft^2) is the least amount of space that is occasionally accepted.

Commuter rail capacity is based on the number of seats. Commuter rail cars in North America are typically 28 m (86 ft) long and with few exceptions have seating for 114 to 185 passengers. The higher levels relate to bi-level or gallery cars and/or cars with 2+3 seating arrangements.

Wheelchair space provisions range from 0.55 to 1.2 m^2 (5.9-12.9 ft^2) , with 0.8 m^2 (8.6 ft^2) typical. This space can include folding or jump seats. Provision must also be made for wheelchair maneuvering and for any requirements to carry push-chairs, baggage and bicycles—particularly on rail lines that serve airports. More space is required for electric chairs and ones whose occupants have a greater leg inclination, less for compact and sports chairs.

The vehicle capacity for existing systems should be based on actual loading levels of a comparable service. Actual levels on a specific system or line should be adjusted for any difference in car size and interior layout—particularly the number of seats.

Maximum, full, and crush loads.

Manufacturer specified passenger loading—*total*, *maximum*, *full*, or *crush load* does not necessarily represent a realistic occupancy level. Rather it reflects applying a set criteria—such as 5 or occasionally 6 passengers per square meter (2.2 to 1.8 ft^2/p)—to the floor space remaining after seating space is deducted. In particular *crush load* can represent the theoretical, and often unattainable, loading used to calculate vehicle structural strength or the minimum traction equipment performance.

Vehicle Specific Calculations

Estimating the person capacity of a vehicle.

Detailed calculations of the person capacity of individual vehicles are not recommended. Given the wide range of peak hour occupancy that is dependent on policy decisions, elaborate determination of interior space usage is generally not practical. Reasonably accurate estimates of vehicle capacity are all that are needed. The following procedures offer a straightforward method.

The first step after obtaining the interior car dimensions is to determine the length of the car side free from doorways. Deducting the sum of the door widths, plus a setback allowance of 0.4 m (16 inches)[7] per double door, from the interior length gives the interior free wall length.

Seating can then be allocated to this length by dividing by the seat pitch:

- 0.69 m (27 inches)[8] for transverse seating, and
- 0.43 m (17 inches) for longitudinal seating.

The result, in lowest whole numbers[9], should then be multiplied by two for longitudinal seating or by 3, 4, or 5 respectively for 2+1, 2+2, or 2+3 transverse seating. The result is the total number of seats. A more exact method would use the specific length between door setbacks. Articulated light rail vehicles should have the articulation width deducted. Four seats can be assigned to the articulation, if desired.

Seating area.

The floor space occupied by seats can then be calculated by multiplying transverse seats by 0.5 m^2 (5.4 ft^2) and longitudinal seats by 0.4 m^2 (4.3 ft^2). These areas make a small allowance for a proportion of bulkhead seats but otherwise represent relatively tight and narrow urban transit seating. Add 10 to 20% for a higher quality, larger seat such as found on BART.

Standing area.

The residual floor area can now be assigned to standing passengers. Light rail vehicles with step wells should have half the step well area deducted. Although prohibited by many systems, passengers will routinely stand on the middle step, squeezing into the car at stops if the doors are treadle operated.

Articulated light rail vehicles should have half the space within the articulation deducted as unavailable for standing passengers, even if the articulation is wider. Many passengers choose not to stand in this space.

Standing passengers can be assigned as follows:

- 5 passengers per square meter, or 0.2 m^2 (2.15 ft^2) per passenger, an uncomfortable near crush load for North Americans with frequent body contact and inconvenience with packages and brief cases. Moving to and from doorways is extremely difficult.

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[7] A lower set-back dimension of 0.3 m (12 inches) may be used if this permits an additional seat/row of seats between doorways.

[8] Increase to 0.8 m (32 inches) for seats behind a bulkhead

[9] For more accurate results, the sidewall should be divided into the lengths between each set of doors (and, when appropriate, between the door and any articulation) and checked, or adjusted, to ensure that an integer of the seat pitch is used. This can be done by dividing the interior free wall length by the number of doorways plus one. The number of integer seat pitches in each space is then determined and used to calculate the total vehicle seating.
However this approach can result in the seating changing radically with a small change in vehicle length, articulation length, or door width, any of which are sufficient to add or remove a row of seats between each set of doors. On a four door car with 2+2 seating this results in the seating adjusting up or down by 20 seats at a time—five rows of four seats. Simple calculations can not substitute for a professional interior layout design that can optimize seating with a combination of transverse and longitudinal seats. Other design criteria can also be accommodated including the provision of wheelchair spaces and maximizing circulation space around doorways.

- 3.3 passengers per square meter, or 0.3 m^2 (3.2 ft^2) per passenger, a reasonable service load with occasional body contact. Moving to and from doorways requires some effort.
- 2.5 passengers per square meter, or 0.4 m^2 (4.3 ft^2) per passenger,[10] a comfortable level without body contact, reasonably easy circulation, and similar space allocation as seated passengers.

The middle level above is slightly relaxed from the often stated standard of four standing passengers per square meter. The so-called crush loads are frequently based on 5 or 6 passengers per square meter (2.2 to 1.8 ft^2/p), the latter being more common in Europe. Asian standards for both maximum and crush loads reach 7 or 8 standing passengers per square meter (1.5 to 1.3 ft^2/p).

The resultant sum of seated and standing passengers provides a guide for the average peak 15-minute service loading level for the specific vehicle. Peak-hour loading should be adjusted by the vehicle loading diversity factor. No specific allowance has been made for wheelchair accommodation or for reduced standing densities away from doorways. The above range of standing densities makes such small adjustments unnecessary. Cars intended for higher density loading should have a greater number of doors. Space inefficiencies at the extremities of a car are unavoidable unless the London Transport Underground arrangement of doors at the very end of each car is adopted.

The above process can be expressed mathematically as:

$$V_c = \left[\frac{(L_c - 0.5L_a)W_c - 0.5D_n W_s D_w}{S_{sp}}\right] + N\left[\left(1 - \frac{S_a}{S_{sp}}\right)\left(\frac{L_c - L_a - D_n(D_w + 2S_b)}{S_w}\right)\right]$$

Equation 3-9

The articulated rail car schematic Exhibit 3-23 shows the principal dimensions of this equation.

where:
V_c = vehicle capacity—peak 15 minutes;
L_c = vehicle interior length (m or ft);
L_a = articulation length for light rail (m or ft);
W_s = stepwell width (certain light rail only) (m or ft);
W_c = vehicle interior width (m or ft);
S_{sp} = space per standing passenger (m or ft):
  0.2 m^2 (2.15 ft^2) maximum,
  0.3 m^2 (3.2 ft^2) reasonable, and
  0.4 m^2 (4.3 ft^2) comfortable;
N = seating arrangement:
  2 for longitudinal seating,
  3 for 2+1 transverse seating,
  4 for 2+2 transverse seating, and
  5 for 2+3 transverse seating;[11]
S_a = area of single seat (m^2 or ft^2):
  0.5 m^2 (5.4 ft^2) for transverse, and
  4.3 ft^2 (0.4 m^2) for longitudinal;
D_n = number of doorways;
D_w = doorway width (ft or m);

---

[10] This upper level is a peak 15-minute occupancy level for standing passengers. Over the peak hour it corresponds closely to Pushkarev(R8) and Jacobs(R6) estimates of a United States rush hour loading average of 0.5 m^2 (5.4 ft^2) per passenger—both seated and standing. It also corresponds to Pushkarev and Batelle's(R4) recommendation for an *adequate* or *comfortable* loading level..

[11] 2+3 seating is only possible on cars with width greater than 3 meters (10 feet), not applicable to light rail or automated guideway transit

S_b = single setback allowance (ft or m);
0.2 m (0.67 ft)— or less; and
S_w = seat pitch (ft or m):
0.69 m (2.25 ft) for transverse, and
0.43 m (1.42 ft) for longitudinal.

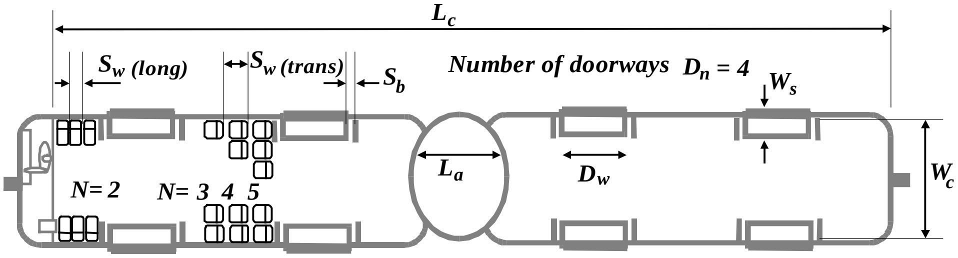


Exhibit 3-23
Schematic LRT Car Showing Dimensions

Default Method

A default method is to divide the gross floor area of a vehicle (exterior length *x* exterior width) by 0.5 m^2 (5.4 ft^2) and use the resultant number of passengers as the average over the peak hour—without applying a vehicle loading diversity factor. An average space over the peak hour of 0.5 m^2 (5.4 ft^2) per passenger is the comfortable loading level on U.S. rail transit systems recommended in several reports and is close to the average loading on all trunk rail transit lines entering the CBD of US cities.

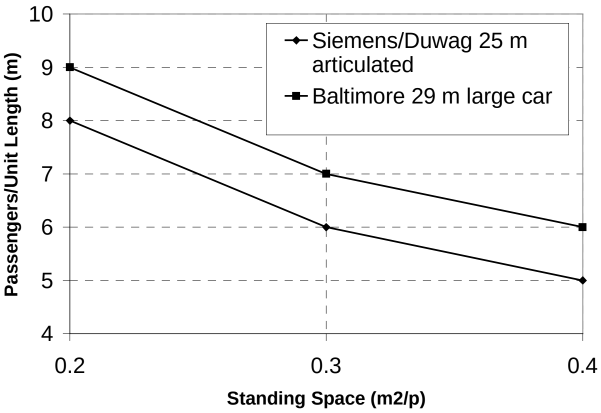
LENGTH

Train length as a surrogate for capacity.

Another default method to approximate loading levels is to assign passengers per unit length. Applying Equation 3-9 produces loading levels in passengers per unit length for two typical light rail vehicles as shown in Exhibit 3-24. As would be expected, the wider and longer Baltimore car has proportionately higher loadings per meter of length. The almost generic Siemens-Düwag car used in nine systems (with some dimensional changes) has a range of 5.0 to 8.0 passengers per meter of car length (1.5 to 2.4 p/ft of car length). The lower level of 5 passengers per meter length (1.5 p/ft length)—with a standing space per passenger of 0.4 m^2 (4.3 ft^2)—corresponds closely with the recommended *quality* loading of an average of 0.5 m^2 (5.4 ft^2) per passenger.

Exhibit 3-24
Linear Passenger Loading—Articulated LRVs

An alternative figure using U.S customary units appears in Appendix A.



Applying Equation 3-9 to selected heavy rail cars produces loading levels in passengers per unit length shown in Exhibit 3-25. As would be expected, the smaller and narrower cars in Vancouver and Chicago have lower loadings per unit length.

The more generic 75-ft (23-m) long cars used in over twelve North American cities have a remarkably close data set for each of the three variations, 4 and 3 door versions, and transverse or longitudinal seating—with a range of 7.0 to 11.5 passengers per meter of car length (2.1-3.5 p/ft of car length). The higher end of this range approaches that of crush loaded conditions.

The lower end of the range, at 7 to 8 passengers per meter length (2.1-2.4 p/ft length)—with a standing space per passenger of 0.4 to 0.3 m^2 (4.3 to 3.2 ft^2)—is an appropriate and tight range for higher use systems. A lower figure of six corresponds closely with the recommended *quality* loading of an average of 0.5 m^2 (5.4 ft^2) per passenger and is appropriate for a higher level of service on new systems. In either case, a reduction by one should be used for smaller, narrower cars.

An alternative figure using U.S. customary units appears in Appendix A.

Exhibit 3-25
Linear Passenger Loading—Heavy Rail Cars

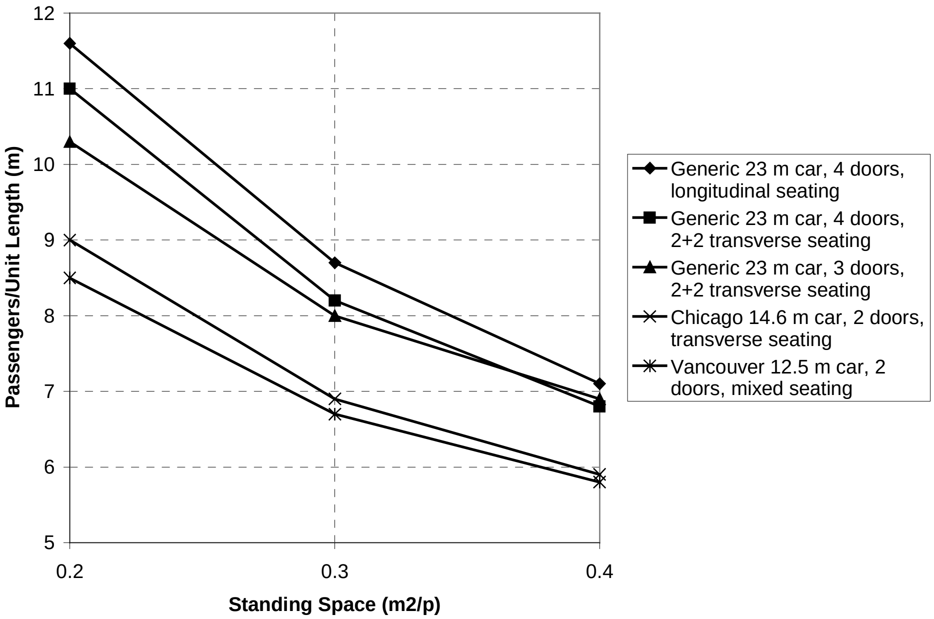


Exhibit 3-26 summarizes the average loading level in passengers per unit length for typical North American rail transit cars.

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

Exhibit 3-26
Summary of Linear Passenger Loading (p/m)

	Average	Median	Standard Deviation
All Systems	6.4	5.9	2.0
Commuter Rail	4.8	4.5	0.7
Heavy Rail	6.8	6.3	2.0
Heavy Rail less New York	5.5	5.6	1.5
NYCT alone	7.9	7.8	1.8

LOADING DIVERSITY

Passengers do not load evenly into cars and trains over the peak hour. Three different types of loading diversity have to be considered.

Loading diversity within a car.

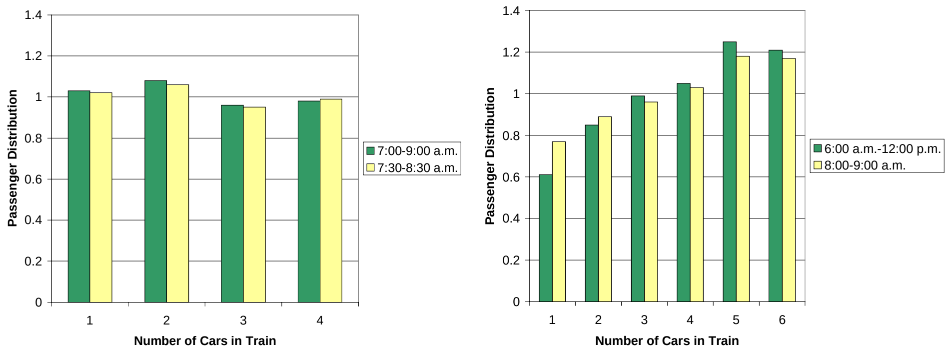
The first level of loading diversity is within a car. In individual cars the highest standing densities occur around doorways, the lowest at the end of the cars. Several European urban rail systems add doors, sometimes only single-stream, at the car ends to reduce this unevenness.

Loading diversity within a train.

A second level of diversity occurs in uneven loading among cars of a train. Cars that are closer to station exits and entrances will be more heavily loaded than more remote cars. This inefficiency can be minimized by staggering platform entrances and exits between ends, centers and third points of the platforms. This is not always possible or practiced. Even so, relatively even loading often occurs due to the duress factor that encourages passengers to spread themselves along the platform during heavily traveled times—or risk being unable to get on the next arriving train.

Few systems count passengers by individual cars when these are *crush* loaded. This is difficult to do with any accuracy and the results differ little from assigning a set *full* load to each car of a fully loaded train. BC Transit has measured car loadings at a station where passengers are regularly passed up, as shown in Exhibit 3-27.

Exhibit 3-27
Peak Hour Passenger Distribution Between Cars of Trains



Vancouver, SkyTrain (Broadway Station)   Toronto, Yonge Subway (Wellesley Station)

NOTE: 1.0 represents even loading.
Vancouver data collected inbound direction Oct. 27, 1994, 50 trains, 6,932 passengers.
Toronto data collected southbound direction Jan. 11, 1995, 99 trains, 66,263 passengers.

In Vancouver there is no significant variation in the average loading diversity between the peak hour and the peak-period, both of which remain within the range of +5% to -6%. The imbalance for cars on individual trains ranges from +61% to -33%. The evenness of loading can be attributed to four factors—the short trains, wide platforms, close headways, and dispersed entrance/exit locations between the stations of this automated, driverless system.

Toronto's Yonge Street subway shows a more uneven loading between cars. In the morning peak-period the rear of the train is consistently more heavily loaded reflecting the dominance of the major transfer station at Bloor Street with the interchange at the northern end of the Yonge subway platform. As would be expected there is less variation in the average car loading diversity between the peak hour and the peak-period due to the pressures on passengers to spread along the platforms at busy times. The average diversity of individual car loading over the peak period has a range of +26% to -39%. The unbalance for cars on individual trains ranges from +156% to -89%.

Loading diversity over the peak period.

It is this peak 15-minute period that provides the third and most important diversity factor, termed the *peak hour factor* and defined by:

$$PHF = \frac{R_{hour}}{4R_{15\,\min}}$$ Equation 3-10

where:

PHF = Peak hour factor;
R_{hour} = Ridership in peak hour; and
R_{15min} = Ridership in peak 15 minutes.

Passengers do not arrive evenly and uniformly on any rail transit system, as shown dramatically over the extended peak period in Exhibit 3-28 for the Toronto Transit Commission's Yonge subway. This shows the realities of day-to-day rail transit operation. The morning peak 15 minutes has a pronounced abnormality at 8:35 a.m. following a short gap in service. The different loading, train by train, is significant and it is difficult to visually pick out the peak hour or the 15-minute peak period.

Exhibit 3-28
Individual A.M. Train Loads, TTC Yonge Subway, Wellesley Southbound (Jan. 11, 1995)

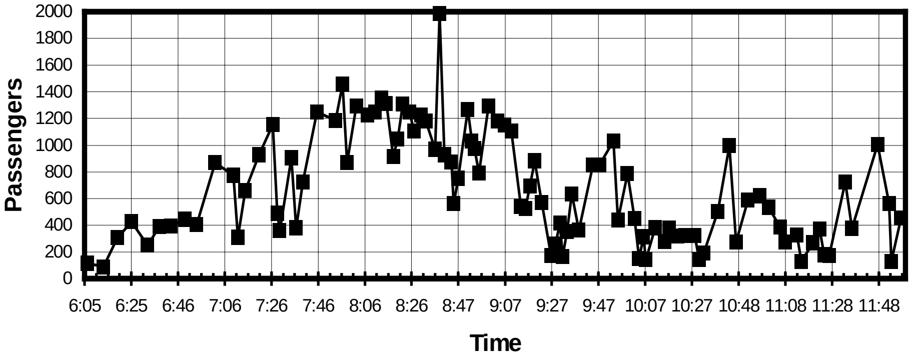
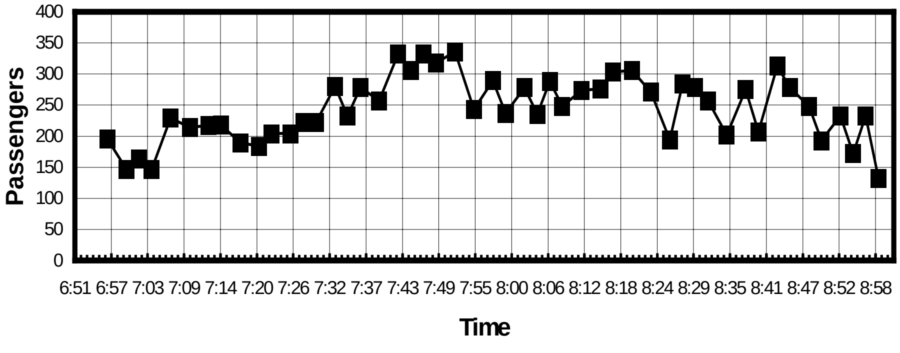


Exhibit 3-29 shows an a.m. peak-period for BC Transit that, although without major delays, shows the irregular loading from train to train due to the interlace of short-turn trains with regular service from 7:30 a.m. onwards.

Exhibit 3-29
Individual A.M. Train Loads, Vancouver, SkyTrain Broadway Station Inbound
(October 27, 1994, 50 trains, 6,932 passengers in Data Set)



The peak hour factors for many North American systems are tabulated in Exhibit 3-30. Diversity of loading within a car and among cars of a train are included in the peak

15-minute recommended loading levels. The peak hour factor is not so included and must be used to adjust passenger volumes from the estimated *design capacity* to a more practical *achievable capacity*. This important peak hour factor is discussed for each mode in the relevant chapter for calculating capacity for that mode. In each chapter suitable values are recommended for use in calculating the maximum achievable capacity.

Exhibit 3-30
Diversity of Peak Hour and Peak 15 Minutes

System (City)	# of Routes	Peak Hour Factor
Commuter Rail		
CalTrain (San Francisco)	1	0.64
GO Transit (Toronto)	7	0.49
Long Island Rail Road (New York)	13	0.56
MARC (Baltimore)	3	0.60
MBTA (Boston)	9	0.53
Metra (Chicago)	11	0.63
Metro-North (New York)	4	0.75
NICTD (Chicago)	1	0.46
New Jersey Transit (Newark)	9	0.57
SCRRA (Los Angeles)	5	0.44
SEPTA (Philadelphia)	7	0.57
STCUM (Montréal)	2	0.71
VRE (Washington, DC)	2	0.35
Light Rail		
CTS (Calgary)	2	0.62
RTD (Denver)	1	0.75
SEPTA (Philadelphia)	8	0.75
Tri-Met (Portland)	1	0.80
Rapid Transit		
SkyTrain (Vancouver)	1	0.84
CTA (Chicago)	7	0.81
MARTA (Atlanta)	2	0.76
Metrorail (Miami)	1	0.63
NYCT (New York)	23	0.81
PATH (New Jersey)	4	0.79
STCUM (Montréal)	4	0.71
TTC (Toronto)	3	0.79

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5. OPERATING ISSUES

INTRODUCTION

Allowance for operating variables.

The previous three chapters have introduced the three major components that control rail transit capacity: *Train Control and Signaling, Station Dwell Times,* and *Passenger Loading Levels.* Operating issues, discussed in this chapter, affect all three components.

Uniformity of train performance.

There is considerable uniformity of performance of the electrical multiple-unit trains that handle over 90% of all North American rail transit, assisted by the wide spread introduction of electronic controls and automatic driving. However there still can be up to a 10% difference in performance between otherwise identical trains due to manufacturing tolerances, aging of components, and variances in set-up parameters, and, in particular on manually driven systems, due to variation in driving techniques and between drivers.

Operating margins.

To accommodate these routine irregularities, two allowances are made in rail transit operations planning and scheduling. An operating margin is added to the minimum train separation time and maximum load point station dwell time to create a minimum headway. This operating margin is, in effect, the amount of time a train can run behind schedule without interfering with the following trains. The operating margin is an important component in determining the maximum achievable capacity.

Schedule recovery.

The second allowance is schedule recovery, an amount of time added to the terminal turn-around time to allow for recovery from accumulated delays on the preceding trip. Schedule recovery time has some effect on achievable capacity and has economic implications as it can increase the number of trains and staff required to transport a given volume of passengers.

OPERATING MARGINS

Operating margin examples.

A starting point for recommending suitable operating margins to incorporate into the determination of the maximum achievable capacity are the operating margins incorporated into the schedules of existing systems. The maximum load point, peak-period, station dwell time, and headways for several rail transit lines are presented in Exhibit 3-31.

The headways in Exhibit 3-31 for Calgary are all multiples of the 80-second traffic signal cycle. The seemingly erratic headways in Calgary are misleading as three routes, forming two interlaced services, share this downtown bus and light rail mall. The exhibit also shows the dwell and headway regularity of interlaced services on BC Transit’s fully automatic SkyTrain and more erratic operation on BART, where there is automatic train operation but poor control of station dwells and headways.

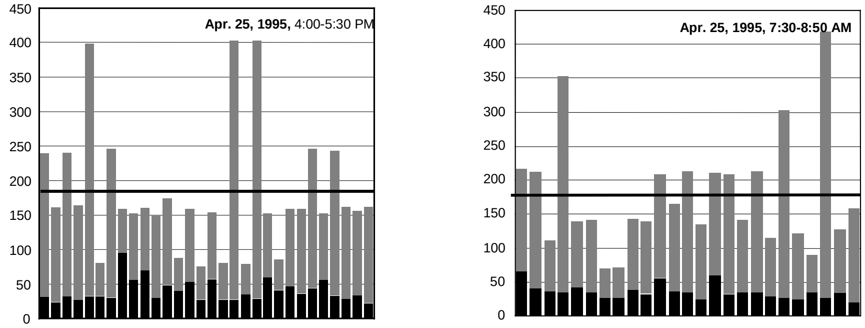
The lower four charts in Exhibit 3-31 show the range of dwell and headway irregularities on manually driven systems. These are not typical of most heavy rail lines throughout the day but represent lines at or near capacity at the peak-point in the peak period. It is at these times that operating margin and schedule recovery times are most needed to correct service irregularities.

Light rail headways on observed systems were generally sufficiently long that any irregularities reflected problems other than schedule interference between trains. One of the closest on-street headways is in Calgary, shown at the top.

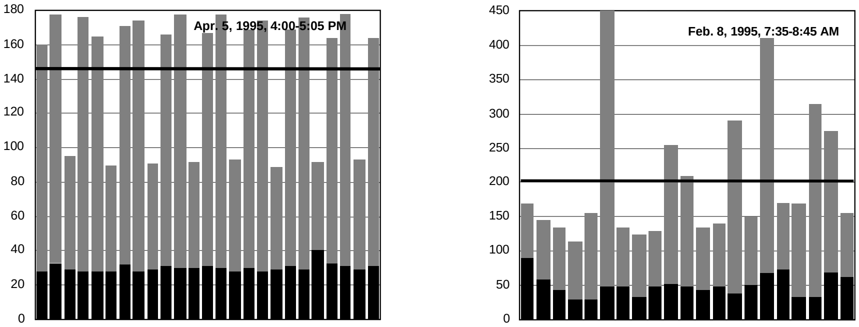
Additional examples of these dwell/headway charts are contained in Chapter 6 of TCRP Report 13, Rail Transit Capacity.(R7)

Exhibit 3-31
Observed Rail Headways and Dwell Times

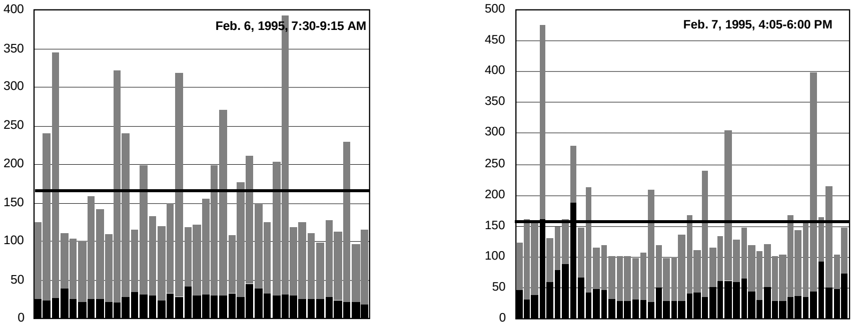
CTS 3rd St. SW EB (Calgary) | CTS 1st St. SW WB (Calgary)



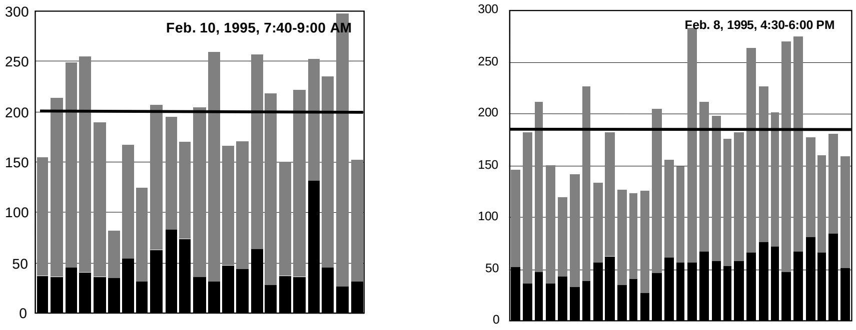
BC Transit Broadway EB (Vancouver) | BART Embarcadero WB (San Francisco)



TTC King SB (Toronto) | TTC Bloor NB (Toronto)



PATH Journal Square W/B (Newark) | NYCT Grand Central N/B Express (New York)



■ *Dwell Time (s)*
▨ *Headway (s)*
— *Average headway*

NB: northbound
SB: southbound
EB: eastbound
WB: westbound

Exhibit 3-32 shows the headway components with the final column indicating the residual time that is a surrogate for the operating margin.[12] Exhibit 3-33 shows this data graphically with the operating margin as the top component of each bar. The bars are arranged in order of increasing headway. Note that the bar furthest to the right is the only off-peak data set. It is included only for comparison and shows the large operating margin available when a system is not at capacity. The operating margins range widely and bear little relationship to system, technology, or loading levels.

Exhibit 3-32
Dwell and Headway Data Summary of Surveyed North American Heavy Rail Transit Lines Operating at or Close To Capacity (1995)

System & City	**Station & Direction**	**Avg. Station Dwell (s)**	**Dwell SD (s)**	**Avg. Hdwy. (s)**	**Dwell as % of Hdwy.**	**Train Control Separation (s)**	**Estimated Operating Margin (s)**
BART San Francisco	Embarcadero WB	49.9	15.7	201.7	24.7	90.0	30.4
CTS Calgary	1st St. SW WB	34.6	11.1	176.6	19.6	80.0	39.9
CTS Calgary	3rd St. SW EB	40.0	16.2	181.4	22.1	80.0	28.9
CTS Calgary	City Hall EB	36.8	20.6	191.4	19.2	80.0	33.4
Muni San Francisco	Montgomery WB	34.4	11.0	146.0	23.6	60.0	29.6
NYCTA New York	Queens Plaza WB	40.7	17.3	134.7	30.2	53.0	6.4
NYCTA New York	Grand Central SB	64.3	16.7	164.7	39.0	53.0	14.1
NYCTA New York	Grand Central NB	53.9	14.8	184.1	29.3	53.0	47.5
PATH Newark	Exchange Place EB	23.3	7.4	115.8	20.1	55.0	22.6
PATH Newark	Journal Square WB	47.3	23.4	199.7	23.7	55.0	50.6
SkyTrain Vancouver	Broadway EB	30.2	2.6	145.6	20.7	40.0	70.2
SkyTrain Vancouver	Burrard WB	26.7	2.5	150.7	17.7	40.0	79.0
SkyTrain Vancouver	Metrotown EB	37.8	10.4	241.3	15.7	40.0	142.8
TTC Toronto	Bloor NB	43.0	15.3	145.5	29.4	55.0	17.0
TTC Toronto	King SB	28.1	5.9	168.3	16.7	55.0	73.4

NB: northbound, SB: southbound, WB: westbound, EB: eastbound
SD: standard deviation, Hdwy.: headway

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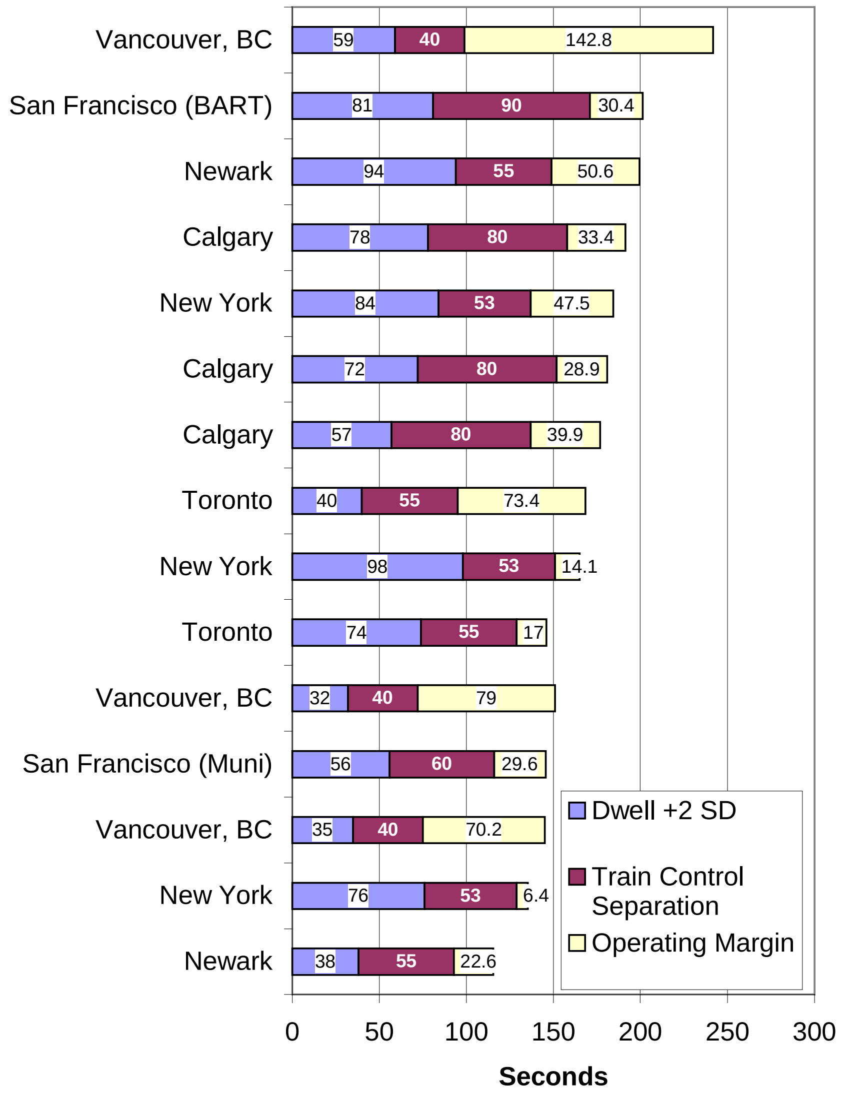
[12] The operating margin is estimated to be:
Operating margin = (average headway) – (avg. station dwell) - 2(standard deviation of station dwell) – (train control separation)

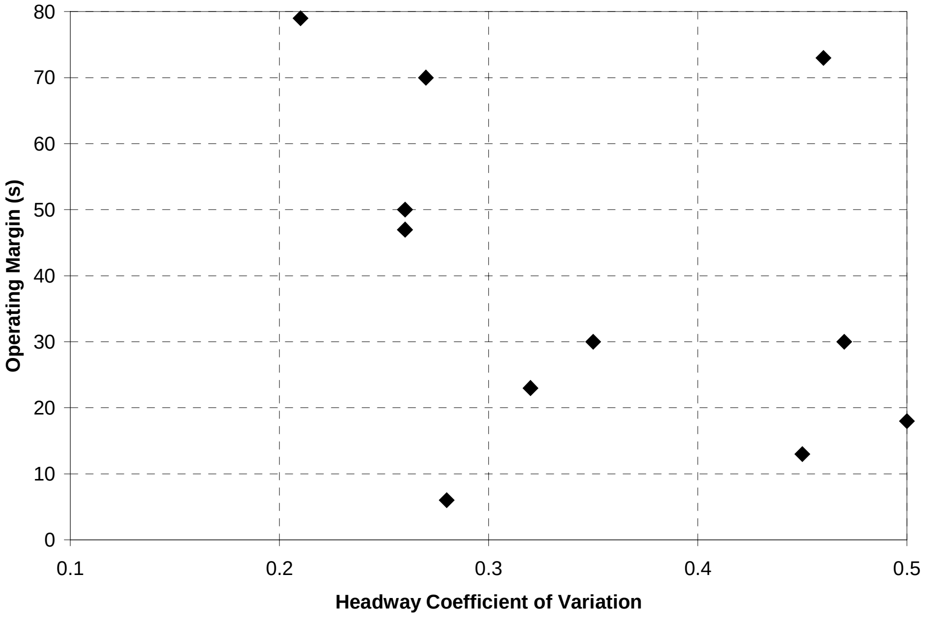
Exhibit 3-33
Headway Components of Surveyed North American Heavy Rail Transit Lines
At or Close to Capacity (seconds)



Headway coefficient of variation.

A proxy for service reliability is the headway coefficient of variation—the standard deviation divided by the mean. There could be expected to be a relationship between operating margin and service reliability, however Exhibit 3-34 shows no such relationship. Some inference can be drawn in that the system with the best headway adherence, SkyTrain in Vancouver, British Columbia, also has the most generous operating margins.

Exhibit 3-34
Relationship Between Operating Margin and the Headway Coefficient of Variation



ESTIMATING MARGINS

Although there is no clear relationship between existing rail transit operating margins and other operating criteria, this important factor, and the related terminal recovery or lay-over time, cannot be discounted. The inevitable headway irregularities and the need for reasonable operating flexibility require the greatest possible operating margin and recovery time to ensure reasonably even service and to achieve maximum capacity. Selecting a recommended operating margin is a dilemma, as too much reduces achievable capacity, but too little will incur sufficient irregularity that it may also serve to reduce capacity.

Suggested operating margin range.

It is recommended that a range be considered for an operating margin. A reasonable level for a system with more relaxed loading levels, where all of the capacity is not needed, should be 35 seconds. On systems where headways prohibit such margin, a minimum level of 10 seconds can be used with the expectation that headway interference is likely.

In between these extremes is a tighter range of 15, 20, or 25 seconds that is recommended. This range is used in estimating achievable capacity in this manual and is recommended as a default value for computations using the complete procedures.

SKIP-STOP OPERATION

Skip-stop operation increases speed but not capacity.

Skip-stop service is used on several of the high capacity rail transit operations in Japan, New York, and Philadelphia, and until recently, in Chicago. Skip stops provide faster travel times for the majority of passengers with less equipment and fewer staff. They do not increase capacity as the constraint remains the dwell time at the maximum load point station at which, by definition, all trains must stop. In fact, capacity can be slightly reduced as the extra passengers transferring between *A* and *B* trains at common stations can increase dwell times. Skip-stop operation is only applicable if the headways are sufficiently short that the “up to two-headway wait” at minor stations is acceptable to passengers.

The common stations on the Japanese skip-stop operations have multiple platforms, typically two island platforms allowing passengers to transfer across the platform between *A* and *B* or between local and express trains.

Advantages of on-demand light rail stops.

Light rail operations may also skip stations when an *on-demand* operating policy is adopted. This requires that an on-board passenger signal to stop the train. Drivers must observe whether there are any waiting passengers as they approach each station. This is a particularly efficient way to increase line schedule speed and reduce operating costs. However, at higher capacity levels all trains will stop at all stations and so the practice has no effect on achievable capacity. Demand stops are rare on new North American light rail systems, even where there are clearly some low-volume stations where during off-peak times on-demand stops could contribute to lower energy consumption, lower maintenance costs, and a faster, more attractive service.

PASSENGER-ACTUATED DOORS

The majority of new North American light rail systems use passenger-actuated doors, increasing comfort by retaining interior heat or air conditioning and reducing wear and tear on door mechanisms. The practice can extend station dwell time but is of little value at higher capacities or busy stations where the use of all doors is generally required. Consequently, some systems use the feature selectively and allow the train operator to override passenger actuation and control all doors when appropriate.

Door cycle times.

A typical heavy rail transit car door will open and close in five seconds. Certain light rail doors, associated with folding or sliding steps, can take double this time in their operation. Obviously a door opening initiated at the end of a station dwell will extend the dwell time by the door opening and closing time plus any added passenger movement time.

A system approaching achievable capacity could not tolerate such dwell extensions but would, in any event, be using all doors which might just as well be under driver control—avoiding any last minute door opening and closing.

OTHER STATION CONSTRAINTS

Inadequate platform exit capacity can reduce capacity.

Many station-related factors can influence demand. Poor location, inconvenient transfers to connecting modes, inadequate or poorly located kiss-and-ride or park-and-ride facilities may all deter usage. However, the only factor that has a potential effect on the achievable capacity of a rail transit line is the rate of exiting from a platform. Adequate passageways, stairways, and escalators must be provided to ensure that a platform can clear before the arrival of the next train. Inadequacies in passenger access to a station may reduce demand but not capacity.

Station exiting requirements are specified by the U.S. National Fire Prevention Association rapid transit standards 130. Exits, emergency exits, and places of refuge must be adequate to allow a platform with one headway’s worth of passengers plus the entire complement of a full-length fully loaded train to be able to be evacuated to a safe location within four minutes—without using elevators and treating escalators as a single width stairway. These regulations ensure that in all but the most unusual circumstances—where there is a disproportionate reliance on emergency exits—full capacity loads can leave the platform before the next train arrives.

On older systems NFPA 130 requirements may not be met. Additional exits must be provided to ensure that achievable capacity is not constrained by platform back-ups. Rates of flow are established for passageways, and up and down stairs and escalators according to width. In emergencies, exit fare payment devices can be placed in a free passage mode. This is not the case in normal operation when adequate exit fare control checks must be provided—on those systems with distance-related fares.

Passenger flow rates though turnstiles and exit gates.

The nominal passenger handling rate for a single coin or magnetic ticket-actuated fare gate or turnstile is 60 passengers per minute. This is optimistic. Actual usage will range between 30 and 40 passengers per minute, possibly longer at stations with a large proportion of tourists or other non-regular transit users. The exit fare gate rate is also reduced by periodic failures and, on systems with distance-related fares, by tickets with inadequate stored value. Typically 10% of fare gates should be assumed to be out-of-service at any time. About one in four thousand transactions will fail with magnetic tickets. Proximity cards are reported to have failure rates two to three times better but there is insufficient use to confirm this. Add-fare requirements can be as low as one in a hundred depending on operator policy—several systems allow a passenger to underpay on the final ride on higher-value stored-value tickets as a form of random discount.

Whether due to a failure to read a ticket or the need to add fare to a card, the exiting fare gate can be obstructed for a considerable period, particularly if the passenger repeats the ticket insertion. It is essential that adequate exiting fare equipment be provided at high capacity stations to ensure that passenger queues do not back up onto a platform.

On-board light rail fare payment.

Fare payment is a particular factor on the few light rail systems that still use on-board payment and checks. The flow rate analysis showed that flat fare payments added one second per boarding passenger, about 25% to an up-stairs board, and 50% to a level board. This is an inefficiency that increases running time, station by station, day by day. These factors however, cannot be applied to the dwell time calculations of Chapter 3, *Station Dwell times*, as the far more drastic impact is the restriction of boarding to a single staffed door. If on-board manual fare collection is used, dwell times must be increased by the above percentages to arrive at achievable capacity. A system using manual on-board fare collection and restricting boarding to driver attended doors only, cannot achieve its maximum capacity.

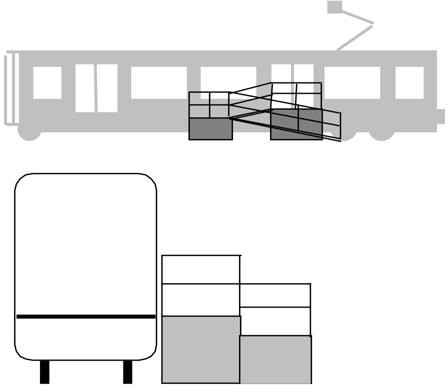
Platform width.

Stations with high mixed flows must also have platforms of adequate width to accommodate the flows. Platform width is also a factor in making it easy for passengers to distribute themselves along the length of a train and so improve the loading diversity factor.

WHEELCHAIR ACCOMMODATIONS

With dwell times being one of the most important components of headway, the time for wheelchair movements is important. Measured lift times run 2-3 minutes with some as low as 60 seconds. Level wheelchair movements are generally faster than walking passengers except where the car or platform is crowded. Level loading is essential to achieve high capacity. Where high platforms or low-floor cars cannot be provided, mini-high or high-block loading arrangements for wheelchairs, shown in Exhibit 3-35, have the least impact on capacity.

Exhibit 3-35
Wheelchair Loading Platform and Ramp



An alternate to the mini-high platform is the Manchester-style profiled platform, shown in Exhibit 3-36. This platform has an intermediate height and is profiled up to a section that is level with one doorway for wheelchair access. All slopes are a maximum of 8.5° to meet Americans with Disabilities Act (ADA) requirements. Most of the platform is only slightly higher than a sidewalk. Where the street arrangement permits, the profiled platform can be raised so that its mid-section—taking up most of the length—is raised one step providing a single step entry to most doors. Alternately the cars can have a slide or fold-out step as shown in Exhibit 3-37.

Folding steps and profiled platforms.

Exhibit 3-36
Profiled Light Rail Platform Providing For One Wheelchair-Accessible Door

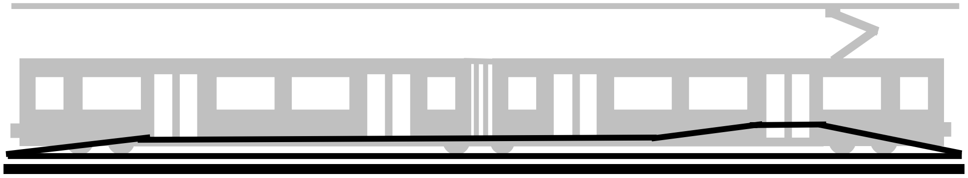
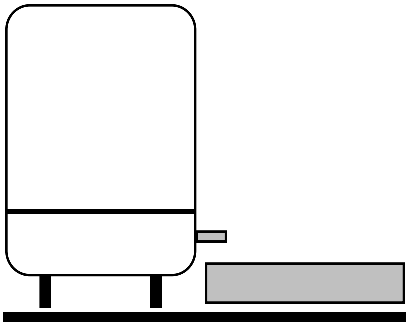


Exhibit 3-37
Profiled Light Rail Platform with Slide-Out or Fold-Down Step



Wheelchair usage.

Of concern is the number of wheelchairs that will elect to use mainstream rail transit when all ADA measures have been implemented. A 1995 survey of heavily used rail transit systems indicated an average of one wheelchair use per 20,000 passengers. Other estimates range from one in 5,000 to one in 10,000. However the usage of lifts can be three to five times higher than this due to use by other passengers not in wheelchairs.

Capacity reduction due to wheelchair space requirements.

As well as boarding and alighting delays, the time for a wheelchair to move to the stow position and use any required tie-downs can be considerable, particularly if the rail car is crowded. The least loss of time is where the wheelchair position is close to the doorway and requires neither a folding seat nor tie downs. Some agencies are overly cautious adopting bus tie-down practice to light rail service. Experience on many rail systems indicates that tie-downs are not necessary on rail service as braking and acceleration is closely controlled and ride quality is smooth.

There are many other types of boarding and alighting delays from passengers, other than those in wheelchairs and generally these are accommodated in the operating margins and schedule recovery times. There is still insufficient information to quantify any impact of ADA on the achievable capacity of rail transit systems.

However, indications are that, in the short term, wheelchair lift use on light rail may cause delays but this use is generally on systems with long headways (6 minutes and above) and have minimal impact at these levels. In the longer term other requirements of ADA and the move to level boarding with low-floor cars, or mini-high and profiled platforms, should sufficiently improve boarding and alighting movements to offset any negative impact of wheelchair use.

6. GRADE-SEPARATED SYSTEMS CAPACITY

INTRODUCTION

The preceding four chapters have developed the methodologies for each of the components in calculating rail transit capacity. This chapter brings these methodologies together for the principal category of grade-separated rail, which accounts for almost 80% of rail transit passenger trips in North America. *Grade-separated rail transit is operated by electrically propelled multiple-unit trains on fully segregated, signaled, double track right-of-way.*

This category encompasses all heavy rail transit, all automated guideway transit, some of the heaviest volume commuter rail lines, and sections of most light rail systems.

Light rail transit.

Light rail operates in a variety of rights-of-way, each of which has specific achievable capacities. Chapter 7, *Light Rail Capacity*, contains the procedures to determine capacity for light rail operating on other than double-track grade-separated sections. Single-track sections, if present, are usually the capacity limitation. However these are rare and achievable capacity is usually controlled by the signaling throughput of grade-separated sections—determined by the procedures of this chapter.

This is due to two reasons. Several light rail systems converge surface routes into a signaled grade-separated section operating at, or close to, capacity. Other, less busy systems, have the signaled grade-separated sections designed economically—not for minimum headways down to two minutes. Typically this signaling is designed for three- to four-minute headways—more restrictive than the headway limitations of on-street operation, with or without varying forms of traffic signal pre-emption. However, signaled grade-separated sections may not always be the prime headway limitation. Chapter 7 explains how to calculate and determine the weak link in the capacity chain for light rail.

Determining the weak link in the capacity chain is also the starting point in this chapter with respect to this main category—grade-separated rail transit.

THE WEAKEST LINK

Chapter 2**,** *Train Control and Signaling*, developed the methodology for the train control system maximum throughput in three situations:

1. the close-in time at the busiest station,
2. junctions, and
3. turnbacks.

Junctions and turnbacks.

In new grade-separated rail systems capacity should not be limited by junctions or turnbacks. Both can be designed to avoid constraints. Chapter 2 shows that a flat junction can handle 200-m (660-ft) trains with standard rail transit performance, under fixed block train control, on non-interference headways down to 102 seconds plus an operating margin. The equivalent time for the same length trains with a moving-block signaling system is 63 seconds plus an operating margin. Chapter 2 recommends that junctions controlled by a three-aspect signaling system should be grade-separated where trains combine to a joint headway below 3 minutes. Only where there are flat junctions with headways for their respective train control systems below these levels, plus a 20-second operating margin, is it necessary to utilize Equation 3-8 to determine the junction throughput limitation.

Chapter 2 similarly shows that a two-track terminal station can turn 200-m (660-ft) trains every 120 seconds with a terminal time of 175 seconds—that is the time required for passenger flows and for the driver to change ends on each train. Chapters 2 and 5 suggest a number of measures to maximize capacity. First, where passenger flows are heavy, dual-faced platforms can be provided. Second, where changing ends is a limitation, then crew set-backs should be used. Third, greater operational flexibility and improved failure management is obtainable by providing turn-back capability both ahead of and behind the station with a storage track for spare or out-of-service rolling stock. Fourth and finally, a three-track terminal station can handle exceptional passenger flows from trains on headways below 90 seconds.

On new systems, turn-backs can be disregarded as a capacity constraint unless economic circumstances or labor practices prevent an optimal terminal design. Only in such exceptional circumstances is it necessary— after determining the minimum headway from this chapter—to apply Equation 3-7 to ensure that adequate terminal time is provided to allow for the anticipated passenger flows and the train operator to change ends.

On older systems, terminal station design may be less than optimal and Equation 3-7 should be checked with the actual station cross-over geometry to ensure there is adequate terminal time. This calculation should then be cross-checked with actual field experience.

The close-in at the busiest station is commonly the weakest link.

In either case a turn-back constraint is only likely if all trains use the terminal station. If peak-period short turns are operated such that only a proportion of trains use the terminal station then a rail line's capacity limitation can be assumed to be the close-in movement at the busiest station.

GROWTH AND ACHIEVABLE CAPACITY

The achievable capacity as defined in this manual is not the capacity which a rail transit line will provide on opening day—or reach after a decade. It is the maximum achievable capacity when the system is saturated and provided with a full complement of rolling stock. That is the long-range design capacity after decades of growth.

A difficult question is what ultimate capacity a rail transit system should be designed for. Certain transportation models can predict passenger demand for several decades ahead. However predictions beyond 10 to 15 years are of decreasing accuracy—particularly in areas without an existing rail transit system or good transit usage. The resulting uncertainty makes the modal split component of the model difficult to calibrate.

Design for mature capacity.

When modeling does not provide a reasonable or believable answer, it is possible to fall back on an old rail transit rule of thumb, namely, to design for three times the initial mature capacity. Mature capacity occurs five to ten years after a system opens, when extensions and branches are complete, modal interchanges—bus feeders and park and ride—have matured, and some of the rail transit-initiated land-use changes, including development and densification around stations, have occurred.

The achievable capacity determined from this manual can be used to establish the train and station platform lengths and the type of train control that will allow this long-term demand to be met—whether obtained from a long-range model or by rule of thumb. This long-term demand may be 30 to 50 years ahead. If this suggests that 180 m (600 ft) long trains and platforms will be required then it does not mean they have to be built initially. Stations can be designed to have platforms expanded in the future. However, underground stations should have the full length cavity excavated—otherwise it can be difficult and expensive to extend platforms while the rail line is operating.

Simple Procedure

With the relative uniformity in the performance of electric multiple-unit trains in urban rail transit service, a simple procedure can be applied to estimate a range of achievable peak hour passenger capacities for grade-separated lines at their maximum capacity.

The necessary choices are only two, the type of train control system and the train length. The range is provided by assigning: (1) a range centered around a typical dwell time plus operating margin, and (2) a small loading range centered around the recommended peak hour average space per passenger of 0.5 m^2 (5.4 ft^2). As this is a peak hour average, no loading diversity factor is required.

Simple capacity model assumptions.

This simple procedure assumes system and vehicle characteristics that are close to the industry norms listed in Exhibit 3-38. It also assumes that there are no speed restrictive curves or grades over 2% on the maximum load point station approach and that the power supply voltage is regulated within 15% of specifications. The procedure, as does the study as a whole, assumes an adequate supply of rolling stock. If any of these assumptions are not met, then the simple procedure may be used only as a guideline and the complete procedure that follows should be used. The simple procedure does not apply to locomotive-hauled commuter rail or to automated guideway transit using a proprietary system with small, narrow vehicles.

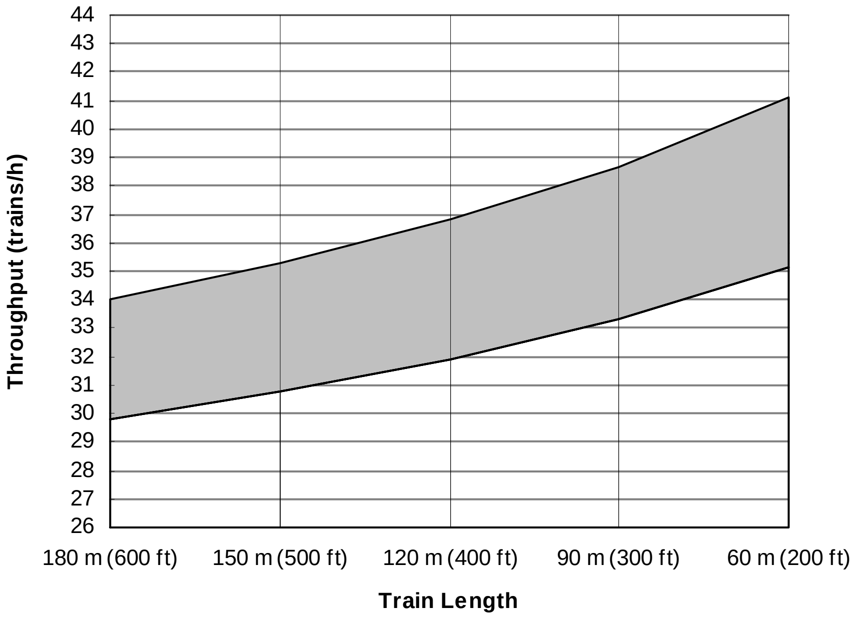
Exhibit 3-38
Grade-Separated Rail Transit Performance Assumptions—Simple Method Capacity Calculation

Term	Description	Default	Unit
G_i	Grade into headway critical station	< ± 2	%
D	distance from front of train to exit block	<10 <35	m ft
K	% service braking rate	75	%
t_{os}	time for overspeed governor to operate	3	seconds
t_{jl}	time lost to braking jerk limitation	0.5	seconds
a_s	service acceleration rate	1.3 4.3	m/s^2 ft/s^2
d_s	service deceleration rate	1.3 4.3	m/s^2 ft/s^2
t_{br}	brake system reaction time	1.5	seconds
v_{max}	maximum line velocity	100 60	km/h mph
t_d	dwell time	35-45	seconds
t_{om}	operating margin	20-25	seconds
l_v	line voltage as % of normal	>85	%
S_{mb}	moving block safety distance	50 165	m ft

The range of trains per hour are shown in Exhibit 3-39 for the above assumptions for cab control systems and in Exhibit 3-40 for moving-block signaling systems. New systems that are designed for maximum capacity would not use the more limited and more expensive three aspect signaling system. Such a system may be used for systems designed for less than maximum throughput—in which case this procedure is not applicable. Consequently, the choice of train control system is limited to cab control and moving-block.

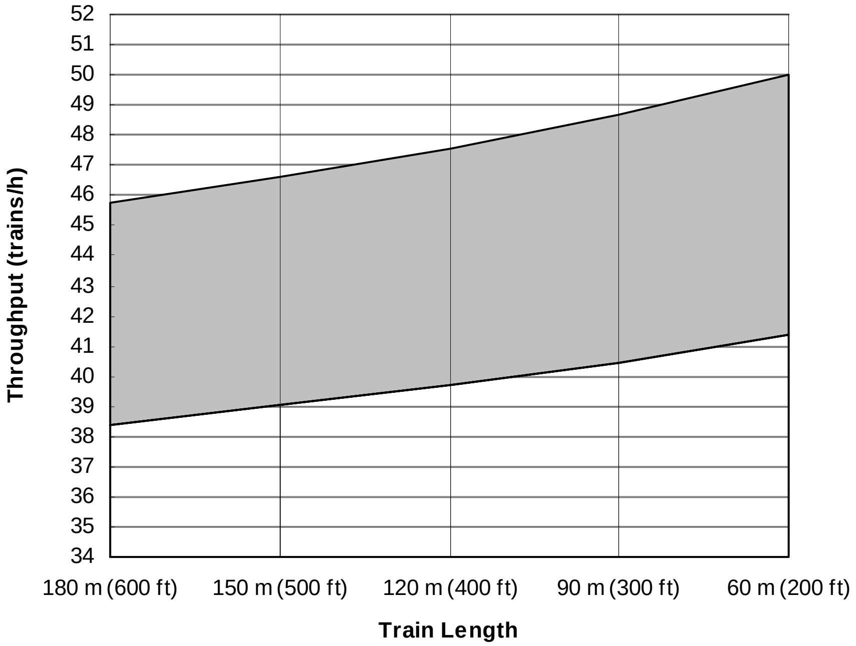
This is a method to determine the maximum capacity of a rail transit line. Consequently, train lengths are shown for typical maximum lengths of 200 and 150 meters (660 and 500 feet)—trains of 8 and 6 heavy rail cars and 120, 90, and 60 meters (400, 300, and 200 feet)—trains of 4, 3, and 2 articulated light rail vehicles, respectively.

Exhibit 3-39
Cab Control Throughput



NOTE: Total of operating margin and dwell time ranges from 55 seconds (lower bound) to 70 seconds (upper bound).

Exhibit 3-40
Moving-Block (Variable Safety Distance) Throughput



NOTE: Total of operating margin and dwell time ranges from 55 seconds (lower bound) to 70 seconds (upper bound).

Linear train loading.

The maximum number of trains per hour can be selected from the above two charts, rounded down, and multiplied by the selected train loading level obtained from Chapter 4, *Passenger Loading Levels*, Exhibit 3-25, which shows a range of linear loading levels for heavy rail cars from 7 to 11 passengers per meter of length (2.1-3.4 p/ft of length).[13]

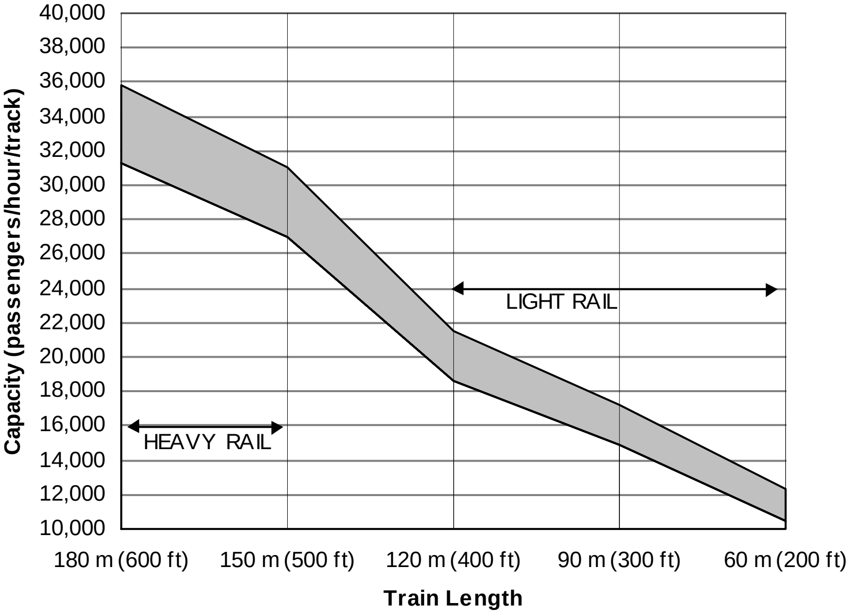
Exhibit 3-24 shows a range of linear loading levels for light rail cars from 5 to 9 passengers per meter of length (1.5-2.7 p/ft of length).

Peak hour factor.

These linear loading levels represent the peak 15 minutes and a peak hour factor should be applied if loading levels in the upper ranges of these charts are selected. When calculating diversity on the capacity of a line in a city with existing rail transit—of the same mode—the existing peak hour factor or near equivalents should be obtained from Chapter 4, *Passenger Loading Levels*. For new systems, a peak hour factor of 0.8 is recommended for heavy rail and 0.7 for light rail.

Applying these loading levels to the throughput ranges above provides a direct range of passengers per peak hour direction per track versus train length, shown in Exhibit 3-41 and Exhibit 3-42.

Exhibit 3-41
Achievable Capacity with Multiple Command Cab-Control Signaling System



NOTE: Assumes peak hour average passenger loading of 0.5 m^2/p. Capacity for one track of a grade-separated rail transit line. Total of operating margin and dwell time ranges from 55 seconds (lower bound) to 70 seconds (upper bound).

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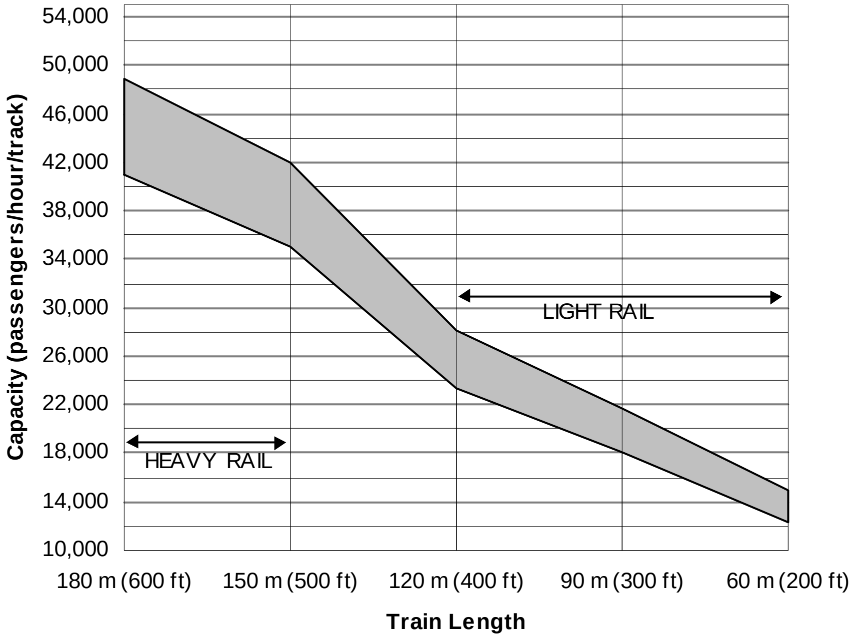
[13] The lower ranges for the short cars in Vancouver and Chicago should not be used in the simple procedure method which is based on 6 to 8 car trains of 23-meter (75-foot) long cars.

Exhibit 3-42
Achievable Capacity With Moving-Block Signaling System



NOTE: Assumes peak hour average passenger loading of 0.5 m^2/p. Capacity for one track of a grade-separated rail transit line. Total of operating margin and dwell time ranges from 55 seconds (lower bound) to 70 seconds (upper bound).

Note that with the exception of San Francisco's Muni Metro, signaled grade-separated light rail lines are rarely provided with the minimum headway capabilities represented by the capacity ranges in Exhibit 3-41 and Exhibit 3-42.

Complete Procedure

The complete procedure to estimate the peak hour capacity of grade-separated rail transit requires sequential steps.

Weakest link.

The first step is to determine the capacity limiting constraint, either the station close-in and dwell time, or junction or turn-back throughput. The approach given at the start of this chapter, *The Weakest Link,* should be followed. If necessary, the junction or turn-back throughput can be calculated from the methodologies and equations of Chapter 2. Should a junction or turn-back appear to be the limitation on train throughput, then the first recourse is to consider design or operating practice changes that will remove or mitigate such limitations.

Constraints at the maximum load point station.

In all but the most exceptional situations, the limitation will be the close-in, dwell, and operating margin time at the maximum load point station. The complete procedure requires that the following values be calculated:

1. the close-in time at the maximum load point station,
2. the dwell time at this station,
3. a suitable operating margin,
4. the peak 15-minute train passenger load, and
5. the peak hour factor to translate from the peak 15 minutes to peak hour.

These procedures can be calculated manually, or by experienced users developing their own computer spreadsheet.

When there is uncertainty about these factors—fully described in Chapter 3, *Station Dwell Times,* Chapter 4, *Passenger Loading Levels,* and Chapter 5, *Operating Issues*—or where several of the performance variables are unknown (for example, the technology or specific vehicle has not been selected), then following the complete procedure is not recommended. The simple procedure provides a *generic achievable capacity range* with less effort—and potentially as much accuracy as the complete method where one or more input factors will have to be estimated.

Step 1: Determining the Maximum Load Point Station

Traditionally, the maximum load point station is the principal downtown station or the downtown station where two or more rail transit lines meet. However, this is not always the case. With increasingly dispersed urban travel patterns, some rail transit lines do not serve the downtown. Los Angeles' Green Line and Vancouver's proposed Broadway-Lougheed light rail line are examples.

Ridership models.

A regional transportation model will usually produce ridership data by station, both ons and offs and direction of travel. Such data are usually for a two hour peak-period or single peak hour and rarely for the preferable 15-minute period. Depending on the number of zones and nodes in the model, data accuracy at the station level can be poor—particularly if there is more than one station in a zone. Nevertheless, this is often the sole source of individual station volumes and without it selection of the maximum load point station requires an educated guess.

Step 2: Determining the Control System's Minimum Train Separation

Chapter 2, *Train Control and Signaling,* developed the methodology for determining the minimum train separation with three types of train control systems, each providing progressively increased throughput:

1. three-aspect signaling system,
2. multiple command cab control, and
3. moving-block signaling system.

Although the equations appear long, the arithmetic is simple and can be implemented using basic functions in a spreadsheet. Before going to this effort, check the availability of the required input parameters in Exhibit 3-43. Parameters can be adjusted for system specific values or left at their default value. Train length is the most important variable. However if most parameters are left at their default values then it would be simpler to refer to Exhibit 3-44, which shows the minimum train control separation against length for the three types of train control system.

Exhibit 3-43
Minimum Train Separation Parameters

Default value	**Term**	**Description**
calculated	$T(s)$	train control separation in seconds
200 m, 660 ft	L	length of the longest train
10 m, 33 ft	D	distance from front of stopped train to start of station exit block in meters or feet
calculated	v_a	station approach speed in m/s or ft/s
27.8 m/s, 88 ft/s	v_{max}	maximum line speed in m/s (27.8 m/s=100 km/h) maximum line speed in ft/s (88 ft/s = 60 mph)
75%	K	braking safety factor—worst case service braking is K% of specified normal rate—typically 75%
2.4 — three-aspect 1.2 — cab control 1 — moving block	B	separation safety factor—equivalent to number of braking distances (surrogate for blocks) that separate trains
3.0 seconds	t_{os}	time for overspeed governor to operate on automatic systems—to be replaced with driver sighting and reaction times on manual systems
0.5 seconds	t_{jl}	time lost to braking jerk limitation
1.5 seconds	t_{br}	brake system reaction time
1.3 m/s^2 ,4.3 ft/s^2	a_s	initial service acceleration rate
1.3 m/s^2, 4.3 ft/s^2	d_s	service deceleration rate
0%	G_i	grade into station, downgrade = negative
0%	G_o	grade out of station, downgrade = negative
90%	l_v	line voltage as percentage of specification
6.25 m, 20.5 ft	P_e	positioning error—moving block only
50 m, 165 ft	S_{mb}	moving-block safety distance—moving block only

The equation for three-aspect and cab control signaling systems, derived from Equation 3-4 in Chapter 2, with dwell and operating margin components removed and grade and voltage factors added, is:

$$T(s) = \sqrt{\frac{2(L+D)}{a_s(1-0.1G_o)}} + \frac{L}{v_a} + \left(\frac{100}{K} + B\right)\left(\frac{v_a}{2d_s}\right)$$

$$+\frac{a_s(1-0.1G_i)l_v^2 t_{os}^2}{20{,}000 v_a}\left(1-\frac{v_a}{v_{\max}}\right) + t_{os} + t_{jl} + t_{br}$$

Equation 3-11

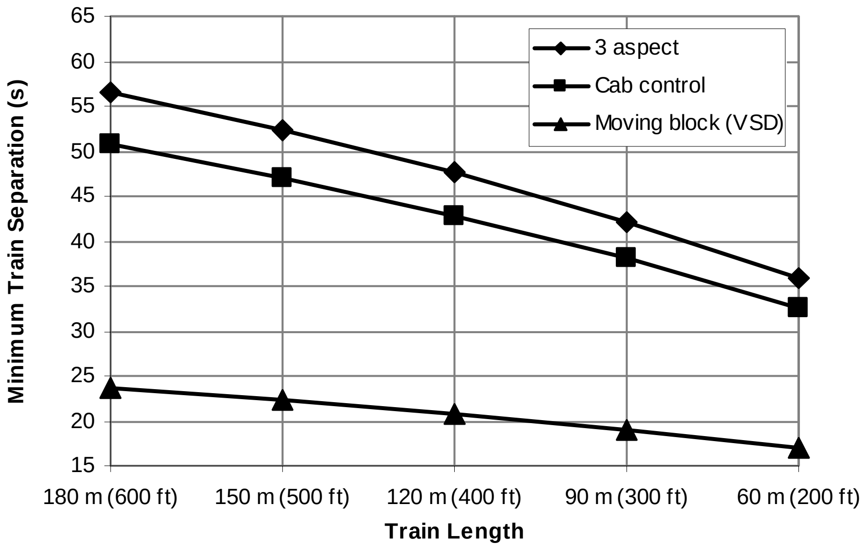
The equation for moving-block signaling systems with a fixed safety separation distance, derived from Equation 3-5 of Chapter 2, with dwell and operating margin components removed is:

$$T(s) = \frac{L+S_{mb}}{v_a} + \frac{100}{K}\left(\frac{v_a}{2d_s}\right) + t_{jl} + t_{br}$$

Equation 3-12

Note that this equation is not affected by either line voltage or station grade. Lower voltages increase the time for a train to clear a station platform. In moving-block systems this time does not affect throughput. When a train starts to leave a station the target point of the following train is immediately advanced accordingly. The worst-case approach grade is included in the determination of the safety distance. This can result in sub-optimal minimum train separation.

Exhibit 3-44
Minimum Train Separation versus Length



Higher throughput is usually obtained with a moving-block signaling system with a variable safety distance comprised of the braking distance at the particular speed plus a runaway propulsion allowance. The equation for such a system, derived from Equation 3-6 of Chapter 2, with dwell and operating margin components removed and a line voltage factor added, is:

$$T(s) = +\frac{L + P_e}{v_a} + \left(\frac{100}{K} + B\right)\left(\frac{v_a}{2d_s}\right)$$

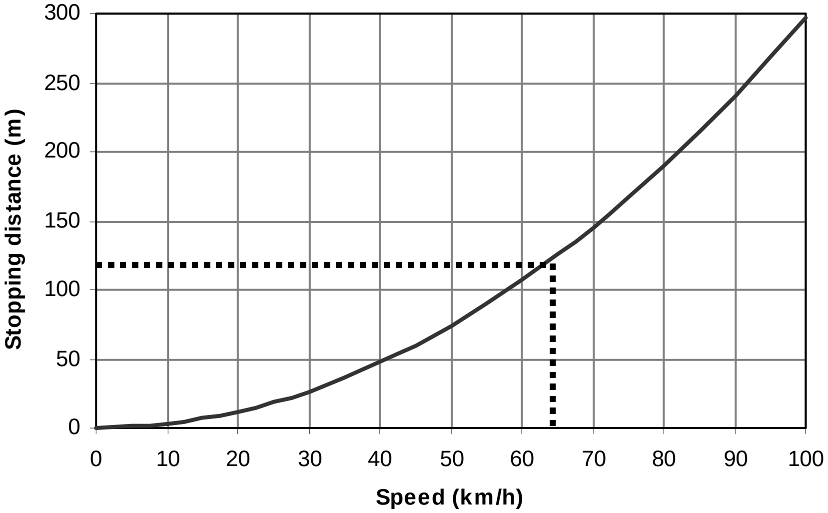
$$+\frac{a_s(1 - 0.1G_i)l_v^2 t_{os}^2}{20{,}000 v_a}\left(1 - \frac{v_a}{v_{\max}}\right) + t_{os} + t_{jl} + t_{br}$$

Equation 3-13

The appropriate equation must be solved for the minimum value of *T(s)*. The approach speed v_a that produces this minimum value must then be checked against any speed restrictions approaching the station from Exhibit 3-45.

An alternative version of this figure in U.S. customary units appears in Appendix A.

Exhibit 3-45
Distance—Speed Braking Into a Station



The dotted line example in Exhibit 3-45 shows that at 120 meters (400 feet)[14] from a station the approaching train will have a speed of 65 km/h (40 mph). If there is a speed limit at this point that is lower than 65 km/h (40 mph) then the minimum train separation *T(s)* must be calculated with the approach speed v_a set to that limit.

Finally, check the results with Exhibit 3-44. The minimum train separation should be close to or moderately greater than the values charted. If lower, there is probably an error as the charted values are the minimums using typical maximum rail transit performance criteria and without applying any corrections for grades or speed restrictions into or out of the station.

Step 3: Determining the Dwell Time

This section deals with station dwell times, to which both an operating margin and the minimum train signal system separation must be added to produce the headway.

The train close-in time at the headway critical station, being dependent on the physical performance and length of a train and other fixed system characteristics, can be calculated with some precision. Station dwell time cannot be determined with the same exactitude. All but one of literature references related to rail transit capacity assigned a set time to dwell time. Many simulations do likewise using typical figures of 15-20 seconds for lesser stations and 30-45 seconds for major stations. The one methodology to determine *controlling dwell*—dwell time plus operating margin—requires knowledge of station dwell times over the peak hour—information only available for existing systems or new lines in areas where a station with similar passenger volumes can be analyzed.[15]

Chapter 3, *Station Dwell Times,* describes the main constituents of dwell time as follows:

- passenger flow time at the busiest door,
- remaining (unused) door open time, and
- waiting to depart time (with doors closed).

Four methods of estimating dwell time or controlling dwell time are provided in this section. The first method is the one used in the simple procedure of this chapter and by

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[14] Distance from the front of the approaching train to the stopping point.
[15] See Reference 1. No operating margin should be added when controlling dwell is calculated.

most of the literature references—simply assigning a reasonable figure to the headway critical station. The second method uses field data from this study allowing the selection of a controlling dwell time from the headway critical station of rail transit lines with similarities to the one being analyzed. These two methods are suitable where information on passenger flows at the headway critical station is not available.

Four methods of estimating controlling dwell.

The third method is only suitable for new lines in cities with existing rail transit systems. Here the method outlined in Chapter 3 of using the mean dwell time plus 2 standard deviations based on a comparable station on the existing network is suggested. The fourth and final method uses the statistical approach of Chapter 4 of determining station dwell times based on peak hour passenger flows. This method is complex and still requires an estimate of the ratio of the busiest door to average door flow.

None of these methods are entirely satisfactory. This explains why practitioners over a period of three decades have resorted to simply assigning a reasonable value to station dwell time.

Method 1: Assigning a Value

Existing rail transit systems operating at or close to capacity have median station dwell times over the peak hour that range from 30 to 50 seconds with occasional exceptional situations—such as the heavy peak hour mixed flow at NYCT's Grand Central Station of over 60 seconds. A tighter range of dwell time values—35 to 45 seconds—is used in the simple procedure and can be used together with the more accurate calculation of the minimum train separation.

Method 2: Using Existing Dwell Time Data

Examples of existing dwell time data from the highest-use station on lines that are close to capacity are summarized in Exhibit 3-46. Selection of a dwell time from this table is less arbitrary than Method 1 and allows some selectivity of mode and the opportunity to pick systems and stations with similar characteristics to those of the one under examination.

The selected median station dwell times range from 27.5 seconds to 61.5 seconds. The highest data are mainly alighting and mixed flow records from manually operated systems with two person crews.

Most station dwell times in Exhibit 3-46 fit into the 35 to 45 second range suggested in the previous method.

Exhibit 3-46
1995 Peak-Period Station Dwell Times for Heavily Used Systems (seconds)(R7)

System & City	Station	Total Pass.	Median Dwell (s)	Median Headway (s)
BART (San Francisco)	Embarcadero	2,298	48.0	155.0
CTS (Calgary)	1st St. SW (LRT)	298	33.0	143.0
CTS (Calgary)	3rd St. SW (LRT)	339	38.0	159.0
CTS (Calgary)	City Hall (LRT)	201	34.0	161.0
NYCT (New York)	Grand Central (4&5) SB	3,488	61.5	142.5
NYCT (New York)	Queens Plaza (E&F)	634	36.0	121.0
PATH (Newark)	Journal Square	478	37.0	204.0
Muni (San Francisco)	Montgomery (LRT)	2,748	32.0	129.0
SkyTrain (Vancouver)	Broadway	257	30.0	166.0
SkyTrain (Vancouver)	Metrotown (off-peak)	263	34.0	271.5
TTC (Toronto)	King	1,602	27.5	129.5
TTC (Toronto)	Bloor	4,907	44.0	135.0

SB: Southbound

Method 3: Using Dwells from the Same System

This method is only applicable where a line of the same mode is being added to an existing system, in which case the controlling dwell time from an existing, similar, peak-point station can be used. Where passenger volumes at the headway critical station of the new line are different from the equivalent station on an existing line, the flow component of dwell time can be adjusted in proportion to hourly passenger movements in the station. Alternatively, the dwell time from an existing station with similar passenger volumes can be used.

Care should be taken if the train control system or operating procedures are different. If this is the case, consideration should be given to adjusting both the station dwell time and the operating margin.

Method 4: Calculating Dwells from Passenger Flows

TCRP Report 13, *Rail Transit Capacity*(R7) develops regression equations to relate passenger flow times to the number of boarding, alighting or mixed flow passengers, and, in turn, to convert this flow time to dwell time. These regression equations can be used to estimate the dwell time from hourly passenger flows into the maximum load point station. However, the best regression fit involves logarithmic functions and the estimation of a constant for the ratio between the highest doorway and the average doorway passenger flow rate. The mathematics are complex and it is uncertain if the results provide any additional accuracy that merits this complexity—particularly if the hourly station passenger volumes by direction are themselves somewhat uncertain.

This method is best suited to new lines in locations without rail transit and with a sufficiently refined and calibrated regional transportation model that can assign hourly passenger flow, by direction, to individual stations. The method is not detailed further in this manual and can be found in full in TCRP Report 13.(R7)

Step 4: Selecting an Operating Margin

Chapter 5, *Operating Issues*, introduced the need to add an operating margin to the minimum train separation and dwell time to create the closest sustainable headway without interference.

Dilemma on at-capacity lines.

Ironically, the closer the trains operate, and the busier they are, the more chance there is of minor incidents delaying service due to an extended station dwell time, stuck door, or late train ahead. It is never possible to ensure that delays do not create interference between trains nor is there any stated test of reasonableness for a specific operating margin.[16] A very small number of rail transit lines in North America are operating at capacity and so can accommodate little or no operating margin. On such lines, operations planners face the dilemma of scheduling too few trains to meet the demand, resulting in extended station dwell times and erratic service, or adding trains to the point that they interfere with one another. Striking a balance is difficult and the tendency in practice is to strive to meet demand—equipment availability and operating budget permitting. While the absolutely highest capacity is so obtained, it is poor planning to omit such an allowance for new systems.

The greater the operating margin that can be incorporated in the headway the better; systems running at maximum capacity have little leeway and the range of operating margins used in the simple procedure—20 to 25 seconds—remains the best guide. The recommended procedure is to aim for 25 seconds and back down to 20 or even to 15 seconds if necessary to provide sufficient service to meet the estimated demand. Where demand is unknown or uncertain in the long-term future—when a rail line in planning reaches maximum capacity—then 25 seconds should be used.

Step 5: Selecting a Passenger Loading Level

Chapter 4, *Passenger Loading Levels*, discusses the wide range of loading levels used in North America. Selecting a loading level is a policy issue and the process for the complete procedure is the same as that of the simple procedure. Use of the passenger occupancy per unit length of train is recommended. In selecting a loading level take into account that this is for the 15-minute peak period and that the average over the peak hour will be more relaxed.

Nominal linear loading levels.

If the line for which capacity is being determined is an addition to an existing system then existing occupancy levels or, where available, existing loading policies can be used. Some cities have a wide variation of peak 15-minute loading levels from line to line. Where this variety exists then the loading level should be selected based on the closest matching line—for example, a heavy trunk serving downtown or a cross-town feeder line.

Exhibit 3-24 and Exhibit 3-25 provide a range of loading levels from 5 to 9 passengers per meter of car length (1.5-2.7 p/ft of length) for light rail, and from 7 to 11 (2.1-3.4 p/ft of length) for heavy rail. For new systems where attempts are being made to offer a higher quality of service, the recommended approach is to base the loading level on the commonly suggested medium comfort level for new rail transit systems of 0.5 m^2 (5.4 ft^2) per passenger, averaged over the peak hour—that is, no loading diversity factor is required. This provides a recommended linear loading level of 6 passengers per meter of train length (1.8 p/ft) for heavy rail and 5 p/m (1.5 p/ft) for light rail.

Actual linear loading levels.

An alternative approach is to base the loading levels on either the nominal capacity of a vehicle or the actual peak hour utilization. The nominal capacity of vehicles, whether specified by the operating agency or manufacturer is arbitrary and for identical vehicles can differ by a factor of almost two. Exhibit 3-47 shows the actual peak 15-minute linear loading levels for major North American trunks, again in descending order. Discounting the uniquely high values in New York, the remaining data offer realistic existing levels to apply in selecting a loading level for a comparable system—or a new line in the same system with similar characteristics.

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[16] A goal for an operating margin, based on an average of one *disturbed* peak period per ten weekdays (two weeks) has been discussed with rail transit planners but has not been documented.

An alternative version of this figure in U.S. customary units appears in Appendix A.

Exhibit 3-47
Passengers per Unit Train Length, Major North American Rail Trunks, 15-Minute Peak

System & City	Trunk Name	Mode	Length (m)	Seats	Avg. Pass/Car	Pass./ m
NYCT (New York)	53rd Street Tunnel	HR	*see note*	50/70	197/227	10.4
NYCT (New York)	Lexington Ave. Local	HR	15.6	44	144	9.3
NYCT (New York)	Steinway Tunnel	HR	15.6	44	144	9.3
NYCT (New York)	Broadway Local	HR	15.6	44	135	8.7
TTC (Toronto)	Yonge Subway	HR	22.7	80	197	8.7
NYCT (New York)	Lexington Ave. Ex.	HR	15.6	44	123	7.9
NYCT (New York)	Joralemon St. Tun.	HR	15.6	44	122	7.8
NYCT (New York)	Broadway Express	HR	15.6	44	119	7.6
NYCT (New York)	Manhattan Bridge	HR	22.8	74	162	7.1
NYCT (New York)	Clark Street	HR	15.6	44	102	6.6
CTS (Calgary)	South Line	LR	24.3	64	153	6.3
GO Transit (Toronto)	Lakeshore East	CR	25.9	162	152	5.9
SkyTrain (Vancouver)	SkyTrain	HR	12.4	36	73	5.9
PATH (New York)	World Trade Center	HR	15.6	31	92	5.9
PATH (New York)	33rd St.	HR	15.6	31	88	5.7
CTA (Chicago)	Dearborn Subway	HR	14.6	46	82	5.6
NYCT (New York)	60th Street Tunnel	HR	22.8	74	126	5.5
NYCT (New York)	Rutgers St. Tunnel	HR	22.8	74	123	5.4
CTS (Calgary)	Northeast Line	LR	24.3	64	125	5.1
CTA (Chicago)	State Subway	HR	14.6	46	75	5.1
CalTrain (San Fran.)	CalTrain	CR	25.9	146	117	4.5
LIRR (New York)	Jamaica - Penn Sta.	CR	25.9	120	117	4.5
Metra (Chicago)	Metra Electric	CR	25.9	156	113	4.4
MARTA (Atlanta)	North/South	HR	22.9	68	82	3.6
MARTA (Atlanta)	East/West	HR	22.9	68	77	3.4

HR: heavy rail, LR: light rail, CR: commuter rail

NOTE: Service through NYCT’s 53rd St. Tunnel is provided by line E, operating 18.35-m cars, and line F, operating 22.8-m cars. Seats and car loadings are presented as “E/F”. The number of passengers per foot given is for the combined lines; individually this value is 3.3 for the E and 3.0 for the F.

Step 6: Determining an Appropriate Peak Hour Factor

The next step is to adjust the hourly capacity from the 15- minute rate within the peak hour to a peak hour rate using a peak hour factor from Chapter 4, *Passenger Loading Levels*. The peak hour factor is calculated according to Equation 3-9 with a summary of results shown in Exhibit 3-48. The peak hour factor was also used in Method Four for calculating the station dwell time. If this method was used then obviously the same peak hour factor must be used. Otherwise, the factor should be selected based on the rail mode and the type of system. A summary table is reproduced below to assist.

Unless there is sufficient similarity with an existing operation to use that specific figure, the recommended peak hour factors are:

- 0.80 for heavy rail,
- 0.75 for light rail, and
- 0.60 for commuter rail operated by electric multiple-unit trains.

Exhibit 3-48
Diversity of Peak Hour and Peak 15-Minute Loading

System & City	Routes	Peak Hour Factor
Commuter Rail		
LIRR (New York)	13	0.56
Metra (Chicago)[1]	11	0.63
Metro-North (New York)	4	0.75
NJT (New Jersey)[1]	9	0.57
SEPTA (Philadelphia)	7	0.57
Light Rail		
CTS (Calgary)	2	0.62
RTD (Denver)	1	0.75
SEPTA (Philadelphia)	8	0.75
Tri-Met (Portland)	1	0.80
Rapid Transit		
BC Transit (Vancouver)	1	0.84
CTA (Chicago)	7	0.81
MARTA (Atlanta)	2	0.76
MDTA (Baltimore)	1	0.63
NYCT (New York)	23	0.81
PATH (New York)	4	0.79
STCUM (Montreal)	4	0.71
TTC (Toronto)	3	0.79

[1] Mainly diesel hauled—not electric multiple unit.
[2] This figure is suspicious.

Step 7: Putting it all Together

The final step in the complete method of determining a grade-separated rail transit line's maximum capacity is to determine the closest (minimum) headway as the sum of the calculated value of the minimum signaling system train separation, plus the calculated or estimated value of dwell time, plus the assigned operating margin.

$$H_{\min} = T(s) + t_d + t_{om}$$

Equation 3-14

The maximum number of trains per hour T_{max} then is:

$$T_{\max} = \frac{3{,}600}{H_{\min}} = \frac{3{,}600}{T(s) + t_d + t_{om}}$$

Equation 3-15

The maximum capacity C_{max} is the number of trains multiplied by their length and the number of passengers per unit length, adjusted from peak-within-the peak to peak hour.

$$C_{\max} = T_{\max} L P_m (PHF) = \frac{3{,}600 L P_m (PHF)}{T(s) + t_d + t_{om}}$$

Equation 3-16

where:
H_{min} = minimum headway (s);
$T(s)$ = minimum train separation (s);
t_d = dwell time (s);
t_{om} = operating margin (s);

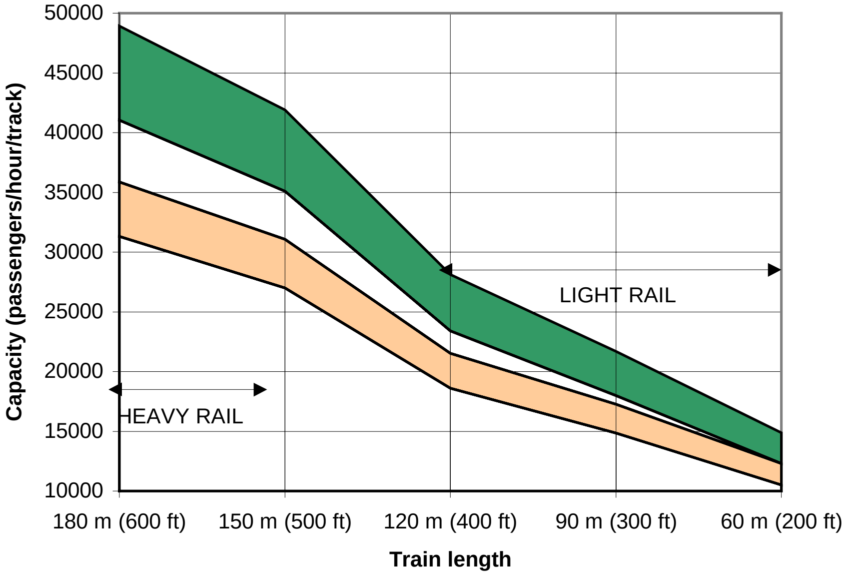
T_{max} = train throughput per hour;
C_{max} = maximum single track capacity in passengers per peak hour direction;
L = train length (m or ft);
P_m = loading level in passengers per meter or foot of train length; and
PHF = peak hour factor.

Given the range of values that can be calculated, estimated, or assigned for the components of Equation 3-16, it is appropriate that the results be expressed as a range.

The results should be checked for reasonableness against typical capacities in Exhibit 3-49, which is based on the simple procedure loading levels of 5 passengers per meter (1.5 passengers per foot) for light rail and 6 passengers per meter (1.8 passengers per foot) for heavy rail—approximately 0.5 m^2 (5.4 ft^2) per passenger. Higher levels are possible only if less comfortable loading levels have been used. Lower levels would result from the assumption that all passengers are seated, inclusion of an excessive operating margin, or errors in the calculation.

This chart is not an appropriate check for electric multiple-unit commuter rail whose signaling systems are usually designed for lower throughput with loading levels based on all seated passengers. Commuter rail capacity based on train length is also affected by the common use of bi-level cars, although few such trains currently fit into the applicable category of electric multiple-unit operation.

Exhibit 3-49
Typical Maximum Passenger Capacities of Grade-Separated Rail Transit—Excluding All-Seated Commuter Rail



NOTE: Assumes peak hour average passenger loading of 5.0 p/m of length for light rail and 6.0 p/m of length for heavy rail. Capacity for one track of a grade-separated rail transit line. Operating margin ranges from 45 seconds (lower bound) to 70 seconds (upper bound).

7. LIGHT RAIL CAPACITY

INTRODUCTION

The key is finding the weakest link.

This chapter covers methods for determining the capacity of light rail transit lines. While the approach used in Chapter 6, *Grade Separated Rail Capacity*, will work in most situations, light rail transit lines often have characteristics such as street running, grade crossings, and single-track sections which are not covered in that chapter but which are of importance in capacity determination. The key to determining the capacity of a light rail transit line is to find the weakest link—the location or factor that limits the capacity of the entire line.

SELECTING THE WEAKEST LINK

Range of light rail right-of-way types.

Determining the capacity of light rail transit lines is complicated by the variety of rights-of-way that can be employed. In the simplest case, a grade-separated right-of-way is used and the capacity calculation techniques given in Chapter 6 can be applied. However, most light rail transit lines use a combination of right-of-way types which can also include on-street operation (often in reserved lanes) and private right-of-way with grade crossings. Other limitations can be imposed by single-track sections and the street block lengths. The line capacity is determined by the weakest link; this could be a traffic signal with a long phase length, but is more commonly the minimum headway possible on a block signaled section. The first portion of this chapter discusses the capacity limitations imposed by right-of-way characteristics.

The right-of-way capacity constraints are discussed in the following sections in the order of their decreasing relative importance for most systems. This order is as follows:

- single track,
- signaled sections,
- on-street operation, and
- private right-of-way with grade crossings.

This order is not definitive for all systems, but it is appropriate for most. System-specific differences, such as short block lengths on signaled sections, will change the relative importance of each item.

Other Capacity Issues

Light rail loading levels.

Car loading levels for light rail transit, for use in the equations in this chapter, should be determined with reference to the passenger loading standards for light rail transit in Chapter 4, *Passenger Loading Levels*. Light rail loading levels are generally lighter than those for heavy rail transit but not as generous as the one seat per passenger policy common on commuter rail.

Light rail train lengths.

Light rail train lengths are more restricted than for heavy rail transit or commuter rail because of lower car and coupler strengths, and street block and station platform lengths. These issues are considered under *Train Length and Station Limitations* later in this chapter.

Access for passenger with mobility limitations.

One additional issue that is of particular importance to light rail operations and capacity is the method of access for passengers with mobility limitations. While the speed of each access method varies, all can have an effect where close headways and tight scheduling prevail. The overall discussion of the impact of the Americans with Disabilities Act related to wheelchair provisions is contained in Chapter 4, *Operating Issues*. More specific light rail accessibility issues are dealt with under *Wheelchair Accessibility Effects* in this chapter.

SINGLE TRACK

Single track reduces capital costs but can add a serious capacity constraint.

Single track is the greatest capacity constraint on light rail lines where it is used extensively. Single-track sections are used primarily to reduce construction costs. Some lines have been built with single track as a cost-saving measure where the right-of-way would permit double track. In other areas single track has been built because widening the right-of-way and structures is impossible. Single-track sections can be very short in order to bypass a particular obstacle; for example, an overpass of a highway.

Determining the potential extent of single track.

While determining the potential extent of single-track construction is possible, the exact layout is highly system specific. Estimates can be made of the number of track kilometers or miles required for a certain number of route kilometers or miles once the intended headway is known.[17] While this does not tell the user *where* the single-track sections can be used, it can provide assistance in determining the possible extent of single track for use in cost estimates.

Calculating Single-Track Headway Restrictions

Single-track occupancy time and distance.

Single-track sections greater than 400-500 meters (0.25-0.30 miles) are potentially the most restrictive capacity constraint for light rail. The headway limitation is very simply twice the time taken to traverse the single-track section, plus an allowance for switch throw and lock—unnecessary for spring switches or gauntlet track[18]—plus an operating margin to minimize the potential wait of a train in the opposite direction.

Single track capacity constraints are site specific.

The time to cover a single-track section is:

$$T_{st} = SM\left(\frac{(N_s+1)}{2}\left(\frac{3v_{\max}}{d_s}+t_{jl}+t_{br}\right)+\frac{L_{st}+L}{v_{\max}}\right)+N_s t_d+t_{om}$$

Equation 3-17

where

T_{st} = time to cover single-track section (s);

L_{st} = length of single-track section (m or ft);

L = train length (m or ft);

N_s = number of stations on single-track section;

t_d = average station dwell time on section(s);

v_{max} = maximum speed reached (m/s or ft/s);

d_s = deceleration rate (m/s^2 or ft/s^2);

t_{jl} = jerk limiting time (s);

t_{br} = operator and braking system reaction time (s);

SM = speed margin; and

t_{om} = operating margin (s).

The results of applying Equation 3-17 are shown graphically in Exhibit 3-51.

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[17] See Allen, Duncan W., *Practical Limits of Single-Track Light Rail Transit Operation* in the bibliography.

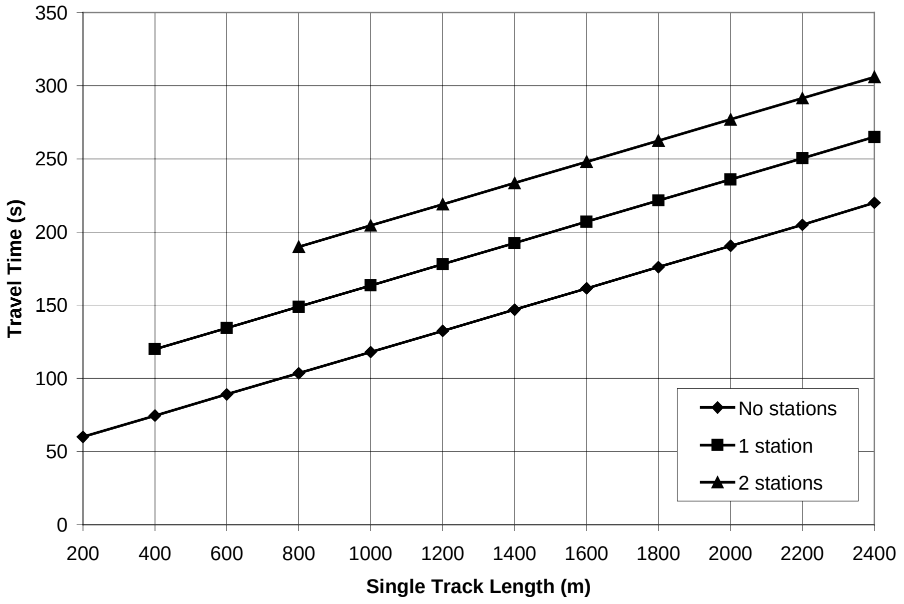
[18] Gauntlet track interlaces the four rails without needing switches, saving capital and maintenance costs and potential operating problems due to frozen or clogged switch points. The disadvantage is that the single-track section cannot be used as an emergency turn-back (reversing) location.

Exhibit 3-50
Data Values for Single Track LRT Travel Time

Term	Value
Jerk limitation time	0.5 seconds
Brake system reaction time	1.5 seconds
Dwell time	15-25 seconds
Service braking rate	1.3 m/s^2 (4.3 ft/s^2)
Speed margin	1.1 to 1.2
Operating margin time	10-30 seconds

Exhibit 3-51
Light Rail Travel Time Over Single Track Section

An alternative version of this figure in U.S. customary units appears in Appendix A.



NOTE: Assumes speed limit of 55 km/h, train length of 55 m, 20-second dwell time, and other data as per Exhibit 3-50. *The recommended closest headway is twice this time plus an operating allowance.*

To estimate best headway multiply single-track time by two and add an operating margin.

The value of the maximum single-track section speed should be the appropriate speed limit for that section. A speed of 55 km/h (35 mph) is a suitable value for most protected, grade separated lines. If the single-track section is on-street then a speed below the traffic speed limit should be used. If there are signalized intersections, an allowance of half the signal cycle should be added to the travel time for each such intersection, adjusted for any improvements possible from traffic signal pre-emption.

Scheduling for single track.

Trains should be scheduled from their termini such that passing locations are not close to the single-track sections. Where there is more than one single-track section this can become difficult but not impossible.

Passing sections.

Lengthy single-track sections can severely limit headways and capacity and may require one or more double track passing sections in the single-track section. These should, wherever possible, be of sufficient length to allow opposing trains to *pass on-the-fly* and to allow some margin for off-schedule trains. Obviously trains should be scheduled to pass at this location.

SIGNALED SECTIONS

Economic signaling constraints.

Restrictions due to signaled sections are largely covered in Chapter 6, *Grade-Separated Systems Capacity*. However, it should be realized that many light rail lines are not signaled with the minimum possible headway in mind but more economically for the minimum planned headway. This can easily make signaled sections the capacity constraint. In this case the signaling system design capacity should be used to determine the maximum throughput of trains. Typical design headways of 3 to 3½ minutes allow 20 and 17 trains per hour respectively.

ON-STREET OPERATION

On-street capacity.

Historically, streetcar operation has achieved throughput in excess of 125 cars per hour on a single track in many North American locations. Even now the Toronto Transit Commission schedules single and articulated streetcars at a peak 15-minute rate of over 60 cars an hour on Queen Street East in Toronto, where several car lines share a four-block stretch. The price of this capacity is low speed, congestion, irregular running, and potential passenger confusion at multiple-car stops.

Reserved lanes for light rail vehicles and streetcars.

Despite this record, on-street operation is often raised as a major capacity constraint for modern light rail systems, yet this is rarely the case on contemporary lines. This is particularly true on most newer lines where light rail trains have exclusive use of road lanes or a reserved center median where they are not delayed by other traffic making turns, queuing at signals, or otherwise blocking the path of the trains. Exclusive lanes for light rail are also being instituted on some of the older streetcar systems.

Even with these improvements in segregating transit from other traffic, light rail trains must still contend with traffic signals, pedestrian movements, and other factors beyond the control of the transit operator. The transit capacity in these situations can be calculated using the equations presented later in this chapter.

Calculating on-street train throughput.

Variability due to traffic congestion has been reduced as a factor as almost all recently built on-street light rail lines operate on reserved lanes. A number of older systems still have extensive operation in mixed traffic and so are subjected to the fluctuation in train throughput this causes by reducing g, the effective green time for trains. Traffic queuing, left turns and parallel parking can all serve to reduce light rail transit capacity.

Signal pre-emption.

Signal pre-emption allows the light rail train to extend an existing green phase or speed the arrival of the next one. Depending on the frequency of intersections and traffic congestion, this can have a substantial impact on the flow of general traffic in the area. As a result, signal pre-emption in congested areas is often limited in its scope so as not to have too negative an effect on other traffic. The degree to which local politicians and traffic engineers will tolerate the effects of pre-emption plays a large role in determining the effectiveness of signal pre-emption schemes.

Signal progression.

Signal progression has supplanted pre-emption in many cases where light rail trains operate in congested downtown areas. This technique gives trains leaving stations a “green window” during which they can depart and travel to the next station on successive green lights. The benefits of progression increase with greater station spacing as less accumulated time is spent waiting for the progression to start at each station. The progression is frequently made part of the normal traffic signal phasing and so is fully integrated with signaling for automobiles on cross-streets. This reduces delays for transit and car drivers alike. Station stops are accommodated by the train missing one signal cycle and proceeding on the next. Ideally the signal cycle length will be slightly longer than a long average dwell time in order to allow the majority of trains to leave shortly after passenger boardings and alightings have ended.

It is useful if the train operator waiting at the first signal in a series of signals can determine when the “green window” will start, as this allows the operator to serve more passengers by maximizing the dwell time at the station. In this way, the train operator only closes the doors when he knows that the train will soon be able to proceed. In some cases this can be done by observing the operation of the other traffic signal phases. However, this may not be possible at some locations and in these cases a special signal display can be added that counts down the time to the start of the light rail phase. Such countdown timers are used at a number of locations on the downtown portion of the San Diego Trolley.

Heritage streetcar operation.

Operating heritage streetcars—vintage trolleys—in conjunction with light rail service can constrain capacity. With care, such services can interact harmoniously, but once established, it may be difficult to remove a heritage service with popular and tourist appeal—if and when that capacity is needed for the principal light rail service(s).

Determining On-Street Capacity

The minimum sustainable headway is double the longest traffic signal cycle.

Single streetcars in classic mixed operation can be treated as similar to buses and capacity determined from the procedures of Part 2 of this manual. Where, as is often the case, light rail train lengths approach the downtown block lengths, then the throughput is simply one train per traffic signal cycle, provided the track area is restricted from other traffic. When other traffic, such as queuing left-turning vehicles, prevents a train from occupying a full block, throughput drops as not every train can proceed upon receiving a green signal. A common rule of thumb is that the minimum sustainable headway is double the longest traffic signal cycle on the at-grade portions of the line. Equation 3-18 can be used to determine the minimum headway between trains operating on-street.

$$h_{os} = \max \left\{ \begin{matrix} \dfrac{t_c + (g/C)t_d + Z_a c_v t_d}{(g/C)} \\ 2C_{\max} \end{matrix} \right\}$$

Equation 3-18

where:

h_{os} = minimum on-street section train headway (s);

g = effective green time (s), reflecting the reductive effects of on-street parking and pedestrian movements (mixed traffic operation only), as well as any impacts of traffic signal pre-emption;

C = cycle length (s) at the stop with the highest dwell time;

C_{max} = longest cycle length (s) in the line’s on-street section;

t_d = dwell time (s) at the critical stop;

t_c = clearance time between trains (s), defined as the sum of the minimum clear spacing between trains (typically 15-20 seconds or the signal cycle time) and the time for the cars of a train to clear a station (typically 5 seconds per car);

Z_a = one-tail normal variate corresponding to the probability that queues of trains will not form, from Exhibit 2-15; and

c_v = coefficient of variation of dwell times (typically 40% for light rail, while streetcars running in mixed traffic have c_v values similar to buses).

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

RIGHT-OF-WAY WITH GRADE CROSSINGS

Private right-of-way with grade crossings is the predominant type of right-of-way for many light rail transit systems. This can take the form of a route which does not follow existing streets or one which runs in the median of a road physically separated from other traffic except at crossings.

Capacity on lines with full signal pre-emption can be determined using the methods for grade-separated rail transit given in Chapter 6. However, allowances for any speed restrictions due to grade crossings must be made. Where full signal pre-emption is not available, the procedures of Part 2 for street running should be used to determine line capacity since it incorporates the cycle length of traffic signals, pre-empted or not.

Signal Pre-emption

Pre-emption delays.

Light rail transit lines operating on private right-of-way are generally given full priority at grade crossings by railroad-type crossbucks, bells and gates, or by traffic signal pre-emption. Gated, railroad-style crossings are used where train and/or traffic speeds are high. Railway-type gated crossings consistently have the longest phase lengths of the three main crossing devices. Crossbucks and bells alone, or pre-empted traffic signals, are used where speeds are lower. Delays to other traffic are reduced when gates are not used since the time taken for gates to be lowered and raised (around 30 seconds) is removed as a factor.

The potential delay to cross traffic at crossings with traditional railroad protection is almost three times longer than with 100% pre-empted signalized intersections. At higher train frequencies these occupancy times will become unacceptable and signalized intersections would be required—potentially reducing light rail speeds, but not the light rail capacity—as the crossing occupancy time is well within a normal green phase.

Grade Crossings and Station Dwell Times

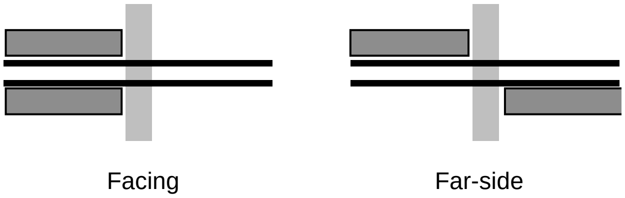
Grade crossings adjacent to stations.

Grade crossing activation and occupancy times can be affected by the presence of a station adjacent to the crossing. If the train must use the crossing after stopping at a station, the activation of the crossing signals is often premature and the crossing is unavailable to other traffic for more than the optimum time. In this case the train is also starting from a stop and so must accelerate through the crossing, adding to the total delay. Where the station platform is on the far-side of the crossing, the arrival time at the crossing can be predicted consistently and premature activation of the crossing is not a factor. The train is also either coasting or braking through the crossing from cruising speed and so will occupy it for less time.

Far-side platforms can be advantageous.

Stations can be designed to place both platforms on one side of the crossing or to locate one platform on each side of the crossing such that trains use the crossing before stopping at the station. Both arrangements are shown in Exhibit 3-52. Using far-side platforms is advantageous for the operational reasons given above, reduced right-of-way requirements, and, for median operation, allowing left turn bays to be readily incorporated into the street.

Exhibit 3-52
Light Rail Platform Options at a Crossing



Avoiding premature activation of crossing gates and signals.

Delays caused by premature activation of crossing gates and signals at near side stations can be reduced using wayside communication equipment. This can be done with the operator being equipped with a control to manually start the crossing cycle before leaving the station or by an automatic method. An example of the latter approach can be found on the San Diego Trolley. The trolley shares some of its track with freight trains and uses a communication device that identifies light rail trains to crossing circuits located on the far-side of stations. If the crossing controller identifies a train as a light rail train, a delay to allow for station dwell time is added before the crossing is activated. This ensures that the crossing remains open for cross traffic for most of the time that the light rail train is stopped in the station. If the controller cannot identify the train as a light rail train, it assumes the train is a freight and activates the crossing gates without delay.

Train to wayside communication.

Other systems use an inductive link between the light rail train and wayside to activate signal pre-emption, switches and, in the future, ADA mandated information requirements. The most common methods are the Philips (Vetag) and SEL systems. The lowest-cost detection approach is the classic overhead contractor. Trolleybus technology using radio signals from the power collection pick-up to coils suspended on the overhead wires is also applicable to light rail but is not used in North America.

TRAIN LENGTH AND STATION LIMITATIONS

Street Block Length

The length of street blocks can be a major limitation for at-grade systems which operate on-street. Most jurisdictions are unwilling to allow stopped trains to block intersections and so require that trains not be longer than the shortest street block where a stop is likely. This issue is especially noteworthy in Portland where unusually short street blocks of 65 m (200 ft) in the downtown area limit trains to two cars. The San Diego Trolley also faced this issue when they operated four-car trains on the East Line for a time. Since three cars is the maximum that can be accommodated by the downtown blocks, trains were split in two sections before entering downtown.

Sacramento is an exception to the street block length rule and is able to operate 4-car trains in the peak hours. These long trains block one intersection when stopped. This situation is almost a necessity as the extensive single track nature of the Sacramento line imposes a minimum headway of 15 minutes on the service. The capacity limitation of this headway restriction is therefore partially made up for by the operation of relatively long trains.

Exclusive lanes can mitigate street block length constraints.

Street block length is also an issue if another vehicle occupies the same lane used by light rail trains in a block. If this would cause the rear of the train to protrude into an intersection then the train must wait for the block to clear before advancing. This fact provides a strong argument for the provision of an exclusive light rail transit lane where street running with long trains occurs. Indeed, as a result of this concern, operation with mixed traffic is very rare on new light rail transit systems. Where buses and light rail transit trains operate alongside each other on transit malls in Baltimore and Calgary, the rail stations, bus stops, and lanes are laid out to cause a minimum of interference between the modes.

Station Limitations

Platform length.

An obvious limitation to train length is the length of station platforms. For most light rail transit routes this is not a problem as stations have been built with current ridership and service levels in mind. The relative importance of this constraint is much greater for commuter rail where platform length is often constrained for historical reasons.

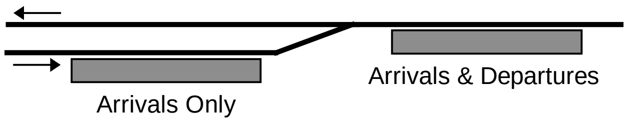
Terminal station design.

A more important restriction can be in the design of terminal stations. Toronto’s streetcars face such terminal design problems where two or more routes share a common terminal and single-track turning loop. This is the case at the Broadview and Dundas

West subway stations where there is heavy transferring activity between the subway and streetcars. The high volumes of transit vehicles and passengers can cause delays to following streetcars while passengers board and alight from the preceding car. Scheduled recovery time for the streetcar operator is hard to accommodate in these conditions as the volume of following cars precludes layover time.

The Baltimore light rail line also uses single-track termini but the level of service (15-minute headway) is not high enough for these to be a capacity limitation. However, the terminals are designed to allow an arriving train to unload passengers before the departing train ahead leaves through the use of an extra platform as shown in Exhibit 3-53. This arrangement allows the location of a station in a relatively narrow right-of-way since the platforms are not adjacent to each other and a wider center platform is not required.

Exhibit 3-53
Light Rail Single Track Terminus with Separate Unloading Platform (Baltimore)



WHEELCHAIR ACCESSIBILITY EFFECTS

Introduction

The accessibility of light rail transit to wheelchairs and other mobility devices (considered together with wheelchairs in this section) is a major issue for light rail transit systems. The relative rarity of level loading with high level platforms on light rail has resulted in a variety of methods to allow wheelchair access to light rail vehicles. Each of the methods is outlined in the sections that follow. Chapter 5, *Operating Issues,* has discussed general capacity issues related to the Americans with Disabilities Act, including typical light rail provisions.

Wheelchair boarding and alighting times.

Boarding and alighting times with non-level loading of wheelchairs tend to be highly variable depending on the skill of the passenger. Experienced users can be remarkably quick in boarding and alighting. Passenger movement times are often lower than for lift-equipped buses as there is more room to maneuver wheelchairs, walkers and scooters in light rail vehicles. Off-vehicle fare collection also helps to speed loading for mobility limited and able-bodied passengers alike. Some agencies require the passenger and wheelchair to be strapped in, a time consuming process which is becoming less common as the policy is not justified by the relatively low deceleration rates experienced on light rail vehicles. Some systems have experienced passenger conflicts over mobility device seating priority when other passengers occupy the folding seats provided to create space for wheelchairs and other mobility devices.

It should be noted that both mobility-impaired passengers and transit agencies prefer access methods which do not single out the mobility impaired for special treatment. Lifts and special ramps cause delays which reduce the reliability of the service while isolating the mobility impaired from other passengers. Mechanical devices such as lifts can also fail and put a train out of service. For these reasons, the popularity of lifts and other special devices for the mobility impaired is decreasing in favor of more reliable and less exclusionary methods such as low-floor cars.

Reducing the delays associated with wheelchair boardings and alightings is an important issue where capacity is constrained, and is a particular concern on lines with single track or operating on a tight schedule.

Exhibit 3-54 illustrates the various kinds of wheelchair access provided in the U.S. and Canada. These access methods are discussed in detail in the following sections.

Exhibit 3-54
Wheelchair Access Examples

High Level (San Francisco—Light Rail)

Low-Floor Car (Portland, OR)

Mini-High Platform (Sacramento)

Curbside Lift (Portland before low-floor cars)

Car-Mounted Lift (San Diego)

Curbside Lift (San Jose)

High Platforms

High platforms allow level movement between the platform and the car floor. This allows universal access to all cars of a train and removes the reliability and exclusionary effects associated with lifts, ramps and special platforms. Passenger flow is speeded for all passengers since there are no steps to negotiate on the car. High platform stations can be difficult to fit into available space and can increase costs. Nevertheless high platforms are used exclusively on a number of systems including Los Angeles, St. Louis, and Calgary. The use of high platforms on the transit mall portion of Calgary's light rail lines illustrates the difficulty accommodating this preferred loading method in on-street locations.

Mixed use of high and low platforms.

High level platforms at stations are also used in Buffalo, Pittsburgh and San Francisco; in combination with low-level loading at other stops. Buffalo is unusual in that a subway, with high level platforms, serves the outer portion of the line while the downtown segment is on a transit mall with low-level loading using fold-out steps and mini high platforms (discussed below) for wheelchair access. Pittsburgh has separate doors for each platform level while the San Francisco Muni uses cars fitted with steps which can be mechanically raised to floor height at high platform stations.

Car-Mounted Lifts

Car-mounted lifts are used only on the San Diego Trolley, one of the first light rail transit systems to be wheelchair accessible. Lifts are mounted in the cars so that the first door on the right side of every train is lift-equipped. When not in use, the lift is stored in a vertical position which blocks the doorway from use by other passengers. While the lift model used initially was prone to failure, the current installation is reliable with a failure rate of about one in 400 operations.[19]

Dwell times with car mounted lifts.

Boarding and alighting times with the car-mounted lifts are around one minute for each passenger movement. However, the need for the train operator to leave the cab to operate the lift adds to the time required and can mean the total station dwell time extends to 1½-2 minutes when the lift is used. If the operator is required to assist in tying down the wheelchair, the dwell can be further extended.

Platform-Mounted Lifts

Platform mounted lifts are used on the San Jose light rail system. They offer advantages over car-mounted lifts in that all car doors are left available for other passengers when the lift is not required, the lift is not subject to car vibration, and the failure of a lift need not remove a car from service. Disadvantages include increased susceptibility to vandalism and an increase in the distance that the train operator must walk to operate the lift.

Dwell times with wayside lifts.

For the San Jose system, wheelchair handling is slow because of their wayside lift arrangement. The lift is stored vertically in an enclosed housing at the front of each platform. To operate the lift, the train operator must raise sliding steel doors on each side of the lift housing, lower the car side of the lift to floor level, lower the platform side to ground level, have the passenger board the lift, raise the lift and board the passenger, store the lift and secure the housing. This procedure takes two to three minutes giving a total train delay (including loading and unloading) of four to six minutes per passenger requiring the lift. These delays can easily consume the train's scheduled terminal recovery time. An average of 25 wheelchairs and scooters are carried each weekday on the San Jose light rail line but this has increased to as many as 50 a day for special events.

Tri-Met in Portland removed its platform lifts in 1997 after adding a low-floor car to each train. The Portland wayside lifts were more efficient than the San Jose device. Under normal circumstances the lift was at ground level ready to receive boarding passengers. The presence of the passenger on the lift signaled the passenger's intention to board to the train operator. The train operator then aligned the first door of the train with the lift and boarded the passenger. The car's steps were bridged by a folding plate on the lift. This configuration speeded the use of the lift but did not prevent it from having an effect on punctuality, as the time for each mobility device movement averaged 1 minute 50 seconds.

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[19] Based on San Diego Trolley data for May 1994. Out of 1,069 lift passengers carried (2,138 lift cycles) only six failures were recorded—giving a failure rate of 0.28%.

Mini-High Platforms

The most common wheelchair loading arrangement.

The most common wheelchair access to high-floor light rail cars is the use of *mini-high* or *high-range* platforms that provide level loading to the wheelchair accessible door of the train. This method is mechanically simple and often uses a folding bridgeplate, manually lowered by the train operator, to provide a path over the stepwell between the platform edge and vehicle floor. The mini-high platform is reached by a ramp or, where space limitations require, by a small lift. In Sacramento, one of the pioneers of mini-high platforms, these lifts are passenger-operated and the boarding passenger must be on the mini high platform for the train operator to board them. The Sacramento system handles about 1,200 wheelchairs and five times as many strollers a month on the mini-high platforms. Mini-high platforms have been adopted for the non-level loading light rail lines in Baltimore and Denver.

Second train stops for mini-high platforms.

The San Francisco Municipal Railway has also installed mini-high platforms at key locations on its surface lines (the downtown subway is high platform). The cars must make a special stop to board and alight passengers using the mini-high platforms as the moveable steps on the car must be raised and the center door aligned with the platform in order for level loading to take place. The steps are usually raised before the car has come to a stop. An elastic gap filler is used between the platform edge and car doorway. No bridge plate is needed and the train operator does not have to leave the cab. This arrangement, aside from the need for a second stop, is very efficient with the time required for a passenger movement being as low as 10 seconds. Two of the major surface stops on the Muni system have been converted entirely to high platforms with proof-of-payment fare collection to speed general passenger flows with the additional benefit of making wheelchair loading and unloading easier. Where no high or mini-high platforms exist, the Muni light rail system is not accessible to wheelchairs.

Pittsburgh's PAT light rail lines are only available to wheelchairs at high platform stations. Street-level stops, as in San Francisco, are not accessible.

Low-Floor Cars

Low-floor cars[20] offer a straightforward solution to the need for universal access to light rail vehicles. By bringing the floor height down to just above the railhead, boarding is simplified for all passengers, as steps are no longer required. Small, extendible ramps and slight increases in platform edge height allow passengers in wheelchairs and other mobility devices to board without the aid of lifts or special platforms. Low-floor cars provide much of the benefit of level loading without the need for high platforms. Typical floor height is 350 mm[21] (14 inches), about double the height of a normal curb. Medium or intermediate height platforms are therefore still required for no step boarding. Bridge plates and the assistance of train operating staff are still required on most designs, although it appears that passengers with pushchairs and many wheelchair users elect to navigate the gap without this assistance.

While low-floor cars have operated in Europe for over a decade, the first North American operation began in Portland in 1997. Boston has also ordered low-floor cars to make its Green Line subway-surface routes accessible. As in Portland, the cars will be compatible with the agency's existing high-floor fleet to allow mixed train operation.

Drawbacks of low-floor designs.

Low-floor cars have some drawbacks which have yet to be fully resolved. Although purchase prices have been falling, cars with a 100% low floor are more expensive to buy and maintain. Certain designs are technically complex and have suffered extensive

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[20] Note the difference between the terms low flow car and low level loading. The former states that the majority of the floor of the car is slightly above curb height, the latter describes cars (low floor cars included) where passengers can enter from street level, without the need for platforms.

[21] Certain low-floor designs ramp down the doorways to achieve a 280-300 mm (13-14 inch) floor height.

teething problems. Most low-floor designs are intended for city streetcar or tramway applications and do not have the top speeds, nor ride quality suitable, for North American light rail operations and track standards. These restrictions can be overcome or reduced by hybrid or partial low-floor cars with up to 70% of the floor at the low height. This design results in a lower cost, higher top speed, and better ride quality on open track. The ends of the car and the driving (end) trucks can be of conventional construction and can retain component and maintenance commonality with conventional high-floor light rail equipment.

Low-floor cars in North America.
Full and partial low floor designs.

Steps inside the car provide access to the high-floor sections. 100% low-floor designs require the use of stub axles, hub motors and other space-saving components. These items add to costs and have not yet been satisfactorily proven for high-speed use or on the lower quality of tracks typical of North America when compared to Western Europe. As a result, the cars purchased for Portland and Boston are of the partial low-floor type. Despite high costs and technical challenges, the substantial benefits of low-floor cars have made them a popular choice in Europe. Many European light rail systems have extensive on-street operation and recent new vehicle procurements have been predominantly low-floor. Manufacturers are rationalizing production to fewer, modular designs. Vehicles designed for on-street operation still remain less than ideal for typical North American light rail systems with their extensive open, segregated trackage.

CAPACITY DETERMINATION SUMMARY

Determining the weakest link for light rail capacity.

Calculating the capacity of light rail transit lines is a complex process because of the varieties of rights-of-way which can be employed for the mode. The basic approach is to find the limiting factor or *weakest link* on the line and base the capacity on this point. The limiting factor for each line could be street-running with long traffic signal phases, a section of single track, or the length of signal blocks where block signaling is used.

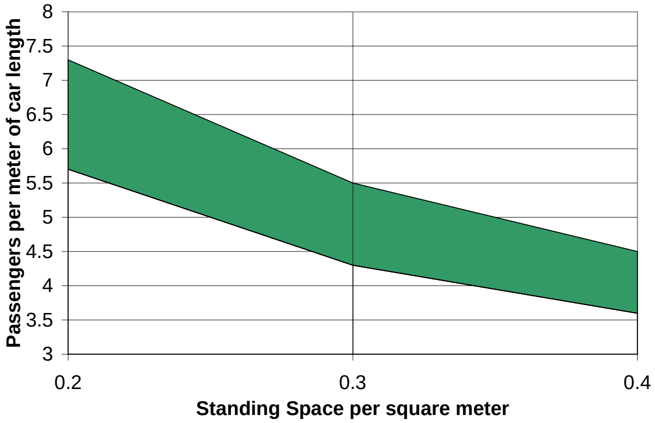
The key factors to be considered are:

1. Single track.
2. Signaled sections. Of particular importance where, for cost reasons, the signaling is not designed to allow minimum possible headway operation.
3. On-street operation. Capacity effects are strongly related to the degree of priority given to light rail vehicles relative to other traffic.
4. Private right-of-way with grade crossings.

The first step in the process is to check the headway capabilities of any single track section over 500 m (1,600 ft) in length, following the procedure given earlier in this chapter. Then compare this with the design headway of the signaling system and with twice the longest traffic signal phase of any on-street section. Select the most restrictive headway in seconds and convert this into trains per hour by dividing into 3,600. The simple procedure provides a reasonable estimate of capacity by using the range of loading levels shown in Exhibit 3-55 with peak hour factors of 0.70 to 0.90.

Exhibit 3-55
Recommended Loading Level Range for Light Rail Vehicles in Simple Capacity Calculation

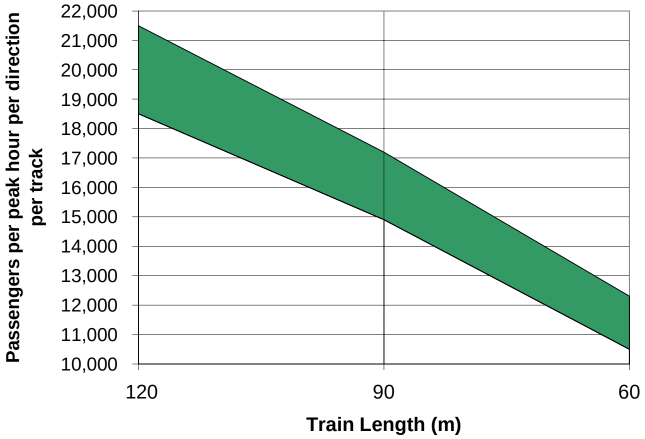
An alternative figure using U.S. customary units appears in Appendix A.



NOTE: Peak hour factor ranges from 0.7 (lower bound) to 0.9 (upper bound).

Exhibit 3-56
Light Rail Capacity on Segregated Right-of-Way With Maximum Cab-Control Signaling

An alternative figure using U.S. customary units appears in Appendix A.



NOTE: Throughput based on a range of dwell times plus an operating margin of 45-70 seconds.

Where there are no single track or on-street constraints, and the signaling system is designed for maximum throughput, the maximum capacity can be determined through the procedures of Chapter 6, *Grade-Separated Systems Capacity*, summarized for shorter light rail trains in Exhibit 3-56. At the upper end of these levels the system has become a segregated heavy rail transit system using light rail technology.

No allowance is contained in Exhibit 3-56 for extended dwells due to low-level (step) loading, wheelchairs, or on-board fare collection. With minimum headways provided by cab-control signals of better than 120 seconds, it is reasonable to expect level loading—whether high or low—and off-vehicle fare collection.

Nor is any allowance made for headway constraints due to junctions or speed restrictions in the maximum load point station approach. Where any of these situations may apply, the complete procedures of Chapter 6 should be followed.

Predominantly segregated light rail lines with block signaling can reach the achievable capacity of some heavy rail systems. At this upper end of the light rail spectrum achievable capacity calculations should follow those of heavy rail transit.

Maximum light rail transit capacities.

Note that no light rail lines in the U.S. and Canada approach volumes of 10,000 passengers per peak hour direction per track, except San Francisco's Muni Metro subway, which is shared by five routes, and Boston's Green Line subway. Achievable capacities to and above 20,000 passengers per peak hour direction are reported in Europe; however, at these levels, the lines, often called light metro, pre-metro or U-bahn, have many or all of the characteristics of heavy rail transit operated by light rail equipment.

8. COMMUTER RAIL CAPACITY

INTRODUCTION

Commuter rail ridership in North America is dominated by the systems in the New York area where the busiest routes use electric multiple-unit trains on dedicated tracks with little or no freight service. The capacity of such systems can best be determined from the procedures of Chapter 6, *Grade-Separated Systems Capacity*. Care must be taken to take into account the sometimes lower vehicle performance and lower throughput of signaling systems where these are based on railroad rather than rapid transit practices.

Elsewhere, with the exception of SEPTA's Philadelphia lines, Chicago's Metra Electric and South Shore lines, and the Mont-Royal tunnel line of the AMT in Montréal, commuter rail uses diesel locomotive-hauled coaches and follows railroad practices. Electric locomotive-hauled coaches are also being used by SEPTA and New Jersey Transit on routes that also see electric multiple unit cars. Dual powered (electric and diesel) locomotives are used by the Long Island Rail Road and Metro-North Railroad in the New York area. All new starts are likely to use diesel locomotive-hauled coaches.

Commuter rail capacity determination is both simple and inexact.

For most commuter rail lines, the determination of capacity is at once both simple and approximate. Unlike the grade-separated rail capacity determination there are no reasonable methodologies that allow the calculation of the train control throughput and controlling station dwell times to produce the achievable passenger capacity of a line.

The number of trains that can be operated in the peak hour is dependent on negotiations with the owning railroad. Many factors are involved, single or double (or more) track, the signaling or train control system, grade crossings, speed limits, freight service, switching services—and the priorities to be accorded to these. Although railroads are becoming more conducive to accommodating commuter rail services—and the revenue and capital upgrading they produce—they have the upper hand and obtaining paths for commuter trains at a reasonable cost can require difficult and protracted negotiations.

Transit agency ownership of track used for commuter rail.

There are an increasing number of exceptions where the operating agency has purchased trackage and/or operating rights and so has more, or total, say in the operation and the priority of passengers over freight. The two New York carriers own the great majority of track they operate on while New Jersey Transit, SEPTA, the MBTA, Metra and Los Angeles Metrolink, among others, own substantial portions of the trackage they use. Some agencies, such as SEPTA, have leverage with the freight railroads as they own track used by the freight carriers as well as the reverse. However, there may still be strict limits on the number of trains that can be operated because of interlockings and grade crossings with other railroads.

Unlike the capacity determination methodologies for other modes, commuter rail is not provided with both simple and complete methods for determining achievable capacity. Once the number of trains that can be operated in an hour has been determined the capacity is not dependent on loading standards but only on the number of seats provided on a train.

TRAIN THROUGHPUT

Determining train throughput requires consulting the railroad agreement or the railroad or agency signaling engineers to determine the maximum permitted number of commuter trains per hour. Generally these numbers will be based on a train of maximum length, so the length-headway variations of Chapter 2, *Train Control and Signaling* will not enter into the picture.

A definitive answer may not always be obtained, particularly with single-track sections that are shared with freight. Freight traffic can be seasonal and available commuter rail trips can vary. Usually the agreement will ensure a minimum number of commuter rail trips per hour. These may be uni-directional—that is all trains must platoon in one direction in each peak period. This is generally not a capacity problem but rather an efficiency issue with respect to equipment and staff utilization. Uni-directional operation is an issue on lines where reverse commuting to suburban work sites is important. For example, Chicago's Metra is planning new services aimed specifically at the growing reverse commuter market.

The number of commuter rail trips available per hour may range from one upwards into the double digits. Ten or more trains per hour is at the upper range of traditional railroad signaling and will exceed it if long, slow freights must be accommodated. At the upper end of this range commuter rail is effectively in sole occupancy of the line for the peak period and is approaching levels where the capacity calculations of Chapter 6, *Grade-Separated Systems Capacity,* should be considered.

Train throughput where commuter rail has exclusive occupancy of the track.

Only in this case can the train separation equation be used as a rough approximation of railroad signaling throughput by using suitably lower braking and acceleration rates, longer train length and adjusting the separation safety factor B from the suggested value of 2.4 for a rapid transit three-aspect signaling system to 3 or 4. This equation, and the associated equation for junction throughput, do not apply in locations and times where freight and commuter rail trains share trackage or where the signaling system is designed solely for freight with long signal blocks.

Operating practices and patterns.

Additional complications are raised by the variety of services operated and the number of tracks available. The busier commuter rail lines tend to offer a substantial number of stopping patterns in order to minimize passenger travel times and maximize equipment utilization. A common practice is to divide the line into zones with trains serving the stations in a zone and then running express to the station(s) in the central business district. Through local trains provide connections between the zones. A number of lines in the Chicago and New York areas are operated this way—Metra's Burlington Northern line to Aurora operates with five zones in the morning peak, Metro-North's New Haven line (including the New Canaan Branch) operates with seven zones. Such operating practices are made possible with three or more tracks over much of the route and the generous provision of interlockings to allow switching between tracks. Grade-separated junctions are also common where busy lines cross or converge. The capacity of this type of operation is hard to generalize and should be considered on a case-by-case basis. Such heavy operations are similar to grade separated rapid transit in many ways but with some notable exceptions, such as the wide range of services operated.

Station Constraints

Train storage at downtown terminals.

Another principal difference between commuter rail and the other rail transit modes is that commuter rail trains are often stored at the downtown terminals during the day. This reduces the need for track capacity in the off-peak direction and allows a higher level of peak direction service to be operated. Metro-North in New York, with 46[22] platform tracks at Grand Central Terminal, is thus able to use three of its four Park Avenue tunnel tracks in the peak direction. Even when one of the tunnel tracks was closed for reconstruction, 23 trains per hour were handled on the remaining two peak direction tracks.

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[22] There is some variation between sources regarding the size of Grand Central Terminal, Metro-North reports 46 platform tracks. A number of other sources give the station a total of 67 tracks, including storage and maintenance tracks.

The situation at New York's Penn Station is less relaxed. The Long Island Rail Road has exclusive use of five tracks and shares four more with Amtrak and New Jersey Transit. Currently the LIRR operates the East River tunnels with two tracks inbound and two tracks outbound with a peak headway of three minutes per track. With limited station capacity, two-thirds of LIRR trains continue beyond Penn Station to the West Side Yard. However, not all tracks used by the LIRR at Penn Station continue to the yard and some trains must be turned in the station. This can be done in as little as 3½ minutes in a rush but five minutes is the minimum scheduled time. Capacity into the station could be increased by improving track connections to the West Side Yard and so further reducing the number of trains which must be turned in Penn Station; this change would permit the East River tunnels to be operated with three tracks in the peak direction and allow the operation of additional trains. This modification would, however, only meet projected demand in the short term. In the longer term, new rail lines and new or expanded terminal facilities will be required.

Station Dwells

Dwells are less critical for commuter rail than for heavy rail transit.

Station dwell times on commuter rail lines are generally not as critical as they are on rapid transit and light rail lines as frequencies are lower and major stations have multiple platforms. In most cases the longest dwells are at the downtown terminals where the train is not blocking others while passenger activity takes place. Passenger flows are generally uni-directional and so are not slowed by passengers attempting to board while others alight and vice-versa. Exceptions are locations where major transferring activity takes place between trains but these are limited. Jamaica station on the Long Island Rail Road is one of the few examples of a station with major transfers as it serves as a funnel where eight lines converge from the east and two major lines diverge to the west. Most transfers are made cross-platform and are scheduled for two or three minutes. SEPTA's four-track regional rail tunnel through Center City Philadelphia is one of the few North American locations where commuter trains run through from one line to another without terminating downtown. SEPTA schedules provide a very generous time of 10 minutes for trains to make two station stops over this 2.3-km (1.4-mi) line segment.[23]

Platform level and commuter rail car door layout.

Commuter rail station dwell times are dependent on the platform level and car door layout. The busiest lines are equipped with high platforms and remotely controlled sliding doors, as on rapid transit cars. Single-level cars often use conventional traps for high and low platform stations but these are time consuming to operate and require a large operating crew. Cars used on lines with both high and low platforms can be fitted with conventional trap doors at the car ends and sliding doors for high-platform use at the center of the car, as on New Jersey Transit, the South Shore in Chicago and the Mont-Royal line in Montréal. Most bi-level and gallery cars are designed for low-platforms and have the lowest step close to the platform for easy and rapid boarding and alighting. Bi-level cars of the type popularized by GO Transit feature two automatic sliding double stream doors per side allowing cars to be emptied in one to two minutes. Gallery cars usually feature one exceptionally wide door (2 meters wide) at the center of each side to allow rapid boarding and alighting with multiple passenger streams.

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[23] While there are three stations on this segment, timetables only provide departure times and so do not include the dwell time at the first Center City station. Another North American example of a downtown commuter rail station where commuter trains run through is Toronto's Union Station.

TRAIN CAPACITY

Except for a few situations where standing passengers are accepted for short distances into the city center, commuter rail train capacity is based solely on the number of seats provided on each train. A peak hour factor of 0.90 or 0.95 is used.

Constant train length.

Where the equipment design is known, the best procedure is to add the number of seats in a train. Unless there is an agency policy of peak hour occupancy at 95% of total seats the 0.90 factor should be used. Where trains are the same length, the commuter rail capacity is simply:

$$(\text{trains per hour}) \times (\text{seats per train}) \times 0.90$$

Equation 3-19

Variable train length.

In many cases train length is adjusted according to demand. The longest train will be the one arriving just before the main business starting time in the morning—and vice-versa in the afternoon. Shorter trains may be used at the extremities of the peak period. In this case the total number of seats provided over the peak hour must be determined and the peak hour factor applied.

Seats per unit of train length and short trains.

Where the rolling stock design is unknown, the number of seats per unit length of train can be used, based on the shortest platform where the service will stop. A number of systems, particularly the older ones, operate trains which exceed the platform length at a number of stations. This situation is particularly common where platforms are constrained by physical and built-up features. Passengers must take care to be in the correct car(s) if alighting at a station with short platforms.[24] Train length on electric lines can also be limited by the amount of current the overhead or third-rail is able to supply.

Characteristics of existing commuter rail cars.

Exhibit 3-57 shows the number of seats and seats per meter length of selected North American commuter rail cars. All cars have substantially the same outside dimensions—the AAR passenger car maximums of 25.2 m (82.7 ft) long and 3.2 m (10.5 ft) wide.

Passenger loads range from over 7 to below 2 passengers per meter of car length (2.1 to 0.6 p/ft of car length). At the high end are the double-deck car types, bi-levels,[25] and gallery cars. A 2+3 seating configuration is needed to reach 7 passengers per meter length (2.1 p/ft length). Such seating is not popular with passengers and the middle seats are not always occupied with some passengers preferring to stand for shorter trips.

A capacity of 7 passengers per meter (2.1 p/ft) can be used as a maximum. A range of 5 p/m (1.5 p/ft) is the upper end for single-level cars, with 4 p/m (1.2 p/ft) preferred. These preferred and recommended levels allow some space for toilets, wheelchairs, and bicycles. If these provisions are extensive then the car capacity should be reduced accordingly.

Obviously the train length should exclude the length of the locomotive(s) and any service cars, and should be adjusted for any low-density club, bar, or food service cars.

An allowance for standing passengers is not recommended. However, if the nature of the service has significant short trips, it may be appropriate to add 10% to the number of seats on the train. Heavy rail standing densities are not appropriate for commuter rail.

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[24] Another common station limitation, lack of park-and-ride capacity, is considered in Chapter 5.

[25] Also called tri-levels on certain systems as there is an intermediate level at each end over the trucks.

Exhibit 3-57
Commuter Rail Car Capacity

System and City	Car Designation	Date Built	Seats	Seats/m (ft)
Bi-level cars				
LIRR (New York)	C-1	1990	190	7.3 (2.4)
MBTA (Boston)	BTC	1991	185	7.1 (2.3)
MBTA (Boston)	CTC	1991	180	6.9 (2.3)
GO Transit (Toronto)	Bi-Level Trailer	1977-91	162	6.3 (2.1)
Metra (Chicago)	TA2D, E, F	1974-80	157	6.1 (2.0)
Tri-Rail (Miami)	Bi-Level III	1988	159	6.1 (2.0)
CalTrain (San Francisco)	Gallery Coach	1985-87	148	5.7 (1.9)
SCRRA (Los Angeles)	Bi-Level V Mod.	1992-93	148	5.7 (1.9)
Metra (Chicago)	Gallery	1995	148	5.7 (1.9)
Single level cars				
NICTD (Chicago)	TMU-1	1992	130	5.0 (1.6)
NJT (New Jersey)	Comet IIB	1987-88	126	4.9 (1.6)
Metro-North (New York)	M-6 D	1993	126	4.9 (1.6)
MBTA (Boston)	CTC-1A	1989-90	122	4.7 (1.55)
NJT (New Jersey)	Comet III	1990-91	118	4.6 (1.5)
LIRR (New York)	M-3	1985	120	4.6 (1.5)
SEPTA (Philadelphia)	JW2-C	1987	118	4.6 (1.5)
MARC (Baltimore)	Coach	1992-3	120	4.6 (1.5)
MARC (Baltimore)	Coach	1985-87	114	4.4 (1.45)
NJT (New Jersey)	Comet II/IIA	1982-83	113	4.4 (1.45)
LIRR (New York)	M-3	1985	114	4.4 (1.45)
MARC (Baltimore)	E/H Cab	1991	114	4.4 (1.45)
VRE (Washington, DC)	Cab	1992	112	4.3 (1.4)
Metro-North (New York)	SPV 2000	1981	109	4.2 (1.4)
NICTD (Chicago)	EMU-2	1992	110	4.2 (1.4)
Metro-North (New York)	M-6 B	1993	106	4.1 (1.35)
MARC (Baltimore)	E/H Cab	1985-87	104	4.0 (1.3)
NJT (New Jersey)	Comet III	1990-91	103	4.0 (1.3)
MBTA (Boston)	BTC-3	1987-88	96	3.7 (1.2)
AMT (Montreal)	MR90 (emu)	1994	95	3.7 (1.2)
NICTD (Chicago)	EMU-1	1982	93	3.6 (1.2)
NJT (New Jersey)	Comet IIB	1987-88	88	3.4 (1.1)
Conn DOT (New York)	SPV 2000	1979	84	3.2 (1.05)

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9. AUTOMATED GUIDEWAY TRANSIT CAPACITY

INTRODUCTION

Automated guideway transit (AGT) fits into the category of *Grade-Separated Rail* whose capacity determination is specified in Chapter 6. However, there are some nuances specific to AGT that must be considered.

AGT has a relatively low share of transit ridership.

AGT is an almost negligible part of urban, public, fixed guideway transit—being used for less than 1/10th of one percent of passenger trips in the U.S.—increasing only when institutional systems are considered, most of which are intra-airport shuttles. Technology ranges widely from the standard gauge advanced light rapid transit downtown people-movers in Detroit and Miami to small-scale monorails in amusement parks. All AGT systems are proprietary designs. As such their performance, acceleration, braking rate, balancing speed and vehicle size and capacity vary greatly.

TRAIN CONTROL SEPARATION

Train control systems on automated guideway transit range from sophisticated moving-block signaling systems to basic manual systems in which only one train may be on a section of line—or the entire line—at a time. Manual or radio dispatching may ensure that a train does not leave a station until the leading train has left the station ahead. One variation uses sectioned power supply. Power is disconnected for a given distance behind an operating train.

These operating variations are not fully accommodated in the methodology of Chapters 2 and 6. If the basic AGT performance criteria are known, then the procedures of Chapter 6 will provide an approximation of the minimum train separation time for a range of AGT train controls—from a moving-block signaling system to a simple fixed block system. A surrogate of this can be roughly simulated by setting the train detection uncertainty factor (*B*) at four times the minimum braking distance. The results are shown in Exhibit 3-58 and Exhibit 3-59 for trains of typical AGT lengths and the specific AGT values in Exhibit 3-60, with terms adjusted from typical rail transit values shaded.

Exhibit 3-58
AGT Minimum Train Separation Times

Train Length	Fixed Block	Moving Block
50 m (160 ft)	48.7 seconds	16.7 seconds
25 m (80 ft)	37.6 seconds	13.4 seconds
12.5 m (40 ft)	20.5 seconds	11.2 seconds

Exhibit 3-59
AGT Train Separation versus Length

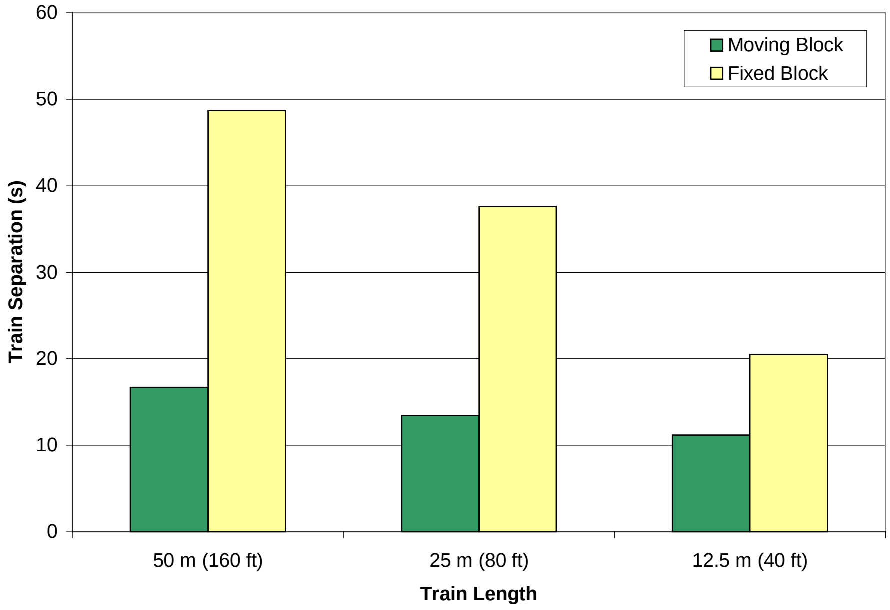

Exhibit 3-60
Suggested AGT Separation Calculation Default Values

An alternative form of this table in U.S. customary units appears in Appendix A.

Term	Unit	Description	Heavy Rail	AGT
P_e	m	positioning error	6.25	6.25
L	m	length of the longest train	200	50
D	m	distance from front of train to exit block	10	0
K	%	% service braking rate	75	75
B		train detection uncertainty constant—fixed block	2.4	4
B		train detection uncertainty constant—moving block	1	1
t_{os}	s	time for overspeed governor to operate	3	1
t_{jl}	s	time lost to braking jerk limitation	0.5	0.5
a_s	m/s^2	service acceleration rate	1.3	0.6
d_s	m/s^2	service deceleration rate	1.3	1.0
t_{br}	s	brake system reaction time	1.5	0.5
v_{max}	km/h	maximum line velocity	100	80
mb_{sd}	m	moving block safety distance	50	25

The results show that separation times with a simulated single aspect block system are two to three times longer than with the more complex—and expensive—moving-block signaling system. The moving-block results agree with those of Auer(R3), the only reference specializing in automated guideway transit train control. Here, typical short train AGT separation with moving-block control was cited at 15 seconds.

The separation range is wide and highly dependent on the train control system of the proprietary AGT system. The best method of determining the minimum train separation is from the system manufacturer or designer. Using the methodology of Chapter 3 should be a last resort when specific train separation information is not available.

PASSENGER FLOW RATES AND DWELLS

AGT systems that are part of a normal transit system can assume flow rates and station dwell times as determined in Chapter 3, *Station Dwell Times.* However, most AGT systems are classed as institutional and the majority of passengers are unlikely to be regular, experienced transit users. Doorways are rarely of typical transit width or configuration. The most common arrangement is the quadruple-flow door with associated platform doors—shown in Exhibit 3-61.

Exhibit 3-61
Orlando Airport People-Mover Doorways

© Tom Parkinson P.Eng 1992

Doorway flow rates on AGT.

Doorway flow rates and the associated station dwell times were monitored on the three C-100 systems at the Seattle-Tacoma Airport in May 1995. The range of users varied greatly and included many people with baggage and a few with baggage carts. After the arrival of a full flight with a preponderance of business passengers, passenger flow rates reached and exceeded standard transit doorway flow rates. At other times doorway flow rates were often well below the transit rates documented in Chapter 3. Under these circumstances calculating flow times—and from them dwell times—is unwise. The results are unlikely to be accurate or may reflect only a very specific sub-set of users.

AGT headways.

The selection of a minimum headway for AGT systems should reflect the train control separation, dwell time and any operating margin, that conforms with existing operations or is suggested by the system manufacturer. The typical headway of airport systems is 120 seconds with a few operating down to 90 seconds. Claims have been made for closer headways with some proprietary systems. Headways shorter than 90 seconds are possible but may limit dwell times and constrain the operating margin. They should be considered with caution unless off-line stations are adopted. Off-line stations make closer headways possible and practical—at a price.

LOADING LEVELS

AGT loading levels tend to be atypical of transit overall.

Loading levels of automated guideway transit cars tend to be atypical of normal transit operations. Those systems that are integral parts of public transit networks—such as the Detroit and Miami downtown people-movers—can use loading levels derived from Chapter 4, *Passenger Loading Levels.*

Other systems range widely. At one extreme are the airport shuttles with wide cars and no or few seats where loading can reach 10 passengers per meter of length (3 p/ft of length) under pressure from arriving business-type flights. Loading diversity on airport systems fluctuates related to flight arrival times, rather than 15-minute peak periods within a peak hour. After an arriving flight three trains at 120-second headways can exceed maximum loading levels—to be followed by a number of under-utilized trains.

At the other extreme are the narrow, all-seated configuration amusement park monorails with loading as low as 2-3 passengers per meter of train length (0.6-0.9 p/ft of length). The peak hour factor on the latter type systems attains unity when arrangements—and continual passenger line-ups—ensure that every seat on every train is occupied—in some cases, through all hours of operation.

The hourly achievable capacity of non-public transit AGT systems requires consultation with the system supplier. The methodologies and calculations of this report should only be used as a last resort—and then treated as a guideline.

OFF-LINE STATIONS

Off-line stations increase capacity.

Off-line stations maximize system capacity. They are used on several rail transit lines in Japan to achieve some of the highest throughput for two-track rapid transit lines in the world. In North America they are the exclusive preserve of the automated guideway transit line in Morgantown, West Virginia.[26]

Off-line stations permit a train throughput that is partly independent of station dwell time. Throughput is that of the train control system plus an allowance for switch operation, lock and clearance and a reduced operating margin.[27] Morgantown and certain other AGT systems use on-vehicle switching techniques where even this allowance—typically 6 seconds—can be dispensed with. In theory, trains or single vehicles can operate at or close to the minimum train control separation—which can be as low as every 15 seconds—refer to Exhibit 3-60.

Major stations with high passenger volumes may require multiple platform berths, otherwise partial dwell times must be added to the train separation times to obtain the minimum headway. The achievable capacity of such specialized systems should be determined through consultation with the system manufacturer or design consultant.

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[26] Systems with multiple platform terminal stations could be regarded as a sub-set of off-line stations. The Mexico City Metro and PATH (New York) are examples of such arrangements. Not coincidentally, these two systems achieve respectively the highest passenger throughput and the closest regular headway on the continent — for two-track rail transit systems.

[27] Operating margins are intended to accommodate irregularities in train control separation and dwell times. Off-line stations remove the need to allow for dwell time variations.

10. REFERENCES

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11. EXAMPLE PROBLEMS

1. High Capacity Heavy Rail
2. Heavy Rail Line with Junction
3. Heavy Rail with Long Dwell
4. Light Rail with Single-Track Section
5. Commuter Rail with Limited Train Paths
6. Automated Guideway Transit with Short Trains
7. Automated Guideway Transit with Off-Line Stations

Example Problem 1

High capacity heavy rail.

The Situation A transit agency is planning to build a heavy rail transit line and wants to determine the minimum train separation possible with a fixed block cab control signal system, and with a variable safety distance moving block signaling system.

The Question

1. What is the minimum train separation (ignoring station dwell time and operating margin effects) with each type of signaling system?

2. What is the minimum headway with typical dwells and operating margins?

3. What is the resultant maximum capacity for a new system with higher quality loading standards?

The Facts

The agency is planning to use trains consisting of a maximum of eight 24.5 m cars. Trains will operate at a maximum of 100 km/h (27.8 m/s) and will be travelling at 52 km/h (14.4 m/s) when entering stations if the cab control system is chosen, and at 55 km/h (15.3 m/s) if a moving block system is selected.[28] The distance from the front of a stopped train to the station exit block is 10 meters. Assume that there are no grades into or out of stations and that no civil speed restrictions limit approach speeds to sub-optimal levels.

Solution required for two signaling systems.

Outline of Solution

1. To answer this question, two equations must be used, one for each signaling system type. Equation 3-4 and Equation 3-6 may be found in Chapter 6. Note that the equations provide allowances for grades and line voltage effects that have been removed as they are not required to answer this question. The values for all variables are summarized as follows:

Value	**Term**	**Description**
calculated	$T(s)$	train control separation in seconds
200 meters	L	length of the longest train
10 meters	D	distance from front of stopped train to start of station exit block in meters
14.4 m/s (cab cont) 15.3 m/s (m block)	v_a	station approach speed in m/s
27.8 m/s	v_{max}	maximum line speed in m/s (27.8 m/s=100 km/h)
75%	K	braking safety factor—worst case service braking is K% of specified normal rate—typically 75%
1.2 (cab control) 1 (moving block)	B	separation safety factor—equivalent to number of braking distances (surrogate for blocks) that separate trains
3.0 seconds	t_{os}	time for overspeed governor to operate on automatic systems—driver sighting and reaction times on manual systems
0.5 seconds	t_{jl}	time lost to braking jerk limitation
1.5 seconds	t_{br}	brake system and operator reaction time
1.3 m/s^2	a_s	initial service acceleration rate
1.3 m/s^2	d_s	service deceleration rate
6.25 meters	P_e	positioning error—moving block only

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[28] Note that these station approach speeds are the optimal speeds to achieve minimum train separation. Solving for the optimal approach speed directly is not a simple task and is best done using a computer spreadsheet's solver or goal seek function to automate the iterative process that is required.

Steps

(a) with cab control signaling

The relevant equation is Equation 3-4, modified to remove dwell and operating margin:

$$T(s) = \sqrt{\frac{2(L+D)}{a_s}} + \frac{L}{v_a} + \left(\frac{100}{K} + B\right)\left(\frac{v_a}{2d_s}\right) + \frac{a_s t_{os}^2}{2v_a}\left(1 - \frac{v_a}{v_{\max}}\right) + t_{os} + t_{jl}$$

Substituting the known variables into the equation produces:

T(s) = 18.0+13.9+(2.53)(5.54)+(0.406)(0.507)+3.0+0.5+1.5

T(s) = 51.1 seconds

(b) with moving block signaling

$$T(s) = + \frac{L + P_e}{v_a} + \left(\frac{100}{K} + B\right)\left(\frac{v_a}{2d_s}\right)$$
$$+ \frac{a_s(1 - 0.1G_i)l_v^2 t_{os}^2}{20{,}000 v_a}\left(1 - \frac{v_a}{v_{\max}}\right) + t_{os} + t_{jl} + t_{br}$$

Substituting the known variables into the equation produces:

T(s) = 13.5+(2.33)(5.88)+(0.382)(0.550)+3.0+0.5+0

T(s) = 30.9 seconds

The net result is that the minimum train separation at stations (negating the effects of station dwells and an operating margin) would be 51.1 seconds with a cab control system, or 30.9 seconds with a variable safety distance moving block system and automatic train operation.

Determine dwell using simple method.

2. In Chapter 6, *Grade-Separated Systems Capacity,* four methods were shown for determining the controlling dwells. Method 2, *Using Existing Dwell Data* is not applicable to a new system. The simplest option is to use Method 1, which recommends a range of dwell values from 35 to 45 seconds. If there are no indications of any single very high volume stations (where the more complicated dwell calculations should be used) then a median value of 40 seconds can be selected.

Determine operating margin.

In Chapter 5, *Operating Issues,* it was suggested that the more operating margin that can be incorporated in the headway the better; with 20 to 25 seconds as the best guide. Here, 25 seconds is selected to provide better reliability. The total of the controlling dwell at the busiest station and the operating margin is then 65 seconds. Adding this to the minimum train separation times, calculated above, results in minimum headways of 116.1 and 97.4 seconds respectively. These should be rounded up to an integral number of trains per hour, that is, 120 seconds—30 trains per hour, and 100 seconds—36 trains per hour.

3. Exhibit 3-25 indicates the lower level of heavy-rail car loading at 7 passengers per linear meter of train length, inclusive of diversity allowances. At this more conservative loading, the specified train of eight 24.5-meter-long cars can carry 8 x 7 x 24.5 = 1,372 passengers. Multiplying this figure by the number of trains per hour provides passengers per peak hour direction per track of 41,160 ppphd and 49,360 ppphd respectively. Reflecting the approximations used in this determination the results should be rounded down to the nearest 1,000—41,000 and 49,000. If a lower ratio of standing passengers is desired, these maximum calculated capacities can be down-rated further by 20-30%.

Example Problem 2

Heavy rail line with junction.

The Situation The transit agency from Example 1 has decided to use a variable safety distance moving block signaling system. The agency would now like to know if it can economize on construction by building a flat junction at a point where two of its lines diverge. The agency's long-term plan is to run a two-minute headway through the junction.

The Question Can a flat junction on this proposed system support a two minute headway or must a flying junction be constructed?

Attempt to save money using flat junction.

The Facts
Many of the variables are the same as those used in the previous example. In addition, the agency plans to build its tracks 5 m apart and use #10 switches, with a throw-to-lock time of 6 seconds, at main line junctions. To make operations through a flat junction reliable, the agency plans to increase the operating margin to 45 seconds, hence the headway increase from 100 to 120 seconds.

Outline of Solution
Solving this problem requires use of Equation 3-8 from Chapter 2.

Steps
Equation 3-8 is:

$$H(j) = H(l) + \sqrt{\frac{2(T+2CS)}{a_s}} + \frac{v_l}{a_s + d_s} + t_s + t_{om}$$

The variables used are summarized in the following table:

Value	Term	Description
calculated	$H(j)$	limiting headway at junction (seconds)
32.4 seconds	$H(l)$	line headway from Example 1(b)
200 m	T	train length (meters)
9.62	C	switch angle factor (9.62 for a #10 switch)
5 m	S	track separation (meters)
1.3 m/s^2	a_s	initial service acceleration rate (m/s^2)
1.3 m/s^2	d_s	service deceleration rate (m/s^2)
27.8 m/s	v_l	line speed in m/s (27.8 m/s=100 km/h)
6.0 seconds	t_s	switch throw and lock time (seconds)
45 seconds	t_{om}	operating margin (seconds)

Substituting the known variables into the equation produces:
$H(j) = 32.4+21.3+10.7+6.0+45$
$H(j) = 115.4$ seconds

Calculations concur with rule of thumb that junctions should be grade separated at headways below three minutes.

While the resulting value of *H(j)* would appear to support two-minute headways, it is only about four seconds less than the planned headway. Based on this narrow margin, it would be prudent to opt for a flying junction rather than risk service disruptions with a flat junction—even with the operating margin increased to 45 seconds. This is consistent with recommendations in Chapter 2 that junctions, where headways are below 3 minutes, should be grade-separated.

Example Problem 3

The Situation A busy heavy rail line operates through a major interchange station with long station dwell times.

Heavy rail with long dwell.

The Question What is the maximum passenger-carrying capacity through this station?

The Facts

- ✓ A generous loading standard means more passengers seated.
- ✓ Service is provided by 10-car trains with each car being 22.8 m long.
- ✓ The transit agency’s loading standard is 6 passengers per meter of car length.
- ✓ The dwell time at the controlling dwell station averages 30 seconds with a standard deviation of 21 seconds.
- ✓ There is a 1.5 percent downgrade into the station.
- ✓ The line is automated using moving block signaling.
- ✓ Train operators are responsible for closing the doors and initiating acceleration, this delay is incorporated into the dwell time.
- ✓ Assume that trains are evenly loaded over their length.

Outline of Solution

The solution consists of three key steps: (a) determining the train capacity, (b) determining the minimum train separation based on the signaling system and train length, and (c) incorporating the station dwell time and an operating margin. To determine the minimum headway, allowances for dwell time and an operating margin must be added to the minimum train separation time. The results of these steps can then be combined to produce the maximum capacity based on the parameters given.

(a) Determining the train capacity

This step is very straightforward and is based on the number of cars in each train, the length of each car, and the number of passenger spaces per unit of car length.

(10 cars/train)(22.8 m/car)(6 passengers/m) = 1,368 passengers/train

(b) Determining the minimum train separation

This step requires use of Equation 3-6. Since consideration of station dwell times and the operating margin are deferred to the next step, they are not included in the equation below.

$$H(s) = +\frac{L+P_e}{v_a} + \left(\frac{100}{K} + B\right)\left(\frac{v_a}{2d_s(1+0.1G)}\right) + \left(\frac{a_s(1-0.1G_i)t_{os}^2}{2v_a}\right)\left(1-\frac{v_a}{v_{\max}}\right) + t_{os} + t_{jl} + t_{br}$$

where:

H(s) = minimum train separation in seconds

L = length of the longest train in meters

Pe = positioning error (default: 6.25 m)

v_a = station approach speed in m/s (55 km/h = 15.3 m/s)

K = braking safety factor—worst case service braking is K% of specified normal rate (default 75%)

B = separation safety factor—equivalent to number of braking distances (surrogate for blocks) that separate trains (default: 1)

v_{max} = maximum line speed in m/s (80 km/h = 22.2 m/s)

a_s = initial service acceleration rate in m/s^2 (default: 1.3 m/s^2)

d_s = service deceleration rate in m/s^2 (default: 1.3 m/s^2)

G = grade into the station (-1.5%)

T_s = time for overspeed governor to operate (default: 3.0 seconds)

t_{br} = braking reaction time (0 for modern air brake equipment)

t_{jl} = jerk limiting time (0.5s)

Substituting the variables in the equation produces:

$$H(s) = +\frac{228+6.25}{15.3} + \left(\frac{100}{75}+1\right)\left(\frac{15.3}{2(1.3)(1+0.1(-1.5))}\right) + \left(\frac{1.3(1-0.1(-1.5))(3)^{2}}{2(15.3)}\right)\left(1-\frac{15.3}{22.2}\right) + 3 + 0.5 + 0$$

H(s) = 15.3+(2.33)(6.92)+(0.440)(0.311)+3+0.5+0
H(s) = 35.1 seconds

(c) Incorporating station dwells and an operating margin
Controlling dwell is average dwell time plus twice the dwell time standard deviation. To determine the headway that can be operated under the conditions given, station dwell times and an operating margin must be incorporated. The line headway is controlled by a controlling dwell. Chapter 4 gives a number of methods of estimating the controlling dwell time from dwell time data. The approach used here estimates the controlling dwell by taking the average dwell time at the controlling dwell station and adding twice the dwell time standard deviation. This method produces a result that also incorporates an operating margin to allow for minor irregularities of operation.

Controlling dwell (including operating margin)	=	avg. dwell time	+	2 (dwell time standard deviation)
	=	30 sec	+	2 (21 sec)
	=	72 sec		

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

Combining this result with the minimum train separation previously arrived at produces a station headway of 107.1 seconds, which should then be rounded off to 112.5 seconds to provide an integral number of 32 trains per hour.

Example Problem 4

Maximum light rail frequency with a long single-track section.

The Situation A light rail line operates with a single-track section.

The Question What is the maximum possible service frequency?

The Facts

- ✓ Service is provided by three- car trains, each car 28m long.
- ✓ Initial acceleration is 1.0 m/s^2.
- ✓ The single track section is 1250 m long with one intermediate stop.
- ✓ The section is on a road with a speed limit of 50 km/h.

Comments

- ✓ It is assumed that there are no other longer single-track sections on the line nor more restrictive limitations imposed by any signaled sections of the line or by any signalized intersections.

Outline of Solution

The maximum possible service frequency is twice the travel time through the single-track section, plus an allowance for operational irregularities.

Steps

Calculate the travel time over the single-track section from Equation 3-17:

A self-guiding spreadsheet with this equation and instructions may be available on the American Public Transit Association's TCRP dissemination web site at http://www.apta.com.

$$t_{st} = SM\left(\frac{\left(N_s + 1\right)}{2}\left(\frac{3v_{\max}}{d_s} + t_{jl} + t_{br}\right) + \frac{L_{st} + L}{v_{\max}}\right) + N_s t_d + t_{om}$$

where:

t_{st} = time to cover single track section (s);
L_{st} = length of single track section (1250 m);
L = train length (84 m);
N_s = number of stations on single track section (1);
t_d = station dwell time (20 s);
v_{max} = maximum speed reached (50 km/h = 13.9 m/s);
d_s = deceleration rate (1.3 m/s^2),
t_{jl} = jerk limiting time (0.5 s);
t_{br} = operator and braking system reaction time (1.5 s);
SM = speed margin (constant, 1.1);
t_{om} = operating margin (20 s).

A 7½- minute headway is often expressed in transit timetables as service every 7-8 minutes.

The resultant time to cover the single track section is 183.1 seconds. The minimum headway on a single-track section is twice this time—366.2 seconds, plus approximately six seconds for the switch to throw. The total should be rounded up from 6 minutes 12 seconds to the nearest even hourly headway of 7½ minutes. If the light rail line has significant on-street operating segments it is unlikely that service can be maintained with sufficient regularity that trains will not be held up at the entrance to the single track section—waiting for the opposing train to clear. In this case it is prudent to increase the minimum headway to the next even interval—trains every 10 minutes.

Single track working in emergencies.

In the event of track maintenance or an emergency such as a traffic accident, failed light rail train or derailment, crossovers are usually provided to permit single track working around the obstruction. For long-term obstructions—such as a track renewal program—temporary crossovers, called *shoo flys*, can be used. Where there is a signaling system this is only possible if the signaling system is equipped for two-way operation on either track or by reverted to a slower manual, line-of-sight operation. Such emergency operation is then limited to a frequency as calculated by Equation 3-17 and line capacity is reduced.

As an example, if normal service is a train every 5 minutes, and a 1250-m section of single track is used to pass an obstruction, service will be limited to 7½ minutes. Nominal capacity will be reduced from 12 to 8 trains per hour or by one third. This reduction is sufficiently small that it may be accommodated temporarily by accepting higher levels of crowding. Passengers are generally willing to accept this in emergency conditions.

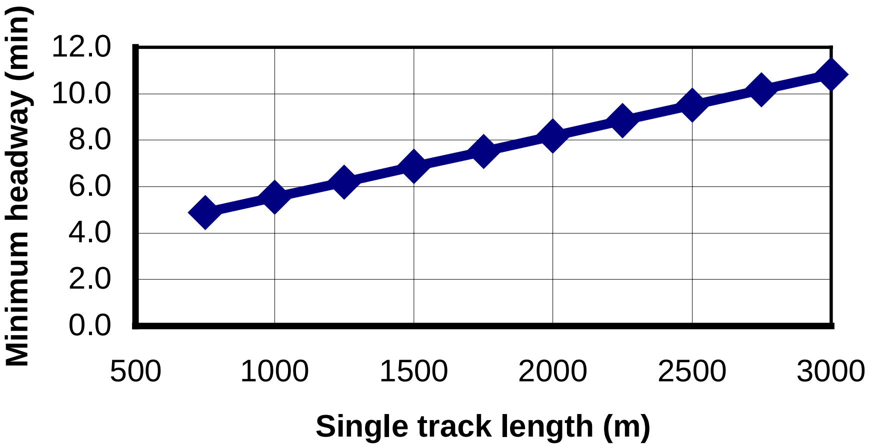
Capacity reduction with single track working.

Longer single-track sections will reduce capacity further. This loss may be made up where operational policies and signaling systems permit, by platooning cars over the single-track section. Two of three trains can follow each other closely under line-of-sight operating practice at lower speeds. Full capacity may be restored but additional trains and drivers will be required to compensate for the slower speeds and waiting time while trains accumulate to form a platoon.

Wrong-side or wrong-way working over line sections with grade crossings on on-street track can be confusing to motorists and pedestrians and can be hazardous. As a result many light rail operators prohibit such operations except where there are no alternatives, i.e., in tunnels or subways. Instead their emergency planning calls for a bus bridge around any blockage that is expected to take a significant time to clear. All North America light rail operators also have or are affiliated with major bus operations and can expect to obtain buses and drivers for such emergency use on short notice — usually by scavenging buses from nearby higher-frequency routes.

The following chart shows the minimum headway for varying single-track lengths using the parameters of the above example—3 car trains, one passenger stop, and 50 km/h maximum speed. The minimum single-track headway is relatively insensitive to train length, more sensitive to maximum operating speed and significantly sensitive to the number of stations or stops—each additional stop will add 1½ to 2 minutes.

Changes in minimum single-track headway with length, not including rounding up to clock headway or adding an allowance for schedule irregularity.



Example Problem 5

Commuter rail with limited train paths.

The Situation An existing commuter rail agency would like to expand its operations to a new route that is owned by a freight railroad.

The Question Based on the constraints given below, can the commuter rail agency provide service on the new line with its current single-level car fleet, or must it order new double level cars for the line?

The Facts

- ✓ The freight railroad will only allow six commuter rail trains per hour to use its line.
- ✓ Physical constraints mean that station platforms on the new line can be no more than eight cars in length.
- ✓ The commuter rail agency currently uses single-level cars that have 120 seats but is considering the purchase of two-level cars with 180 seats, although it would prefer to purchase more single-level cars to maintain a standard fleet.
- ✓ The agency has a policy of planning service based on cars being at 90% of seated capacity.
- ✓ The agency would like to be able to accommodate a flow of 6,000 passengers per hour in the peak hour.
- ✓ Train scheduling can be adjusted to meet the peak 15-minute demand, provided no more than six trains are operated per hour.
- ✓ Trains are limited by railroad contract but can be spaced through the peak hour to best match demand.

Outline of Solution

To determine which car type, if either, can satisfy the agency's capacity needs, the hourly capacity of the line using each car type must be determined. This procedure is simplified in this example by the agency's ability to schedule trains to meet the peak 15-minute demand, avoiding the need to consider the temporal distribution of travel. The capacity that can be provided with each car type should be considered independently.

hourly capacity = (passengers per car) x (cars per train) x (trains per hour)

(a) Single-level cars

The effective capacity per car is 90% of 120 or 108 passengers. An eight car train of single-level cars could thus carry 864 passengers. With six trains per hour, the capacity is 5,184 passengers per hour.

(b) Two-level cars

The effective capacity per car is 90% of 180 or 162 passengers. An eight-car train of two-level cars could thus carry 1,296 passengers. With six trains per hour, the capacity is 7,776 passengers per hour.

Double-deck cars needed to handle capacity.

Since eight-car trains of single-level cars are unable to handle the predicted demand, it appears that the agency should plan on ordering two-level cars for use on this route. The calculation above shows that the two-level cars can accommodate the projected demand with some room for ridership growth.

Longer trains that overhang platform are a poor compromise.

The only alternative to purchasing the two-level cars would be to operate longer trains and assign passengers to cars according to their destination station since not all cars would be adjacent to a platform at all stations. This would only work if the platforms at major terminal stations could accommodate all the cars of each train. As this complicates train operations and would likely create passenger confusion, the option of purchasing two-level cars is preferable.

Example Problem 6

Automated guideway transit with short trains.

The Situation A feeder line is planned from a new suburban office development to an existing heavy rail station.

The Question Based on use the of advanced train control systems, what is the maximum capacity of this line?

The Facts

The developer wants to incorporate the automated guideway transit stations in an elevator lobby on the second floor of each building, which limits station length to 25 meters. Although the line is short, the developer wants to offer a high-quality service in which half of all passengers are seated. Most AGT systems are proprietary and the manufacturer would provide capacity capabilities. In this case, the developer does not wish to approach a manufacturer at this stage.

In practice trains cannot run as close as suggested by theory.

Outline of Solution

Exhibit 3-58 shows that an AGT moving-block train control system can provide a minimum train separation of 13.4 seconds with 25-meter-long trains. Adding the recommended typical dwell time of 40 seconds and the recommended operating margin of 25 seconds would result in a minimum headway of 78.4 seconds. This should be rounded up to 80 seconds. Chapter 9 states that “headways shorter than 90 seconds are possible but may limit dwell times and constrain the operating margin. They should be considered with caution unless off-line stations are adopted.” As the developer has indicated a relatively relaxed loading level it is realistic to expect dwells to be lower than normal and hence the 80-second headway can be accepted as practical. This equates to 3600/80 or 45 trains an hour.

The 25-meter-long platform can hold two 12-m cars, a common AGT size and comparable to a city bus. As no specific car design can be assumed it is reasonable that wide double doors will take up 4 meters of each car side leaving 8 meters for seating. At a pitch of 900mm this allows 8 rows of seats. The seats will be 2+2 with five abreast at each end (there are no driving cabs on an automated AGT). Such a car can thus accommodate 8 x 4 +2 for a total of 34 seats. The desired maximum of half the passengers standing brings the total car passenger capacity to 68. Note that an AGT car of this size, on a short distance line, would normally be rated for 100 passengers, most of whom would stand.

The resultant maximum capacity at the preferred loading level is 3,060 passengers per peak hour direction. As always with such calculations where there are approximations, the number should be rounded down, in this case to 3,000 ppphd.

Example Problem 7

The Situation The above developer is expanding his suburban office development to include a major shopping complex and recreation facility with an ice hockey arena.

Automated guideway transit with off-line stations.

The Question How can the automated guideway transit be expanded to handle this load?

The Facts

- ✓ Ridership estimates are that the system will handle 25% of the arena's maximum capacity of 24,000 people, plus an estimated demand of 1,200 passengers per hour from the shopping complex.
- ✓ Two adjacent stations serve the sports arena while the shopping center has three stations.
- ✓ The developer has contracted with the office building tenants to run trains at least every six minutes until midnight each day, including weekends and holidays.

Outline of Solution

To handle 24,000/4 + 1,200 = 7,200 passengers per hour, one solution would be to operate longer trains with higher occupancy and to omit stops in the office buildings with their short stations. The 45 train per hour capacity is no longer practical as heavy loads at the two sports arena stations will extend dwells and longer trains will increase the minimum train separation. The capacity is downrated to 40 trains an hour—90-second headways. Ten of these trains, one every 6 minutes, will remain short to serve the office complex. These ten trains have an estimated capacity of 150 passengers each with a higher proportion of sports fans standing. The remaining 30 trains must carry 5,700 passengers an hour. (7,200 - 10 x 150). This is 5,700/30 or 190 passengers per train. Because of the high number of seats, capacity only averages 75 passengers and three-car trains would be required to meet the demand.

Longer trains could skip stations with too-short platforms.

In Chapter 9 it was stated that off line stations permit headways that are partly independent of station dwell time with throughput that of the control system minimum train separation, plus an allowance for switch operation, lock and clearance and a reduced operating margin. Exhibit 3-58 shows that a moving-block signaling system with 25-meter-long trains has a minimum train separation of 13.4 seconds. Allowing an operating allowance for merging trains of 45 seconds and rounding up should permit headways down to 60 seconds — 60 trains per hour. In this case the demand of 7,200 passengers per hour with 150 passengers per train can be met by 48 trains —well within the 60-train maximum.

Off-line stations would permit trains to operate directly from each arena station to the heavy rail station. However, economics enter the picture. It is unlikely that the developer would be willing to build more expensive off-line stations and purchase addition rolling stock for a sports arena demand that only occurs a few days a year. It is more likely that the system would be designed for maximum office and shopping complex demands. When a sports event takes place the automated guideway transit system would be filled to capacity and the overload handled by transit authority buses—of which there is a surplus at the off-peak hours typical of sport event starts and finishes.

It is not always economic to meet occasional peak demands with rail transit.

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APPENDIX A. EXHIBITS IN U.S. CUSTOMARY UNITS

Exhibit 3-5a
Station Headway for Lines at Capacity

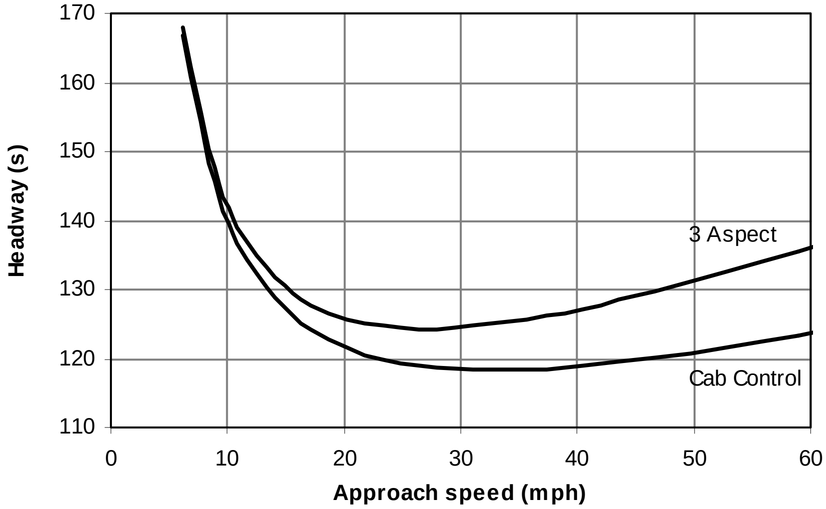


Exhibit 3-6a
Speed Limits on Curves and Switches

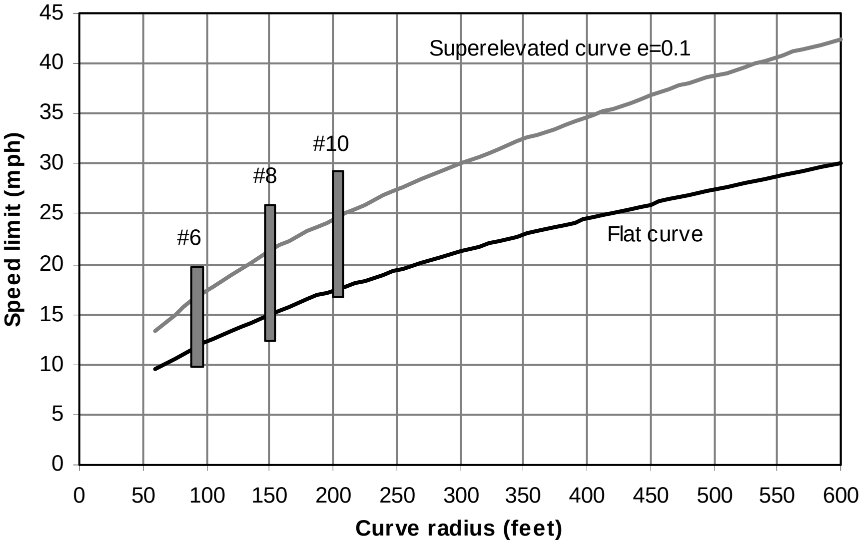


Exhibit 3-7a
Distance-Speed Chart

Exhibit 3-10a
Moving Block Headways with 45-Second Dwell and 20-Second Operating Margin
Compared with Conventional Fixed Block Systems

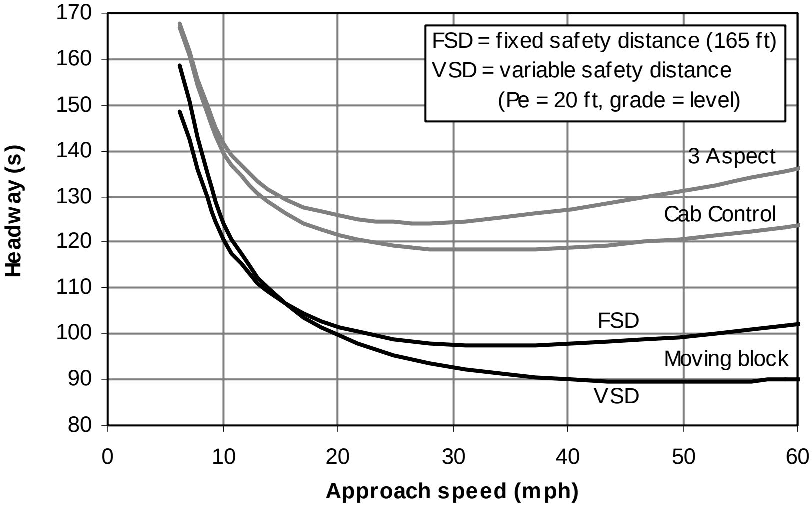


Exhibit 3-24a
Linear Passenger Loading—Articulated LRVs

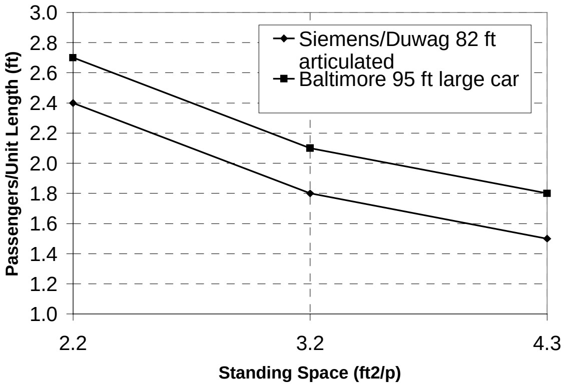


Exhibit 3-25a
Linear Passenger Loading—Heavy Rail Cars

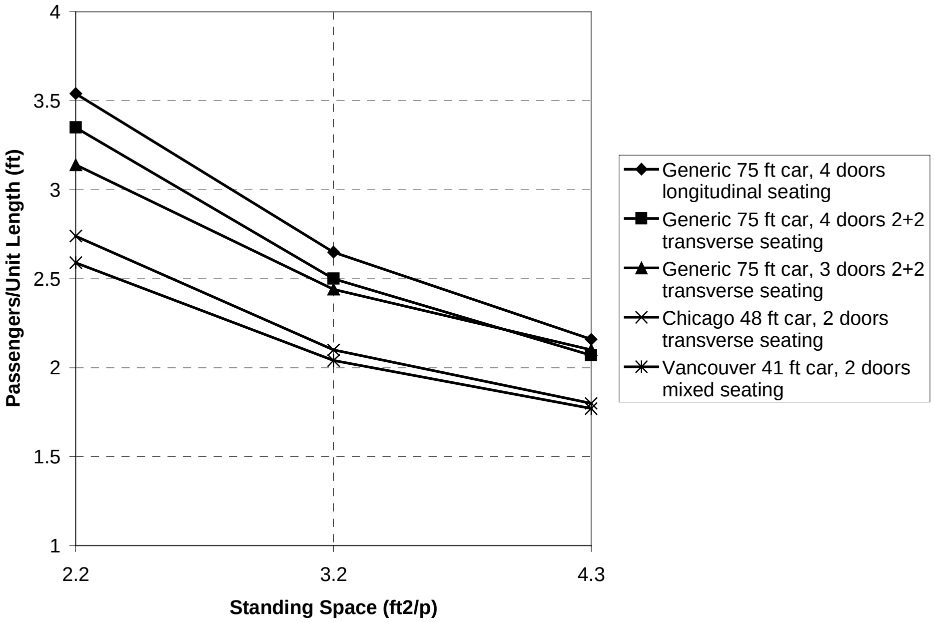


Exhibit 3-26a
Summary of linear passenger loading (p/ft)

	Average	**Median**	**Standard Deviation**
All Systems	2.0	1.8	0.6
Commuter Rail	1.5	1.4	0.2
Heavy Rail	2.1	1.9	0.6
Heavy Rail less New York	1.7	1.7	0.5
NYCTA alone	2.4	2.4	0.5

Exhibit 3-45a
Distance—Speed Braking Into a Station

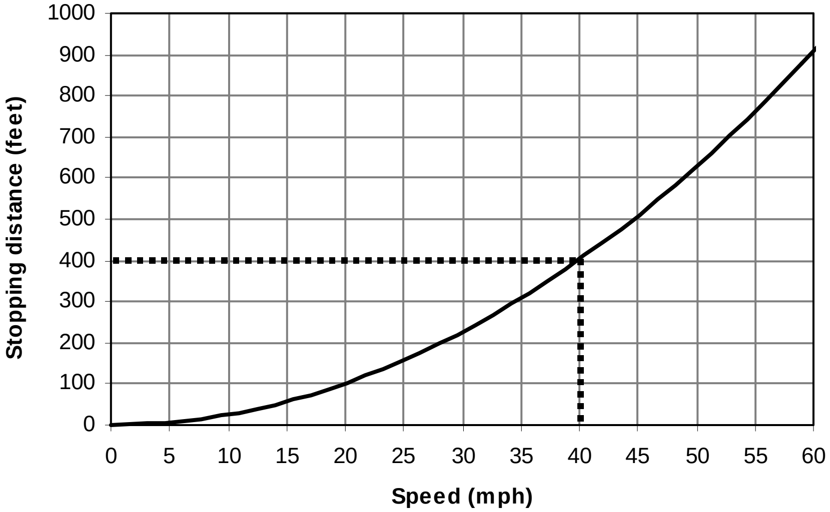


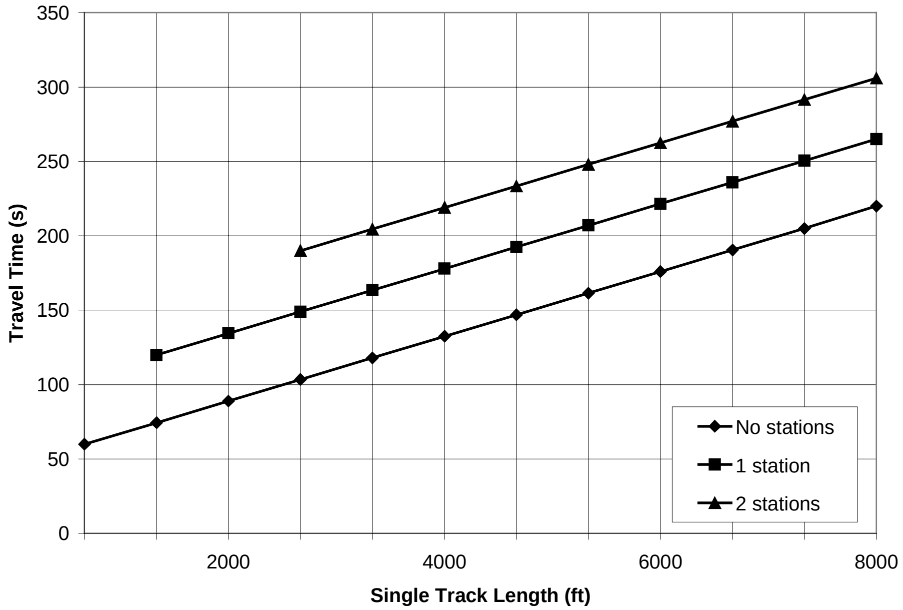
Exhibit 3-47a
Passengers per Unit Train Length, Major North American Trunks, 15-Minute Peak

System & City	Trunk Name	Mode	Length (ft)	Seats	Avg. Pass/Car	Pass./ ft
NYCTA (New York)	53rd Street Tunnel	HR	*see note*	50/70	197/227	3.2
NYCTA (New York)	Lexington Ave. Local	HR	51.0	44	144	2.8
NYCTA (New York)	Steinway Tunnel	HR	51.0	44	144	2.8
NYCTA (New York)	Broadway Local	HR	51.0	44	135	2.7
TTC (Toronto)	Yonge Subway	HR	74.5	80	197	2.7
NYCTA (New York)	Lexington Ave. Ex.	HR	51.0	44	123	2.4
NYCTA (New York)	Joralemon St. Tun.	HR	51.0	44	122	2.4
NYCTA (New York)	Broadway Express	HR	51.0	44	119	2.3
NYCTA (New York)	Manhattan Bridge	HR	74.7	74	162	2.2
NYCTA (New York)	Clark Street	HR	51.0	44	102	2.0
CTS (Calgary)	South Line	LR	79.6	64	153	1.9
GO Transit (Toronto)	Lakeshore East	CR	85.0	162	152	1.8
BCT (Vancouver)	SkyTrain	HR	40.7	36	73	1.8
PATH (New York)	World Trade Center	HR	51.0	31	92	1.8
PATH (New York)	33rd St.	HR	51.0	31	88	1.7
CTA (Chicago)	Dearborn Subway	HR	48.0	46	82	1.7
NYCTA (New York)	60th Street Tunnel	HR	74.7	74	126	1.7
NYCTA (New York)	Rutgers St. Tunnel	HR	74.7	74	123	1.6
CTS (Calgary)	Northeast Line	LR	79.6	64	125	1.6
CTA (Chicago)	State Subway	HR	48.0	46	75	1.6
CalTrain (San Fran.)	CalTrain	CR	85.0	146	117	1.4
LIRR (New York)	Jamaica - Penn Sta.	CR	85.0	120	117	1.4
Metra (Chicago)	Metra Electric	CR	85.0	156	113	1.3
MARTA (Atlanta)	North/South	HR	75.0	68	82	1.1
MARTA (Atlanta)	East/West	HR	75.0	68	77	1.0

HR: heavy rail, LR: light rail, CR: commuter rail

NOTE: Service through NYCT’s 53rd St. Tunnel is provided by line E, operating 60.2-ft cars, and line F, operating 74.7-ft cars. Seats and car loadings are presented as “E/F”. The number of passengers per foot given is for the combined lines; individually this value is 3.3 for the E and 3.0 for the F.

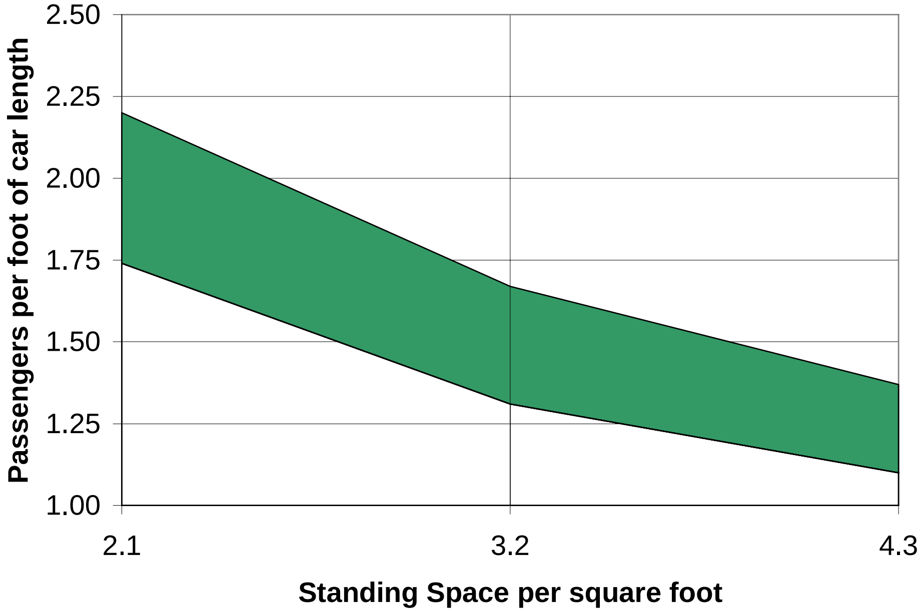
Exhibit 3-51a
Light Rail Travel Time Over Single Track Section



NOTE: Assumes speed limit of 35 mph, train length of 185 ft, 20-second dwell time, and other data as per Exhibit 3-50. *The recommended closest headway is twice this time plus an operating allowance.*

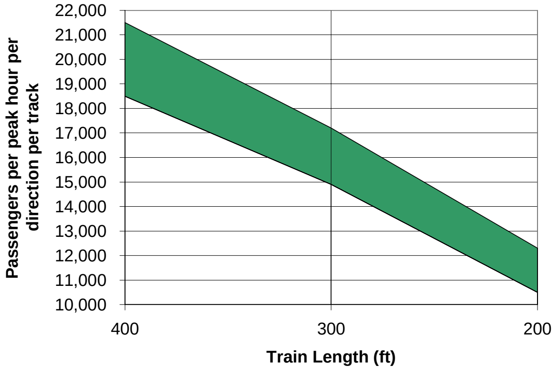
To estimate best headway multiply single track time by two and add an operating margin.

Exhibit 3-55a
Recommended Loading Level Range for Light Rail Vehicles in Simple Capacity Calculation



NOTE: Loading diversity factor ranges from 0.7 (lower bound) to 0.9 (upper bound).

Exhibit 3-56a
Light Rail Capacity on Segregated Right-of-Way With Maximum Cab-Control Signaling



NOTE: Throughput based on a range of dwell times plus an operating margin of 45-70 seconds.

Exhibit 3-60a
Suggested AGT Separation Calculation Default Values

Term	Unit	Description	Heavy Rail	AGT
P_e	ft	positioning error	20	20
L	ft	length of the longest train	660	165
D	ft	distance from front of train to exit block	35	0
K	%	% service braking rate	75	75
B		train detection uncertainty constant—fixed block	2.4	4
B		train detection uncertainty constant—moving block	1	1
t_{os}	s	time for overspeed governor to operate	3	1
t_{jl}	s	time lost to braking jerk limitation	0.5	0.5
a_s	ft/s^2	service acceleration rate	4.3	2.0
d_s	ft/s^2	service deceleration rate	4.3	3.3
t_{br}	s	brake system reaction time	1.5	0.5
v_{max}	mph	maximum line velocity	60	50
mb_{sd}	ft	moving block safety distance	165	80