PART 5
RAIL TRANSIT CAPACITY

CONTENTS

LIST OF EXHIBITS

CHAPTER 1. RAIL CAPACITY FUNDAMENTALS

OVERVIEW

Rail transit systems encompass a variety of technologies, vehicle sizes, and applications. Despite these variations, a few basic factors—in particular, dwell time and the train signal control system—typically control the number of trains that can be operated along a section of a line during an hour. The number of cars per train and the diversity of passenger demand control how many people those trains can carry.

Organization of Part 5.

Part 5 of the *Transit Capacity and Quality of Service Manual* (TCQSM) presents methods for calculating the capacity of a variety of rail modes and right-of-way types. The majority of the material in this part has been condensed from TCRP Report 13, "Rail Transit Capacity."[R15] The accompanying CD-ROM includes spreadsheets originally developed by TCRP Project A-8 for calculating grade-separated and single-track rail capacity using the procedures described in Part 5.

- *Chapter 1* introduces the fundamental concepts and factors associated with rail capacity.
- Chapter 2 describes the basic operation of train control and signaling systems and their relationship to the minimum train headway.
- Chapter 3 examines the factors that influence station dwell time and presents methods for estimating dwell time.
- Chapter 4 discusses passenger space requirements and methods for estimating passenger design loads based on the length of a rail car.
- Chapter 5 presents operating and system design issues that influence capacity.
- Chapter 6 provides planning-level capacities for rail modes, based on typical U.S. and Canadian operations.
- Chapter 7 develops a procedure for calculating the capacity of grade-separated rail systems; this procedure forms the basis for many of the procedures presented in subsequent chapters.
- Chapter 8 gives procedures for calculating the capacity of sections of light rail lines that are not grade-separated.
- Chapter 9 identifies the factors that influence the capacity of commuter rail lines that either use diesel locomotives or are not grade-separated.
- Chapter 10 adapts the basic grade-separated capacity procedure for use with automated guideway transit systems.
- Chapter 11 covers the capacity of surface and aerial ropeway modes.
- Chapter 12 is a list of references used in Part 5.
- Chapter 13 provides example problems demonstrating the procedures covered in Part 5.
- Appendix A provides substitute exhibits in metric units for Part 5 exhibits that use U.S. customary units only.
- Appendix B lists characteristics of U.S. and Canadian rail transit routes.

Exhibits that also appear in Appendix A are indicated by a margin note like this.

LINE CAPACITY

Line capacity and vehicle capacity, both relating to the number of trains that can be operated per hour, are equivalent terms for rail.

Ideally, station dwell time and the minimum train separation produced by the signaling system will control line capacity, but other factors may need to be considered.

Line capacity is the maximum number of trains that can be operated over a section of track in a given period of time, typically 1 hour. Ideally, the combination of the train signaling system being used and the station with the longest dwell time will control the line capacity. However, under less-than-ideal conditions, any of a number of other factors may control line capacity. These include

- Signaling systems designed for the minimum planned train headway, rather than maximum capacity,
- Speed restrictions due to sharp curves or steep downgrades on the approach to the station with the longest dwell time,
- Line crossings and merges, particularly at-grade track junctions,
- Time required to turn back a train at a terminal station, and
- Mode-specific issues, such as light rail trains operating in mixed traffic or commuter rail trains sharing tracks with freight trains.

Power supply limitations can also constrain line capacity.

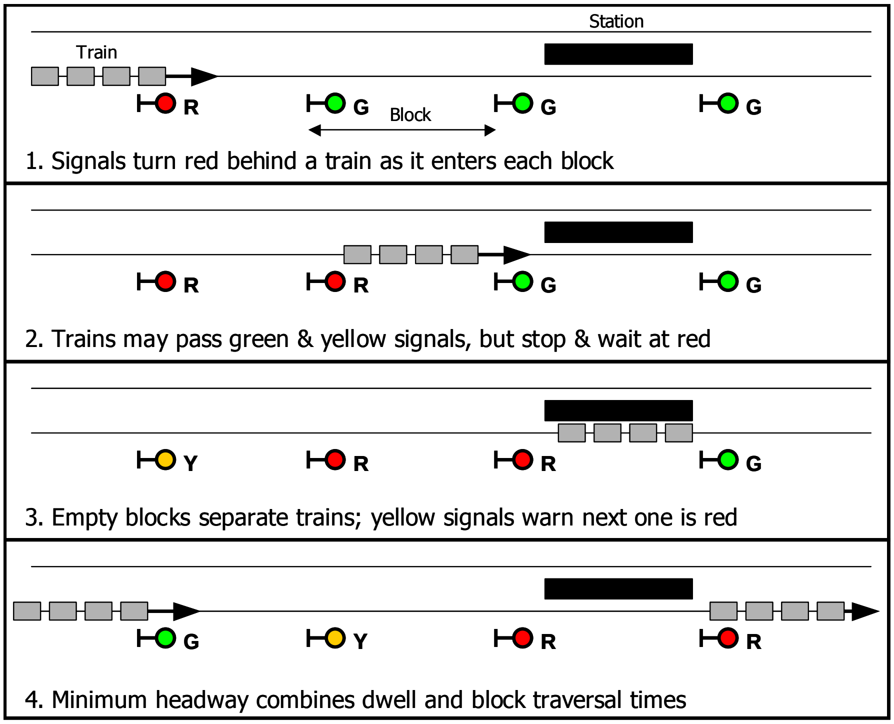
The factor providing the lowest capacity—the weakest link—will constrain the capacity of a given section of a line.

Train Control and Signaling

Streetcars and portions of some light rail systems that operate at low speeds do not use train signals. Multiple trains may be allowed to berth at stations where space permits.

Most major rail modes rely on signaling systems to, among other things, maintain safe separation between trains. The minimum distance between trains must be long enough for a train to come to a complete stop, with a suitable safety margin between it and the train ahead. All urban rail transit train control systems are based on dividing the track into sections known as *blocks* and ensuring that trains are separated by a suitable and safe number of blocks. The longer the time required for a train to traverse (pass through) a block—whether due to long block lengths, low train speeds, or station dwell time—the longer the minimum headway between trains, and the lower the line capacity. Train control is discussed in detail in Chapter 2. Exhibit 5-1 illustrates the operation of a typical three-aspect (red/yellow/green) signal system.

Exhibit 5-1
Basic Train Signal Operation



Dwell Time

Dwell time is frequently the dominant factor in determining the minimum train headway and, thus, the line capacity. The three main components of dwell time are

- Door open and close time, and time waiting to depart once the doors close,
- Passenger flow time, and
- Time the doors remain open after passenger flow ceases.

Of these three factors, passenger flow time is the largest and the hardest to control. It is dependent on passenger volumes at stations, the number of doors on a train, the door widths, the level of crowding inside the train and on the platform, and congestion between boarding and alighting passengers at the train door. The other two factors are, to a great degree, under an agency's control. Minimizing the time spent in a station without passenger flows occurring is important in maintaining reliable train operations, particularly when a line is operating near capacity. The calculation of dwell times is described in Chapter 3.

Dwell time at the station with the highest passenger volumes often will control line capacity.

Operating Margin

When a rail system is operating close to its capacity, small irregularities in service can lead to delays, as a train is not able to approach a station until the train ahead departs. These irregularities can be caused by variations in station dwell times, variations in train performance, and—on manually driven systems—variations between operators. To compensate for these variations, when creating a minimum headway, most rail systems add an operating margin to the combination of the signal system's minimum train separation time and the critical station dwell time. The operating margin is, in effect, the amount of time a train can run behind schedule without interfering with the following trains and, consequently, is an important component of line capacity. Operating margins are discussed in Chapter 5.

An operating margin is "slack time" built into the minimum headway to accommodate small irregularities in service. If a train is late by more than the operating margin, following trains will be delayed.

Turnbacks

A typical terminal station will have a center (island) platform, allowing passengers to board trains on either side. A number of designs are possible, but a common, lower-cost (but also potentially capacity-constraining) design is to locate a crossover in advance of the station. This crossover allows entering trains to be sent to either platform, and exiting trains to be sent to the correct departure track. When a line operates at short headways, the amount of time required to load and unload passengers, and for the operator to change ends, inspect the train, and check train integrity and braking will be longer than the headway between trains. As a result, a second train will arrive and occupy the other platform while the first train is still preparing to depart. A capacity constraint will result if the first train is unable to clear the crossover before a third train arrives to use the platform that the first train is vacating. Exhibit 5-2 shows this process.

Alternative terminal station designs are discussed in Chapter 2.

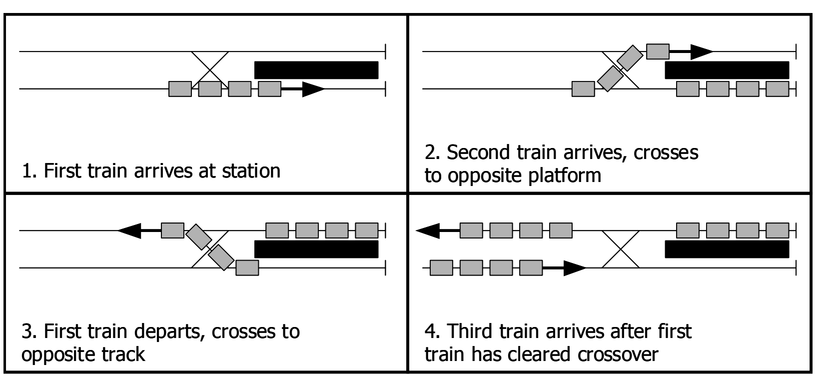


Exhibit 5-2
Turnback Operation with Crossover Located in Advance of Station

As described in Chapter 2, when turnbacks are correctly designed and operated, they should not control capacity on a new rail system. However, turnbacks can be a constraint on older systems, where physical constraints—particularly in subways—may have resulted in less-than-optimal designs, or when passenger demand has generated the need for more service than the system was originally designed for.

Junctions

Locations where lines merge, diverge, or cross at-grade can constrain capacity, or introduce the likelihood of interference, when scheduled headways approach 2 to 2.5 minutes. Two trains may need to use the space where the tracks cross, but only one train can occupy that space at a time. The minimum interval between trains on a given line at an at-grade ("flat") junction is a combination of

1. The time required for an opposing train to move through the junction,
2. The time required to move ("throw") and lock the switches,
3. The delay incurred in decelerating from and accelerating to line speed, and
4. The minimum headway imposed by the signaling system on the line.

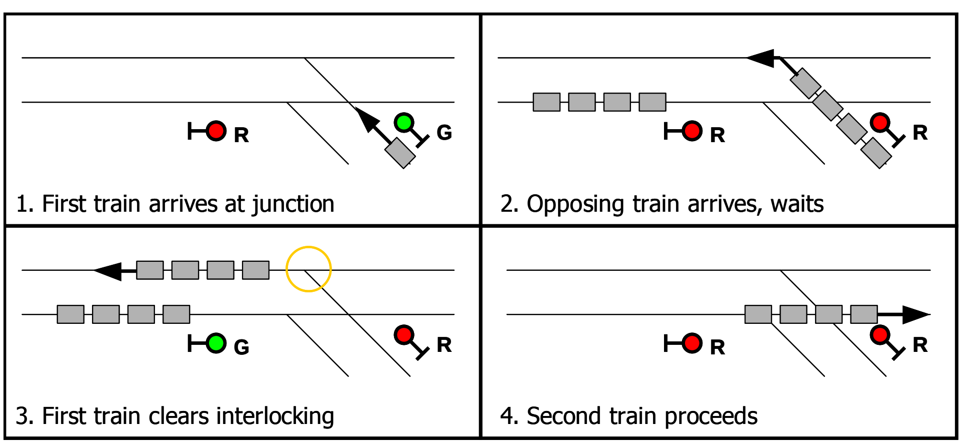
Conceptually, the process is similar to that used for calculating headway based on dwell time at a station, in that both headways are based on the minimum train separation on the lines plus the time a train is stopped. In this case, time stopped is spent waiting for another train at a junction rather than waiting to serve passengers.

It is not desirable for one train to have to wait for another. When more capacity is required, grade-separated ("flying") junctions are typically used. Exhibit 5-3 depicts the two types of junctions. Exhibit 5-4 illustrates the operation of a flat junction. Chapter 2 discusses junctions in more detail.

Exhibit 5-3
Types of Rail Junctions

(a) Flat (Pittsburgh) (b) Flying (Paris)

Exhibit 5-4
At-grade ("Flat") Junction Operation



Mode-Specific Issues

The capacity factors discussed thus far are applicable to most major rail modes, particularly heavy rail (rail rapid transit), and one of these factors will generally control line capacity. Sometimes, though, issues unique to a particular mode may need to be considered as well. Chapters 8 through 11 discuss the following issues:

- *Light Rail*—single-track operations, on-street operations (either in mixed traffic or in an exclusive right-of-way).
- *Commuter Rail*—mixed freight and passenger operations, limits on the number of trains imposed by the owner of the tracks being used, differences in locomotive power, single-track operations.
- *Automated Guideway Transit*—widely varying technology, potential for off-line stations that allow trains to bypass stations and other trains.
- *Ropeway*—line length, line speed, vehicle or carrier spacing.

PERSON CAPACITY

Person capacity defined.

Person capacity is the maximum number of people that can be carried in one direction over a section of track in a given period of time, typically 1 hour, under specified operating conditions without unreasonable delay, hazard, or restriction, and with reasonable certainty.

The definition of person capacity is less absolute than the definition of line capacity, as it depends on the number of trains operated, the length of those trains, passenger loading standards, and variations in passenger demand between trains and between individual cars of a given train.

The *theoretical capacity* is the number of cars per hour per direction, times the maximum design load of each car.

Person capacity accounts for variations in passenger arrivals and distribution, and is lower than the theoretical capacity.

This last factor, known as *loading diversity,* provides an important distinction between a line's theoretical capacity and a more realistic person capacity that can actually be achieved on a sustained basis. The theoretical capacity assumes that all the offered capacity can be used by passengers. In practice, this only occurs when a constant queue of passengers exists to fill all available seats and standing room—a situation that is undesirable in a transit operation, as it leads to crowded platforms and passenger delay. Transit passengers generally do not arrive at an even rate over the course of an hour, and generally do not distribute themselves evenly among the cars of a train. Accounting for loading diversity allows one to determine the number of people that can be accommodated during an hour without pass-ups occurring.

How many people *can* be carried vs. how many people *could* be carried.

Constraints on staff and equipment resources must also be considered. Line capacity considers how many trains *could* be operated, assuming no constraints on the supply of cars to form trains, nor any constraints on the number of operators available to drive those trains. Knowing, and designing for, the ultimate person capacity of a line is often important in long-term planning. However, it may be just as important to know in the short term how many trains *can* be operated and the person capacity of those trains, given existing resources.

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: (1) loading diversity within a car, (2) loading diversity among cars of a train, and (3) unevenness of passenger demand during the peak hour.

Loading diversity within a car.

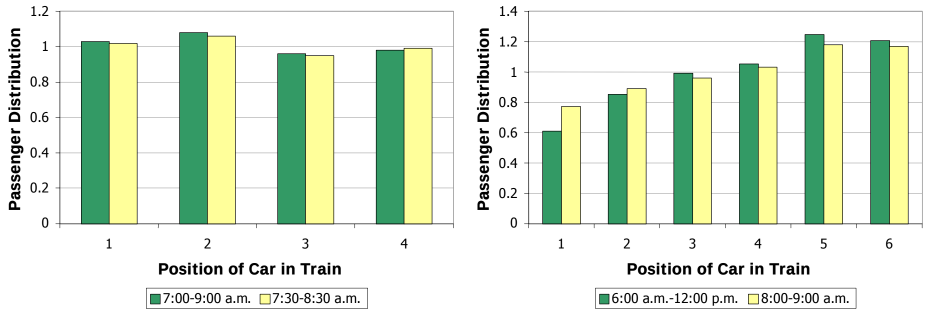
The first type of loading diversity is within a car. In individual cars, the highest standing densities occur around doorways while the lowest densities occur at the ends of the cars. Several European urban rail systems add doors, sometimes only single-stream, at the car ends to reduce this unevenness.

Loading diversity within a train.

A second type 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 the cars 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 5-5.

Exhibit 5-5
Average Peak Hour Passenger Distribution Between Cars of Trains[R15]



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

NOTE: 1.0 represents an individual car load equal to the average load of all cars in the train.
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 cars of a train in either the peak hour or the peak 2-hour period, both of which are within the range of +5% of an average (mean) load to -6%. However, the imbalance between cars on individual trains ranges from +61% to -33%. The average evenness of loading can be attributed to four factors: short trains, wide platforms, close headways, and dispersed entrance/exit locations among the system's stations.

Toronto's Yonge Street subway shows a more uneven average loading between cars. During the morning peak period, the rear of the train is consistently more heavily loaded. This pattern reflects the dominance of the major transfer station at Bloor Street, with the interchange occurring at the rear (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 morning 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 imbalance for cars on individual trains ranges from +156% to -89%.

Loading diversity within the peak hour.

The third and most important type of diversity is the unevenness of passenger demand over the peak hour. This aspect of diversity is measured by the *peak hour factor,* which is defined as:

Equation 5-1

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

where:
PHF = peak hour factor;
P_h = passenger volume during the peak hour (p); and
P_{15} = passenger volume during the peak 15 minutes (p).

The PHF ranges from 0.25 (all volume occurs during the peak 15 minutes) to 1.00 (volumes are even throughout the hour).

When 30-minute peak periods are used, P should represent 30-minute volumes, and $2P_{30}$ should be substituted for $4P_{15}$.

Passengers do not arrive evenly and uniformly on any rail transit system, as shown dramatically over the extended peak period in Exhibit 5-6 for Toronto's Yonge Street subway. This exhibit 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 peak 15 minutes.

Exhibit 5-7 shows an a.m. peak period for Vancouver's SkyTrain 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. onward.

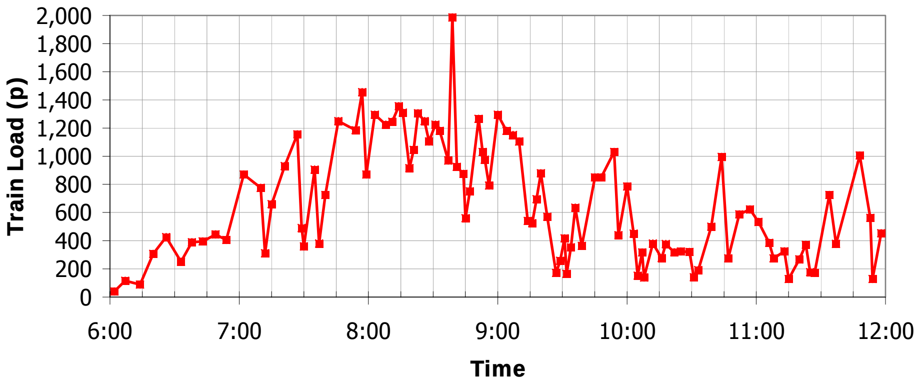


Exhibit 5-6
Individual A.M. Train Loads, Toronto Yonge Subway, Wellesley Southbound (Jan. 11, 1995)(R15)

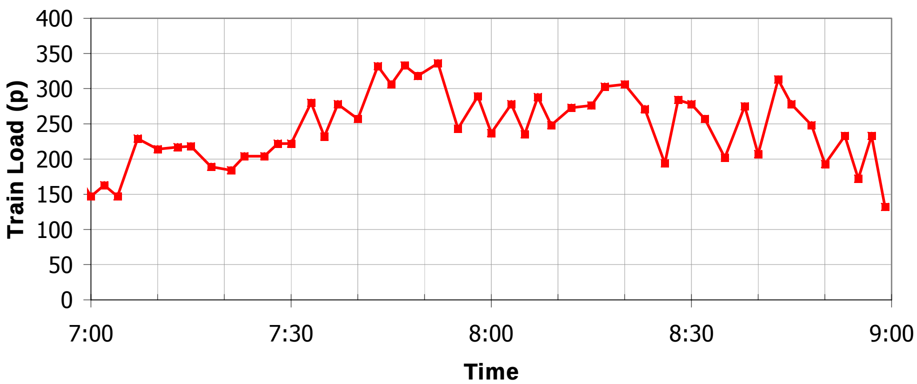


Exhibit 5-7
Individual A.M. Train Loads, Vancouver, SkyTrain Broadway Station Inbound (October 27, 1994)(R15)

Peak hour factors observed at many U.S. and Canadian rail systems are tabulated in Exhibit 5-8. Recommended values for the peak hour factor for specific modes are presented in the mode-specific chapters later in Part 5.

Number of Cars

The number of cars in a train is a major determinant of person capacity—the longer the train, the more people it can carry. However, there are limits to how many cars can be added to a train, set by the lengths of platforms, the supply of cars, and (for light rail) city block lengths.

Platform Lengths

Station platforms are designed for the longest train the system plans to operate. When platforms are located above or below grade, they are difficult to lengthen once constructed. In some instances, for example at New York's South Ferry subway station and at some older commuter rail stations, the platform is shorter than the train length, and passengers wishing to exit trains must do so from the front cars only. However, this kind of operation is not generally desirable and is not typical practice for new systems.

Exhibit 5-8
Observed Peak Hour Factors (1994-95)(R15)

System (City)	# of Routes	Peak Hour Factor
Commuter Rail		
AMT (Montréal)	2	0.71
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*	9	0.57
SCRRA (Los Angeles)*	5	0.44
SEPTA (Philadelphia)	7	0.57
VRE (Washington, D.C.)*	2	0.35
Light Rail		
CTS (Calgary)	2	0.62
RTD (Denver)	1	0.75
SEPTA (Philadelphia)	8	0.75
TriMet (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
STM (Montréal)	4	0.71
TTC (Toronto)	3	0.79

*Mainly diesel-hauled—not electric multiple unit.

Car Supply

Even when the platform design allows for longer trains, a shortage of cars may preclude operating longer trains. For example, the Washington, D.C., Metro platforms can accommodate up to eight-car trains, but the supply of cars has limited typical train lengths to four to six cars. This kind of constraint is typically financial—new rail cars averaged $1.2 to 2.5 million each in 2000-2001, depending on the type of car,(R4) and additional staff are required to maintain the additional cars.

Street Block Lengths

Street block lengths 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, Oregon, where unusually short street blocks of 200 ft (65 m) in the downtown area limit trains to two cars. The San Diego Trolley also faced this issue when it operated four-car trains on the East (Orange) Line for a time. Since three cars is the maximum that can be accommodated by the downtown city blocks, trains were split into two sections before entering downtown.

Sacramento is an exception to the street block length rule and can operate four-car trains in the peak hours. These long trains block one intersection when stopped. This situation was almost a necessity as the original extensive single-track nature of the Sacramento line (now being addressed by double-tracking) imposed a minimum headway of 15 minutes on the service. The capacity limitation of this headway restriction was therefore partially made up by the operation of relatively long trains.

Street block length is also an issue when another vehicle occupies the lane used by light rail trains. If a vehicle in the lane would cause the rear of the train to protrude into an intersection, then the train would need to wait for the lane to clear before advancing. This issue provides a strong argument for providing 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. (An exception to this rule, the Portland Streetcar, operates one-car trains.) 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 minimum interference between the modes.

Exclusive lanes can mitigate street block length constraints.

Number of Trains

The maximum number of trains that can be operated during an hour is generally set by the line capacity. However, power supply limitations can also constrain the number of trains that can use a given section of a line. For example, the downtown section of the Portland, Oregon, light rail line has a line capacity of 30 trains per hour (2-minute headways), based on the downtown traffic signal cycle, but the existing power system was designed for 3-minute headways. Outer portions of Pittsburgh's light rail lines have power system upgrades planned in order to accommodate 28 additional cars by 2004.(R0)

Electrically powered trains require a considerable amount of energy, particularly when accelerating: the San Diego Trolley's vehicles, for example, use 500 to 550 kW when accelerating from a stop, and 150 to 165 kW while in motion.(R20)

Calculation Procedure

The person capacity of a rail route at its maximum load section *under prevailing conditions* is determined by multiplying the number of cars operated during the peak hour by the agency's scheduled design load for each car and by a peak hour factor:

Equation 5-2

$$P = P_c C_h (PHF)$$

where:
P = person capacity (p/h);
P_c = maximum design load per car (p/car);
C_h = cars operated per hour (car/h); and
PHF = peak hour factor.

Maximum design load can be determined using the procedures in Chapter 4.

The person capacity of a rail route at its maximum load section *when operated at line capacity* is determined by multiplying the number of trains per hour by the number of cars per train, the agency's scheduled design load for each car, and a peak hour factor, as shown in Equation 5-3. Line capacity, assuming no power supply constraints, can be determined from the procedures given later in Part 5.

Equation 5-3

$$P = TN_c P_c (PHF)$$

where:
P = person capacity (p/h);
T = line capacity (train/h);
N_c = number of cars per train (car/train);
P_c = maximum schedule load per car (p/car); and
PHF = peak hour factor.

P_c is set by agency policy and is less than the car's "crush" or maximum load.

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CHAPTER 2. TRAIN CONTROL AND SIGNALING

INTRODUCTION

The role of signaling is to safely separate trains from each other and protect specific paths through interlockings (switches) 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 failures—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 error. 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 the following types of rail transit train control systems: fixed-block, cab, and moving-block. The chapter is applicable to the main rail transit grouping of electrically propelled, multiple-unit, grade-separated systems.

Automatic train control.

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 (e.g., in a station approach), and can be longer between stations where trains operate at speed.

Track circuits.

Fixed-block systems provide a coarse indication of train location.

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.

In the simplest two-aspect (red/green) 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: red/yellow/green), shorter block lengths, and overlay systems that electronically divide blocks into 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—irrespective of technology.

Conventional train control systems can support a throughput of 30 trains/track/hour.

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.

A trip stop is a mechanical device next to the track that activates a train's emergency brakes when a train passes a red signal.

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 50, 40, 30, 20, and 0 mph (80, 70, 50, 35, and 0 km/h).

MOVING-BLOCK SYSTEMS

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 continuously or frequently calculating the clear (safe) distance ahead of each train and then relaying the appropriate speed, braking, or acceleration rate to each train.

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

This system requires continuous or frequent two-way communication with each train, and precise knowledge of a train's location, speed, and length, and of fixed details of the line—curves, grades, interlockings, and stations. With this information, a computer can calculate the next stopping point of each train—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, and 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 transmitted signals to and from antennas on the train, while counting the transpositions determined 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 and reliability and that messages are received by, and only by, the train they are intended for.

The computers that 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.

Communication can be made secure.

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 can be predicted.

HYBRID SYSTEMS

There are times when an urban rail transit system shares tracks with other services, such as long-distance passenger 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.

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

AUTOMATIC TRAIN 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.

Automated train operation systems often also provide for manual operation.

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 systems in Europe and Vancouver, B.C.

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

Automatic train operation (ATO), with or without attendants or drivers, allows a train to follow the optimum speed envelope more closely 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%.

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

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 ATO, 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).

TRAIN THROUGHPUT

One of the difficulties in determining commuter rail capacity when tracks are shared with freight trains is that passenger and freight trains operate at varying intervals and speeds.

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 modern system, junction or turnback constrictions or bottlenecks should not occur. A flat junction can theoretically handle trains with a consolidated headway approaching 2 minutes. However, delays may occur and systems designed for such close headways will usually 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 2 minutes. In this chapter, the limitations on headway will be calculated for all three possible bottlenecks: station stops, junctions, and turnbacks.

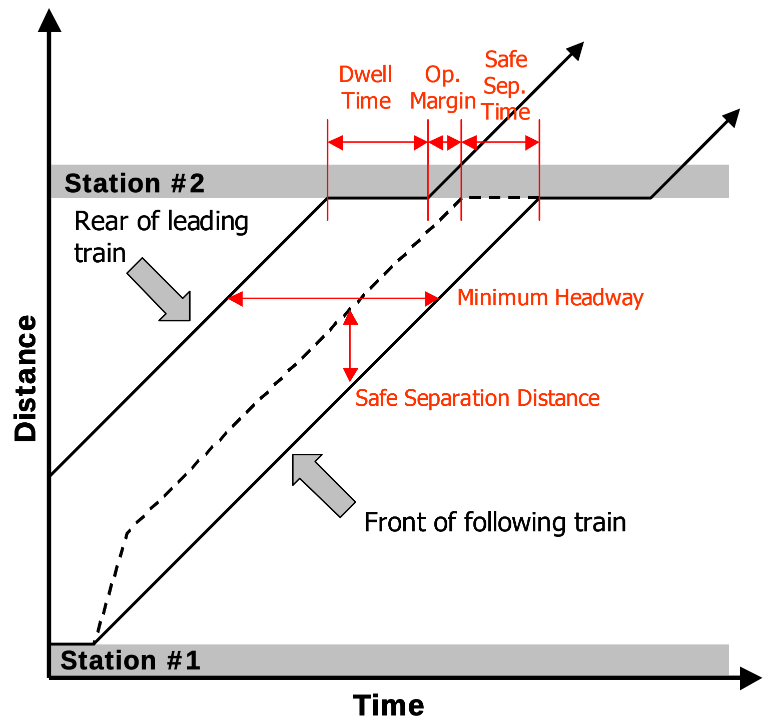
Station Close-In Time

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. The approach speed—and thus capacity—can be reduced by sharp curves or downgrades on station approaches. 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 5-9 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, a junction, or a turnback. If a model or actual operating data are not available, then the minimum headway can be calculated from the procedures in Chapter 7.



NOTE: Acceleration and braking curves omitted for clarity.

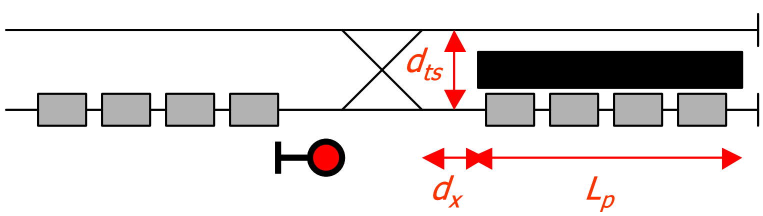
Exhibit 5-9
Distance-Time Plot of Two Consecutive Trains(R15)

Turnbacks

Turnbacks should not be a constraint on capacity.

Correctly designed and operated turnbacks should not be a constraint on capacity. Key dimensions of a typical terminal station arrangement with the preferred[1] center (island) platform are shown in Exhibit 5-10.

Exhibit 5-10
Key Turnback Dimensions(R15)



The worst case is based on the arriving train (lower left) being held at the crossover approach signal while a train departs. It must, moving from a stop, traverse the crossover and be fully berthed in the station before the next exiting train (lower right) can leave. The exiting train must then clear the crossover and the interlocking switches must be reset before another train can enter the station. The difference between the scheduled headway and the time required to make these maneuvers, doubled for a two-berth station such as the one illustrated, is available for terminal layover. The terminal layover time must be sufficient to accommodate passenger movements, and allow time for the driver to change ends, inspect the train, and check train integrity and braking. The maximum time available per track for terminal layover is given by Equation 5-4.

1 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.

Equation 5-4

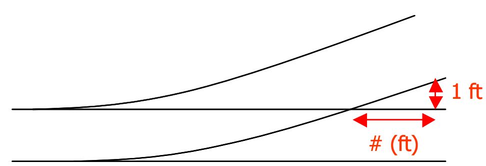
$$t_l \le 2\left(h - t_s - \sqrt{\frac{2(L_p + d_x + f_{sa} d_{ts})}{a + d}} - \sqrt{\frac{(L_p + d_x + f_{sa} d_{ts})}{2a}} \right)$$

where: *[typical heavy rail values shown in brackets]*

t_l = terminal layover time (s);
h = train headway (s); *[120 s]*
t_s = switch throw and lock time (s); *[6 s]*
L_p = platform length (ft, m); *[660 ft, 200 m]*
d_x = distance from cross-over to platform (ft, m); *[65 ft, 20 m]*
d_{ts} = track separation (ft, m),
= platform width + 5.25 ft (1.6 m); *[33 ft, 10 m]*
f_{sa} = switch angle factor (see also Exhibit 5-11):
— 5.77 for #6 turnout,
— 6.41 for #8 turnout, and
— 9.62 for #10 turnout;
a = initial service acceleration rate (ft/s², m/s²); and *[4.3 ft/s², 1.3 m/s²]*
d = service deceleration rate (ft/s², m/s²). *[4.3 ft/s², 1.3 m/s²]*

Exhibit 5-11
Turnout Numbers[R23]

Turnout numbers are based on the ratio of the number of feet moved longitudinally per foot moved out at the "frog" (device located where the tracks cross). The higher the number, the smaller the departure angle and the higher the permitted speed.



A typical terminal layover time can be calculated using the typical parameters given in the brackets above, including a headway of 120 seconds. The terminal layover time, t_l, 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 crossover. 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.

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 mph (34 km/h) on a stop-to-stop approach, and 29 mph (47 km/h) 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.

The maximum permitted terminal time can be calculated for the specific system and terminal parameters. There are numerous corrective possibilities where the time is insufficient. These include moving the crossover as close to the platform as possible; however, structures can restrict the crossover location in subways.

Toronto's streetcars face 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 the 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 the following cars precludes layover time.

The Baltimore light rail line also uses single-track termini but the train frequency (17-minute headways) is not high enough for these to be a capacity limitation. However, some terminals are designed to allow an arriving train to unload passengers before the departing train ahead leaves. This is accomplished through the use of an extra platform as shown in Exhibit 5-12. 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.

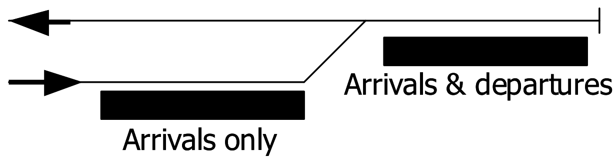


Exhibit 5-12
Light Rail Single-Track Terminus with Separate Unloading Platform (Baltimore)(R15)

If passenger dwell is a limiting factor, then this issue can be reduced with the use of dual-faced platforms. At terminals with exceptionally heavy passenger loading, multiple-track layouts may be needed. Another alternative, used at SEPTA's 69th Street, New York's South Ferry, and Chicago's Howard and Forest Park termini, are loops—however, these are rare luxuries for heavy rail transit. However, some older streetcar-based light rail lines still incorporate terminal loops.

Dual-faced platforms and loops can reduce dwell times.

Crew turnaround time can be expedited with *set-back crewing*, where a crew from a previous train is pre-positioned at the far end of the train. At a leisurely walking pace of 3 ft/s (1 m/s), it would take 200 seconds for an operator to walk the length of a 650-ft (200-m) heavy rail train, more if the operator 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.

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. Alternatively, 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.

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

More expensive ways to improve turnbacks 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 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.

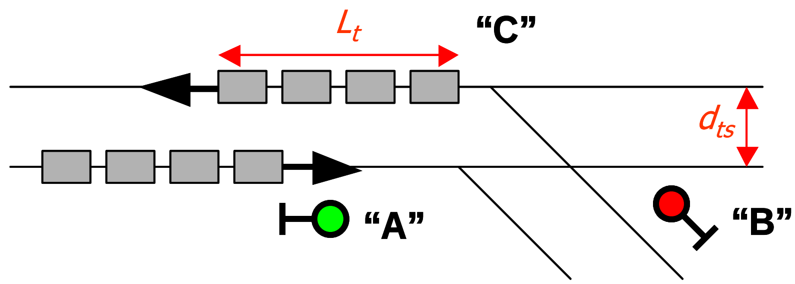
Junctions

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.

Junctions should not constrain capacity.

The capacity of a flat junction can be calculated in a similar manner to the terminal station approach. The junction dimensions are shown in Exhibit 5-13.

Exhibit 5-13
Flat Junction Dimensions(R15)



The worst case is based on a train (lower left) held at signal "A" while a train of length L_t moves from signal "B" to clear the interlocking at "C." The minimum operable headway is the line headway of train "A" (imposed by the line's signaling system), 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:

Equation 5-5

$$h_j = h_l + \sqrt{\frac{2(L_t + 2 f_{sa} d_{ts})}{a}} + \frac{v_l}{a+d} + t_s + t_{om}$$

where: *[typical heavy rail values shown in brackets]*

- h_j = limiting headway at junction (s);
- h_l = line headway (s); *[32 s]*
- L_t = train length (ft, m); *[650 ft, 200 m]*
- d_{ts} = track separation (ft, m); *[33 ft, 10 m]*
- f_{sa} = switch angle factor (see also Exhibit 5-11):
  - — 5.77 for #6 turnout,
  - — 6.41 for #8 turnout, and
  - — 9.62 for #10 turnout;
- a = initial service acceleration rate (ft/s², m/s²); *[4.3 ft/s², 1.3 m/s²]*
- d = service deceleration rate (ft/s², m/s²); *[4.3 ft/s², 1.3 m/s²]*
- v_l = line speed (mph, km/h); *[60 mph = 91 ft/s, 100 km/h = 27.8 m/s]*
- t_s = switch throw and lock time (s); and *[6 s]*
- t_{om} = operating margin time (s).

Higher-speed turnouts have smaller angles between the diverging tracks. They require a longer distance for the tracks to separate from each other, but trains can move onto the branch at a higher speed.

Although 120-second headways are possible, junctions generally should be grade-separated for headways below 150-180 seconds.

Substituting the typical values shown above into the equation results in a junction limiting headway of 102 seconds. An operating margin should then be added to this headway. While in theory a flat junction should allow a 120-second headway, 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. This system adjusts train performance and station dwells to avoid conflicts at the junction. That is, trains will not have to stop or slow down at the junction except 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 savings associated with a moving-block signaling system.

CHAPTER 3. STATION DWELL TIMES

INTRODUCTION

Station dwell times are the major component of headways at short frequencies. The 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.

Station dwell times are a major component of headway.

Controlling dwells.

DWELL TIME COMPONENTS

Dwell time consists of the time passenger flow occurs, the time before the doors are closed, and the time waiting to depart with the doors closed. Exhibit 5-14 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. MTA-NYCT 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. 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 Exhibit 5-14(c), which shows two services, including a short-turn service with shorter dwells that ends about halfway down the graph. All data represent the heaviest-used doorway(s) on the train.

Peak period dwell times on four selected systems.

Regularity of fully automated systems.

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.

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

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

DOORWAY FLOW RATES

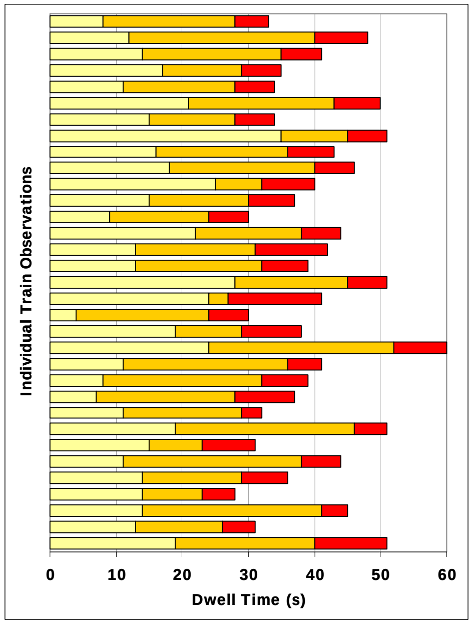
Flow time is the time in seconds for a single entering or exiting passenger to cross the threshold of the rail transit car doorway, per single stream of doorway width. Extensive rail transit door flow rate data collection took place in 1995 as part of TCRP Project A-8, Rail Transit Capacity. Data were collected from a representative set of high-use systems and categorized by the type of entry—level entry being the most common, followed by light rail with door stairwells, with and without fare collection at the entrance. The data sets were partitioned into mainly boarding, mainly alighting, and mixed flows. The results are summarized in Exhibit 5-15.

Exhibit 5-14
Dwell Time Components of Four Rail Transit Stations[R15]

- Doors Open, Passenger Flow
- Doors Open, No Passenger Flow
- Doors Closed, Waiting to Depart

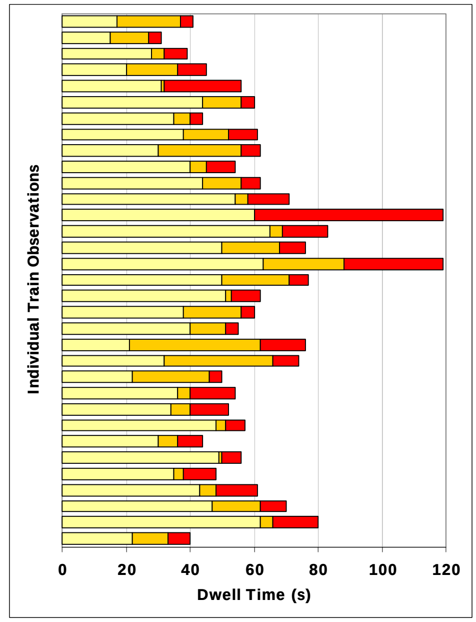
Note that the scale of the Grand Central Station chart is twice that of the other charts in this series.

These four charts are representative of 61 data sets of door flows collected in early 1995 for TCRP Project A-8. Data are from systems operated at, or close to, the capacity of their respective train control systems. Each bar represents an observation of an individual train.



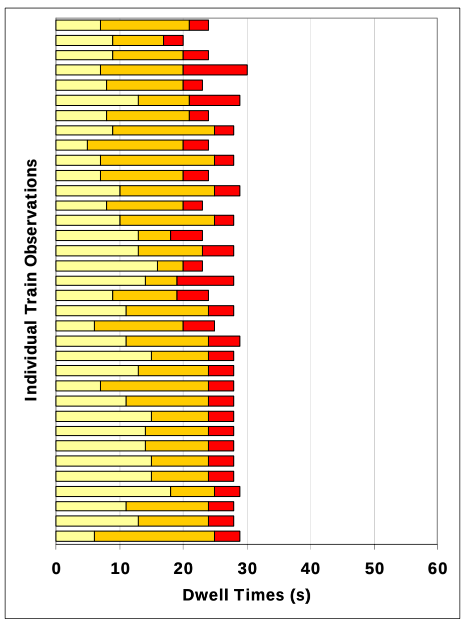
Average headway: 153 seconds
Number of passengers observed: 586
Flow time averages 38% of total dwell

(a) San Francisco, BART (Montgomery Station)



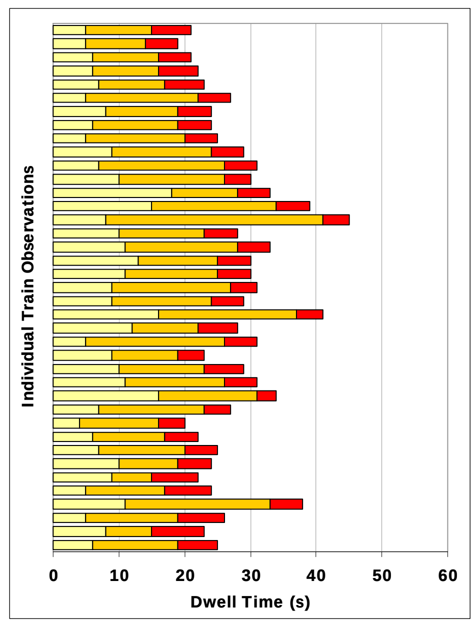
Average headway: 160 seconds
Number of passengers observed: 1,143
Flow time averages 64% of total dwell

(b) New York, NYCT (Grand Central Station)



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

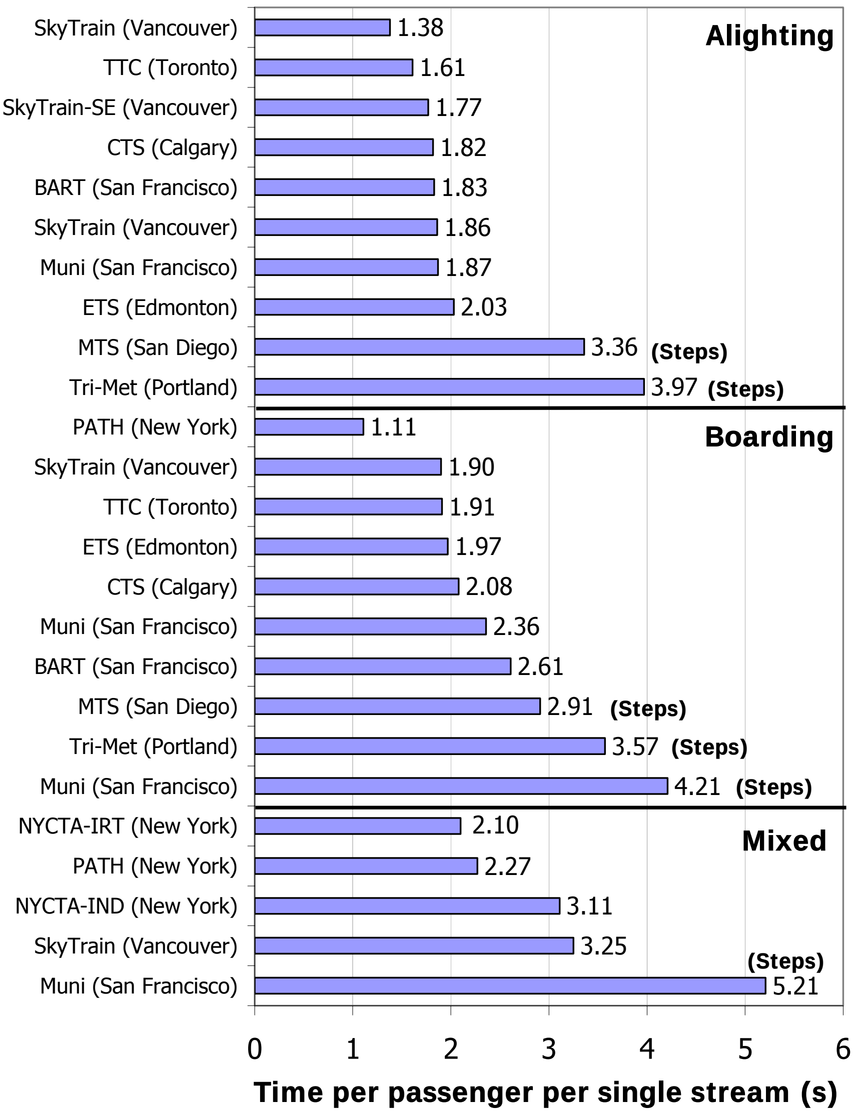
(c) Vancouver, SkyTrain (Burrard Station)



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

(d) Toronto, TTC (King Station, southbound)

Exhibit 5-15
Selection of Rail Transit Door Flow Times (1995)[R15]

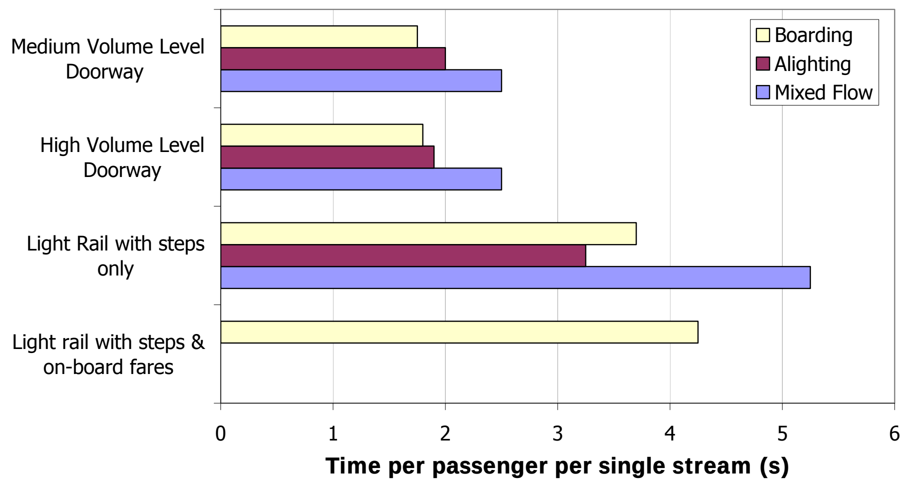


NOTE: Level boarding, except up or down steps where indicated.

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 5-16.

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

Exhibit 5-16
Summary of Rail Transit Average Door Flow Times(R15)

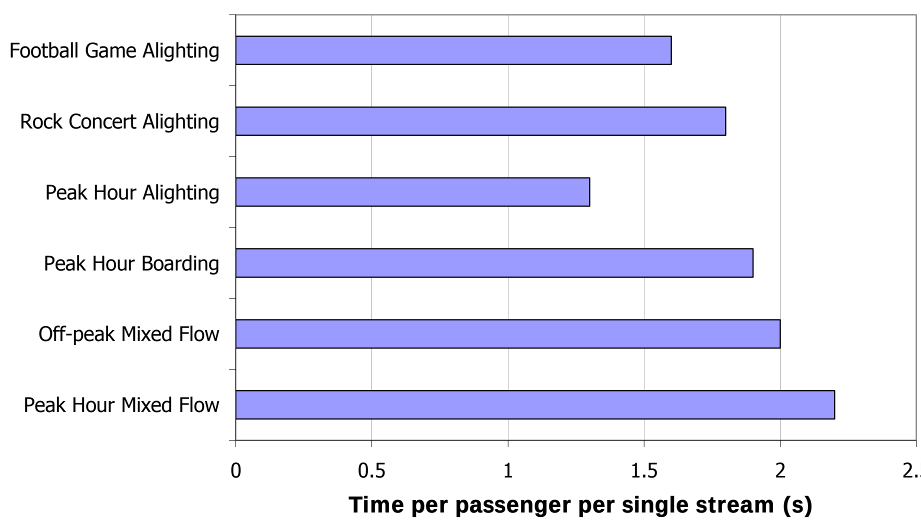


Doorway steps double boarding and alighting times.

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. Exact fare collection adds an average of about 1 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 Vancouver's SkyTrain and compared with peak period flows, as summarized in Exhibit 5-17.

Exhibit 5-17
SkyTrain (Vancouver) Door Flow Rate Comparisons(R15)



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

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 (now TransLink) has also measured car occupancy differences between normal peak hour operation and after service delays. In the ensuing pressure to travel after a delay, passenger space almost doubled from a mean of 3.8 ft^2 per passenger to 2.2 ft^2 per passenger (2.8 passengers per m^2 to 5 passengers per m^2).

Effect of Door Width on Passenger Flow Times

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

Extensive doorway flow data have failed to show any meaningful relationship between door width and flow rate. Within the 3.75 to 4.5 ft (1.14 to 1.37 m) 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.

All observed doors were essentially double-stream.

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 5-18. Wide doors have been a characteristic of the ADtranz C100 automated guideway transit vehicle used in many airports and on Miami's MetroMover. This four-stream 8-foot (2.4-meter) door is shown below.

Exhibit 5-18
Quadruple-Stream Doorways

(a) Tokyo

(b) Miami

Effect of Number of Door Channels on Dwell Times

The total number of door channels available (related to door width and the number of doors) will determine total passenger service time.

Station dwell time is related to the time required to serve all passengers through the busiest door. The greater the number of door channels, the less time required to serve a given passenger flow. Door channels can be provided through a combination of the number of doors and the width of those doors. Newer London Underground cars, for example, provide two double-width doors toward the middle of the cars and two single-channel doors at the ends of the cars, for a total of six door channels per side of the car. The greater the number of doors, the better the opportunity to spread out passengers on station platforms (and thus reduce passenger congestion around the doors), and the smaller the effect that a non-functioning door will have on passenger service times at the car's remaining doors. A tradeoff involved with having more doors or door channels is that less area is available inside the car for seats. Also, a car's design (for example, driver's compartment and wheel locations) will constrain potential door sizes and locations.

ESTIMATING DWELL TIMES

Relating passenger volumes, and flow rates and times, to 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 transformations 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."(R15)

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.

When controlling dwell is calculated using the mean plus two standard deviations, an operating margin is usually unnecessary.

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 are available to estimate the dwell standard deviation over a 1-hour or even a 15-minute peak period. In these cases, or as an alternate approach in situations where data are available, an operating 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 25-second operating margins on existing systems are shown in Exhibit 5-19.

Exhibit 5-19
Controlling Dwell Limits (s) (1995)(R15)

System & City	Mean	SD	# of samples	Upper Limit (Mean+SD) One SD	Two SD	Operating margin (s) +15	+25
BART (San Francisco)	46.3	12.0	290	58.3	70.2	61.3	71.3
CTS (Calgary)	35.7	15.7	91	51.5	67.0	50.7	60.7
ETS (Edmonton)	24.7	8.8	18	33.6	42.3	39.7	49.7
NYCT (New York)	30.7	20.9	380	51.6	72.6	45.7	55.7
PATH (New Jersey)	51.3	23.0	252	64.3	97.3	66.3	76.3
TriMet (Portland)	32.0	19.4	118	51.4	70.8	47.0	57.0
MTS (San Diego)	51.1	17.9	34	69.1	86.8	66.1	76.1
Muni (San Francisco)	50.4	21.8	75	72.2	93.9	65.4	75.4
TTC (Toronto)	36.6	23.2	322	59.8	83.0	51.6	61.6
SkyTrain (Vancouver)	30.7	7.2	82	37.9	45.1	45.7	55.7

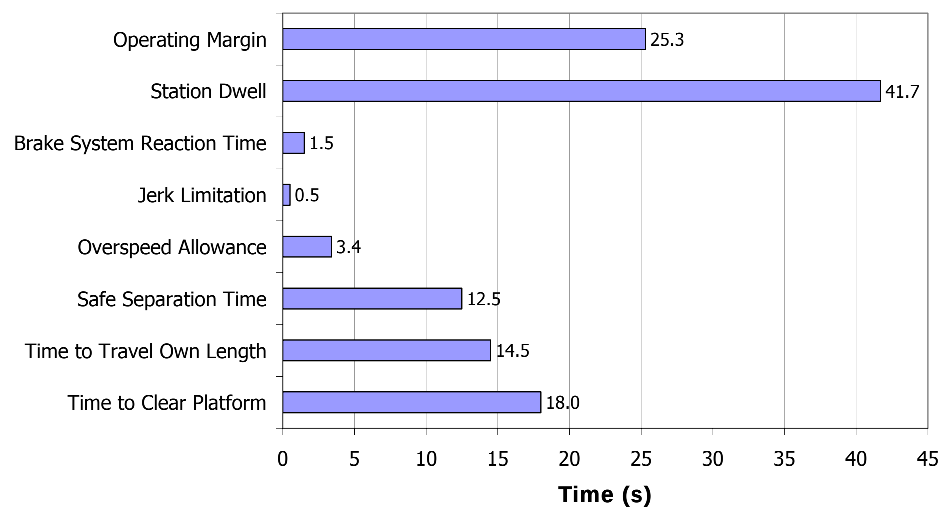
SD: standard deviation

One standard deviation provides an 84% confidence level and two provide a 97.5% confidence level (i.e., 97.5% of all dwells will be less than the average plus two standard deviations.)

The third method is often the most practical, involving selection of dwell times and operational allowances from comparable existing systems.

Exhibit 5-20 shows that dwell time is the dominant component of the minimum headway. Chapter 5 provides additional examples of existing controlling dwells; discusses the need for, and approaches to, estimating a reasonable operating margin; and discusses the time required to load wheeled mobility aids and strollers.

Exhibit 5-20
Typical Headway Components(R15)



NOTE: Based on a heavy rail system operating at 120-s headways, with cab signaling.

CHAPTER 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 5-21 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 1.8 ft^2/p (0.125 m^2/p).

Exhibit 5-21
Passenger Space on Selected North American Heavy Rail Systems During Peak 15 Minutes (1995)[R9]

	Passenger Space (based on gross floor space)	
System (City)	**(ft^2/p)**	**(m^2/p)**
NYCT (New York)	4.0 into CBD	0.38 into CBD
CTA (Chicago)	7.0 into CBD	0.67 into CBD
SEPTA (Philadelphia)	8.0 into CBD	0.77 into CBD
MBTA (Boston)	5.0 into CBD	0.50 into CBD
BART (San Francisco)	5.75-9.0	0.53-0.83
WMATA (Washington)	5.0-12.0	0.50-1.11
MARTA (Atlanta)	6.75-7.5	0.63-0.71
TTC (Toronto)	4.5-6.0	0.42-0.56
STM (Montréal)	3.4-4.0	0.31-0.38

CBD: central business district

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 trunk routes averages 0.82. Outside New York, the peak-within-the-peak period tends to be more pronounced and the peak hour factor is lower. This is due in part 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 in 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

The Batelle Institute[R8] 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 5-22 for males:

Exhibit 5-22
Male Passenger Space Requirements[R8]

These are suggested minimum spaces.

Situation	Projected Area (ft^2)	Projected Area (m^2)
Standing	1.6-2.2	0.15-0.20
... with briefcase	2.7-3.2	0.25-0.30
... with daypack	3.2-3.8	0.30-0.35
... with suitcases	3.8-5.9	0.35-0.55
... with stroller	10.2-12.4	0.95-1.15
... with bicycle (horizontal)	17.2-20.4	1.60-1.90
Holding on to stanchion	2.7	0.25
Minimum seated space	2.7-3.2	0.25-0.30
Tight double seat	3.8 per person	0.35 per person
Comfortable seating	5.9 per person	0.55 per person
Wheelchair space (ADA)	10.0 (30 in x 48 in)	0.93 (0.76 m x 1.22 m)

NOTE: Stroller and bicycle dimensions based on review of manufacturer specifications.

Pushkarev et al.[R17] suggest *gross vehicle floor area* as a readily available measure of car occupancy, recommending the following standards for the peak hour:

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

Commuter rail capacity is based on the number of seats, reduced by a peak hour factor. Commuter rail cars in North America are typically 86 ft (28 m) 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 (“two-by-three”) seating arrangements.

Wheeled mobility aid space provisions range from 5.9 to 12.9 ft^2 (0.55 to 1.2 m^2); the ADA uses a 30-in. by 48-in. (760-mm by 1220-mm) space. This space can include folding or jump seats. Provision must also be made for wheelchair maneuvering and for any requirements to carry strollers, baggage, and bicycles. More space is required for powered wheeled mobility aids and ones whose occupants have a greater leg extension, less for compact and sports chairs.

The 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 (0.45 to 0.56 p/ft^2)—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 16 in. (0.40 m) per double door,[2] from the interior length gives the interior free wall length.

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

- 27 in. (0.69 m) for transverse seating,[3] and
- 17 in. (0.43 m) for longitudinal seating.

The result, in lowest whole numbers,[4] should then be multiplied by 2 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 5.4 ft² (0.5 m²) and longitudinal seats by 4.3 ft² (0.4 m²). These areas make a small allowance for bulkhead seating but otherwise represent relatively tight and narrow urban transit seating. Add 10 to 20% for a higher quality, larger seat such as that 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:

- 2.15 ft²/p (5 p/m²), an uncomfortable near-crush load for North Americans with frequent body contact and inconvenience with packages and briefcases. Moving to and from doorways is extremely difficult.
- 3.2 ft²/p (3.3 p/m²) a reasonable service load with occasional body contact. Moving to and from doorways requires some effort.
- 5.4 ft²/p (2.0 p/m²),[5] a comfortable level without body contact, reasonably easy circulation, and similar space allocation as seated passengers.

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

3 Increase to 32 in. (0.8 m) for seats behind a bulkhead.

4 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 cannot 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.

5 This upper level is a peak 15-minute occupancy level for standing passengers. Over the peak hour it corresponds closely to Pushkarev's[(R17)] and Jacobs'[(R12)] estimates of a U.S. rush hour loading average of 5.4 ft²/p (0.5 m²/p)—both seated and standing. It also corresponds to Pushkarev's and Batelle's[(R8)] recommendations for *adequate* or *comfortable* loading levels.

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 (0.45 to 0.56 p/ft²), the latter being more common in Europe. Asian standards for both maximum and crush loads reach 7 or 8 standing passengers per square meter (0.67 to 0.77 p/ft²). 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 divided by the peak hour factor to get equivalent peak 15-minute loading levels. No specific allowance has been made for wheelchair, bicycle, stroller, or other wheeled device 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 Underground arrangement of doors at the very end of each car is adopted.

The above process can be expressed mathematically as:

Equation 5-6

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

The articulated rail car schematic in Exhibit 5-23 shows the principal dimensions of this equation.

where:

C_c = car capacity—peak 15 minutes (p/car);
L_c = car interior length (ft, m);
L_a = articulation length for light rail (ft, m);
W_s = stepwell width (certain light rail only) (ft, m);
W_c = car interior width (ft, m);
S_{sp} = space per standing passenger (ft², m²):
2.15 ft² (0.2 m²)—crush load,
3.2 ft² (0.3 m²)—maximum schedule load, and
5.4 ft² (0.5 m²)—comfortable standing load;
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;[6]
S_a = area of single seat (ft², m²):
5.4 ft² (0.5 m²) for transverse, and
4.3 ft² (0.4 m²) for longitudinal;
D_n = number of doorways;
D_w = doorway width (ft, m);
S_b = single setback allowance (ft, m):
0.67 ft (0.2 m)— or less; and
S_w = seat pitch (ft, m):
2.25 ft (0.69 m) for transverse, and
1.42 ft (0.43 m) for longitudinal.

6 2+3 seating is only possible on cars with width greater than 10 ft (3 m), and is not applicable to light rail or automated guideway transit.

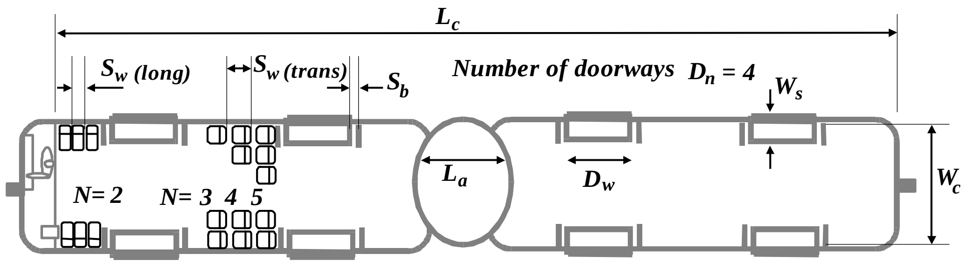


Exhibit 5-23
Schematic LRT Car Showing Dimensions(R15)

Default Method

A default method is to divide the gross floor area of a vehicle (exterior length multiplied by exterior width) by 5.4 ft² (0.5 m²) and use the resultant number of passengers as the average over the peak hour—without applying a peak hour factor. An average space over the peak hour of 5.4 ft² (0.5 m²) 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 U.S. 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 5-6 to two typical light rail vehicles produces the loading levels in passengers per unit length shown in Exhibit 5-24. 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 1.5 to 2.4 passengers per foot of car length (5.0 to 8.0 p/m length). The lower level of 1.5 passengers per foot length (5.0 p/m length)—with a standing space per passenger of 4.3 ft² (0.4 m²)—corresponds closely with the recommended *comfortable* loading of an average of 5.4 ft² (0.5 m²) per passenger.

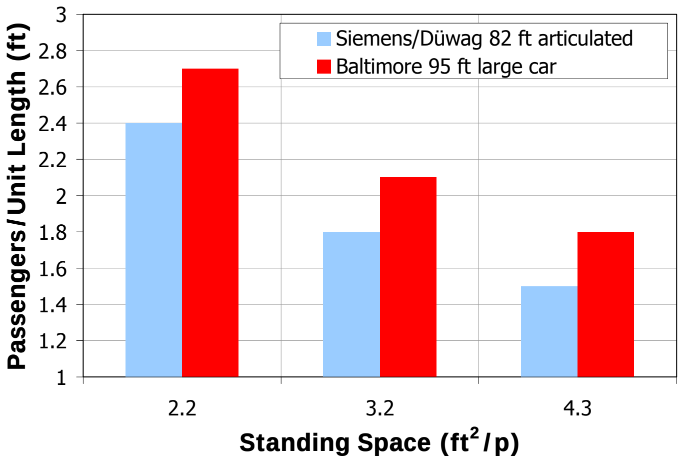


Exhibit 5-24
Linear Passenger Loading—Articulated LRVs(R15)

An alternative figure using metric units appears in Appendix A.

Applying Equation 5-6 to selected heavy rail cars produces the loading levels in passengers per unit length shown in Exhibit 5-25. 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) cars used in more than 12 U.S. and Canadian cities have a remarkably close data set for each of the three variations of door and seating configurations, with a range of 2.1 to 3.5 passengers per foot of car length (7.0 to 11.5 p/m of car length). The higher end of this range approaches that of crush loaded conditions.

The lower end of the range, at 2.1 to 2.4 passengers per foot length (7 to 8 p/m length)—with a standing space per passenger of 4.3 to 3.2 ft² (0.4 to 0.3 m²)—is an appropriate and tight range for higher use systems. A lower figure of 1.8 p/ft length (6 p/m length) corresponds closely with the recommended *comfortable* loading of an average of 5.4 ft² (0.5 m²) per passenger and is appropriate for a higher level of service on new systems. In either case, a reduction by 0.3 p/ft length (1.0 p/m length) should be used for smaller, narrower cars.

Exhibit 5-25
Linear Passenger Loading—Heavy Rail Cars(R15)

An alternative figure using metric units appears in Appendix A.

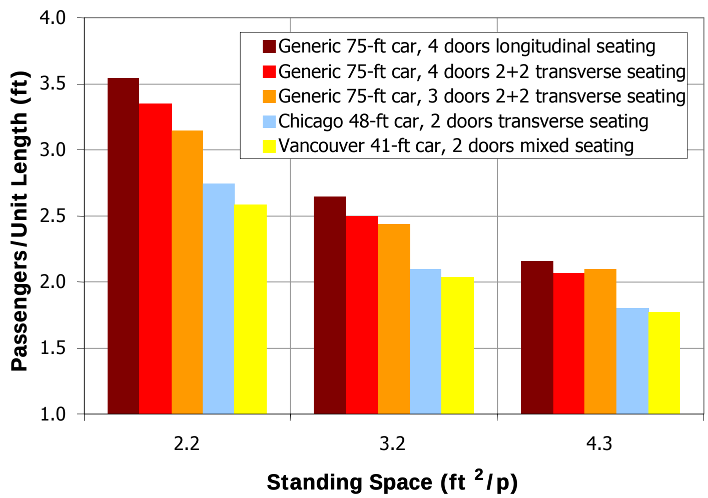


Exhibit 5-26 summarizes the average loading level in passengers per foot length for typical U.S. and Canadian rail transit cars.

Exhibit 5-26
Summary of Linear Passenger Loading (p/ft) (1995)(R15)

An alternative table using metric units appears in Appendix A.

	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
MTA-NYCT alone	2.4	2.4	0.5

SUMMARY

Passenger space can be designed on a per-person or more generic per-unit-vehicle-length basis. When designing for a new system, an average of 5.4 ft² (0.5 m²) per passenger over the peak hour is appropriate to provide a higher (i.e., more comfortable) level of service. This recommended passenger space corresponds to a linear loading level of 1.8 passengers per foot length (6 passengers per meter length) for heavy rail cars and 1.5 passengers per foot length (5 passengers per meter length) for light rail cars, which are somewhat narrower.

Passengers with luggage, daypacks, strollers, and other items will take up more space than unencumbered passengers and may need to be accounted for in design in certain circumstances. A recommended minimum space is 3.2 ft² (0.3 m²) per passenger, corresponding to 2.4 passengers per foot (8 passengers per meter) for heavy rail and 2.1 passengers per foot (7 passengers per meter) for light rail.

CHAPTER 5. OPERATING ISSUES

INTRODUCTION

Allowance for operating variables.

The previous three chapters have introduced the three major factors 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 factors.

Uniformity of train performance.

There is considerable uniformity of performance of the electrical multiple-unit trains that handle more than 90% of all U.S. and Canadian rail transit, assisted by the widespread 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—particularly on manually driven systems—due to variations in driving techniques 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 also 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.

As a starting point for recommending a suitable operating margin, the operating margins incorporated into the schedules of existing systems can be reviewed. The maximum load point, peak-period, station dwell time, and headways for several rail transit lines are presented in Exhibit 5-27.

The headways in Exhibit 5-27 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 Vancouver's fully automatic SkyTrain.

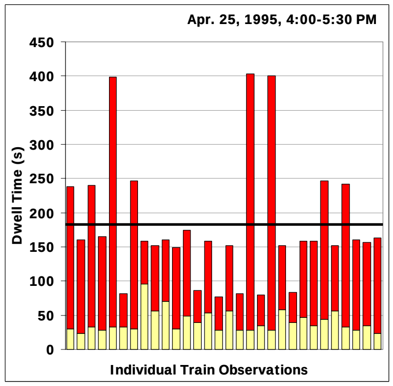
The lower four charts in Exhibit 5-27 show the range of dwell and headway irregularities on manually driven systems. These are not typical of most heavy rail lines throughout the day, but represent lines at or near capacity at the peak-point in the peak period. It is at these times that operating margin and schedule recovery times are most needed to correct service irregularities.

Exhibit 5-28 shows the headway components with the final column indicating the residual time that is a surrogate for the operating margin.[7]

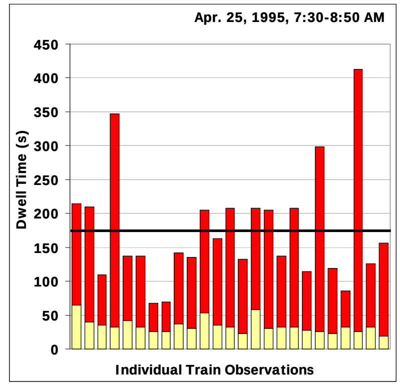
[7] The operating margin is estimated to be:
Operating margin = (average headway) – (avg. station dwell) – 2(standard deviation of station dwell) – (train control separation)

Exhibit 5-27
Observed Rail Headways and Dwell Times[R15]

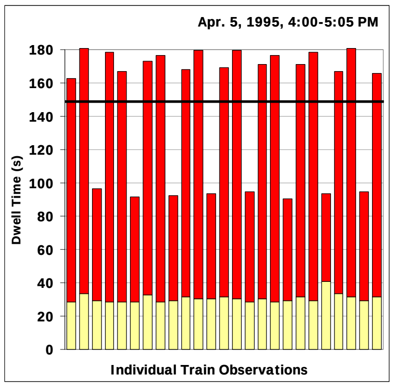
Light rail headways on observed systems were generally sufficiently long that any irregularities reflected problems other than schedule interference between trains. One of the closest on-street headways is in Calgary, shown at the top. Note that the scales of the graphs vary.



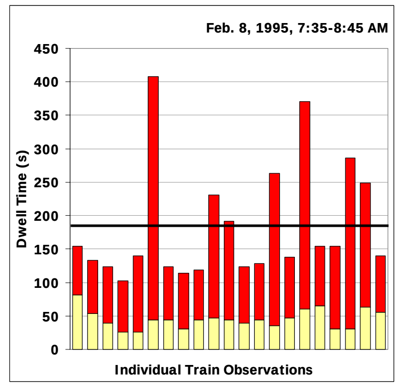
(a) CTS 3rd St. SW EB (Calgary)



(b) CTS 1st St. SW WB (Calgary)

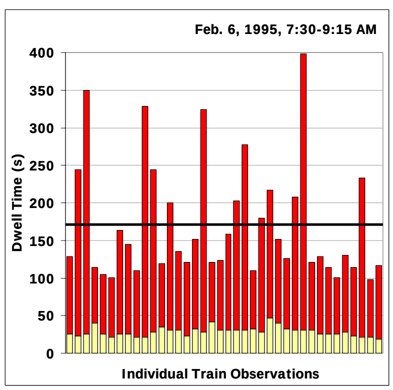


(c) SkyTrain Broadway EB (Vancouver)

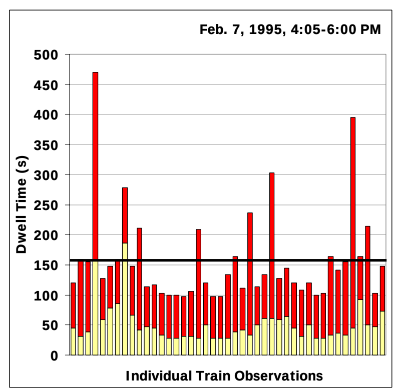


(d) BART Embarcadero WB (San Francisco)

Additional examples of these dwell/headway charts are contained in Chapter 6 of *TCRP Report 13*, "Rail Transit Capacity."[R15]

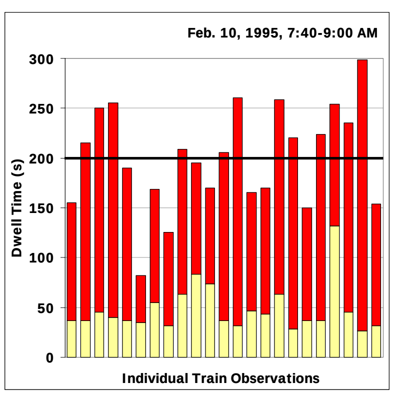


(e) TTC King SB (Toronto)

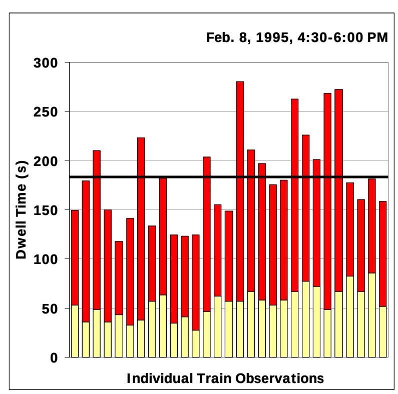


(f) TTC Bloor NB (Toronto)

Dwell Time (s)
Headway (s)
Average headway (s)
NB: northbound
SB: southbound
EB: eastbound
WB: westbound



(g) PATH Journal Square WB (Newark)



(h) NYCT Grand Central NB Express (New York)

Exhibit 5-28
Dwell and Headway Data Summary of Surveyed Rail Transit Lines Operating at or Close to Capacity (1995)(R15)

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

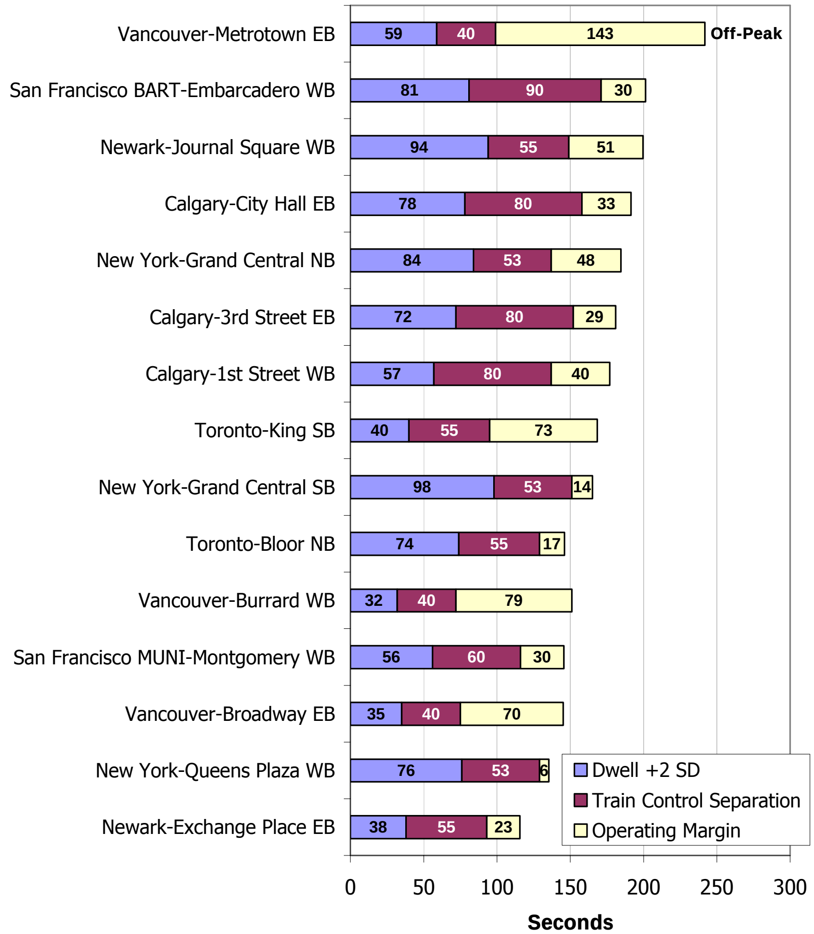
NB: northbound, SB: southbound, WB: westbound, EB: eastbound
SD: standard deviation, Hdwy.: headway

Exhibit 5-29 shows the headway components graphically, with the operating margin as the end component of each bar. The bars are arranged in order of increasing headway. Note that the bar at the top 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.

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, *TCRP Report 13*(R15) found no such relationship. Some inference can be drawn in that the system with the best headway adherence identified in *TCRP Report 13,* Vancouver's SkyTrain, also has the most generous operating margins.

Exhibit 5-29
Headway Components of Surveyed Heavy Rail Transit Lines Operating at or Close to Capacity(R15)



NOTE: NB = northbound, SB = southbound, WB = westbound, EB = eastbound

Estimating Operating 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 layover 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 incurs sufficient irregularity that it may also serve to reduce capacity.

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.

Suggested operating margin range.

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 detailed procedures.

SKIP-STOP AND EXPRESS OPERATION

Skip-stop operation increases speed but not capacity.

Skip-stop service (where a given train stops at every other station) is used on several of the heavy rail transit operations in Japan, New York, Philadelphia, and, until recently, Chicago. Skip stops provide faster travel times for most passengers, and require 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 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.

Four light rail lines (Philadelphia's 100-series lines and New Jersey's Hudson-Bergen line) operate a form of express service, where a following train skips stops to catch up to—but not pass—the train in front.

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 line 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.

Directional capacity with express service.

New York's Lexington Avenue express tracks carry 80% the number of trains of the local tracks.

Most trunk routes in New York[8] 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 diverging 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.

PASSENGER-ACTUATED DOORS

The majority of new light rail systems have passenger-actuated doors, which increase 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 frequencies 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 5 seconds. Certain light rail doors, associated with folding or sliding steps, can take double this time to operate. 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 its 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.

[8] 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 B 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.

OTHER STATION CONSTRAINTS

Inadequate platform exit capacity can reduce line capacity, as dwell times of following trains increase.

Many station-related factors can influence demand. Poor location, inconvenient transfers to connecting modes, and 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 line 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.

Part 7 of the TCQSM covers NFPA station exit requirements in greater detail.

Station exiting requirements are specified by the U.S. National Fire Protection Association (NFPA) rapid transit standard 130.[R14] 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 4 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.

NFPA 130 requirements may not be met on older systems. 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.

Out-of-service fare gates and escalators have the potential to create station platform congestion, if the remaining in-service equipment does not have sufficient capacity.

Even when NFPA 130 requirements are met, constraints posed by out-of-service fare gates, escalators, or other station components can potentially create congestion that could cause passenger queues to back up onto station platforms, if these components are being operated close to their capacity. Part 7 of the TCQSM provides procedures for calculating the passenger-handling capacity of various station components.

On-board light rail fare payment.

Fare payment is a particular factor on the few light rail systems that still use manual on-board payment. Exhibit 5-16 showed that exact fare payments add an average of 1.5 seconds per boarding passenger. This is an inefficiency that increases running time, station by station, day by day.

However, the far more drastic impact of manual on-board fare collection is the restriction of boarding to a single staffed door. Not only do all passengers take more time to board individually, the efficiency of loading several passengers at once through multiple doors is lost, resulting in dwell times that are potentially three to four times as long as they would be without on-board fare collection. Exhibit 5-30(c) shows an extreme case of platform congestion resulting from manual on-board fare collection and a surge of passengers from a nearby tourist attraction. A system using manual on-board fare collection, and restricting boardings to driver-attended doors only, cannot achieve its maximum capacity.

A few systems provide on-board fare machines, combined with random fare checks. These machines allow passengers to board through all doors and then make their way inside the car to the fare machine. This addresses the dwell time issue, but can substitute a crowding and circulation issue inside the car, in the vicinity of the fare machine. On low-volume or mainly pre-paid lines such as the Portland Streetcar (which operates mainly within a fare-free area), congestion within the car may not be an issue. However, on high-volume systems with on-board fare machines, such as trams in Melbourne, Australia, it can be an issue.

Exhibit 5-30
On-Board Fare Collection

(a) Farebox (Pittsburgh)

(b) Self-service machine (Portland Streetcar)

(c) Farebox, with passenger surge (Cleveland)

(d) Smart card reader (San Francisco)

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 peak hour 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 to 3 minutes, with some as low as 60 seconds. The movement of wheelchairs on level surfaces is 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, described later in this section, have the least impact on capacity. The vertical and horizontal gap between the edge of platform and the door is often a major problem for passengers in wheeled mobility aids.

Wheelchair boarding rates.

An unknown 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 1 wheelchair use per 20,000 passengers.[R15] Other estimates range from 1 in 5,000 to 1 in 10,000. However, usage is usually dependent on other streetscape amenities and demographic factors as well. The usage of lifts can be three to five times higher than these rates due to use by other passengers not using wheeled mobility aids.

In addition to any boarding and alighting delays, the time for a wheelchair to move to a securement position and use any required securement or restraint systems can be considerable, particularly if the rail car is crowded. However, experienced users can be remarkably quick in boarding and alighting, and passenger movement times are often lower than for lift-equipped buses, as there is more room to maneuver wheelchairs, walkers, and scooters within rail vehicles. Off-vehicle fare collection also helps to speed loading for mobility limited and able-bodied passengers alike. The least loss of time is when the wheelchair position is close to the doorway and requires neither a folding seat nor the use of a securement system. 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.

Some agencies are overly cautious in adapting bus securement procedures to light rail service. Consideration of wheelchair securement is necessary for light rail vehicles operating on-street, due to the possibility of rapid braking as a result of traffic. However, many systems' experience indicates that wheelchair securement systems are not necessary for off-street rail service, as braking and acceleration is closely controlled and ride quality is smooth.

Impact of wheelchairs on line capacity.

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 insufficient information to quantify the impact of wheelchair accessibility on line capacity. Indications are that in the short term, wheelchair lift and bridging plate 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 on capacity at these levels. In the longer term, other accessibility requirements of the 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.

Wheelchair Boarding Methods

High-level loading is invariably used on heavy rail systems and is typically used on automated guideway transit systems. The relative rarity of level loading with high level platforms on other rail modes has resulted in a variety of methods to allow wheelchair access to rail vehicles. Each of the methods is outlined by mode in the sections that follow.

It should be noted that both mobility-impaired passengers and transit agencies prefer access methods which do not single out people with mobility impairments for special treatment. Lifts and special ramps cause delays which reduce the reliability of the service, while isolating people with mobility impairments 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 use by people with mobility impairments is decreasing in favor of more reliable and less exclusionary methods such as low-floor cars.

Light Rail

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, because of the need for an ADA-accessible sloped ramp to get between street level and platform level, which 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.

The Los Angeles Waterfront vintage trolley uses high platforms, in combination with a platform bridge across the gap for use by wheeled mobility aids.

High platforms are also used at stations in Buffalo, Pittsburgh, and San Francisco; in combination with low-level loading at other stops.[9] Buffalo is unusual in that a subway, with high 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, combined with high-platform stubs for wheelchair access. Pittsburgh has separate doors for each platform level, while the San Francisco Muni uses cars fitted with steps that can be mechanically raised to floor height at high-platform stations.

Mixed use of high and low platforms.

Examples of high-platform stations and vehicles used in mixed high- and low-platform environments are shown in Exhibit 5-31.

Exhibit 5-31
High-Platform Station and Adjustable Door Height Examples

(a) On-street station in median (San Francisco)

(b) Partial platform (Buffalo)

(c) Adjustable vehicle steps (San Francisco)

(d) Separate door levels (Pittsburgh)

Low-Floor Cars

Low-floor cars[10] 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 using wheeled mobility aids to board without the aid of lifts or special platforms. Boarding

Low-floor cars improve access for everyone, not just persons using mobility aids.

9 Low-level surface stops on Pittsburgh's light rail lines are not accessible. The Port Authority is constructing high platforms on the renovated Overbrook Line and at selected other stops as part of its light rail reconstruction project. In San Francisco, the Market Street subway and stations along the Mission Bay extension have high platforms. Stations along the historic streetcar "F" line Embarcadero extension and selected on-street stops on other lines have mini-high platforms. Where neither high nor mini-high platforms exist, the Muni system is not accessible.

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

by persons with strollers, bicycles, and luggage, and by persons who have difficulty climbing steps is also greatly simplified. Exhibit 5-32 presents examples of low-floor cars used in North America.

Exhibit 5-32
Low-Floor Cars

(a) Portland, Oregon (light rail) (b) Jersey City, New Jersey

On-street stations used by low-floor vehicles are more compact than high-platform stations would be.

Low-floor cars provide much of the benefit of level loading without the need for high platforms. The typical floor height is 14 in. (350 mm),[11] about double the height of a normal curb. Medium- or intermediate-height platforms are therefore still required for no-step boarding, but long ramps are unnecessary. Buttons located at a lower height than the separate passenger-actuated door buttons on the inside and outside of the car allow wheelchair users to deploy the ramp on demand to bridge the gap between the car and the platform.

Low-floor cars in North America.

While low-floor cars have operated in Europe for more than a decade, the first North American operation began on the Portland light rail system in 1997. Portland's cars are compatible with its existing high-floor fleet, allowing two-car trains formed from one high-floor and one low-floor car. Low-floor cars have subsequently been placed in service on New Jersey Transit's Hudson-Bergen and Newark City Subway lines, the Portland Streetcar, and the Tacoma Link, and low-floor cars are on order for lines in Houston, Minneapolis, and Boston.

Drawbacks of 100% 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 teething problems. Most low-floor designs are intended for city streetcar or tramway applications and have neither the top speeds nor the ride quality suitable for U.S. and Canadian 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.

Full and partial low-floor designs.

Steps inside the car provide access to the high-floor sections. Cars with 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 the United States and Canada, compared with Western Europe. As a result, the cars purchased in North America to date 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

11 Certain low-floor designs ramp down the doorways to achieve a 13- to 14-in. (280- to 300-mm) floor height.

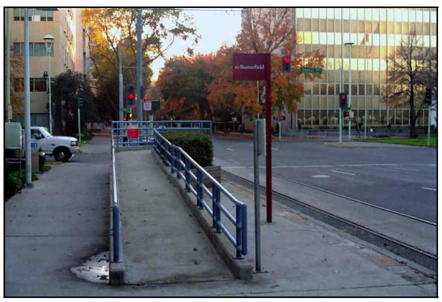
designed for on-street operation still remain less than ideal for typical U.S. and Canadian light rail systems with their extensive open, segregated trackage.

Mini-High Platforms

The most common wheelchair loading arrangement.

The most common wheelchair access method to high-floor light rail cars are *mini-high* or *high-range* platforms that provide level loading to the 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, a small lift. A canopy is sometimes provided over the ramp. 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 per month on the mini-high platforms. Mini-high platforms also have been adopted for the light rail lines in Baltimore, Denver, and Salt Lake City, and for Cleveland's Waterfront Line. Exhibit 5-33 provides examples of mini-high platforms used in North America.

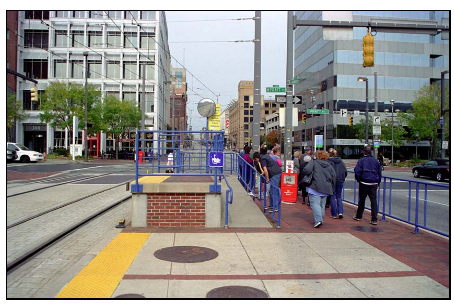
Exhibit 5-33
Mini-High Platforms



(a) Sacramento

(b) Denver

(c) San Francisco



(d) Baltimore

Second train stops for mini-high platforms.

The San Francisco Municipal Railway has also installed mini-high platforms at key locations on its surface light rail lines.[12] 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.

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[12] Muni's historic streetcar fleet also requires a second stop at mini-high platforms because the mini-high platform ramps block the doors of the relatively short streetcars. (See Exhibit 5-33c.)

Profiled platform as an alternative to mini-high platforms.

An alternative to the mini-high platform is the Manchester-style profiled platform, shown in Exhibit 5-34. This platform has an intermediate height and is profiled up to a section that is level with one doorway for wheelchair access. Maximum platform slopes are shown in Exhibit 5-35.

Exhibit 5-34
Profiled Light Rail Platform Providing for One Accessible Door(R15)

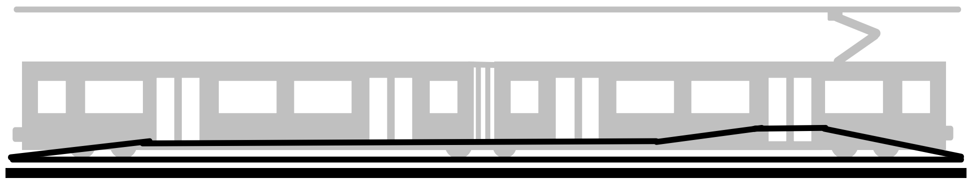


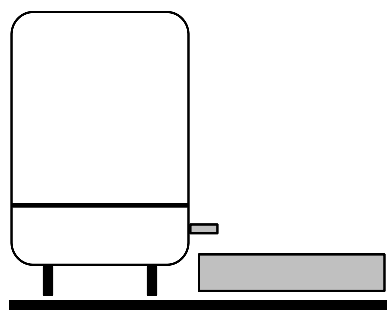
Exhibit 5-35
ADA Maximum Platform Slopes

Maximum Rise		Maximum Slope	
Rise ≤ 3 in.	Rise ≤ 7.5 cm	1:4	14.04°
3 in. < Rise ≤ 6 in.	7.5 cm < Rise ≤ 15 cm	1:6	9.46°
6 in. < Rise ≤ 9 in.	15 cm < Rise ≤ 22.5 cm	1:8	7.13°
Rise > 9 in.	Rise > 22.5 cm	1:12	4.76°

Folding steps and profiled platforms.

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 single-step entry to most doors. Alternatively, cars can have a slide or fold-out step as shown in Exhibit 5-36.

Exhibit 5-36
Profiled Light Rail Platform with Slide-Out or Fold-Down Step(R15)



Car-Mounted Lifts

Car-mounted lifts, illustrated in Exhibit 5-37, were introduced on the San Diego Trolley, one of the first light rail transit systems to be wheelchair accessible. In San Diego, 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 that 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 1 in 400 operations.[13] The Kenosha, Wisconsin, vintage trolleys use a car-mounted lift that folds flat against the side of the door when not in use, which allows other passengers to use the door when the lift is not in use. Trains used on New Orleans' Waterfront and Canal Street lines use car-mounted lifts located at a high-level door not used by other passengers.

Dwell times with car mounted lifts.

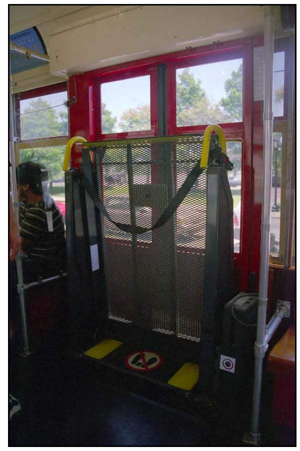
Boarding and alighting times with the car-mounted lifts are around 1 minute for each passenger movement. However, the need for the train operator to leave the cab to operate the lift adds to the time required and can mean the total station dwell time extends to 1.5 to 2 minutes when the lift is used. If the operator is required to assist in securing the wheelchair, the dwell can be further extended.

13 Based on San Diego Trolley data for May 1994. Out of 1,069 lift passengers carried (2,138 lift cycles) only 6 failures were recorded—giving a failure rate of 0.28%.

Exhibit 5-37
Car-Mounted Lifts

(a) San Diego

(b) Kenosha, Wisconsin



(c) New Orleans

Platform-Mounted Lifts

Platform mounted lifts are used on the San Jose light rail system.[14] 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.

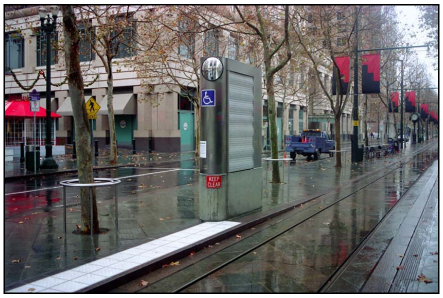
Dwell times with wayside lifts.

Wheelchair loading is slow in San Jose because of the 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 2 to 3 minutes, giving a total train delay (including loading and unloading) of 4 to 6 minutes per passenger requiring the lift. These delays can easily consume the train's scheduled terminal recovery time. In 1995, an average of 25 wheelchairs and scooters were carried each weekday on the San Jose light rail line, but this increased to as many as 50 per day for special events.

Portland removed its platform lifts in 1997 after adding a low-floor car to each train. Under normal circumstances, the Portland lift, illustrated in Exhibit 5-38(b), 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.

14 A few streetcar stops on Market Street in San Francisco also use curbside lifts, due to space limitations preventing installation of a mini-high platform.

Exhibit 5-38
Platform-Mounted Lifts



(a) San Jose

(b) Portland, Oregon (before low-floor cars)

Commuter Rail

Bridgeplates are often used to span the gap between platform and train.

Commuter rail systems use many of the same kinds of access methods as light rail systems. The main difference is that these methods are often supplemented with a bridgeplate to span the gap between platform and train when a form of level boarding is used. The vertical and/or horizontal gap between the train and platform for "level" boarding typically is greater for commuter rail than for light rail. The bridgeplate can be portable or built into the train.

High-level platforms provide the easiest and fastest boarding for all passengers. The Electric Division of Chicago's Metra, MTA-Long Island Rail Road, MTA-Metro North Railroad, and Vancouver's West Coast Express are among the commuter rail lines that use high-level platforms. However, it is often not possible to provide high-level platforms on lines that are shared with freight trains, as freight wide-loads will need to be accommodated.(R11)

High-level platforms are usually not possible on lines shared with freight trains.

Mini-high platforms, combined with a bridgeplate, are a frequently used option on lines with low-level platforms. Toronto, Los Angeles, San Diego, and Tri-Rail in South Florida are examples of systems using this method. Platform lifts are used by CalTrain in the San Francisco Bay Area and at some New Jersey Transit commuter rail stations. Metra's diesel-powered lines in Chicago provide cars with on-board lifts. Exhibit 5-39 provides examples of commuter rail wheelchair loading treatments.

Exhibit 5-39
Commuter Rail Wheelchair Loading Examples

(a) San Diego

(b) Tracy, California

Ropeway Modes

Inclined Planes

Because each inclined plane in North America is unique, so are the means of providing access; due to their age, many inclined planes are inaccessible as a result of the vehicle and/or station design.

Access is much easier to provide when the car floor is level, rather than when the seats are tiered (as is the case on most inclined planes). Johnstown, Pennsylvania, has level loading from each end. The Horseshoe Curve funicular, near Altoona, Pennsylvania, provides level loading from each side of the car.

Several access methods have been developed for tiered cars. The funicular at the Industry Hills Resort in California was designed to carry golf carts and has a series of terraced ramps leading to each car tier. Pittsburgh's Monongahela Incline has an elevator inside the lower station to take wheelchairs to the top tier loading area; wheelchairs exit on the level at the top station. Los Angeles' Angels Flight (closed as of 2001) used an inclined platform lift (like those used on stairways) to bring wheelchairs to the top car level; wheelchairs exited on the level at the top station.

Aerial Ropeways

In the past, gondola access required that the entire system be brought to a stop to load and unload wheelchairs because boarding normally occurred as the carriers circulated through the station while moving (typically at 50 ft/min or 15 m/min) and there was a vertical gap between the cabin floor and the platform that needed to be overcome. Newer designs provide a trench in the platform floor that the gondola passes through, allowing level loading. Clutching equipment allows an individual carrier to be brought to a near-stop to load wheelchairs, without stopping the entire system. Aerial tramways provide level boarding from the platform into the cabin; however, elevators or ramps may be needed to access the platform.

SYSTEM DESIGN

Although the procedures in Part 5 are focused on normal operating conditions, it is prudent to consider the impacts of abnormal conditions. Three areas in particular to consider are (1) the potential impacts of disabled trains on system operation, (2) routine track maintenance, and (3) handling special event crowds.

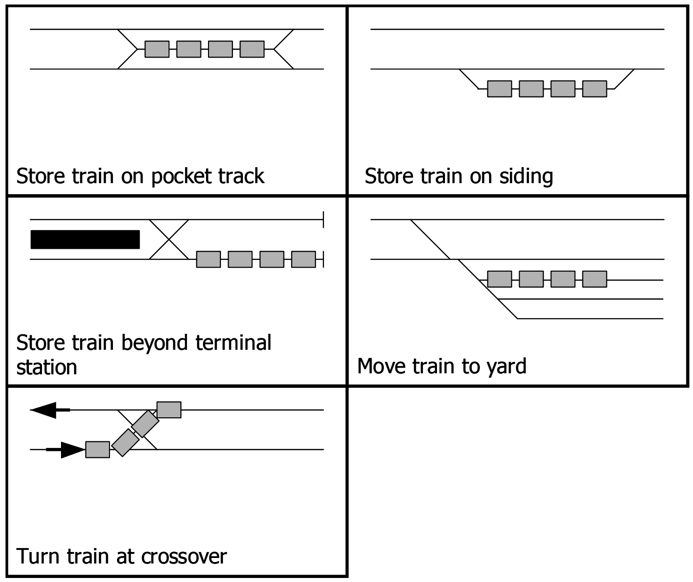
Disabled Trains

When a train needs to be taken out of service, it is desirable to get it off the main line as quickly as possible. In a typical two-track operation, this means moving it to a place where it can be temporarily stored, moving it into a yard, or turning it back on the opposite track. The train will likely not be able to move at its normal speed, which means that the trains following it will catch up to it and be delayed. The longer the disabled train remains on the line, the more trains will be delayed. Because the disabled train, and the ones delayed behind it, will occupy signal blocks for longer periods of time, train headways will increase and line capacity will decrease. The longer headways mean that more passengers will accumulate on platforms between trains, potentially leading to platform crowding. In addition, passengers on a disabled train will need to be off-loaded; the station where they off-load will have passengers of its own on the platform waiting to board the train, and the platform should be designed to accommodate all of those passengers. Finally, when a system operates close to capacity, any significant delay will use up a train's terminal recovery time, resulting in potential delays later on in the reverse direction. As can be imagined, a disabled train can quickly cause delays and crowding that ripple along the line, and which may take a long time to clear up.

Crossovers can be used to short-turn trains to help recover from delays.

Exhibit 5-40 shows examples of ways that a rail system can be designed to accommodate disabled trains. Trains can be stored off the main line in a pocket track accessible to both main tracks (allowing the train to be reversed later if needed), on a siding accessible to only one direction, or in a storage track beyond a terminal station. If a yard is convenient to the train's location, it can be removed from the line altogether. Finally, a train can be turned back at a crossover—either to get to a storage track or to move it in a direction where it will delay fewer people. Crossovers can also be used to short-turn trains in advance of their scheduled terminus—this can help to fill a gap in the sequence of trains in the reverse direction, helping to reduce the time needed to recover from the delay, at the expense of further delaying passengers traveling beyond the station where the train makes its short turn.

Exhibit 5-40
System Design Features for Accommodating Disabled Trains



Guidance on estimating line capacity with a disabled train.

The spacing of storage tracks and crossovers requires balancing initial capital costs when constructing the system with the amount of delay a system is willing to tolerate when a train breaks down. Physical constraints, particularly when tracks are elevated or underground, must also be considered. Train headways and the resulting line capacity as a result of a disabled train can be estimated from agency experience, or by using an assumed disabled train operating speed, the resulting block traversal time, and increased dwell times for subsequent trains resulting from the longer headways and greater passenger accumulations in stations.

Track Maintenance

Many rail systems do not operate 24 hours a day, in order to provide a window of time to conduct routine track maintenance when the tracks are out of service (e.g., from 1 a.m. to 4 a.m.). However, some projects may require more time than this window allows, or an agency may have a need for 24-hour operation. An alternative means of moving passengers must be developed when a track needs to be taken out of service during regular service hours.

Single-track rail operation.

If passenger demand is low, the remaining in-service track can be used in single-track operation to move trains around the work area if signaling is provided for the wrong-side direction. However, the capacity of both directions will be greatly reduced. The single-track capacity procedures in Chapter 8 can be used in these circumstances, given a known distance between crossovers.

If single-track operation does not provide sufficient capacity to meet passenger demand, another alternative is to provide a bus bridge. In this situation, trains are turned back on either side of the work area, and passengers transfer to buses to meet a train on the other side of the work area or to reach a destination station within the work area.

Bus bridges.

MTA-New York City Transit is able to take advantage of the third and fourth tracks that exist on many of its major lines to close tracks for maintenance and maintain two-direction operations.

Use of express tracks.

Special Events

Special events—such as sporting events, concerts, and community festivals—can generate very large passenger demands during a short span of time. While passengers are willing to tolerate longer delays and greater levels of crowding under these circumstances than they might otherwise, system design should still consider any special train storage needs in order to make sure that crowds can be transported away from the event site in a reasonable period of time. San Diego, for example, designed its Qualcomm Stadium station with storage for 18 cars—enough room for five 3- to 4-car trains. For Super Bowl XXXII, San Diego closed the Mission San Diego station, a terminal station one station east of the stadium, which allowed storage on the main tracks for twenty-one 3- to 4-car trains. Light rail was able to transport 29,800 passengers—30% of the Super Bowl's attendance—within 2 hours following the end of the game.[R22]

Train storage needs.

Crowd management is another issue requiring consideration. Security personnel are usually needed to keep passengers off tracks and to limit platform access to avoid overcrowding problems. Providing pre-sold return tickets and/or providing mobile ticket sales outlets minimizes crowds and delays at ticket machines. Platforms should be sized to accommodate expected special event crowds, and additional temporary space may be required to queue passengers when there are constraints on platform space. For example, Muni's 2nd & King light rail station, adjacent to San Francisco's baseball stadium, is located in a street median and has little platform room for large event crowds. Instead, passengers are queued using portable fences in the adjacent closed-off street following games, and are allowed onto the platform when a train arrives. San Diego's Qualcomm Stadium station has three platforms, allowing trains to be loaded from both sides, minimizing dwell time.

Crowd management.

Demand management measures can be used to spread out passenger demand following sporting events, and thus minimize platform crowding. During the sold-out first season at Safeco Field, for example, the Seattle Mariners provided post-game trivia contests and a ceremonial closing of the stadium's retractable roof to encourage a portion of the fans to linger after the game.

Demand management.

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CHAPTER 6. PLANNING APPLICATIONS

INTRODUCTION

Growth and Capacity

"Capacity," as defined in this manual, is the maximum achievable capacity when the system is saturated and provided with a full complement of rolling stock. It is not the capacity that a rail transit line will provide on opening day or reach after a decade. Instead, it 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 5 to 10 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 line 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 the demand is 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 600-ft (180-m) trains and platforms will be required, 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.

Planning Assumptions

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 planning procedures require two main inputs: (1) train control system and (2) train length

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 5.4 ft^2 (0.5 m^2). As this is a peak hour average, no peak hour factor is required.

Key assumptions are:
- Flying junctions or no junctions
- No turnback constraints
- The sum of dwell time and operating margin at the critical station is no more than 70 s
- No speed-restrictive curves or grades on the critical station approach
- Adequate supply of rolling stock

This procedure assumes system and vehicle characteristics that are close to the industry norms listed in Exhibit 5-41. It also assumes that there are no speed-restrictive curves or grades over 2% on the approach to the station with the longest dwell time, and that the power supply voltage is regulated within 15% of specifications. Finally, it assumes an adequate supply of rolling stock, and a system design that ensures that junctions (including multiple line merges) and turnbacks will not be the capacity constraint.

If any of these assumptions are not met, then the planning procedures should be used only as guidelines and the detailed procedures in the following chapters should be used to determine capacity.

Exhibit 5-41
Rail Transit Performance Assumptions for Planning Applications(R15)

Description	Default
Grade into headway critical station	< ± 2%
Distance from front of train to station exit block	<35 ft (<10 m)
% service braking rate	75%
Time for overspeed governor to operate	3.0 s
Time lost to braking jerk limitation	0.5 s
Service acceleration rate	4.3 ft/s^2 (1.3 m/s^2)
Service deceleration rate	4.3 ft/s^2 (1.3 m/s^2)
Brake system reaction time	1.5 s
Maximum line velocity	60 mph (100 km/h)
Dwell time	35-45 s
Operating margin	20-25 s
Line voltage as % of normal	>85%
Moving block safety distance	165 ft (50 m)
Average peak hour passenger loading level—light rail	1.5 p/ft length (5 p/m)
Average peak hour passenger loading level—heavy rail	1.8 p/ft length (6 p/m)
Car length—light rail	100 ft (30 m)
Car length—heavy rail	80 ft (25 m)

Capacity Analysis Categories

For capacity analysis, heavy rail, light rail, commuter rail, AGT, and ropeway modes are grouped into unique categories based on alignment, equipment, train control, and operating practices. Each of these categories has its own detailed procedures within the subsequent chapters. Because of the uniformity of equipment used by heavy rail, light rail, and commuter rail using electric multiple-unit vehicles, default values can be applied to the detailed procedures for these modes to develop planning-level capacity estimates. Planning-level capacities for ropeway modes are also provided in this chapter.

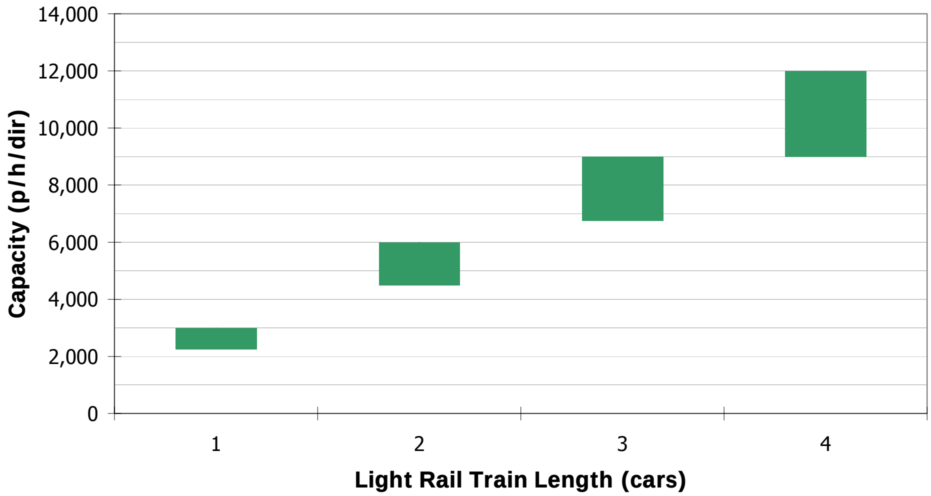
Commuter rail that uses diesel locomotives or shares tracks with other types of trains is not covered by the planning-level procedures, because of the wide range of locomotive performance, and because of the significant influence of location-specific characteristics, such as infrastructure design and the mix and volume of other trains. As an alternative, Appendix B can be consulted to identify the number of trains per hour per direction currently operated by North American commuter rail systems during the peak hour.

AGT uses proprietary designs and widely varying vehicle sizes. In addition, the use of off-line stations on certain AGT systems is unique to this mode and requires separate examination. Consequently, no planning-level procedures are provided. However, Chapter 10 can be consulted for detailed methods on calculating AGT capacity.

GRADE-SEPARATED RAIL CAPACITY

Systems Designed for Economy

Systems that are designed economically for the minimum *planned* train headway, rather than the minimum *possible* train headway—typically, light rail systems—will design the signal and power system to accommodate this minimum planned headway. In these cases, line capacity is directly related to the signaling constraint built into the system (assuming no significant single-track sections), and person capacity is then directly related to the line capacity and the train length. Exhibit 5-42 shows the hourly directional person capacity of light rail systems designed for a particular minimum planned headway and a particular maximum train length.



NOTE: Signal system design headway ranges from 3 minutes (upper bound) to 4 minutes (lower bound).

Exhibit 5-42
Capacity of Light Rail Systems Designed for Minimum Planned Headway

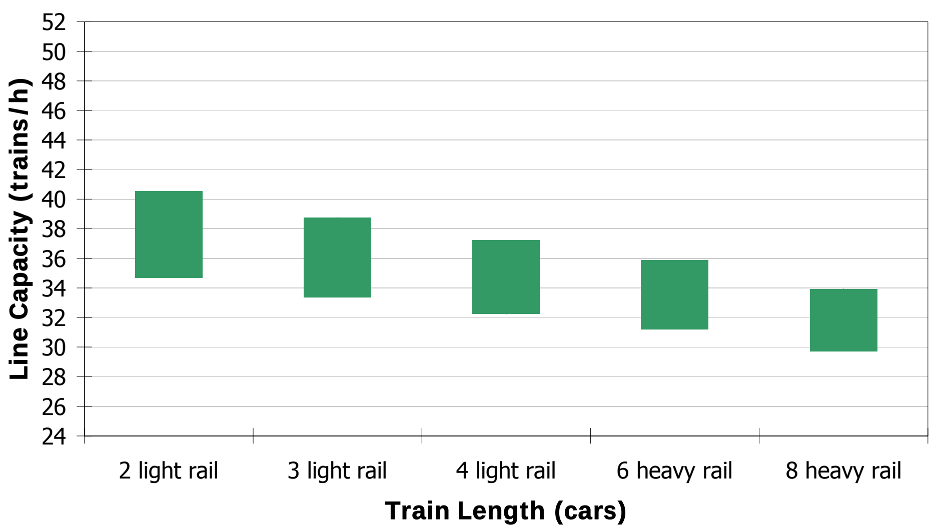
This exhibit assumes no significant (longer than 0.25 mi or 400 m) single-track sections.

Systems Designed for Maximum Capacity

As described in Chapter 2, three types of signaling systems are possible: fixed-block, cab, and moving-block. New systems that are designed for maximum capacity would not use the more limited and more expensive (due to the number of signal installations required) three-aspect fixed-block signaling system. A fixed-block system may be used for systems designed for less than maximum throughput, in which case Exhibit 5-42 should be used. Consequently, the choice of train control system is limited to cab and moving-block signaling. Exhibits 5-43 through 5-46 give line capacity and person capacity for both cab and moving-block signaling systems, based on the assumptions given in Exhibit 5-41.

A three-aspect fixed-block system typically can support no more than 30 trains per hour—and less if a line has flat junctions or a station with extended dwell times.

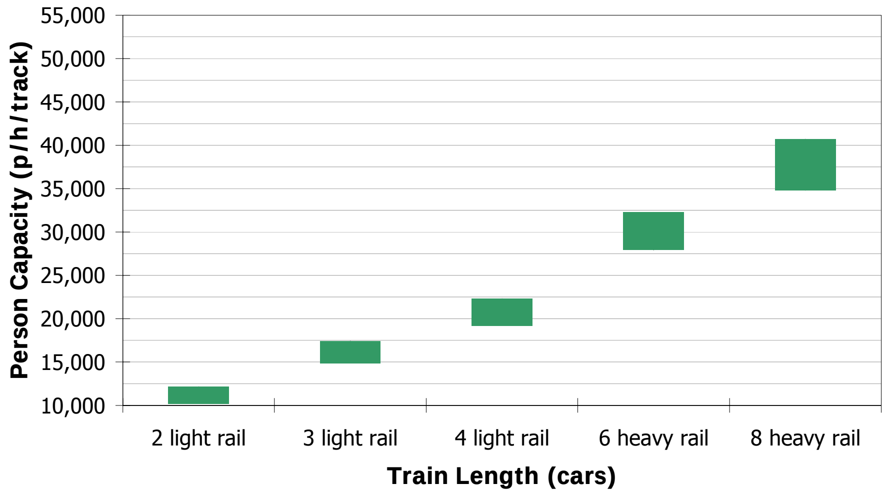
Note that with the exception of San Francisco's Muni Metro, signaled grade-separated light rail lines are rarely provided with the minimum headway capabilities represented by the capacity ranges in Exhibit 5-43 and Exhibit 5-45. Also, operating experience in North America suggests a maximum of 30 trains per hour for conventional rapid transit lines. It is apparent from the observed operating experience in New York and Washington that higher dwell times at critical stations prevent the achievement of capacities greater than 30 trains per hour.



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

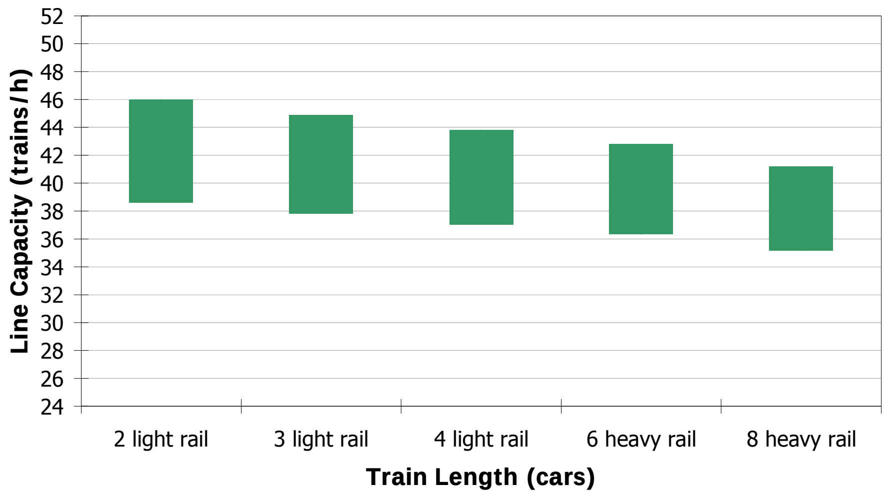
Exhibit 5-43
Grade-Separated Line Capacity—Cab Signaling

Exhibit 5-44
Grade-Separated Person Capacity—Cab Signaling



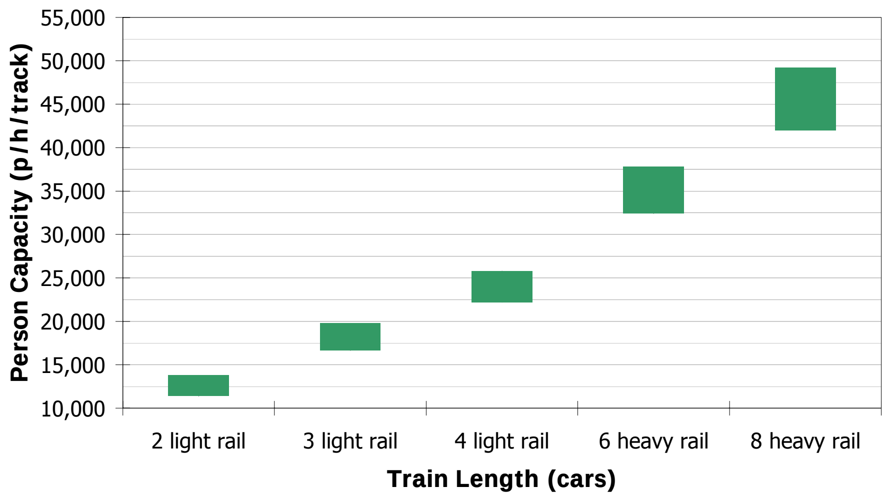
NOTE: Combination of dwell time and operating margin ranges from 55 s (upper bound) to 70 s (lower bound).

Exhibit 5-45
Grade-Separated Line Capacity—Moving-Block Signaling



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

Exhibit 5-46
Grade-Separated Person Capacity—Moving-Block Signaling



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

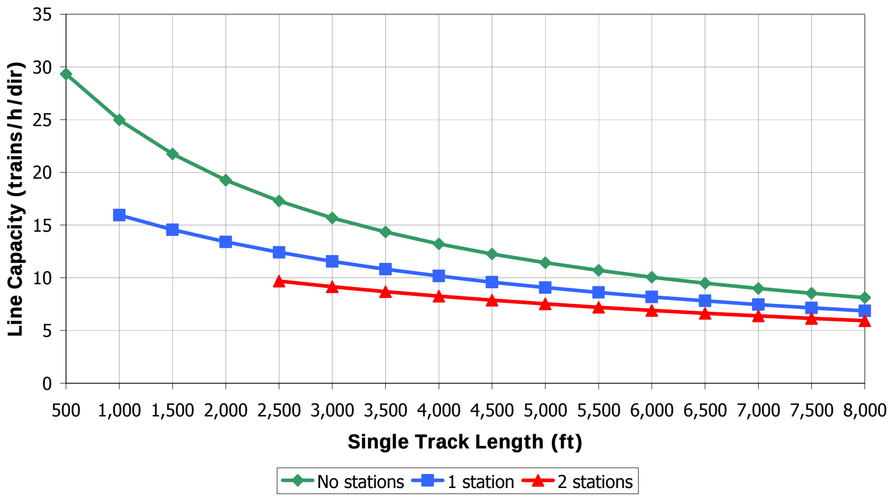
LIGHT RAIL CAPACITY

Light rail can operate in a variety of rights-of-way, each of which can potentially control capacity. The first of these types, grade-separated, was covered in the previous section. The remaining types—single-track, exclusive lane, and private right-of-way with grade crossings—are covered in this section. Definitions and examples of each right-of-way type can be found in Chapter 8. The lowest capacity of the various right-of-way types along the line will control the overall capacity.

Single Track

Single-track sections with two-way operation will typically be the capacity constraint when they are present. Exhibit 5-47 provides the directional line capacity of single-track sections of various lengths, with and without stations within the single-track section. Exhibit 5-48 provides the directional person capacity. The exhibits are for 2-car trains. The line capacity for longer trains will be slightly lower for short single-track sections with no stations (approximately 5% lower for a 650-ft [200-m] long section), but nearly the same for long sections, or when stops are made within the single-track section.

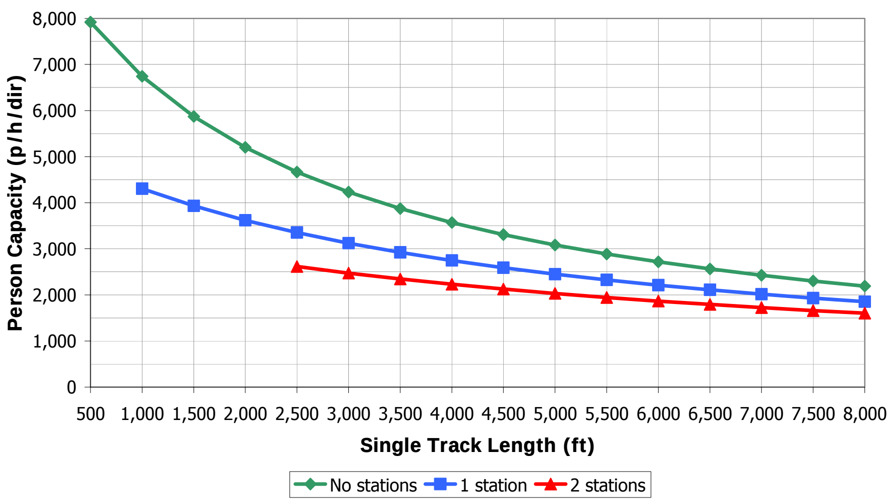
Exhibit 5-47
Single-Track Line Capacity—Two-Car Light Rail Trains



NOTE: Assumes 35-mph speed limit, 180-ft train length, 20-s dwell time, and 20-s operating margin.

An alternative figure using metric units appears in Appendix A.

Exhibit 5-48
Single-Track Person Capacity—Two-Car Light Rail Trains



NOTE: Assumes 35-mph speed limit, 180-ft train length, 20-s dwell time, and 20-s operating margin.

An alternative figure using metric units appears in Appendix A.

Exclusive Lane Operation

The minimum sustainable headway in exclusive lane on-street operations is typically twice the longest traffic signal cycle length. When cycle lengths are long and no signal priority is provided for light rail, exclusive lane operation may constrain capacity. Exhibit 5-49 provides the line capacity for a variety of signal cycle lengths, and Exhibit 5-50 provides the corresponding person capacity. These exhibits are not applicable to streetcar operation where more than one streetcar can occupy a station or stop at a time or where streetcars operate in mixed traffic.

Exhibit 5-49
Light Rail Line Capacity—Exclusive Lane Operation

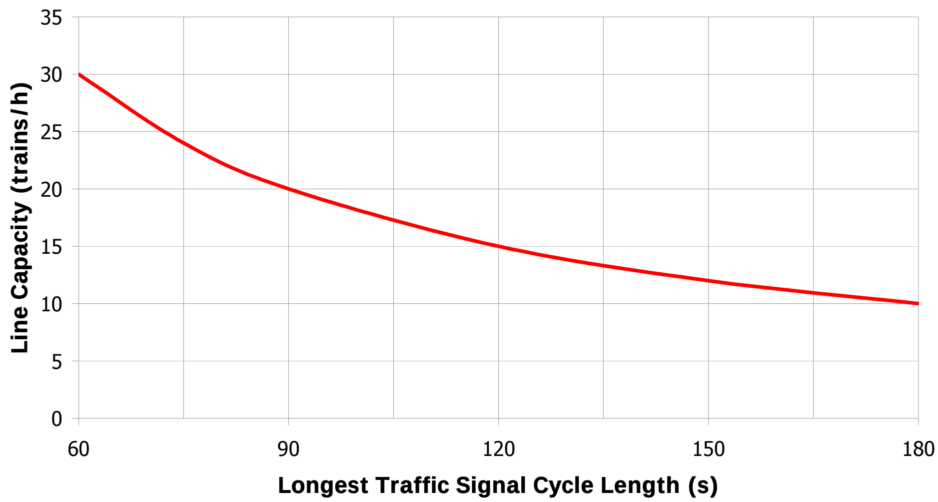
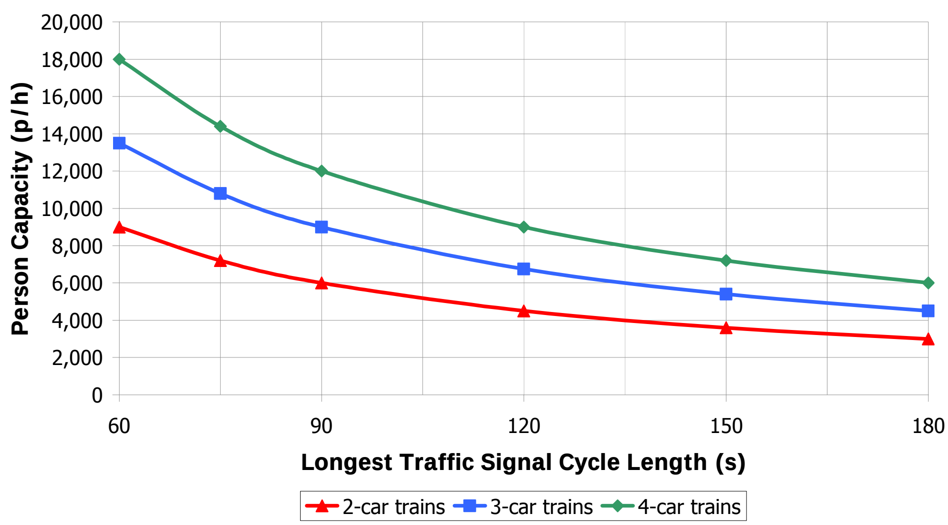


Exhibit 5-50
Light Rail Person Capacity—Exclusive Lane Operation

Exclusive lane, on-street operation is unlikely to be the capacity constraint when traffic signal cycle lengths are relatively short.



Private Right-of-Way with Grade Crossings

This category includes railroad-type operations, with street crossings controlled by gates, and operations within street medians, with street crossings controlled by traffic signals. When trains have full pre-emption of traffic (e.g., at gated crossings, or when full signal pre-emption is provided at traffic signals), use the grade-separated capacity charts. Additional dwell time may need to be allowed when station exits are located near grade crossings and pre-emption of the crossing is not allowed until passenger movements have ceased and the train is ready to leave the station. When trains do not have full pre-emption of traffic, use the exclusive-lane charts above.

COMMUTER RAIL CAPACITY

The capacity of commuter rail systems operated with electric multiple-unit trains on exclusive rights-of-way can be determined using the procedures for grade-separated systems given earlier in this chapter. The capacity of other types of commuter rail systems—those using diesel locomotives and/or sharing tracks with other types of trains—is best determined using simulation. The factors that prevent the development of either planning-level or detailed capacity methodologies for the latter types of commuter rail are discussed in Chapter 9. Appendix B can be consulted to find out the number of trains currently being operated by various North American commuter rail systems.

Commuter rail capacity often is best determined using simulation.

AUTOMATED GUIDEWAY TRANSIT CAPACITY

AGT systems often operate with electrically powered vehicles and always on exclusive rights-of-way. However, there are a number of different proprietary designs for AGT systems, each with its own vehicle performance characteristics, minimum train separations, and vehicle sizes. These variations prevent the description of a "typical" AGT system, and therefore no planning-level methodology is provided. Consult Chapter 10 for detailed capacity procedures for AGT.

No planning method is provided for AGT due to wide variations in system characteristics.

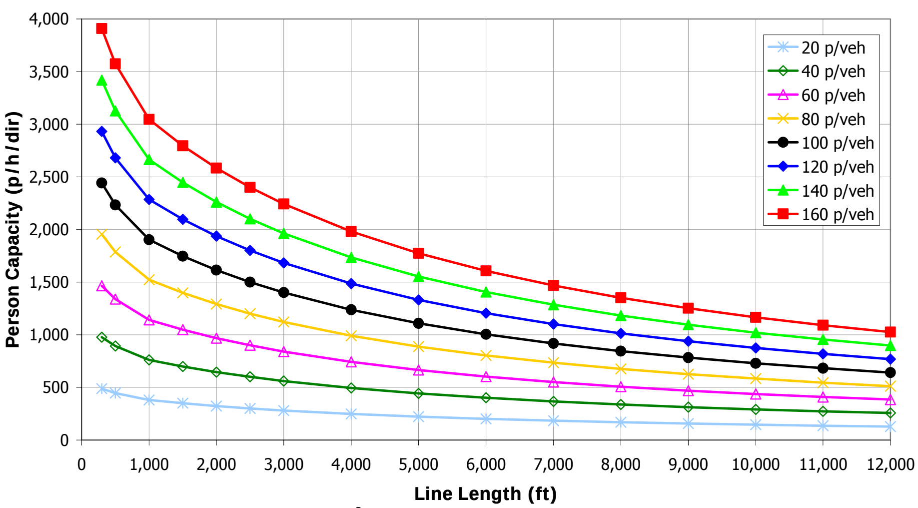
ROPEWAY CAPACITY

Ropeway systems can be classified into two categories for capacity analysis: (1) reversible systems, where one or two vehicles shuttle back and forth along a line, and (2) continuously circulating systems, where vehicles or cabins circulate around a loop. Reversible modes include aerial tramways and inclined planes. Circulating modes include gondolas and cable-hauled automated people movers.

Reversible System Capacity

The line capacity of a reversible system is dependent mainly on the length of the line and the speed at which a vehicle (train or cabin) can move from one end of the line to the other. Acceleration and deceleration delays and station dwell time are also major components of line capacity for shorter systems. Exhibit 5-51 provides the person capacity of reversible systems of various lengths and vehicle sizes, assuming two-vehicle operation and line speeds toward the upper end of modern aerial tramways and inclined planes.

Exhibit 5-51
Reversible Ropeway Person Capacity



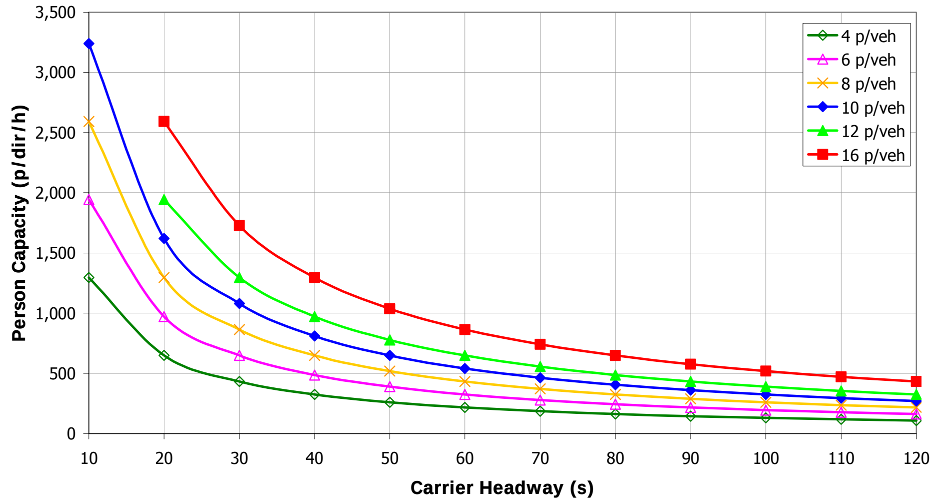
NOTE: Assumes 33 ft/s line speed, 0.66 ft/s^2 acceleration, two-vehicle operation, no intermediate stations, 90-s dwell time, and 0.90 PHF.

An alternative figure using metric units appears in Appendix A.

Exhibit 5-52
Gondola Person Capacity

Continuously Circulating System Capacity

The line capacity of a continuously circulating system is dependent solely on the spacing of carriers or vehicles on the line. Person capacity, therefore, is simply a function of line capacity, vehicle size, and passenger arrival characteristics. Exhibit 5-52 provides the person capacity of detachable-grip gondola systems with different cabin sizes and headways.



NOTE: Assumes a peak hour factor (PHF) of 0.90.

CHAPTER 7. GRADE-SEPARATED SYSTEMS

INTRODUCTION

Earlier chapters developed the methodologies for each of the components affecting rail transit capacity. Chapter 6 provided planning-level estimates of rail capacity. Chapter 7 now brings the prior methodologies together by developing detailed capacity calculations for the principal category of grade-separated rail, which accounts for almost 80% of rail transit passenger trips in North America.

Grade-separated rail defined.

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 AGT, some of the heaviest-volume commuter rail lines, and sections of most light rail systems.

Light rail transit.

Light rail transit operates in a variety of rights-of-way, each of which has specific line capacities. Chapter 8 contains the procedures to determine capacity for the sections of light rail that are not double-track grade-separated sections. Single-track sections, when present, are usually the capacity limitation. However, these are rare and line capacity is usually controlled by the signaling throughput of grade-separated sections—determined by the procedures of this chapter.

This control on line capacity is due to two possible reasons. First, several light rail systems converge surface routes into a signaled grade-separated section operating at, or close to, capacity. Second, other less busy systems have the signaled grade-separated sections designed economically, rather than for maximum train throughput. Typically, this signaling is designed for 3- to 4-minute headways, rather than minimum 2-minute headways, and will usually prove to be more restrictive than the headway limitations of on-street operation, with or without varying forms of traffic signal priority. However, signaled grade-separated sections may not always be the prime headway limitation, and Chapter 8 explains how to calculate and determine the weak link in the capacity chain for light rail.

Rail capacity is determined by the weak link in the capacity chain—whether dwell time, turnback time, junction constraints, signaling type, or right-of-way type.

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

DETERMINING THE WEAKEST CAPACITY LINK

Chapter 2 developed the methodology for the train control system maximum throughput in two special situations: junctions and 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 650-ft (200-m) 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 5-5 to determine the junction throughput limitation.

Chapter 2 similarly shows that a two-track terminal station can turn 650-ft (200-m) 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. Chapter 2 suggests 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, turnbacks 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 5-4 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 5-4 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 movement 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.

GRADE-SEPARATED CAPACITY CALCULATION PROCEDURE

When junctions and turnbacks are not the capacity constraint, the combination of station close-in and dwell time will be the constraint. Should a junction or turnback 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 capacity 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.

A spreadsheet that implements the grade-separated capacity procedure is provided on the accompanying CD-ROM.

Consider using the planning graphs in Chapter 6 when input variables must be defaulted.

These values can be calculated manually or by using the spreadsheet provided on the accompanying CD-ROM. When there is uncertainty about these values—fully described in Chapters 3 through 5—or where several of the performance variables are unknown (e.g., the technology or specific vehicle has not been selected), then the use of this procedure is not recommended. The planning graphs found in Chapter 6 provide *generic achievable capacity ranges* 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 extensions to Vancouver's SkyTrain are examples.

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 2-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.

Ridership models.

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

This step develops the methodology for determining the minimum train separation with three types of train control systems, each providing progressively increased throughput:

1. Three-aspect fixed-block signaling system,
2. Multiple-command cab signaling, and
3. Moving-block signaling system.

Although the equations that follow appear long, the arithmetic is simple and can be implemented using basic functions in a spreadsheet. However, before going to this effort, check the availability of the required input parameters in Exhibit 5-53. Parameters can be adjusted for system specific values or left at their default value. Train length is the most important variable. If most parameters are left at their default values, it would be simplest to refer to Exhibit 5-54, which shows the minimum train control separation against train length for the three types of train control system.

Exhibit 5-53
Minimum Train Control Separation Parameters(R15)

Default Value	Term	Description
calculated	t_{cs}	train control separation in seconds
650 ft, 200 m	L	longest train length
35 ft, 10 m	d_{eb}	distance from the front of stopped train to start of station exit block in feet or meters
calculated	v_a	station approach speed in ft/s or m/s
88 ft/s, 27.8 m/s	v_{max}	maximum line speed (88 ft/s = 60 mph , 27.8 m/s=100 km/h)
75%	f_{br}	braking safety factor—worst-case service braking is f_{br}% of specified normal rate—typically 75%
2.4—three-aspect, 1.2—cab, 1.0—moving block	b	separation safety factor—equivalent to number of braking distances (surrogate for blocks) that separate trains
3.0 s	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 s	t_{jl}	time lost to braking jerk limitation
1.5 s	t_{br}	brake system reaction time
4.3 ft/s^2, 1.3 m/s^2	a	initial service acceleration rate in ft/s^2 or m/s^2
4.3 ft/s^2, 1.3 m/s^2	d	service deceleration rate in ft/s^2 or m/s^2
32 ft/s^2, 10 m/s^2	a_g	acceleration due to gravity in ft/s^2 or m/s^2
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
20.5 ft, 6.25 m	P_e	positioning error—moving block only, in feet or meters
165 ft, 50 m	S_{mb}	moving-block safety distance—moving block only, in feet or meters

Exhibit 5-54
Minimum Train Separation versus Length(R15)

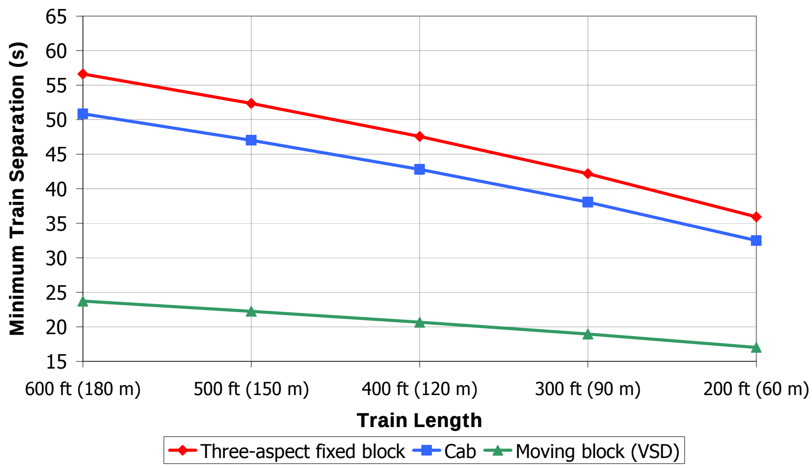
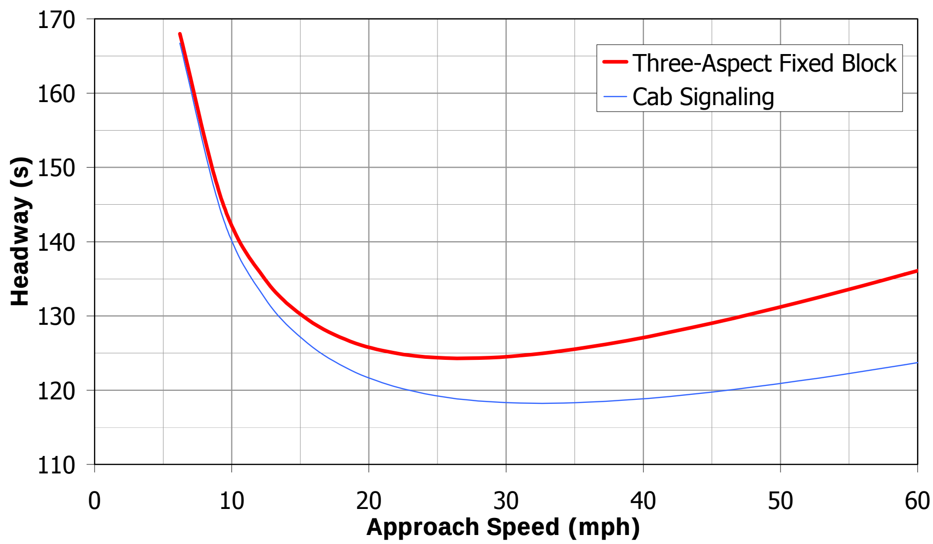


Exhibit 5-55 shows minimum station headways achieved using the typical values shown in Exhibit 5-53, derived from the equations presented later in this section, and including an assumed dwell time and operating margin. The optimum approach speeds shown in this exhibit should be compared with the maximum speeds imposed by switches and curves in the vicinity of the maximum load point station.

Exhibit 5-55
Station Headway for Lines at Capacity(R15)

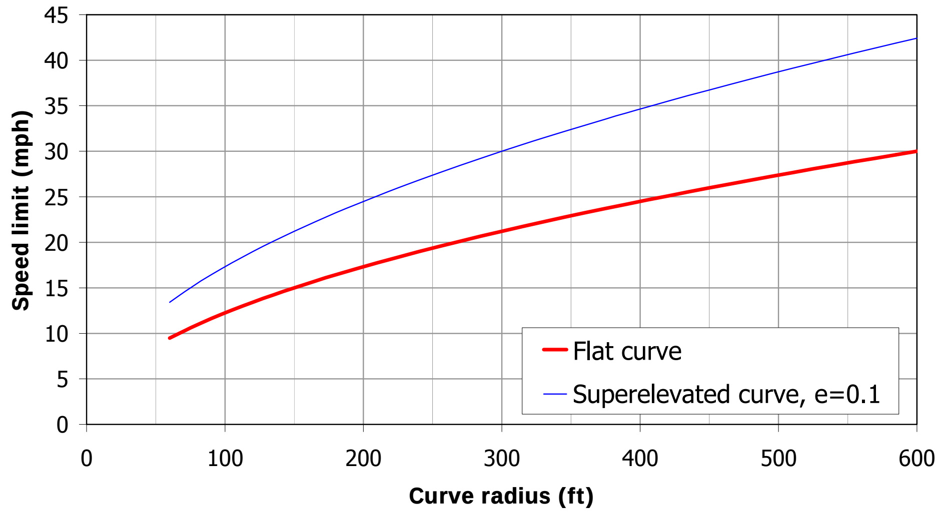
An alternative figure using metric units appears in Appendix A.



NOTE: dwell = 45 s, operating margin = 20 s.

Optimum approach speeds.

Exhibit 5-55 shows that the optimum approach speed for three-aspect fixed-block signaling in this situation is 28 mph (45 km/h), while, for cab signaling, the optimum approach speed is 32 mph (52 km/h). 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 curves and turnouts (switches) are shown in Exhibit 5-56 and Exhibit 5-57, respectively. Determine any such station approach speed restrictions and their distance from the station stopping point. Next, compare this speed restriction with the normal approach speed at that distance from the station as shown in Exhibit 5-58. The most restrictive approach speed must then be used in the equations presented in this section.



NOTE: Transition spirals are not taken into account.

Exhibit 5-56
Speed Limits on Curves(R15)

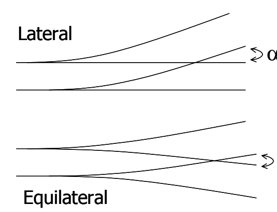
Curves and turnouts (switches) impose speed restrictions.

An alternative figure using metric units appears in Appendix A.

Turnout Number	Lateral Turnout mph	Lateral Turnout km/h	Equilateral Turnout mph	Equilateral Turnout km/h
#6	15	24	21	34
#8	20	32	28	45
#10	25	40	35	57
#20	50	81	70	113

SOURCE: AREMA Manual for Railway Engineering (R6)
NOTES: Speeds shown are based on freight trains using level turnouts with curved switch points. Intercity passenger and rail transit cars are designed for greater roll through curves and can operate comfortably at somewhat higher speeds than shown. Many agencies have their own speed limits for turnouts that differ from those shown. For example, Denver RTD uses speeds for lateral turnouts that are 5 mph (8 km/h) *slower* than those shown.

Exhibit 5-57
Speed Limits on Turnouts



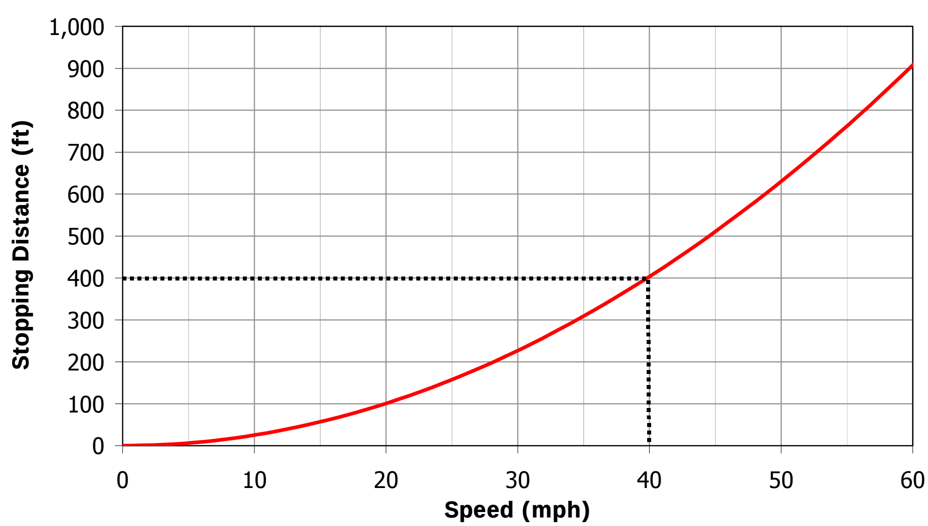


Exhibit 5-58
Distance-Speed Chart(R15)

Use this chart to find how far from the station a computed optimal approach speed will occur, then determine if there is a lower speed limit at that location.

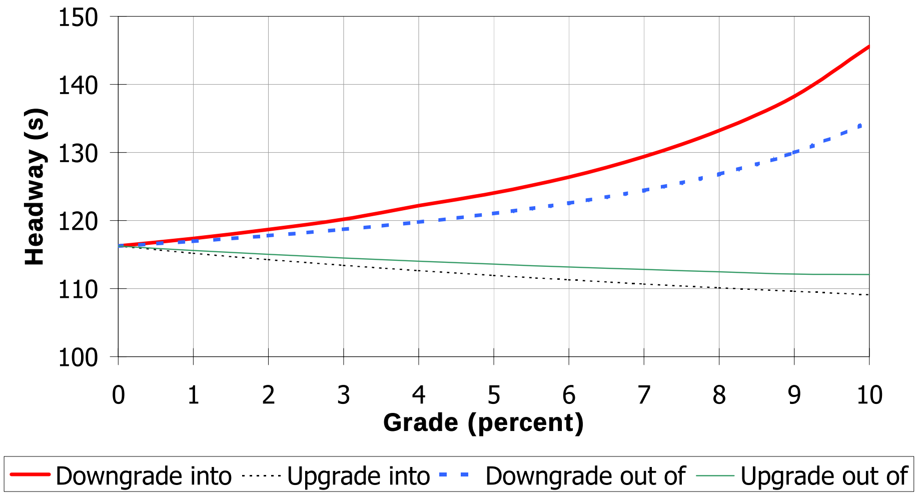
An alternative figure using metric units appears in Appendix A.

The dotted line example in Exhibit 5-58 shows that at 400 ft (120 m)[15] from a station, the approaching train will have a speed of 40 mph (64 km/h). If there is a speed limit at this point that is lower than 40 mph (64 km/h), then the minimum train separation, t_{cs}, must be calculated with the approach speed, v_a, set to that limit.

15 Distance from the front of the approaching train to the stopping point.

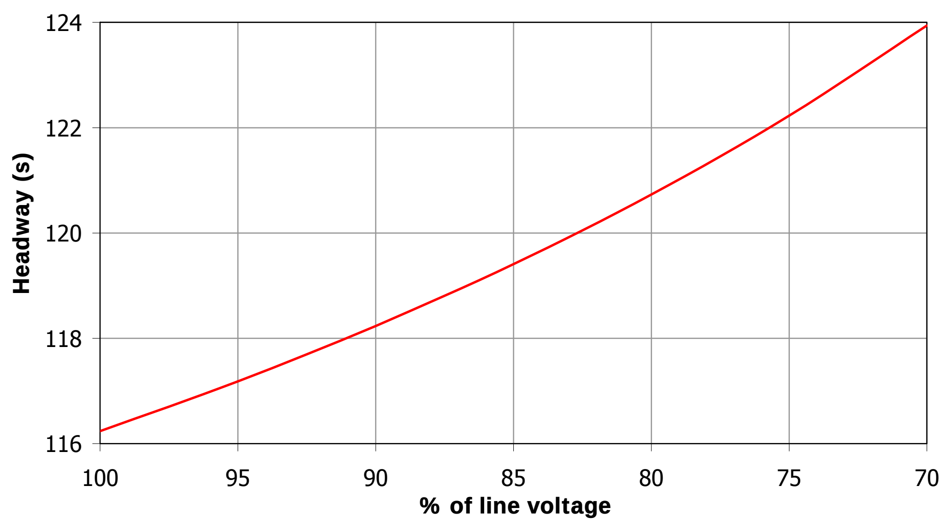
Two other factors affect minimum headways. Grades into or out of a station will change the acceleration and braking rates. Line voltage will drop below the nominal value on heavily used systems and reduce train performance. The results of grades and voltage drops are shown in Exhibit 5-59 and Exhibit 5-60, 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 5-59 and Exhibit 5-60, and the calculations adjusted by the appropriate number of seconds.

Exhibit 5-59
Effect of Grade on Station Headway(R15)



NOTE: cab signals, dwell = 45 s, operating margin = 20 s.

Exhibit 5-60
Headway Changes with Voltage(R15)



Fixed-Block and Cab Signaling Throughput

The minimum train control separation for fixed-block and cab signal systems is given by Equation 5-7, with variables as shown in Exhibit 5-53:

Equation 5-7

$$t_{cs} = \sqrt{\frac{2(L_t + d_{eb})}{a(1-0.1G_o)}} + \frac{L_t}{v_a} + \left(\frac{100}{f_{br}} + b\right)\left(\frac{v_a}{2d}\right) + \frac{a(1-0.1G_i)l_v^2 t_{os}^2}{20{,}000 v_a}\left(1 - \frac{v_a}{v_{max}}\right) + t_{os} + t_{jl} + t_{br}$$

Compare the approach speed producing the minimum train separation to any speed restrictions on the station approach.

This equation should be solved for the minimum value of t_{cs}. The approach speed, v_a, that produces this minimum value must then be checked against any speed restrictions approaching the station from Exhibit 5-58.

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 5-8 determines the train control separation for a moving-block signaling system with fixed safety separation, with variables as given in Exhibit 5-53. Note that the time for the overspeed governor to operate is incorporated into the safety distance and so does not appear in the equation.

Equation 5-8

$$t_{cs} = \frac{L + S_{mb}}{v_a} + \frac{100}{f_{br}}\left(\frac{v_a}{2d}\right) + t_{jl} + t_{br}$$

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.

Higher throughput is usually obtained with a moving-block signaling system with a variable safety distance consisting of the braking distance at the particular speed plus a runaway propulsion allowance. The minimum train control headway of such a system is given by Equation 5-9, with variables and default values as given in Exhibit 5-53.

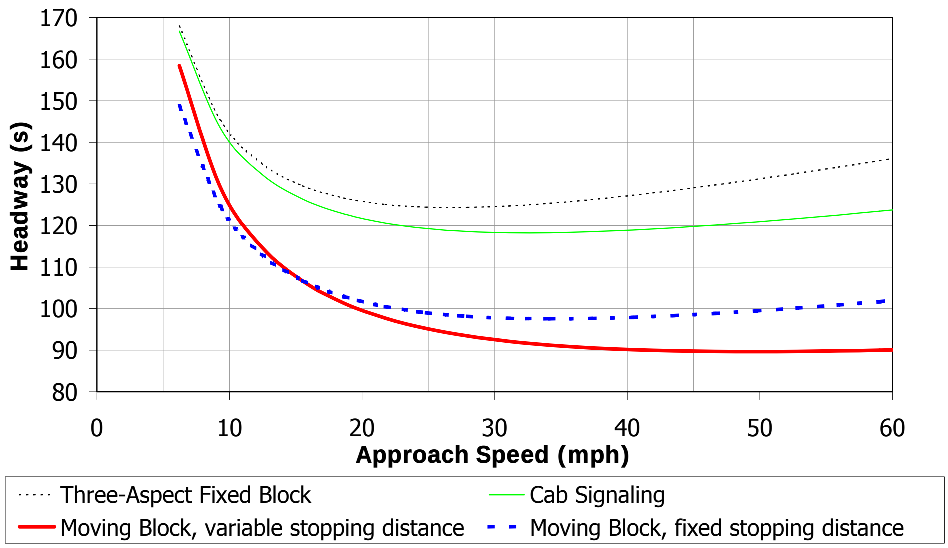
Equation 5-9

$$t_{cs} = \frac{L_t + P_e}{v_a} + \left(\frac{100}{f_{br}} + b\right)\left(\frac{v_a}{2d}\right) + \frac{a\left(1 - \frac{a_g}{100}G_i\right)l_v^2 t_{os}^2}{20{,}000 v_a}\left(1 - \frac{v_a}{v_{max}}\right) + t_{os} + t_{jl} + t_{br}$$

Equation 5-9 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.

The results of Equation 5-8 and Equation 5-9 are shown in Exhibit 5-61. The resultant minimum station headway of 97 seconds occurs at an approach speed of 35 mph (56 km/h). The respective curves for a conventional three-aspect fixed-block signaling system and a cab signaling 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 8-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 5-61
Moving-Block Station Headways Compared with Conventional Fixed-Block Systems(R15)



NOTE: dwell time = 45 s, operating margin = 20 s.

Clear capacity increases with a moving-block signaling system.

An alternative version of this exhibit appears in Appendix A.

Compare the approach speed producing the minimum train separation to any speed restrictions on the station approach.

The appropriate equation above should be solved for the minimum value of t_{cs}. The approach speed, v_a, that produces this minimum value must then be checked against any speed restrictions approaching the station from Exhibit 5-58.

Checking Results

Compare the results obtained from these equations with Exhibit 5-54. The calculated 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 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. An operating margin and the minimum train signal system separation must be added to the station dwell time to produce the headway.

The train close-in time at the headway critical station is dependent on a train's physical performance and length, as well as other fixed system characteristics, and therefore can be calculated with some precision. Station dwell time cannot be determined with the same exactitude. Virtually all the literature references related to rail transit capacity assign a set time to dwell time. Many simulations do likewise, using typical figures of 15 to 20 seconds for lesser stations and 30 to 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, which is information only available for existing systems or for new lines in areas where a station with similar passenger volumes can be analyzed.[16]

16 See Alle (R2). No operating margin should be added when controlling dwell is calculated.

Chapter 3, *Station Dwells*, 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 Chapter 6 planning applications and by most of the literature references—simply assigning a reasonable figure to the headway critical station. The second method uses field data from TCRP Project A-8 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 two standard deviations based on a comparable station on the existing network is suggested. The fourth and final method uses a statistical approach 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 more than 60 seconds. A tighter range of dwell time values—35 to 45 seconds—is used in the Chapter 6 planning procedures 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 5-62. 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 5-62 fit into the 35 to 45 second range suggested in the previous method.

Exhibit 5-62
Peak-Period Station Dwell Times for Heavily Used Systems (1995)(R15)

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

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

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,"(R15) 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. This method is not detailed further in this manual.

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.[17] A very small number of rail transit lines in the United States and Canada 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 the United States and Canada. Selecting a loading level is a policy issue and the process for this procedure is the same as that of the planning-level procedure presented in Chapter 6. Use of the passenger occupancy per unit length of train is recommended. When selecting a loading level, take into account that this level 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, 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 5-24 and Exhibit 5-25 provide a range of loading levels from 1.5 to 2.7 p/ft length (5 to 9 p/m length) for light rail, and 2.1 to 3.4 p/ft length (7 to 11 p/m 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 5.4 ft^2 (0.5 m^2) per passenger, averaged over the peak hour—that is, no peak hour factor is required. This provides a recommended linear loading level of 1.8 p/ft length (6 p/m length) for heavy rail and 1.5 p/ft length (5 p/m length) 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 5-63 shows the actual peak 15-minute linear loading levels for major North American trunks, 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.

17 A goal for an operating margin, based on an average of one *disturbed* peak period per 10 weekdays (2 weeks) has been discussed with rail transit planners but has not been documented.

Exhibit 5-63
Passengers per Unit Train Length, Major North American Rail Trunks, 15-Minute Peak (1995)[R15]

System & City	Trunk Name	Mode	Car Length (ft)	Seats	Avg. Pass/Car	Pass/ ft
NYCT (New York)	53rd Street Tunnel	HR	*see note*	50/70	197/227	3.2
NYCT (New York)	Lexington Ave. Local	HR	51.0	44	144	2.8
NYCT (New York)	Steinway Tunnel	HR	51.0	44	144	2.8
NYCT (New York)	Broadway Local	HR	51.0	44	135	2.7
TTC (Toronto)	Yonge Subway	HR	74.5	80	197	2.7
NYCT (New York)	Lexington Ave. Ex.	HR	51.0	44	123	2.4
NYCT (New York)	Joralemon St. Tun.	HR	51.0	44	122	2.4
NYCT (New York)	Broadway Express	HR	51.0	44	119	2.3
NYCT (New York)	Manhattan Bridge	HR	74.7	74	162	2.2
NYCT (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
SkyTrain (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
NYCT (New York)	60th Street Tunnel	HR	74.7	74	126	1.7
NYCT (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 Street Tunnel in 1995 was provided by line E, operating 60-ft cars, and line F, operating 75-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. The F was moved to the 63rd Street Connector in December 2001, and a new line V shared the 53rd Street Tunnel with line E.

An alternative figure using metric units appears in Appendix A.

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 5-1, with a summary of results for North American systems shown in Exhibit 5-64. The peak hour factor was also used in the optional Method 4 for calculating the station dwell time. If this method was used, then the same peak hour factor must be used to adjust the hourly capacity. Otherwise, the factor should be selected based on the rail mode and the type of system.

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.

When passenger loading is designed for a higher quality of service, with the loading standard based on an average over the peak hour rather than over the peak 15 minutes, a peak hour factor of 1.00 can be used in place of the above values.

Exhibit 5-64
Diversity of Peak Hour and Peak 15-Minute Loading(R15)

System & City	Routes	Peak Hour Factor
Commuter Rail		
LIRR (New York)	13	0.56
Metra (Chicago)*	11	0.63
Metro-North (New York)	4	0.75
NJT (New Jersey)*	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
TriMet (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
STM (Montréal)	4	0.71
TTC (Toronto)	3	0.79

* Mainly diesel-hauled—not electric multiple unit.

Step 7: Putting It All Together

The final step in the method of determining a grade-separated rail transit line's maximum capacity is to determine the closest (minimum) headway, h_{gs}, 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.

Equation 5-10

$$h_{gs} = t_{cs} + t_d + t_{om}$$

The maximum number of trains per hour, T, (line capacity) then is:

Equation 5-11

$$T = \frac{3{,}600}{h_{gs}} = \frac{3{,}600}{t_{cs} + t_d + t_{om}}$$

PERSON CAPACITY

The maximum person capacity, P, 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.

Equation 5-12

$$P = TLP_m(PHF) = \frac{3{,}600LP_m(PHF)}{t_{cs} + t_d + t_{om}}$$

where:

P = person capacity (p/h);
T = line capacity (trains/h);
L = train length (ft, m);
P_m = linear passenger loading level (p/ft length, p/m length);
PHF = peak hour factor;
t_{cs} = minimum train control separation (s);
t_d = dwell time at critical station (s); and
t_{om} = operating margin (s).

Given the range of values that can be calculated, estimated, or assigned for the components of Equation 5-12, it is appropriate that the results be expressed as a range.

The results should be checked for reasonableness against typical capacities in Exhibit 5-44 and Exhibit 5-46, which are based on the planning-level loading levels of 1.5 p/ft length (5 p/m length) for light rail and 1.8 p/ft length (6 p/m length) for heavy rail—approximately 5.4 ft^2 (0.5 m^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.

These charts are not appropriate checks for electric multiple-unit commuter rail, whose signaling systems are usually designed for lower throughput with loading levels based on all passengers being seated. 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.

CHAPTER 8. LIGHT RAIL CAPACITY

INTRODUCTION

The key is finding the weakest link in the capacity chain.

This chapter covers methods for determining the capacity of light rail transit lines. While the approach used in Chapter 7, *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.

DETERMINING 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 7 can be applied. However, most light rail transit lines use a combination of right-of-way types which can include on-street operation (often in reserved lanes) and private right-of-way with grade crossings. 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 with two-way operation,
- Signaled sections,
- On-street operation in exclusive lanes or mixed traffic, 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. The latter issues were discussed in Chapter 1.

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. A discussion of the impact of the ADA related to wheelchair provisions can be found in Chapter 5.

SINGLE TRACK

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

This constraint only applies to two-way operation; not to one-way operation, such as on a downtown one-way street grid.

Determining the potential extent of single track.

Single-track sections with two-way operation are the greatest capacity constraint on light rail lines where they are 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.

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 miles or kilometers required for a certain number of route miles or kilometers once the intended headway is known.[18] 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 capacity constraints are site-specific.

Single-track sections greater than 0.25 to 0.30 miles (400 to 500 meters) are potentially the most restrictive capacity constraint for light rail. The headway limitation is 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[19]—plus an operating margin to minimize the potential wait of a train in the opposite direction.

The time to cover a single-track section is:

Equation 5-13

$$t_{st} = S_m\left(\frac{(N_{st}+1)}{2}\left(\frac{3v_{\max}}{d}+t_{jl}+t_{br}\right)+\frac{L_{st}+L_t}{v_{\max}}\right)+N_{st}t_d+t_s+t_{om}$$

where:

t_{st} = time to cover single-track section (s);
L_{st} = length of single-track section (ft, m);
L_t = train length (ft, m);
N_{st} = number of stations on single-track section;
t_d = station dwell time (s);
v_{max} = maximum speed reached (ft/s, m/s);
d = deceleration rate (ft/s^2, m/s^2);
t_{jl} = jerk limitation time (s);
t_{br} = operator and braking system reaction time (s);
S_m = speed margin;
t_s = switch throw and lock time (s); and
t_{om} = operating margin (s).

The speed margin is an allowance for out-of-specification equipment and train operators that do not drive at exactly the maximum permitted speed. It typically ranges from 1.08 to 1.20.

The minimum headway is:

Equation 5-14

$$h_{st} = 2t_{st}$$

where:

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

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18 See Allen (R3) for more information.

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

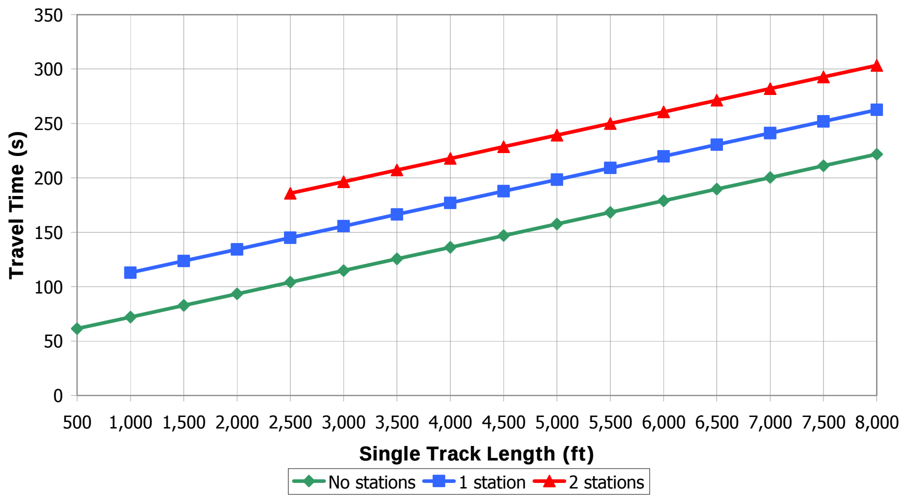
Default values for use with Equation 5-13 are given in Exhibit 5-65. The results of applying these default values are depicted in Exhibit 5-66. A spreadsheet that calculates the single-track capacity is included on the accompanying CD-ROM.

A spreadsheet for calculating single-track capacity is included on the accompanying CD-ROM.

Exhibit 5-65
Default Data Values for Single Track LRT Travel Time(R15)

Term	Value
Jerk limitation time	0.5 s
Brake system reaction time	1.5 s
Dwell time	15-25 s
Switch throw-and-lock time	6 s
Service braking rate	4.3 ft/s^2 (1.3 m/s^2)
Speed margin	1.1 to 1.2
Operating margin time	10-30 s

Exhibit 5-66
Light Rail Travel Time Over Single-Track Section(R15)



An alternative figure using metric units appears in Appendix A.

NOTE: Assumes speed limit of 35 mph, 180-foot train length, 20-s dwell time, 20-s operating margin, and other data as per Exhibit 5-65. *The recommended closest headway is twice this time.*

To estimate best headway multiply single-track time by two.

The value of the maximum single-track section speed should be the appropriate speed limit for that section. A speed of 35 mph (55 km/h) 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 priority.

Scheduling for single track.

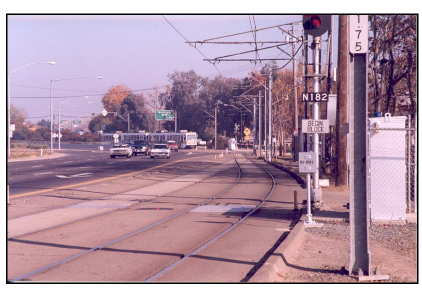
Trains should be scheduled from their termini such that passing locations are not close to the single-track sections. Where there is more than one single-track section, this can become difficult but not impossible.

Passing sections.

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

Exhibit 5-67
Single-Track Examples

(a) Seattle



(b) Sacramento

The Seattle vintage trolley example shows the effect of a short passing section: one train must wait for the other.

SIGNALED SECTIONS

Economic signaling constraints.

Restrictions due to signaled sections are largely covered in Chapter 7. 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.

Exhibit 5-68
Signaled Section Examples

(a) Portland, Oregon

(b) Denver

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 more than 60 cars per 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. Exhibit 5-69 shows examples of on-street light rail rights-of-way.

Exhibit 5-69
On-Street Light Rail Right-of-Way Types

(a) Mixed Traffic—Center Lane (Toronto)

(b) Mixed Traffic—Curb Lane (Portland, Oregon)

(c) Exclusive Lane (Salt Lake City)

(d) Exclusive Lane—Contraflow (Denver)

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 priority.

Traffic signal priority 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 priority 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 priority plays a large role in determining the effectiveness of signal priority 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 or she 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.

Vintage trolley operation.

Operating 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

Streetcars operating in mixed traffic use capacity procedures similar to buses.

Single streetcars in classic mixed operation can be treated as similar to buses and capacity determined from the procedures of Part 4 of this manual, with suitable modifications reflecting longer vehicle lengths and differences in dwell time variability.

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

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 5-15 can be used to determine the minimum headway between trains operating on-street in exclusive lanes or mixed traffic.(R13,R15)

Equation 5-15

$$h_{os} = \max\left\{ \begin{array}{l} \dfrac{t_c + (g/C)t_d + Zc_v t_d}{(g/C)} \\ 2C_{\max} \end{array} \right\}$$

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;

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

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 s or the signal cycle time) and the time for the cars of a train to clear a station (typically 5 s/car);

Z = standard normal variable corresponding to a desired failure rate, from Exhibit 4-6; and

c_v = coefficient of variation of dwell times (typically 40% for light rail, 60% for streetcars).

PRIVATE RIGHT-OF-WAY WITH GRADE CROSSINGS

Private right-of-way with grade crossings (Exhibit 5-70) 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.

Exhibit 5-70
Light Rail Private Right-of-Way Examples

(a) Private right-of-way (Philadelphia)

(b) Street median (Los Angeles)

Capacity on lines with full signal pre-emption can be determined using the methods for grade-separated rail transit given in Chapter 7. However, allowances for any speed restrictions due to grade crossings must be made. Where full signal pre-emption is not available, Equation 5-15 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 s) 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 will 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

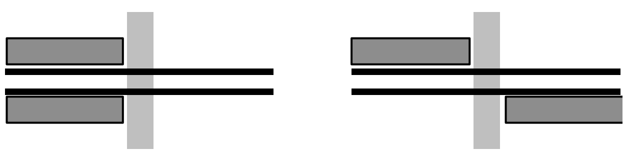
Grade crossings adjacent to stations.

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.

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 5-71. 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 5-71
Light Rail Platform Options at a Crossing[R15]

Far-side platforms can be advantageous.



(a) Facing (b) Far-side

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 (as in Portland) or by an automatic method. An extra 10 seconds dwell time is an appropriate allowance when station exits are adjacent to grade crossings, and train operators manually initiate the crossing cycle after passenger movements at the station have finished.

Additional dwell time may need to be allowed when grade crossings adjacent to station exits are manually activated.

An example of the automatic 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 contactor. 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 the United States or Canada.

TRAIN THROUGHPUT

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 that 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*—use Equation 5-13 or Exhibit 5-66.
2. *Signaled sections*—if designed for the minimum *planned* headway, use this headway; otherwise, use the procedures of Chapter 7 to find the minimum *possible* headway.
3. *On-street operation*—use Equation 5-15. Capacity effects are strongly related to the degree of priority given to light rail vehicles relative to other traffic.
4. *Private right-of-way without signal pre-emption*—use Equation 5-15. Where station exits are located adjacent to grade crossings, additional dwell time may need to be added if the crossing is activated manually by the train operator after passenger movements have ceased.
5. *Private right-of-way with grade crossings and signal pre-emption*—use the procedures of Chapter 7.

The first step in the process is to check the headway capabilities of any single-track section over 1,600 ft (500 m) in length, following the procedure given earlier in this chapter. Next, compare this headway with the design headway of the signaling system and with twice the longest traffic signal cycle of any on-street section. Select the most restrictive headway in seconds and convert this into trains per hour (line capacity) by dividing into 3,600. The following equations describe this mathematically:

Equation 5-16

$$h_{lr} = \max\begin{cases} h_{st} \\ h_{gs} \\ h_{os} \end{cases}$$

where:

h_{lr} = minimum light rail headway (s);
h_{st} = minimum single-track headway (s), from Equation 5-13;
h_{gs} = minimum grade-separated headway (s), from Equation 5-10; and
h_{os} = minimum on-street headway (s), from Equation 5-15.

The line capacity, T, in trains per hour is:

Equation 5-17

$$T = \frac{3{,}600}{h_{lr}}$$

PERSON CAPACITY

The maximum person capacity, P, 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.

$$P = TLP_m(PHF) = \frac{3{,}600 LP_m(PHF)}{h_{lr}}$$

Equation 5-18

where:

P = person capacity (p/h);
T = line capacity (trains/h);
L = train length (ft, m);
P_m = linear passenger loading level (p/ft length, p/m length);
PHF = peak hour factor;
3,600 = number of seconds in an hour; and
h_{lr} = minimum light rail headway (s).

Where there are no single-track or on-street constraints, and the signaling system is designed for maximum throughput, the person capacity can be determined through the procedures of Chapter 6, summarized for shorter light rail trains in Exhibit 5-44 and Exhibit 5-46. 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 either of these exhibits for extended dwells due to low-level (step) loading, wheelchairs, or on-board fare collection. With minimum headways provided by cab 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 procedures of Chapter 7 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 United States 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 six 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.

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CHAPTER 9. 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 7. 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.

Use the grade-separated rail procedures for commuter rail operated using electric multiple-unit trains on dedicated tracks.

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 used by SEPTA and New Jersey Transit on routes that also run electric multiple-unit cars. Dual-powered (electric and diesel) locomotives are used by the Long Island Rail Road (LIRR) and Metro-North Railroad in the New York area. All new starts are likely to use diesel locomotive-hauled coaches.

For the remaining lines, there is no easy answer for calculating capacity. Unlike rapid and light rail transit, whose vehicles have similar performance characteristics within their respective modes, the performance of diesel locomotives used by various U.S. commuter operations varies considerably. This performance, measured by the *power-to-weight (P/W) ratio,* ranges from 2 to 10 for commuter rail operations, which makes it difficult to develop a "standard" commuter rail performance for use in capacity calculations. For comparison, a typical diesel Amtrak intercity train has a P/W ratio of 4 to 6, while electric high-speed corridor trains (such as the Metroliner used in the Washington-New York-Boston corridor) have P/W ratios of 10 and higher.[R10] Exhibit 5-72 shows the effect of different P/W ratios on the time and distance needed to accelerate from a stop, and the delay incurred as a result.

Commuter rail capacity determination is inexact.

	Power-to-Weight (P/W) Ratio				
	2	4	6	8	10
Distance to accelerate (mi)	23.0	7.3	3.6	2.5	1.9
Distance to accelerate (km)	37.0	11.8	5.8	4.0	3.1
Acceleration time (min)	23.7	7.7	4.3	3.0	2.3
Time lost (min)	3.7	2.3	1.6	1.2	1.0

Exhibit 5-72
Effect of P/W Ratio on Train Acceleration to 80 mph (128 km/h)[R10]

There are other issues affecting commuter rail capacity that make it difficult to provide a simple analytical technique. First, many smaller commuter rail lines do not own the tracks they use, and therefore the number of trains they can operate will depend on negotiations with the owning railroad. Second, the mix of users of the tracks—and their impacts on capacity—will vary greatly from location to location. Generally, simulation is the only tool available for calculating the capacity of these commuter rail lines. Finally, the number of platforms available at terminal stations may constrain capacity. Consequently, this chapter does not present any equations for calculating commuter rail capacity. Instead, it focuses on the factors that impact capacity and potential means of improving capacity.

Simulation is often the only tool available for calculating commuter rail capacity. For comparison, Appendix B identifies the number of trains operated by, and passengers served by, various commuter rail systems.

TRACK OWNERSHIP AND USAGE

For commuter rail lines that use tracks owned by another railroad, the number of trains that can be operated in the peak hour is dependent on negotiations with the owning railroad. As the number of trains using a track increases—particularly when only a single track is available—the average speed of all trains decreases. Train meets have a compounding impact on capacity: each meet produces delay to the train that must wait, and each delay produces an increased probability of additional future meets. The impact of meets is even more severe when different classes of trains with different characteristics (e.g., passenger and freight trains) share the same tracks.(R21)

One concern that a freight railroad will have when passenger trains are proposed to be added to its tracks will be the impacts on train running times. Train crews have a maximum permitted number of hours they can work at a time, and an increase in train travel time may put them at risk of exceeding that limit if any unexpected delay occurs. Freight railroads may also need to reserve capacity (paths) for freight trains to service local customers during hours that passenger service is being contemplated, or to get trains to a certain location by a certain time.(R18)

There are a number of consumers of track capacity, some recurring but most not. The most common consumers of capacity are(R21)

- Trains (not all use the same amount),
- Track patrols,
- Track maintenance,
- Track deterioration requiring temporary speed restrictions,
- Passenger station stops,
- Industrial switching,
- Freight yard interactions,
- Train or train control system failures,
- Incidents (e.g., crossing accidents, deer, and trespassers), and
- Weather.

Trains will be assigned different levels of priority, and there may be different levels of priority within a particular class of trains. For example, passenger train types can include high-speed intercity, conventional intercity, commuter zone express, commuter local, and deadhead (non-revenue) passenger trains. Freight train types include intermodal, manifest, bulk commodity, and local freight. An individual train's priority may also be raised or lowered depending on special circumstances. For example, early trains will have lower priority, trains whose crews are nearing their legal work hour limit will have higher priority, and heavy trains may be given higher priority, particularly on grades, because of the time required to regain their speed after a stop. The relative priority of each train will determine which one is delayed when two trains meet or one overtakes another.(R18)

Although railroads are becoming more receptive 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 commuter railroads own the great majority of track they operate on; however, in the case of MTA-Metro North Railroad, priorities must be determined between Metro North's commuter operations and Amtrak's Northeast Corridor services. New Jersey Transit, SEPTA in Philadelphia, MBTA in Boston, Metra in Chicago, and Metrolink in Los Angeles, among others, also 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. However, even when an agency owns track or trackage rights, there may still be strict limits on the number of trains that can be operated because of interlockings and grade crossings with other railroads.

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 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 has services aimed specifically at the growing reverse commuter market.

Signal blocks for freight trains are considerably longer than for rail transit operations, due to the length of the trains, and the amount of time and distance required to bring a long, heavy freight train to a stop. Trains are the only means of land transport that cannot stop within their range of vision.[R19] Because of these long stopping distances and the resulting longer block lengths, and the lower speed of freight trains compared with rail transit, both commuter and freight trains take longer to traverse a signal block than their rail transit counterparts. This longer block transit time translates into significantly longer headways between trains and, therefore, lower capacity.

Line Capacity Range

The number of commuter rail trips available per hour may range from one to 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 7 can be considered.

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

Only in this case can the grade-separated train separation equation (Equation 5-7) be used as a rough approximation of railroad signaling throughput. The input values should be adjusted using suitably lower braking and acceleration rates and longer train lengths, and by 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 commuter 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 CBD. 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 have 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 platform tracks[20] 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.

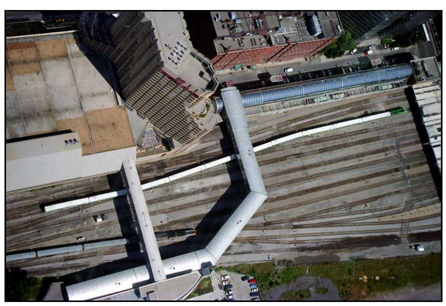
The situation at New York's Penn Station is less relaxed. The LIRR has exclusive use of five tracks and shares four more with Amtrak and New Jersey Transit. Currently the LIRR operates the East River tunnels with two tracks inbound and two tracks outbound with a peak headway of 3 minutes per track. With 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 3.5 minutes in a rush, but 5 minutes is the minimum scheduled time.

Station Dwells

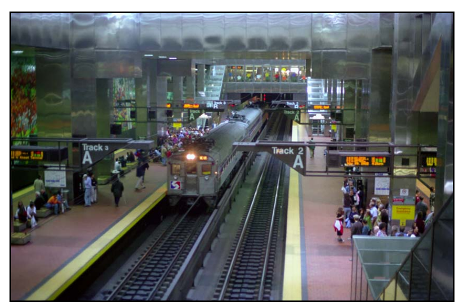
Dwells are less critical for commuter rail than for heavy rail transit.

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, such as those shown in Exhibit 5-73. In most cases, the longest dwells are at the multiple-platform downtown terminals where the train is not blocking others while passenger activity takes place.

Exhibit 5-73
Multiple-Platform Commuter Rail Terminal Examples



(a) Toronto



(b) Philadelphia

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 LIRR 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 2 or 3 minutes. SEPTA's four-track regional rail tunnel through Center City Philadelphia is one of the few North American locations where commuter trains

20 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.

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 1.4-mi (2.3-km) line segment.[21]

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 1 to 2 minutes. Gallery cars usually feature one exceptionally wide door (6.5 ft or 2 m) at the center of each side to allow rapid boarding and alighting with multiple passenger streams.

MEANS OF INCREASING LINE CAPACITY

If the line capacity is determined to be insufficient for the desired level of commuter rail operations, there are three main ways that capacity can be increased: (1) add another track, (2) reduce running times between sidings, and (3) reduce the delay resulting from train meets and overtakes.[(R1)]

Methods that do one or more of these things are described below, along with a qualitative discussion of each method's potential benefits and potential constraints. Simulation will be required to quantify the effects of a particular method for increasing capacity.

Double Tracking

Double tracking allows some trains to meet without having to stop. Double-track sections can be formed by joining or extending existing sidings, but need to be at least three signal blocks (4.5 to 7.5 mi or 7 to 12 km) long in order to be effective. Longer double-track sections should provide crossovers to allow both meets and overtakes to occur within the double-track section.[(R1)]

Avoid ending sidings and double-track sections

- On or near grades,
- On curves, and
- Near grade crossings.

The ends of sidings or double-track sections should not be located on or near heavy grades (1% or more), because of the difficulty of starting and stopping heavy trains. Curves should also be avoided at the ends of double-track sections, because of the difficulty of installing and maintaining switches located on curves. Finally, grade crossings should not be located near the ends of double-track sections, because they would be blocked by a train stopped for a meet or overtake.[(R1)]

Double-tracking an entire line, while very beneficial from a capacity standpoint, is also very costly.

At the extreme, the entire line can be double-tracked. Adding double track to all of Tri-Rail's line in South Florida will allow it to increase service from one passenger train per direction per hour to three. However, the cost of double-tracking a long rail line can be very high, particularly when bridges or tunnels are required, or when additional right-of-way must be acquired.

21 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.

Sidings are short sections of double track not long enough for trains to pass without one having to stop.

Adding and Lengthening Sidings

Shorter sections of double track are known as sidings. When trains meet at a siding, one will need to stop and wait for the opposing train to pass (sections of the line that are considered "double track" are long enough for some trains to meet without having to stop). Trains experience two types of delay at sidings, *fixed* and *variable.* Fixed delay includes delay associated with decelerating, stopping, and accelerating, as well as any difference in operating speed between the siding and the main line. Variable delay consists of time that a train must wait for the opposing train once it is in the siding.(R23)

Increasing the number of sidings reduces variable delay, as trains can be directed to a siding closer to the time a meet will occur, but does not change the fixed delay associated with stopping. The capacity benefit diminishes as each new siding is added, because the variable delay is reduced by smaller and smaller increments, but the fixed delay remains.(R1)

Lengthening sidings reduces variable delay, because the distance between the ends of sidings is reduced. However, it adds to fixed delay, because the amount of time required to transit a siding increases as the siding's length increases.(R1)

Increasing the siding entry speed may also require improvements to the siding itself.

Providing Higher-Speed Siding Entries and Exits

Fixed delay is reduced when trains can enter and exit the main line at higher speeds. A siding's entry and exit speed is controlled by the angle of departure of the siding from the main line, which is measured by the switch number (see Exhibit 5-11). The higher the switch number, the faster the entry and exit speed. Additionally, the siding must permit speeds at least as high as the entry and exit speeds, it must be signaled, and it must be long enough to allow a train to stop from the higher entry speed.(R1)

Train Control System Improvements

Signals can be moved closer together, which shortens block lengths and permits trains to run closer together, within the limits created by the safe braking distance needed for the worst-case train. Changing the signal spacing mainly reduces delay when one train overtakes another, as the overtaken train can depart sooner once the other train has passed. Shortening the lengths of blocks can also create a minor improvement in meet delay, as dispatchers have better information about train positions to help them make decisions about which siding to have a train make a meet at.(R1)

Improving track conditions to improve train speeds may not improve capacity, if blocks have to be lengthened to accommodate faster trains.

Infrastructure Improvements

Track conditions on a railroad being considered for commuter rail service may restrict trains' maximum speed. The Federal Railroad Administration defines various track classes, based on such factors as curvature, superelevation, track condition, number of crossties per unit length, and so forth, and sets maximum allowed passenger and freight train speeds based on those classes. Infrastructure improvements to upgrade the track class will improve train operating speeds; however, capacity may not change, as signal blocks may need to be lengthened to safely accommodate the higher speeds, resulting in little or no net change in time to transit a block. Exhibit 5-74 shows the maximum speeds allowed for different track classes.

Track Class	Passenger mph	Passenger km/h	Freight mph	Freight km/h
Excepted	Not allowed	Not allowed	10	16
1	15	24	10	16
2	30	48	25	40
3	60	96	40	64
4	80	128	60	96
5	90	144	80	128

NOTE: Track classes 6 and higher, not shown, are used for high-speed intercity passenger rail.
SOURCE: Code of Federal Regulations, Title 49, Part 213.

Exhibit 5-74
U.S. Railroad Track Classes

Other infrastructure issues can create capacity constraints:(R1)

- *Junctions* are often under the control of different dispatchers, requiring a train to be held at a junction, blocking the exit. Providing a siding at the junction can mitigate this problem.
- Trains operate more slowly when entering and exiting *freight yards.* Providing the ability to bunch trains, either through closer signal spacing or additional tracks can mitigate impacts on capacity. Older freight yards may have been designed for shorter trains; the yard entry track needs to be sufficiently long to hold an entire train without blocking the mainline, while yard switches are lined manually.
- Cars may be temporarily stored on the mainline during *switching operations* on industrial tracks. A service track to store these cars can be constructed to mitigate this problem.

COMMUTER RAIL OPERATING SPEEDS

Exhibit 5-75 gives average commuter rail operating speeds, including station stops, for different combinations of P/W ratios, station spacings, and dwell times. The exhibit assumes conventional block signaling, track conditions providing a passenger train speed limit of 80 mph (128 km/h), no grades, and no delays due to other trains. Note that in most cases, except for the higher P/W ratios and longer station spacings, a train will not be able to accelerate to the assumed speed limit before it has to slow for the next station. When the characteristics of the line (e.g., grades and station locations) and equipment to be used are known, a train simulator should be used to estimate operating speeds. A dwell time of 30 seconds would be difficult to achieve on a higher-volume line, but might be appropriate for lower-volume lines and off-peak periods.(R10)

Station Spacing (mi)	Average Operating Speed (mph) P/W = 3.0	P/W = 5.8	P/W = 9.1
Average Dwell Time = 30 s			
1.0	16.8	20.3	22.3
2.0	25.8	30.9	35.0
4.0	36.4	44.1	48.6
5.0	40.3	48.7	52.7
Average Dwell Time = 60 s			
1.0	14.8	17.4	18.8
2.0	23.3	27.4	30.6
4.0	33.8	40.4	44.1
5.0	37.8	45.0	48.5

NOTE: P/W = power-to-weight ratio
Assumes 80-mph speed limit, no grades, and no delays due to other trains.

Exhibit 5-75
Average Commuter Rail Operating Speeds(R10)

An alternative figure using metric units appears in Appendix A.

PERSON 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 to allow for variations in passenger boarding demand.

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:

Equation 5-19

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

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 that 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.[22] 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 5-76 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 82.7 ft (25.2 m) long and 10.5 ft (3.2 m) wide.

Passenger loads range from more than 2 to less than 0.6 p/ft length (7 to 2 p/m length). A 2+3 seating configuration is needed to reach 2.1 p/ft length (7 p/m 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 2.1 p/ft length (7 p/m length) can be used as a maximum. A range of 1.5 p/ft length (5 p/m length) is the upper end for single-level cars, with 1.2 p/ft length (4 p/m length) preferred. These preferred and recommended levels allow some space for toilets, wheeled mobility aids, strollers, luggage, 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.

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

Exhibit 5-76
Commuter Rail Car Capacity[R15]

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

NOTE: Identical car models listed more than once reflect different seating configurations.

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CHAPTER 10. AUTOMATED GUIDEWAY TRANSIT CAPACITY

INTRODUCTION

AGT fits into the category of *Grade-Separated Rail,* whose capacity determination was specified in Chapter 7. 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 0.1% of passenger trips in the United States—increasing only when institutional systems are considered, most of which are intra-airport shuttles. Technology ranges widely from standard-gauge advanced light rapid transit, to 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, and braking rate vary greatly, as does their balance between speed, vehicle size, and capacity.

TRAIN CONTROL SEPARATION

Train control systems on AGT 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 7. If the basic AGT performance criteria are known, then the procedures of Chapter 7 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 5-77 for trains of typical AGT lengths, using the specific AGT values in Exhibit 5-78, with terms adjusted from typical rail transit values shaded.

Exhibit 5-77
AGT Minimum Train Separation Times[R15]

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

Exhibit 5-78
Suggested AGT Separation Calculation Default Values[R15]

An alternative figure using metric units appears in Appendix A.

Default Value			
Heavy Rail	**AGT**	**Term**	**Description**
20 ft	20 ft	P_e	positioning error
650 ft	165 ft	L	length of the longest train
35 ft	0 ft	d_{eb}	distance from front of train to exit block
75%	75%	f_{br}	braking safety factor—% of maximum braking rate
2.4	4	b	train detection uncertainty constant— fixed block
1	1	b	train detection uncertainty constant— moving block
3 s	1 s	t_{os}	time for overspeed governor to operate
0.5 s	0.5 s	t_{jl}	time lost to braking jerk limitation
4.3 ft/s^2	2.0 ft/s^2	a	service acceleration rate
4.3 ft/s^2	3.3 ft/s^2	d	service deceleration rate
1.5 s	0.5 s	t_{br}	brake system reaction time
60 mph	50 mph	v_{max}	maximum line velocity
165 ft	80 ft	S_{mb}	moving-block safety distance

NOTE: shaded lines indicate AGT default values that differ from heavy rail default values.

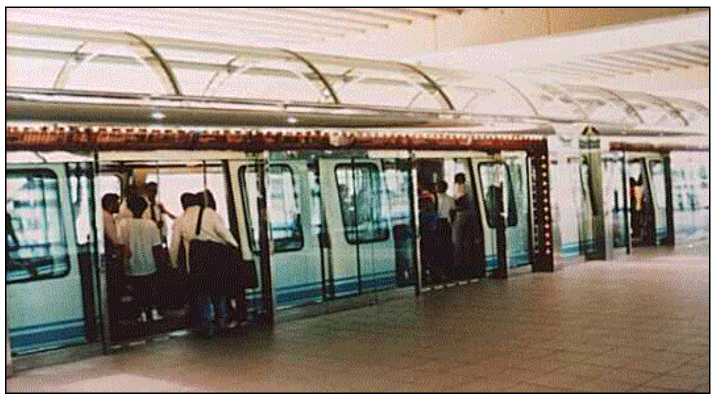
The results show that separation times with a simulated single aspect block system are two to three times longer than with the more complex—and expensive—moving-block signaling system. The moving-block results agree with those of Auer,[R7] the only reference specializing in AGT train control. Here, typical 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 7 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. 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 screen doors—shown in Exhibit 5-79.

Exhibit 5-79
Orlando Airport People-Mover Doorways



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 AGT 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.

Other systems range widely. At one extreme are the airport shuttles with wide cars and no or few seats where loading can reach 3 p/ft length (10 p/m 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 0.6 to 0.9 p/ft length (2 to 3 p/m length). The peak hour factor on the latter type systems attains unity when arrangements—and continual passenger queues—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 manual 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 AGT line in Morgantown, West Virginia.[23]

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 and a reduced operating margin.[24] 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 5-78.

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.

23 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.

24 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.

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CHAPTER 11. ROPEWAY CAPACITY

INTRODUCTION

Ropeways in North America are more commonly used by private owners than by public transit agencies.

This chapter covers the capacity of transit modes that are hauled by cable (wire rope). Although these modes are not widely used in North America for public transit, they are sometimes considered as modal alternatives in transit feasibility studies, and have been constructed as part of a number of private developments, particularly ski areas. In Europe, funicular railways can be found in a number of hilly urban settings, and both funiculars and aerial tramways are used for access to some remote villages inaccessible by road.

Surface modes include some of the oldest mechanized purely urban transportation systems, discounting extensions of intercity rail networks into city centers. Vehicles are either permanently attached to the rope or can attach and detach from the rope by means of a grip mechanism. In either case, the motor driving the rope is located in a remote location, not on the vehicle itself, and the vehicle operates on a guideway. As described in Part 2, surface ropeway modes include *cable cars*,[25] *inclined planes* (funicular railways), and *cable-hauled automated people-movers*.

Aerial ropeways suspend the carrier (comprising the cabin, hanger, and grip) from a rope. The cable may serve to suspend and haul the carrier (*monocable*); two ropes may be used, a fixed track rope for suspension and a moving haul rope for propulsion (*bicable*); or multiple ropes may be used to provide greater wind stability. Carriers can operate in a back-and-forth, shuttle operation, or can be part of a continuously circulating system. The motor driving the haul rope(s) is located at a remote location (one end or the other of the line). The common aerial ropeway modes are *aerial tramways* and *aerial lifts* (gondolas, ski lifts, and funitels).

For the purposes of this chapter, two capacity categories are used: (1) reversible systems and (2) continuously circulating systems. These categories include both surface and aerial ropeway modes as members.

REVERSIBLE SYSTEM CAPACITY

A reversible system typically provides two vehicles that are always attached to a rope and that move back and forth along the line at the same time. When one vehicle is at one terminal, the other vehicle will be at the opposite terminal. Vehicles are accelerated to line speed by increasing the speed of the haul rope and decelerated by slowing the haul rope. Passenger loading and unloading occurs while the vehicle is stopped. Modes that fall into this category are inclined planes and aerial tramways.

The line capacity of a reversible system is dependent on the length of the line, the line speed, and dwell times at stations. Reversible systems are usually designed with only two stations. A third station, if used, desirably should be located exactly halfway along the line so that both vehicles can be in the station at the same time. If the station is not located exactly halfway, then each vehicle will make two intermediate stops: one while at the station and one while the other vehicle is at the station.

Manufacturers claim line speeds of up to 33 to 46 ft/s (10 to 14 m/s) for modern funiculars and up to 39 ft/s (12 m/s) for aerial tramways. The average line speed will be somewhat less, due to acceleration and deceleration needs, and (for aerial tramways) any slowing of the line required as the carrier passes over towers.

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[25] Some aerial tramways are also called "cable cars." As used here, the term refers to the surface mode that now is only found in San Francisco.

Equation 5-20 provides the directional line capacity of a reversible system.

Equation 5-20

$$T = \frac{1{,}800 N_v}{(N_s t_d) + \frac{L_l}{v_l}}$$

where:

T = line capacity (trains/h, carriers/h);
1,800 = number of seconds in an hour, divided by two;
N_v = number of vehicles (1 or 2);
N_s = number of stops per direction:
1—two-station system,
2—three-station system, with middle station exactly halfway, and
3—three-station system, with offset middle station;
t_d = average dwell time (s);
L_l = line length (ft, m); and
v_l = average line speed (ft/s, m/s).

CONTINUOUSLY CIRCULATING SYSTEM CAPACITY

A continuously circulating system provides multiple carriers, cars, or trains that move around a route that forms a loop. Vehicles can be attached to the rope at all times (*fixed-grip)* or can be attached and detached as needed (*detachable grip*).

The concept of moving at high speed along the line and detaching from the line at stops and stations is shared by all detachable-grip modes, including detachable-grip aerial lifts, funitels, cable-hauled automated people movers (APMs), and cable cars. At stops or stations, passenger loading takes place while the vehicle is stopped (cable cars and some APMs), or while moving at creep speed (0.8 ft/s or 0.25 m/s). Manufacturers claimed line speeds range up to 20 ft/s (6 m/s) for detachable-grip gondolas, to 23 ft/s (7 m/s) for funitels, and 26 ft/s (8 m/s) for cable-hauled APMs.

Fixed-grip modes do not detach from their haul rope. Fixed-grip ski lifts load and unload passengers at line speed, but for other applications, the rope must be brought to either a full stop or creep speed at stations. To minimize the number of stops that passengers must make between stations, many fixed-grip gondola systems are designed as *pulse* systems, with three or four carriers attached in a series. At the station, all of the carriers in the series can be loaded and unloaded at the same time, thus minimizing the number of intermediate stops and improving overall travel speeds. Fixed-grip gondolas have a maximum claimed line speed of 23 ft/s (7 m/s).

The line capacity of a continuously circulating system is dependent on the average line speed and the spacing between carriers. For APMs, which can have multiple stations, dwell time is used to develop the minimum safe spacing between trains, following the procedure described in Chapter 7 for grade-separated systems. Platform doors are often used both for safety (keeping passengers from falling onto the tracks or between cars of a train), and to control dwells, by keeping late-arriving passengers on the platform from holding the train doors open. For fixed-grip aerial lifts, dwell time is incorporated in the average line speed. Dwell time is not a factor for detachable-grip aerial lifts and funitels, as the carriers circulate through the station at a constant, low speed, without stopping. Equation 5-21 provides the directional line capacity of a continuously circulating system.

$$T = 3{,}600 \frac{v_l}{d_c}$$

Equation 5-21

where:
T = line capacity (trains/h, cars/h, carriers/h);
v_l = average line speed (ft/s, m/s); and
d_c = average carrier/train/car spacing on the line (ft/carrier, m/carrier).

PERSON CAPACITY

Manufacturers' stated capacities typically do not account for loading diversity.

Manufacturers of ropeway systems tend to state *theoretical* person capacities, based on the maximum number of people that can be carried over the course of an hour, assuming all passenger space within each vehicle is occupied. For some applications that may experience constant queues, such as ski areas, this may be a reasonable assumption. However, for public transit use, as well as any other application where minimizing passenger wait time is desired, a peak hour factor should be applied. The PHF accounts for the system's inability to fill every seat in every vehicle, as some capacity is reserved to handle surges in passenger demand.

The person capacity of an aerial ropeway cannot be easily increased, except for gondola systems designed with future expansion in mind.

Changing the person capacity of aerial ropeway systems is difficult, because the infrastructure (e.g., towers, rope size, vertical clearances) is designed around a particular number and size of carriers. Changing the carrier size typically requires major changes to the infrastructure. However, it is possible to design a gondola system for a larger number of carriers than will be used initially. This reduces initial capital costs and allows the provided capacity to be matched to demand, as additional carriers can be added later as needed, up to the maximum number for which the system was designed.

Because the number of carriers used on detachable-grip systems can be varied by the operator, the person capacity of these systems can be adjusted over time by adding additional carriers. In this case, consideration should be given to differentiating between capacities that can currently be achieved with a given number of carriers, and the maximum capacity that could be achieved.

The size of the cabins used by the various modes addressed in this chapter vary greatly. Once a particular cabin size is selected, it is difficult—if not impossible—to add person capacity by using larger carriers, without rebuilding much of the system. Other infrastructure elements (e.g., towers, platforms, clearances) are designed around a particular carrier and may not be able to accommodate a larger carrier. Exhibit 5-80 provides typical ranges of cabin sizes for each mode.

Exhibit 5-80
Typical Cabin Sizes of Ropeway Modes

Mode	Capacity (p/car)	Comments
	Surface Modes	
Inclined plane/funicular	20-175	Two-car trains possible
Automated people mover	30-140	Multiple-car trains possible
	Aerial Modes	
Aerial tramway	20-180	Double-decked at upper limit
Gondola	4-15	
Funitel	24-30	

SOURCE: Manufacturer data.

The person capacity of a ropeway system is the line capacity (in carriers per hour) multiplied by the cabin size and a peak hour factor, as shown in Equation 5-22.

$$P = TC_c(PHF)$$

Equation 5-22

where:
P = person capacity (p/h);
T = line capacity (carriers/h);
C_c = carrier capacity (p/carrier); and
PHF = peak hour factor.

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CHAPTER 13. EXAMPLE PROBLEMS

Solution required for two signaling systems.

Example Problem 1

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 cab signaling 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 25-m cars. Trains will operate at a maximum of 100 km/h (27.8 m/s) and will be traveling at 52 km/h (14.4 m/s) when entering stations if the cab signaling system is chosen, and at 55 km/h (15.3 m/s) if a moving-block system is selected.[26] The distance from the front of a stopped train to the station exit block is 10 m. Assume that there are no grades into or out of stations and that no civil speed restrictions limit approach speeds to sub-optimal levels.

Outline of Solution

To answer this question, two equations must be used, one for each signaling system type. Equations 5-7 and 5-9 are found in Chapter 7. Note that these 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_{cs}	train control separation
200 m	L_t	length of the longest train
10 m	d_{eb}	distance from front of stopped train to start of station exit block in meters
14.4 m/s (cab) 15.3 m/s (moving block)	v_a	station approach speed
27.8 m/s	v_{max}	maximum line speed (27.8 m/s = 100 km/h)
75%	f_{br}	braking safety factor—worst-case service braking is f_{br}% of specified normal rate—typically 75%
1.2 (cab) 1 (moving block)	b	separation safety factor—equivalent to number of braking distances (surrogate for blocks) that separate trains
3.0 s	t_{os}	time for overspeed governor to operate on automatic systems—driver sighting and reaction times on manual systems
0.5 s	t_{jl}	time lost to braking jerk limitation
1.5 s	t_{br}	brake system reaction time
1.3 m/s^2	a	initial service acceleration rate
1.3 m/s^2	d	service deceleration rate
6.25 m	P_e	positioning error—moving block only

26 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

1. Determine train control separation

(a) with cab signaling

The relevant equation is Equation 5-7, modified to remove dwell, operating margin, voltage, and grade:

$$t_{cs} = \sqrt{\frac{2(L_t + d_{eb})}{a}} + \frac{L_t}{v_a} + \left(\frac{100}{f_{br}} + b\right)\left(\frac{v_a}{2d}\right) + \frac{at_{os}^2}{2v_a}\left(1 - \frac{v_a}{v_{max}}\right) + t_{os} + t_{jl} + t_{br}$$

$$t_{cs} = 18.0 + 13.9 + (2.53)(5.54) + (0.406)(0.507) + 3.0 + 0.5 + 1.5$$

$$t_{cs} = 51.1\,\text{s}$$

Compare the approach speed producing the minimum train separation with any speed restrictions on the station approach.

(b) with moving-block signaling

The relevant equation is Equation 5-9, modified to remove dwell, operating margin, voltage, and grade:

$$t_{cs} = \frac{L_t + P_e}{v_a} + \left(\frac{100}{f_{br}} + b\right)\left(\frac{v_a}{2d}\right) + \frac{at_{os}^2}{2v_a}\left(1 - \frac{v_a}{v_{max}}\right) + t_{os} + t_{jl} + t_{br}$$

$$t_{cs} = 13.5 + (2.33)(5.88) + (0.382)(0.550) + 3.0 + 0.5 + 1.5$$

$$t_{cs} = 32.4\,\text{s}$$

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 signaling system or 32.4 seconds with a variable safety distance moving-block system and automatic train operation.

2. Determine controlling dwell

In Chapter 7, *Grade-Separated Systems,* 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 dwell using simple method.

3. Determine the 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.

4. Determine passenger loading and capacity

Chapter 4 indicates that a recommended comfortable heavy-rail car loading for a new system is 6 passengers per linear meter of train length, inclusive of diversity allowances. At this loading level, the specified train of eight 25-meter-long cars can carry 8 x 6 x 25 = 1,200 passengers.

The Results

Multiplying the number of passengers per train by the number of trains per hour provides passengers per peak hour direction per track of 36,000 p/h/dir and 43,200 p/h/dir, respectively. Reflecting the approximations used in this determination, the results should be rounded down to the nearest 1,000—36,000 and 43,000.

Comments

The planning-level graphs in Chapter 6 also could have been used to answer the third question about person capacity. The results obtained above correspond to the lower bounds of the capacity ranges in Exhibits 5-44 and 5-46. The lower bounds in the graphs correspond to a combined dwell time and operating margin of 70 seconds, whereas this example used a combined time of 65 seconds. The reason the calculated results are not higher than the graphs' lower bounds was the decision made in Step 3 to use clock headways, which resulted in 1 fewer train per hour and, thus, 1 fewer train's worth of person capacity (approximately 1,200 people). Exhibit 5-28 shows that many North American rail systems operating at or close to capacity do not use clock headways.

Example Problem 2

The Situation

The transit agency from Example Problem 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 2-minute headway through the junction.

The Question

Can a flat junction on this proposed system support a 2-minute headway or must a flying junction be constructed?

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 meters apart and use #10 turnouts (switches) with a throw-and-lock time of 6 seconds at mainline junctions. To make operations through a flat junction reliable, the agency plans to increase the operating margin to 45 seconds, hence the headway increases from 100 to 120 seconds.

Outline of Solution

Solving this problem requires the use of Equation 5-5.

Steps

Equation 5-5 is:

$$h_j = h_l + \sqrt{\frac{2(L_t + 2 f_{sa} d_{ts})}{a}} + \frac{v_l}{a+d} + t_s + t_{om}$$

The variables used in the equation are summarized in the following table:

Value	Term	Description
Calculated	h_j	limiting headway at junction
32.4 s	h_l	line headway, from Example Problem 1, Step 1b
200 m	L_t	train length
9.62	f_{sa}	switch angle factor (9.62 for a #10 switch, from Equation 5-5)
5 m	d_{ts}	track separation
1.3 m/s^2	a	initial service acceleration rate
1.3 m/s^2	d	service deceleration rate
27.8 m/s	v_l	line speed (27.8 m/s = 100 km/h)
6.0 s	t_s	switch throw and lock time
45 s	t_{om}	operating margin

Substituting the known variables into the equation produces:

$$h_j = 32.4 + 21.3 + 10.7 + 6.0 + 45$$

$$h_j = 115.4 \text{ s}$$

The Results

While the resulting value of *H(j)* would appear to support 2-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 that recommendation in Chapter 2 that junctions should be grade-separated at headways below 3 minutes.

Calculations concur with the rule of thumb that junctions should be grade-separated at headways below 3 minutes.

Example Problem 3

The Situation

A busy heavy rail line operates through a major transfer station with long station dwell times.

The Question

What is the maximum person capacity through this station?

The Facts

- A generous loading standard means more passengers seated.
- The transit agency's loading standard is 6 passengers per meter of car length during the peak 15 minutes.
- Service is provided by 10-car trains with each car being 22.8 m long.
- The dwell time at the controlling dwell station averages 30 seconds with a standard deviation of 21 seconds.
- There is a 1.5% downgrade into the station.
- The line is automated and uses moving-block signaling.
- Train operators are responsible for closing the doors and initiating acceleration; this delay is incorporated into the dwell time.
- Trains are evenly loaded over their length.

Outline of Solution

The solution consists of three key steps: (1) determining each train's passenger capacity, (2) determining the minimum train separation based on the signaling system and train length, and (3) 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.

Steps

1. Determine the train capacity

When a PHF is and is not needed.

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. Because the agency's loading standard is based on peak-within-the-peak conditions, a peak hour factor must be used. In the absence of other information, a PHF of 0.80 is appropriate for heavy rail. This factor accounts for lower passenger demand during the other 45 minutes of the peak hour, which would result in unused capacity. If the agency policy had been to maintain an average loading of 6 p/m length during the peak hour, resulting in more crowded peak-within-the-peak conditions, no PHF would have been needed.

$$(10 \text{ cars/train})(22.8 \text{ m/car})(6 \text{ p/m})(0.80) = 1{,}094 \text{ p/train}$$

2. Determine the minimum train separation

This step requires use of Equation 5-9. Since consideration of station dwell times and the operating margin are deferred to the next step, they are not included in the equation below:

$$t_{cs} = \frac{L_t + P_e}{v_a} + \left(\frac{100}{f_{br}} + b\right)\left(\frac{v_a}{2d}\right) + \frac{a(1-0.1G_i)l_v^2 t_{os}^2}{20{,}000 v_a}\left(1 - \frac{v_a}{v_{max}}\right) + t_{os} + t_{jl} + t_{br}$$

The values for all variables are summarized as follows:

Value	Term	Description
calculated	t_{cs}	train control separation
200 m	L_t	length of the longest train
10 m	d_{eb}	distance from front of stopped train to start of station exit block in meters
15.3 m/s	v_a	station approach speed
22.2 m/s	v_{max}	maximum line speed (22.2 m/s = 80 km/h)
75%	f_{br}	braking safety factor—worst-case service braking is f_{br}% of specified normal rate—typically 75%
1	b	separation safety factor—equivalent to number of braking distances (surrogate for blocks) that separate trains
3.0 s	t_{os}	time for overspeed governor to operate on automatic systems—driver sighting and reaction times on manual systems
0.5 s	t_{jl}	time lost to braking jerk limitation
1.5 s	t_{br}	brake system reaction time
1.3 m/s^2	a	initial service acceleration rate
1.3 m/s^2	d	service deceleration rate
-1.5%	G	grade into the station
6.25 m	P_e	positioning error—moving block only

Substituting the variables in the equation produces:

$$t_{cs} = 15.7 + (2.33)(6.92) + (0.440)(0.388) + 3.0 + 0.5 + 1.5$$

$$t_{cs} = 37.0 \text{ s}$$

3. Incorporate 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 7 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. The average dwell time is 30 seconds. Adding twice the dwell time standard deviation of 21 seconds produces a controlling dwell, incorporating operating margin, of 72 seconds.

No additional operating margin is needed when the dwell plus two standard deviations method is used.

The Results

Combining the controlling dwell with the minimum train separation produces a station headway of 109 seconds, which can be rounded up to 112.5 seconds to provide an integral number of 32 trains per hour. With a passenger load of 1,094 p/train, the line can carry approximately 35,000 passengers during the peak hour in the peak direction through this station.

Example Problem 4

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 3-car trains, with each car 90 ft long.
- The single track section is 4,000 ft long with one intermediate station, with a dwell time of 20 s.
- The section is on a road with a speed limit of 30 mph.

Assumptions

- 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

A self-guiding spreadsheet with this equation and instructions is provided on the accompanying CD-ROM.

Calculate the travel time over the single-track section from Equation 5-13:

$$t_{st} = S_m\left(\frac{(N_{st}+1)}{2}\left(\frac{3v_{\max}}{d}+t_{jl}+t_{br}\right)+\frac{L_{st}+L_t}{v_{\max}}\right)+N_{st}t_d+t_s+t_{om}$$

The values for all variables are summarized as follows:

Value	Term	Description
calculated	t_{st}	time to cover single-track section
1.1	s_m	speed margin
1	N_{st}	number of stations on the single-track section
44.0 ft/s	v_{max}	maximum line speed (44.0 ft/s = 30 mph)
0.5 s	t_{jl}	time lost to braking jerk limitation
4.3 ft/s^2	d	deceleration rate
1.5 s	t_{br}	brake system reaction time
4,000 ft	L_{st}	length of single-track section
270 ft	L_t	train length
20 s	t_d	dwell time
6.0 s	t_s	switch throw-and-lock time
20 s	t_{om}	operating margin (middle of range from Exhibit 5-65)

Substituting these results into the equation produces:

$$t_{st} = 1.1\ [\ (1)(30.7 + 0.5 + 1.5) + 97.0\ ] + 20 + 6 + 20$$

$$t_{st} = 189 \text{ s}$$

The Results

The resultant time to cover the single-track section is 189 seconds. The minimum headway on a single-track section is twice this time, or 378 seconds, which should be rounded up to the nearest even hourly headway of 480 seconds (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, or trains every 10 minutes.

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

Comments

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 a signaling system is used, this operation is only possible if either (1) the signaling system is equipped for two-way operation on either track, or (2) operations are reverted to a slower manual, line-of-sight operation. Such emergency operation is then limited to a frequency as calculated by Equation 5-13 and line capacity is reduced.

Single track working in emergencies.

As an example, if normal service is a train every 5 minutes, and a 4,000-ft 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 (i.e., 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.

Longer single-track sections will reduce capacity further. This loss may be made up where operational policies and signaling systems permit platooning trains over the single-track section. Two or 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.

Capacity reduction with single track working.

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, such as 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 high-frequency routes.

Exhibit 5-47 presents the line capacity for varying single-track lengths for 2-car trains and a 35-mph maximum speed. Line capacity 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, as a result of dwell times for trains traveling in each direction and the associated acceleration and deceleration delays.

Example Problem 5

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.

Steps

The hourly capacity, P, is determined as follows:

$$P = \text{(passengers per car) x (cars per train) x (trains per hour) x (PHF)}$$

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.

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.

The Results

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 platforms 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

The Situation

An automated feeder line is planned from a new suburban office development to an existing heavy rail station.

The Question

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

The Facts

The developer wants to incorporate the AGT stations in an elevator lobby on the second floor of each building, which limits station length to 85 feet. Although the line is short, the developer wants to offer a high-quality service in which 50% of the 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.

Outline of Solution

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

Exhibit 5-77 shows that an AGT moving-block train control system can provide a minimum train separation of 13.4 seconds with 80-foot 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 10 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 3,600/80 or 45 trains per hour.

The 85-foot platform can hold two 40-foot cars, a common AGT size and comparable to a city bus. As no specific car design can be assumed, it is reasonable to assume that wide double doors will take up 12 feet of each car side, leaving 28 feet for seating. At a pitch of 3.5 feet, 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 (6 x 4) + (2 x 5) for a total of 34 seats. The desired maximum of 50% of 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 Results

The resultant maximum capacity at the preferred loading level is the number of trains per hour (45), multiplied by the number of passengers per train (68), or 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 p/h/dir. Note that this is a *maximum* capacity; the result would need to be multiplied by a peak hour factor to determine the number of people that could be accommodated without exceeding the preferred loading level during the hour.

Example Problem 7

The Situation

The developer from Example Problem 6 is expanding the suburban office development to include a major shopping complex and recreation facility with an ice hockey arena.

The Question

How can the AGT line 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 6 minutes until midnight each day, including weekends and holidays.

Outline of Solution and Results

Longer trains could skip stations with too short platforms.

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 decreased to 40 trains per hour, or 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 (two cars per train multiplied by 75 p/car, assuming that a higher proportion of sports fans will stand, compared with office tenants). The remaining 30 trains must carry 5,700 passengers per hour (7,200 – (10 x 150)). This results in 5,700/30 or 190 passengers per train. Three-car trains holding 75 p/car would be required to meet the demand.

A peak hour factor is not applied to special event person capacity calculations, as the offered capacity is generally fully utilized and passengers do not expect to be able to board the first train that arrives.

In Chapter 10, 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 5-77 shows that a moving-block signaling system with 80-foot trains has a minimum train separation of 13.4 seconds. Allowing an operating allowance for merging trains of 45 seconds and rounding up results in permitted headways as low as 60 seconds, or 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.

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

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 AGT line would be filled to capacity and the overload would be handled by transit authority buses—of which there is a surplus at the off-peak hours typical of sport event starts and finishes.

Example Problem 8

The Situation

A university hospital is located on a bluff above a river. The university has run out of room to expand on the bluff and is seeking to move some of its operations to a new campus along the riverfront. For the two campuses to function efficiently as a single entity, good transportation links will need to be provided between them. The university is exploring various means to provide these links, including shuttle buses and roadway and parking improvements. Another option under consideration is a direct link between the two campuses using an aerial ropeway, either an aerial tramway or a detachable-grip aerial lift (gondola) system.

The Questions

1. For the aerial tramway, how large will the carriers need to be to handle the projected passenger demand?
2. For the gondola, how many carriers will be needed?

The Facts

Based on the university functions to be located on the riverfront and an estimate of total faculty, staff, and student sizes at build-out, the university estimates that a total of 750 persons will need to be carried in the peak direction during the peak hour. The line would be approximately 800 m long, with no intermediate stations. A decision on a specific manufacturer has not been made; however, as a starting point, assume that the aerial tramway cabin door would be wide enough that three people can walk through at a time and that the gondola carriers would seat eight people each.

Aerial tramway dwell time includes the time to unload and load passengers from the cabin, plus an assumed allowance of 60 seconds to (1) clear exiting passengers from the platform and (2) perform communications checks prior to the carrier departing. Maximum acceleration and deceleration is 0.2 m/s^2.

Gondola carriers take 60 seconds to traverse each station after detaching from the line. The carriers move at creep speed (0.25 m/s) through the station to allow passenger loading and unloading.

Outline of Solution

Aerial Tramway

Aerial tramway capacity is based on the number of carriers used (one or two, two is typical), the number of stops per direction (one, in this case), station dwell time (not yet known), line length (given), line speed (a user decision), and the size of the carriers (a user decision). Passenger service time will be based on the time to clear a full cabin, and then load a full cabin. Several combinations of line speeds and cabin sizes may need to be tried in developing a solution.

Gondola

Gondola capacity is based on the spacing between carriers (not yet known) and the average line speed (a user decision). To solve this problem, the minimum number of carriers needed to serve the demand will be calculated by working backward from the required capacity.

Solution

Aerial Tramway

As a starting point, a 60-passenger cabin and the fastest possible line speed (12 m/s) will be selected. At a maximum acceleration rate of 0.2 m/s², it takes 60 seconds (12 divided by 0.2) to reach line speed. The average speed during acceleration is half the line speed, or 6 m/s. As a result, the carrier would travel 360 m (60 s multiplied by 6 m/s) during acceleration. The carrier would travel another 360 m during deceleration, meaning that it would only travel 80 m at line speed (800 m line length, minus two times 360 m). The total trip time would be about 127 seconds.

Spending only 10% of the trip length at line speed would be inefficient, so a lower line speed should be tried. At a line speed of 10 m/s, acceleration and deceleration would take 50 seconds each and would cover a total distance of 500 m. As a result, the carrier could travel at line speed for 300 m (more than 40% of the distance) and could cover that distance in 30 seconds. The total trip time would be about 130 seconds. The corresponding average line speed would be 800 meters divided by 130 seconds, or 6.15 m/s.

In the absence of other data, Exhibit 5-15 can be consulted to determine average passenger boarding and alighting times. From a review of the data provided in the exhibit, 1.85 seconds per alighting passenger per door channel and 2.1 seconds per boarding passenger per door channel can be chosen as median values. With three door channels, it takes 37 seconds on average for passengers to exit a full 60-passenger cabin (60 p times 1.85 s/p, divided by 3 door channels), and 42 seconds to board. The total dwell time, including the 60-second allowance discussed in the facts of the problem, is 139 seconds.

All the information needed to calculate line capacity is now known. Entering this information into Equation 5-20 gives:

$$T = \frac{1{,}800 N_v}{(N_s t_d) + \dfrac{L_l}{v_l}} = \frac{(1{,}800\ \text{s/h})(2\ \text{veh})}{(1)(139\ \text{s}) + \dfrac{(800\ \text{m})}{(6.15\ \text{m/s})}} = \frac{3{,}600\ \text{veh-s/h}}{269\ \text{s}} = 13\ \text{veh/h}$$

Multiplying 13 carriers per hour by 60 passengers per carrier gives a theoretical directional capacity of 780 passengers per hour, which is more than the required 750 passengers per hour. However, because passengers are not likely to arrive evenly throughout the hour, a peak hour factor should be applied. Using a PHF of 0.90, the directional person capacity of the system is about 700 passengers per hour, which is insufficient to avoid pass-ups.

Repeating the above process with an 80-passenger cabin results in a 165-second dwell time, with all other input values remaining the same. The resulting line capacity is 12 carriers per hour, which provides a directional person capacity of about 865 passengers per hour when a peak hour factor of 0.90 is applied.

Gondola

Since the only thing known about the gondola system is an assumed carrier size (8 passengers), the number of carriers required will be determined by working backward from the required capacity. Using a PHF of 0.90, a theoretical directional capacity of 833 passengers per hour is needed (demand of 750 passengers per hour, divided by 0.90). Dividing this capacity by 8 passengers per carrier results in 105 eight-passenger carrier arrivals per hour required at a station. However, because each carrier will make more than one trip each hour, the number of actual carriers required will be smaller.

A carrier traveling at a line speed of 6 m/s (the maximum for a detachable-grip lift) requires 134 seconds to travel the length of the line. Therefore, a round trip on the line takes 268 seconds. In addition, the carriers take 1 minute to travel through each station at creep speed, adding another 120 seconds to the round-trip journey. Consequently, a carrier makes one round trip every 388 seconds, or 9.28 round trips per hour. The number of carriers that will provide the required number of hourly station arrivals is 105 arrivals per hour divided by 9.28 arrivals per carrier per hour, or 12 carriers (rounded up).

The Results

Although the aerial tramway carrier travels twice as fast as a gondola at their respective maximum line speeds, it takes much longer to accelerate and decelerate the aerial tramway carrier. As it turned out, the travel times of the two modes were nearly the same over the length of the relatively short route. The headway between aerial tramway carriers is approximately 5 minutes, while the headway between gondolas is about 32 seconds.

APPENDIX A: EXHIBITS IN METRIC UNITS

Exhibit 5-24m
Linear Passenger Loading—Articulated LRVs(R15)

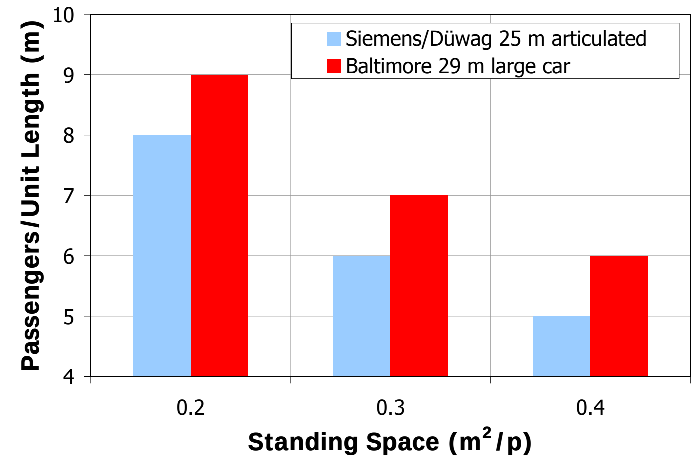


Exhibit 5-25m
Linear Passenger Loading—Heavy Rail Cars(R15)

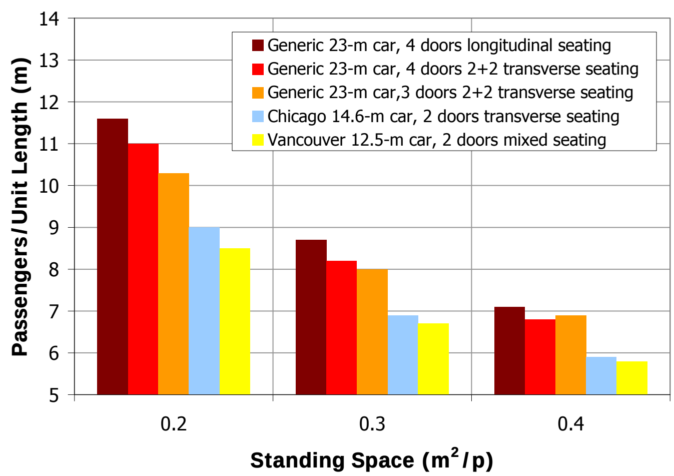
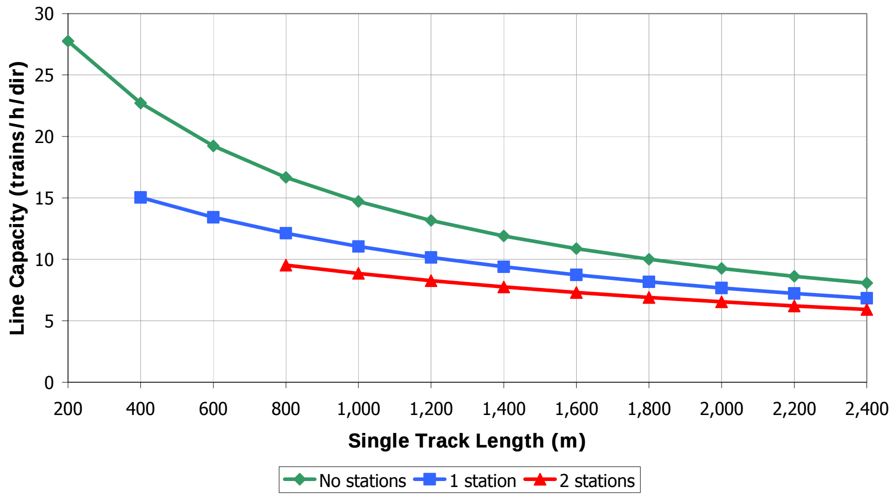


Exhibit 5-26m
Summary of Linear Passenger Loading (p/m) (1995)(R15)

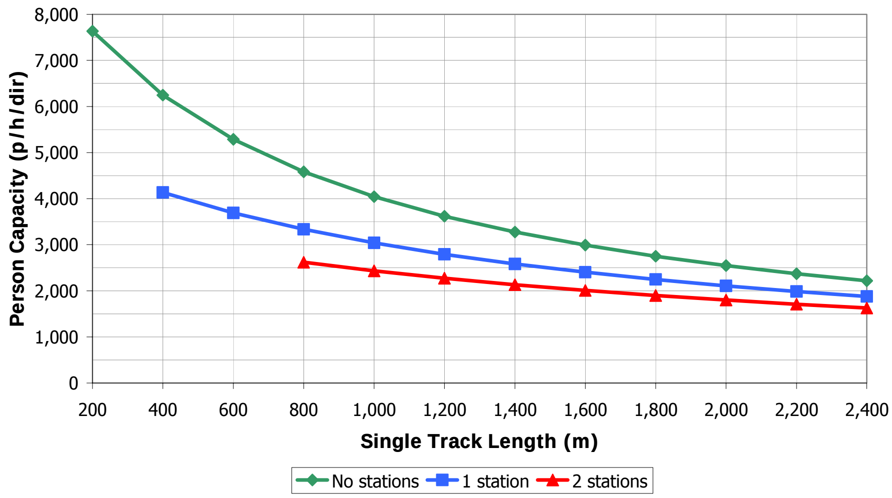
	Average	Median	Standard Deviation
All Systems	6.4	5.9	2.0
Commuter Rail	4.8	4.5	0.7
Heavy Rail	6.8	6.3	2.0
Heavy Rail less New York	5.5	5.6	1.5
MTA-NYCT alone	7.9	7.8	1.8

Exhibit 5-47m
Single-Track Line Capacity—Two-Car Light Rail Trains



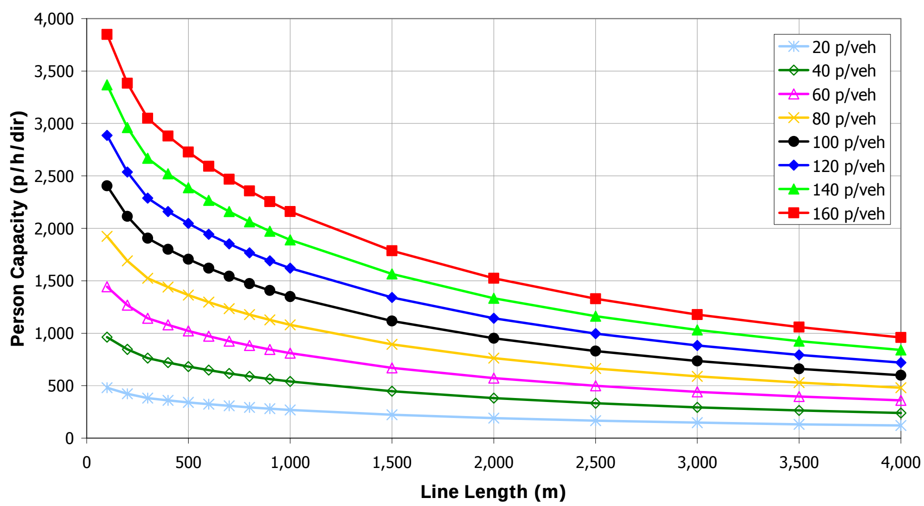
NOTE: Assumes 55-km/h speed limit, 55-m train length, 20-s dwell time, and 20-s operating margin.

Exhibit 5-48m
Single-Track Person Capacity—Two-Car Light Rail Trains



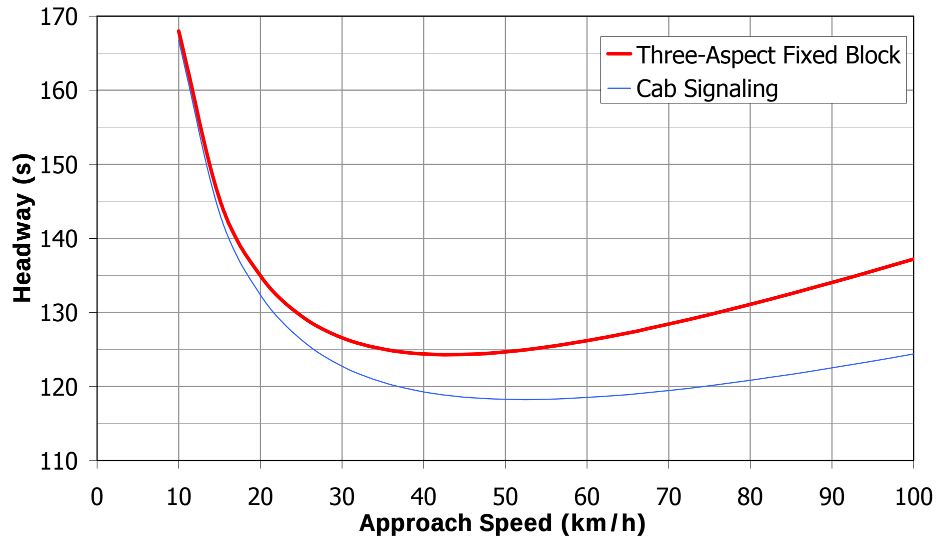
NOTE: Assumes 55-km/h speed limit, 55-m train length, 20-s dwell time, and 20-s operating margin.

Exhibit 5-51m
Reversible Ropeway Person Capacity



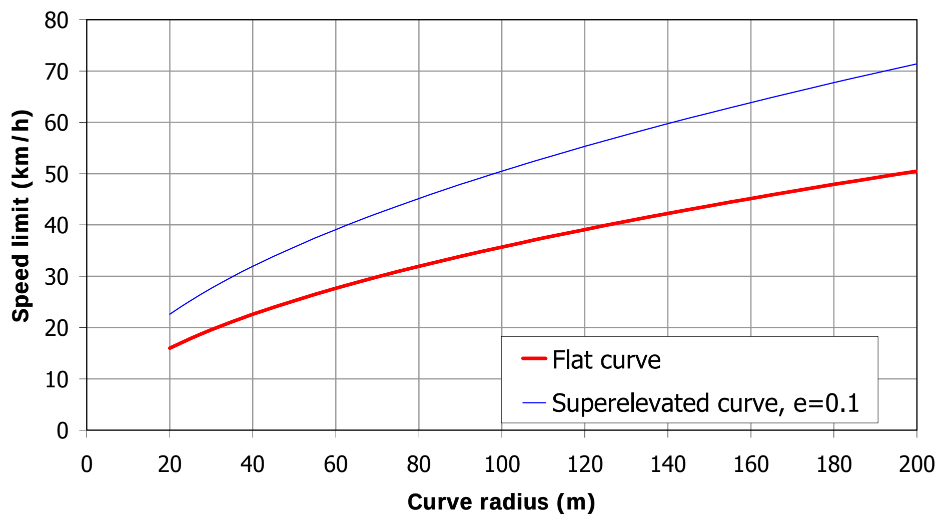
NOTE: Assumes 10 m/s line speed, 0.2 m/s^2 acceleration, two-vehicle operation, 90-s dwell time, and 0.90 PHF.

Exhibit 5-55m
Station Headway for Lines at Capacity(R15)



NOTE: dwell = 45 s, operating margin = 20 s.

Exhibit 5-56m
Speed Limits on Curves(R15)



NOTE: Transition spirals are not taken into account.

Exhibit 5-58m
Distance-Speed Chart(R15)

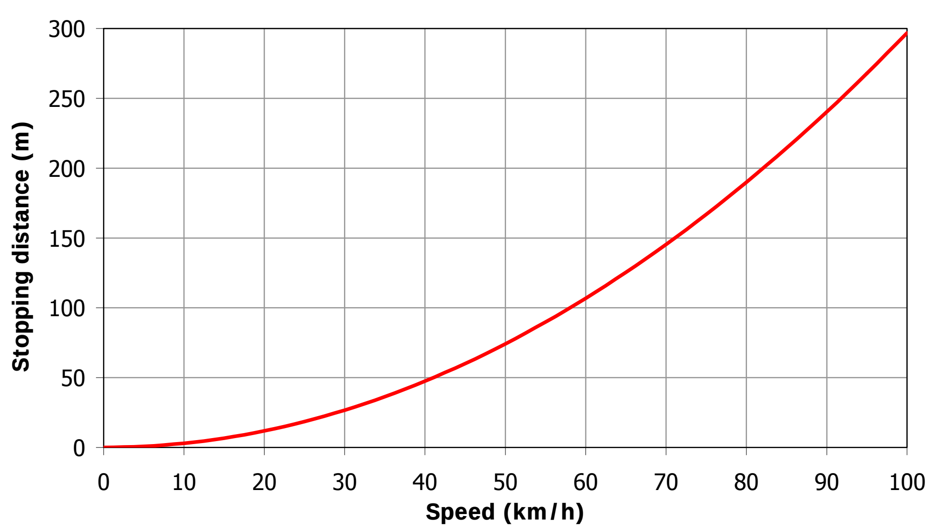


Exhibit 5-61m
Moving-Block Station Headways Compared with Conventional Fixed-Block Systems(R15)

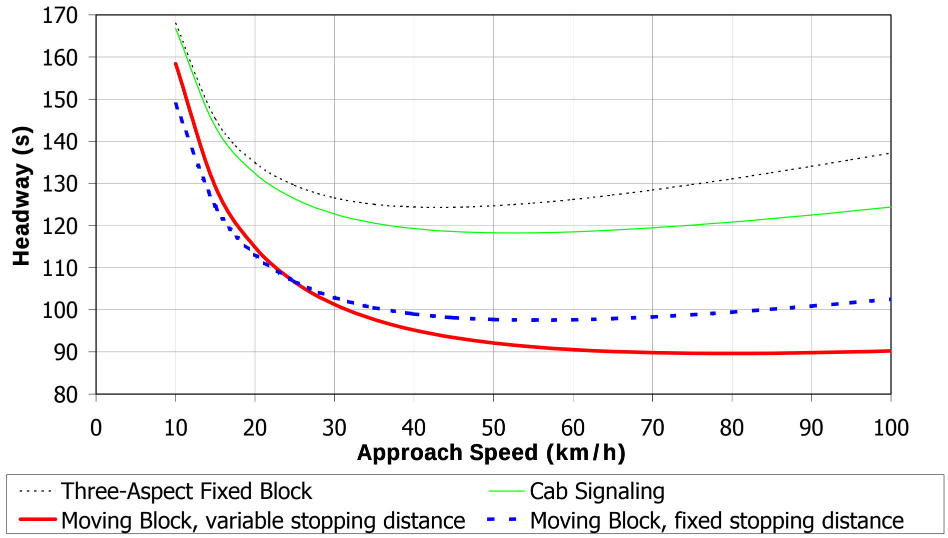


Exhibit 5-63m
Passengers per Unit Train Length, Major North American Rail Trunks, 15-Minute Peak (1995)(R15)

System & City	Trunk Name	Mode	Car 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 Street Tunnel in 1995 was 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 meter given is for the combined lines; individually this value is 10.8 for the E and 9.8 for the F. The F was moved to the 63rd Street Connector in December 2001, and a new line V shared the 53rd Street Tunnel with line E.

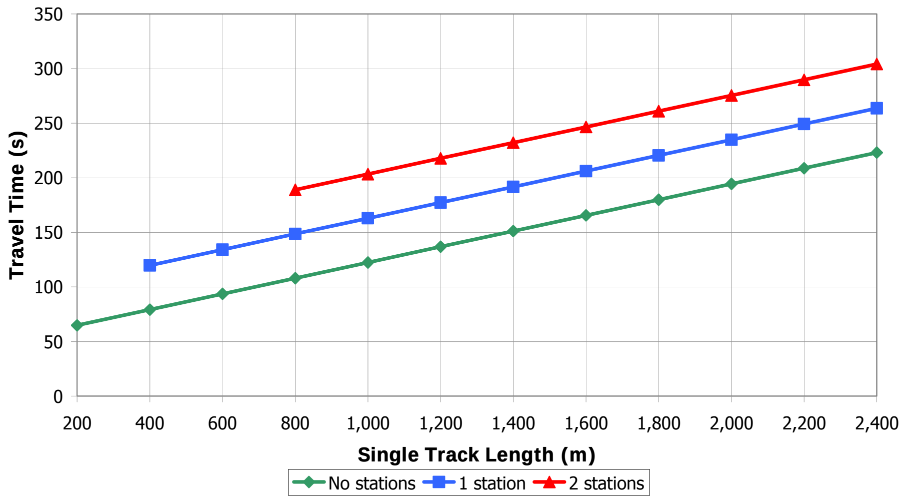


Exhibit 5-66m
Light Rail Travel Time Over Single-Track Section(R15)

NOTE: Assumes speed limit of 55 km/h, train length of 55 m, 20-s dwell time, 20-s operating margin, and other data as per Exhibit 5-65. *The recommended closest headway is twice this time.*

Exhibit 5-75m
Average Commuter Rail Operating Speeds(R10)

Station Spacing (km)	Average Operating Speed (km/h) P/W = 3.0	P/W = 5.8	P/W = 9.1
Average Dwell Time = 30 s			
1.6	27.0	32.7	35.9
3.2	41.5	49.7	56.4
6.4	58.6	71.0	78.2
8.0	64.9	78.4	84.8
Average Dwell Time = 60 s			
1.6	23.8	28.0	30.3
3.2	37.5	44.1	49.3
6.4	54.4	65.0	71.0
8.0	60.9	72.5	78.1

NOTE: P/W = power-to-weight ratio
Assumes 128-km/h speed limit, no grades, and no delays due to other trains.

Exhibit 5-78m
Suggested AGT Separation Calculation Default Values(R15)

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

NOTE: shaded lines indicate AGT default values that differ from heavy rail default values.

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APPENDIX B: RAIL ROUTE CHARACTERISTICS

Exhibit 5-81
Light Rail Route Characteristics and Ridership (2002)

Region	Route	Length mi	Length km	Stations	Weekday Ridership	Peak Hour Pass.	Peak Hour Trains	Peak Hour Cars
Baltimore (MTA)	Hunt Valley-Cromwell	57.6	92.7	32	24,700		17	33
Baltimore (MTA)	Penn Station-BWI							
Boston (MBTA)	B-Boston College	6.4	10.3	19	30,700			
Boston (MBTA)	C-Cleveland Circle	5.1	8.2	14	14,500			
Boston (MBTA)	D-Riverside	13.5	21.7	24	21,800			
Boston (MBTA)	E-Heath	5.6	9.0	14	14,600			
Boston (MBTA)	Red (Mattapan)	2.6	4.2	8	7,800			
Buffalo (NFTA)	Metro Rail	6.4	10.3	8	25,000		10	22
Calgary (CTS)	201-Fish Creek*	1.2	2.0	11				
Calgary (CTS)	202-Whitehorn	8.9	14.3	9	60,200	5,900	16	48
Cleveland (GCRTA)	67X-Blue	30.8	49.6	35	11,800			
Cleveland (GCRTA)	67AX-Green							
Dallas (DART)	Red	44	72	34	51,200			
Dallas (DART)	Blue							
Dallas (DART)	M-Line Streetcar	3.8	6.1		1,000			
Denver (RTD)	C-Orange	13	21	12				
Denver (RTD)	D-Green	14.0	22.4	20	31,400	3,400	12	26
Edmonton (ETS)	LRT	7.6	12.3	10	38,000	3,800		30-31
Galveston (Island Tr.)	Trolley	2.6	4.2	15			4	4
Guadalajara (STEU)	1-North/South	9.4	15.5	19			12	24
Guadalajara (STEU)	2-East/West	5.3	8.5	10			8	16
Houston (Metro)	METRORail	7.5	12.1	16	scheduled 2004 opening			
Jersey City (NJT)	Bayonne	9.5	15.3	16				
Jersey City (NJT)	West Side Avenue							
Kenosha (Kenosha Tr.)	Electric Streetcar	1.0	1.6		150		1	1
Little Rock (CATA)	River Rail Streetcar	2.1	3.4	8	scheduled 2004 opening			
Los Angeles (LACMTA)	Blue	21.3	34.3	22	72,300		19	39
Los Angeles (LACMTA)	Gold	13.6	21.9	13	opened 2003			
Los Angeles (LACMTA)	Green	19.9	32.0	14	33,400		12	12
Memphis (MATA)	Main Street Trolley*	2.9	4.7					
Mexico City (STEDF)	Tren Ligero	16	26	18				11
Minneapolis (Metro Tr.)	Hiawatha Line	11.6	18.7	17	scheduled 2003-04 opening			
Monterrey (Metrorrey)	1-East/West	11.5	18.5	19			19	
Monterrey (Metrorrey)	2-North/South	2.8	4.5	6				
New Orleans (RTA-NO)	Canal	5.6	9.3		scheduled 2003-04 opening			
New Orleans (RTA-NO)	Riverfront	1.6	2.6	10	1,400			4
New Orleans (RTA-NO)	St. Charles	6.6	10.6	57	11,600			15
Newark (NJT)	City Subway	6.0	9.7	12	16,900	1,800		
Ottawa (OCT)	O-Train	5.0	8.0	5	5,800		1	2
Philadelphia (SEPTA)	10-Overbrook	5.9	9.5	44	7,600			
Philadelphia (SEPTA)	11-Darby	6.7	10.8	48	8,200			
Philadelphia (SEPTA)	13-Yeadon/Darby	7.0	11.2	49	8,600			
Philadelphia (SEPTA)	15-Girard	8.2	13.2		scheduled 2004 opening			
Philadelphia (SEPTA)	34-Angora	5.0	8.0	31	7,300			
Philadelphia (SEPTA)	36-Eastwick	7.1	11.4	49	8,700			
Philadelphia (SEPTA)	100-Norristown	13.5	21.7	22	7,800			16
Philadelphia (SEPTA)	101-Media	8.5	13.7	35	7,300			19
Philadelphia (SEPTA)	102-Sharon Hill	5.3	8.5	27				
Pittsburgh (PAT)	42L-Library	8.1	13.0	46	5,100			
Pittsburgh (PAT)	42S-South Hills†	10.5	16.9	36	19,300			
Pittsburgh (PAT)	52-Allentown	2.5	4.0		700			
Pittsburgh (PAT)	Overbrook	5.5	8.9	8	scheduled 2003 opening			
Portland (TriMet)	Blue-East/West	32.4	52.1	46	70,300		9	18
Portland (TriMet)	Red-Airport	12.8	20.6	19	10,500	500	4	4
Portland (TriMet)	Yellow-Interstate	7.2	11.6	17	scheduled 2004 opening			
Portland (City)	Portland Streetcar	2.4	3.9	18	4,200		4	4
Sacramento (SRTD)	Light Rail*	20.6	33.1	30	29,000	1,500	8	32
St. Louis (Bi-State)	MetroLink*	45.7	73.5	26	42,400		22	44
Salt Lake City (UTA)	701-North/South	12.3	19.8	15	29,500		7	21
Salt Lake City (UTA)	702-University*	2.5	4.0	5				
San Diego (SDT)	Blue*	25.2	40.5	31	50,000		18	54
San Diego (SDT)	Orange	21.6	34.8	24	24,500		9	29
San Francisco (SF Muni)	F-Market & Wharves	6.0	9.7	30	19,200			
San Francisco (SF Muni)	J-Church*	15.7	25.3		15,200			
San Francisco (SF Muni)	K-Ingleside	13.2	21.2		25,300			
San Francisco (SF Muni)	L-Taraval	5.4	8.7		29,900			
San Francisco (SF Muni)	M-Ocean View	6.8	10.9		33,300			
San Francisco (SF Muni)	N-Judah	13.2	21.2		45,600			

Table continues on the next page.

Exhibit 5-81 (cont'd.)
Light Rail Route Characteristics and Ridership (2002)

Region	Route	Length mi	Length km	Stations	Weekday Ridership	Peak Hour Pass.	Peak Hour Trains	Peak Hour Cars
San Jose (VTA)	Baypointe-Sta. Theresa†	18.0	29.0	31	24,600			
San Jose (VTA)	Mountain View-Milpitas	11.5	18.5	19	5,600			
Seattle (KC Metro)	Waterfront Streetcar	1.9	3.0	9	600			
Tacoma (Sound T)	Tacoma Link	1.6	2.6	5	opened 2003		2	2
Tampa (Hartline)	TECO Line Streetcar	2.3	3.7	10	1,200		4	4
Toronto (TTC)	501-Queen	15.2	24.5	210	45,100	1,100		12
Toronto (TTC)	502-Downtowner	6.5	10.5	90	4,300	340		6
Toronto (TTC)	503-Kingston Road	5.7	9.2	83	2,000	350		6
Toronto (TTC)	504-King	7.9	12.7	125	50,700	1,500		28
Toronto (TTC)	505-Dundas	6.7	10.8	105	36,600	700		11
Toronto (TTC)	506-Carlton	9.2	14.8	154	40,300	900		15
Toronto (TTC)	508-Lake Shore	5.9	9.5	140	1,100	210		3
Toronto (TTC)	509-Harbourfront	2.8	4.5	29	2,400	300		6
Toronto (TTC)	510-Spadina	3.5	5.6	42	40,200	2,000		32
Toronto (TTC)	511-Bathurst	2.9	4.7	42	14,800	800		14
Toronto (TTC)	512-St. Clair	4.4	7.1	56	32,200	1,500		22
Trenton (NJT)	Southern New Jersey	34	55	20	scheduled 2003 opening			

*Extension of existing line underway in 2002.
†Data include all branches of the route.

SOURCES: Operator survey, APTA (R5)

NOTES: Routes that entirely duplicate other routes (e.g., the S-Castro/Embarcadero shuttle in San Francisco and the 703-Sandy/University route in Salt Lake City) not included. Only vintage trolleys operated by public transit agencies are included. The Tandy Subway in Fort Worth was a privately operated light rail line open to the public; it closed in 2002.

Because of overlapping routes, the sum of individual route lengths and stations may be greater than the actual system totals. Some systems included overlaps in length totals; others did not. Lengths are for a single direction of a route.

Most Toronto streetcar lines serve subway stations at their outer ends and run through downtown, giving them effectively four peak points per line. They also serve many short trips and have high off-peak use. This accounts for the exceptionally low ratio of peak hour to daily ridership.

Exhibit 5-82
Heavy Rail Route Characteristics and Ridership (2002)

Region	Route	Length mi	Length km	Stations	Weekday Ridership	Peak Hour Pass.	Peak Hour Trains	Peak Hour Cars
Atlanta (MARTA)	East/West†	16.0	25.8	16	71,400	3,000	8	60
Atlanta (MARTA)	North/South†	22.2	35.7	18	117,900	5,100	8	58
Baltimore (MTA)	Metro	29.4	47.3	14	48,500		9	54
Boston (MBTA)	Blue	5.9	9.5	12	57,000			
Boston (MBTA)	Orange	11.2	18.0	19	157,000			
Boston (MBTA)	Red†	20.5	33.0	22	227,000			
Chicago (CTA)	Blue†	34.2	55.1	44	125,600	8,400	15	120
Chicago (CTA)	Brown	11.3	18.2	28	79,300	9,500	18	108
Chicago (CTA)	Green†	21.1	33.9	29	38,600	3,200	8	48
Chicago (CTA)	Orange	12.4	19.9	17	39,400	5,800	11	88
Chicago (CTA)	Purple	16.2	26.1	25	24,500	3,400	7	42
Chicago (CTA)	Red	21.7	34.9	34	200,200	11,900	19	152
Chicago (CTA)	Yellow	5.0	8.1	2	3,400	800	9	18
Cleveland (GCRTA)	66X-Red	19.1	30.8	17	24,100		14	28
Los Angeles (LACMTA)	Red†	16.0	25.7	16	105,600	30,600	14	70
Mexico City (STC)	1	11.7	18.8	20	852,000¤			
Mexico City (STC)	2	14.5	23.4	24	853,000¤			
Mexico City (STC)	3	14.7	23.6	21	767,000¤			
Mexico City (STC)	4	6.6	10.7	10	88,000¤			
Mexico City (STC)	5	9.8	15.7	13	238,000¤			
Mexico City (STC)	6	8.6	13.9	11	127,000¤			
Mexico City (STC)	7	11.7	18.9	14	247,000¤			
Mexico City (STC)	8	12.5	20.1	19	355,000¤			
Mexico City (STC)	9	9.5	15.3	12	334,000¤			
Mexico City (STC)	A	10.6	17.0	10	263,000¤			
Mexico City (STC)	B	14.7	23.7	21	282.000¤			
Miami (MDT)	Metrorail*	21.1	34.0	21	46,300		15	86
Montréal (STM)	1-Green	13.7	22.1	27	369,800	21,900		
Montréal (STM)	2-Orange	15.4	24.8	28	407,700	24,400		
Montréal (STM)	4-Yellow	2.7	4.3	3	56,900	10,900		
Montréal (STM)	5-Blue	6.0	9.7	12	85,600	6,400		

Table continues on the next page.

Exhibit 5-82 (cont'd.)
Heavy Rail Route Characteristics and Ridership (2002)

Region	Route	Length mi	Length km	Stations	Weekday Ridership	Peak Hour Pass.	Peak Hour Trains	Peak Hour Cars
New York (NYCT)	1-Clark St NB	36	58	57		6,400	9	90
New York (NYCT)	1-66th St SB					10,400	11	110
New York (NYCT)	2-Clark St NB	48	77	49		7,100	10	100
New York (NYCT)	2-66th St SB					7,100	9	90
New York (NYCT)	3-72nd St SB	12	19	18		12,100	11	110
New York (NYCT)	4-Borough Hall NB	38	61	54		13,600	15	150
New York (NYCT)	4-86th St SB					16,600	12	120
New York (NYCT)	5-Borough Hall NB	47	76	45		9,200	10	100
New York (NYCT)	5-86th St SB					13,600	10	100
New York (NYCT)	6-68th St SB	24	39	38		25,900	21	210
New York (NYCT)	7-Vernon Jackson SB	15	24	21		22,500	24	264
New York (NYCT)	A-High St NB†	49	79	70		19,000	17	150
New York (NYCT)	A-125th St SB					12,100	10	86
New York (NYCT)	B-72nd St SB	18	29	26		4,600	6	48
New York (NYCT)	C-High St NB	36	58	48		6,300	8	64
New York (NYCT)	C-72nd St SB					5,700	6	48
New York (NYCT)	D-125th St SB	19	31	18		9,300	9	72
New York (NYCT)	E-23rd St-Ely Ave SB	25	40	32		17,000	11	110
New York (NYCT)	F-York St NB	43	69	55		12,600	14	112
New York (NYCT)	F-23rd St-Ely Ave SB					21,300	17	136
New York (NYCT)	G	10	16	17				
New York (NYCT)	J,Z-Marcy Ave SB	21	34	30		8,600	11	88
New York (NYCT)	L-Bedford Ave NB	16	26	24		19,300	16	128
New York (NYCT)	M-Court St NB	27	43	37		3,700	7	56
New York (NYCT)	M-Marcy Ave SB					5,100	6	48
New York (NYCT)	N-Court St NB	33	53	45		3,300	6	56
New York (NYCT)	N-Queensboro Plz SB					10,000	7	66
New York (NYCT)	Q-DeKalb Ave NB	24	39	25		18,900	16	144
New York (NYCT)	R-Court St NB	35	56	45		3,600	6	48
New York (NYCT)	R-Queens Plaza SB					11,400	8	66
New York (NYCT)	S-Franklin Ave	2	3	4				
New York (NYCT)	S-42nd St	1	2	2				
New York (NYCT)	S-Grand St	2	3	3				
New York (NYCT)	S-Rockaway	5	8	5				
New York (NYCT)	V			24				
New York (NYCT)	W-Pacific St NB	32	51	28		9,500	9	72
New York (NYCT)	W-Queensboro Pl. SB					8,100	6	48
New York (SIR)	Staten Island Railway	23.0	37.0	22	14,400			
Newark (PATH)	Hoboken-33rd Street	3.5	5.6	6	47,800	6,700	14	98
Newark (PATH)	Journal Sq.-Hoboken	3.3	5.3	4	9,200	1,300	8	56
Newark (PATH)	Newark-33rd Street	11.4	18.3	9	126,800	17,800	12	84
Philadelphia (SEPTA)	Market-Frankford	12.2	19.6	28	172,200			
Philadelphia (SEPTA)	Broad-Ridge†	11.4	18.3	24	111,400			
Philadelphia (PATCO)	PATCO Speedline	14.2	22.9	13	36,000	6,800	23	138
San Francisco (BART)	Dublin-Pl./Daly City*	39.0	62.9	17	54,700	2,300	4	36
San Francisco (BART)	Fremont/Daly City	38.7	62.4	19	48,400	3,600	4	38
San Francisco (BART)	Pittsburg/Colma	44.8	72.3	22	124,300	6,200	11	103
San Francisco (BART)	Richmond/Daly City	27.6	44.5	19	50,500	4,400	4	37
San Francisco (BART)	Richmond/Fremont	36.1	58.2	18	59,800		4	26
San Juan	Tren Urbano	21.4	34.4	18	scheduled 2003 opening			
Toronto (TTC)	Bloor-Danforth	16.3	26.2	31	465,900	20,200	25	150
Toronto (TTC)	Yonge-Univ.-Spadina	18.8	30.2	32	614,000	26,200	25	150
Toronto (TTC)	Scarborough RT	4.0	6.4	6	42,300	4,100	17	68
Vancouver (TransLink)	Expo††	17.9	28.8	20	144,600	15,000	35	140
Vancouver (TransLink)	Millennium*	25.7	41.4	27**	opened mid-2002		25	††
Washington (WMATA)	Red	31.6	50.8	26**		12,700	20	120
Washington (WMATA)	Blue*	26.9	43.2	25		5,000	10	54
Washington (WMATA)	Orange	26.2	42.1	26		10,600	20	104
Washington (WMATA)	Yellow	10.6	17.1	12		4,700	10	56
Washington (WMATA)	Green	22.8	36.6	21		7,400	10	60

*Extension of existing line underway in 2002. SOURCE: Operator survey
**Additional infill station under construction in 2002.
†Data include all branches of the route.
††Expo line figures are prior to the opening of the Millennium line. The total number of cars operated on the Expo and Millennium lines combined ranges from 180 to 198, depending on the proportions of Mark I and Mark II trains used.
¤Estimates based on 2001 annual route, 2001 annual system, and 2001 weekday system ridership.

NOTES: Routes that entirely duplicate other routes (e.g., S-63 Street/6 Avenue shuttle in New York) not included.

Because of overlapping routes, the sum of individual route lengths and stations may be greater than the actual system totals. Some systems included overlaps in length totals; others did not. Lengths are for a single direction of a route.

Exhibit 5-83
Commuter Rail Route Characteristics and Ridership (2002)

Region	Route	Length mi	Length km	Stations	Weekday Ridership	Peak Hour Pass.	Peak Hour Trains	Peak Hour Cars
Baltimore	Brunswick†	73.4	118.1	19				
Baltimore	Camden	36.8	59.2	11				
Baltimore	Penn	76.5	123.1	14				
Boston	Attleboro/Providence	43.6	70.2	8	10,300			
Boston	Fairmount	9.5	15.3	4	1,300			
Boston	Fitchburg	49.5	79.6	18	4,100			
Boston	Franklin	30.3	48.8	13	9,100			
Boston	Greenbush	18	29	7	scheduled 2006 opening			
Boston	Haverhill/Reading	32.9	52.9	13	5,000			
Boston	Kingston/Plymouth†	35.7	57.4	6	3,800			
Boston	Lowell	25.5	41.0	8	5,000			
Boston	Mid'borough/Lakeville	35.3	56.8	6	3,600			
Boston	Needham	13.7	22.0	11	4,800			
Boston	New Bedford/Fall Riv.†	47.6	76.6	8	scheduled 2005 opening			
Boston	New'port/Rockport†	35.3	56.8	18	8,300			
Boston	Rockport/Ipswich†	18.8	30.2	3	1,700			
Boston	Worcester/Fr'ham	44.3	71.3	15	8,200			
Burlington	Champlain Flyer	12.5	20.1	5	200		1	2
Chicago	BNSF	37.5	60.3	27	57,900	13,800	14	112
Chicago	Electric Div. Main Line	31.5	50.7	34	33,300	8,300	14	80
Chicago	Electric Div. Blue Is.	4.4	7.1	7	2,900	950	4	10
Chicago	Electric Div. S. Chicago	4.7	7.6	8	8,100	2,000	4	18
Chicago	Heritage Corridor	37.2	60.0	6	2,200	1,000	2	9
Chicago	Milwaukee North Line	49.5	79.6	21	22,500	5,000	6	39
Chicago	Milwaukee West Line	39.8	64.0	23	22,100	5,300	7	51
Chicago	North Central Service	52.8	85.0	14	4,400	1,400	2	11
Chicago	Rock Island	46.8	75.3	25	36,200	9,400	9	68
Chicago	South Shore	89.7	144.4	21	13,400	3,200	4	32
Chicago	SouthWest Service	28.9	46.5	10	6,900	2,700	3	24
Chicago	UP North Line	51.6	83.0	26	28,500	5,800	7	42
Chicago	UP Northwest Line†	70.5	113.4	22	38,100	9,200	10	79
Chicago	UP West Line	35.5	57.1	17	28,600	6,900	7	55
Dallas-Ft. W.	Trinity Railway Express	34.0	55.8	9	7,800		5	
Los Angeles	91 Line	61.5	99.0	10	900	320	2	6
Los Angeles	Antelope Valley	76.6	123.3	10	6,000	1,300	3	11
Los Angeles	Inland Empire-Or. Cty.	100.1	161.1	13	5,800	1,200	3	12
Los Angeles	Orange County	87.3	140.5	13	5,800	1,700	3	12
Los Angeles	Riverside	58.7	94.5	7	4,300	1,100	2	10
Los Angeles	San Bernardino	56.5	90.9	13	10,100	2,200	3	17
Los Angeles	Ventura County	66.3	106.7	11**	3,900	750	2	7
Miami	Tri-Rail	72.0	115.8	18	9,500	3,200	4	14
Montréal	Blainville	29.2	47.0	9	7,300			
Montréal	Delson	14.9	24.0	7	700			
Montréal	Deux Montagnes	16.9	27.2	12	27,000	2,500		
Montréal	Dorion-Rigaud	40.0	64.4	18	12,900	3,500		
Montréal	Saint-Hilaire	17.4	28.0	4	800			
New Haven	Shore Line East	32.8	52.8	7	1,100			
New Jersey	Atlantic City	67.9	109.3	8	1,500	220	2	
New Jersey	Boonton	47.9	77.1	20	5,700	1,900	5	
New Jersey	Main/Bergen County	95.2	153.1	31	17,100	4,700	10	
New Jersey	Montclair	12.8	20.6	6	1,200	340	2	
New Jersey	Morris & Essex†	60.2	96.9	33	25,700	4,800	13	
New Jersey	North Jersey Coast	66.7	107.4	25	37,300	6,900	7	
New Jersey	Northeast Corridor†	60.8	97.9	14	54,100	6,700	8	
New Jersey	Pascack Valley	30.6	49.3	17	6,100	1,900	4	
New Jersey	Raritan Valley	43.4	69.9	19	12,800	3,000	6	
NY-Long Isl.	Babylon†	36.9	59.4	15	68,300	13,000	14	132
NY-Long Isl.	Far Rockaway	21.5	34.6	17	12,900	2,800	5	36
NY-Long Isl.	Flatbush Terminal	9.3	15.0	4		6,500	12	86
NY-Long Isl.	Hempstead	20.1	32.4	15	14,100	3,200	5	36
NY-Long Isl.	Hunterspoint Terminal							
NY-Long Isl.	Long Island City Term.	9.0	14.5	7		120	2	11
NY-Long Isl.	Long Beach	23.4	37.7	11	20,100	5,000	6	56
NY-Long Isl.	Montauk	106.9	172.0	22	7,300	1,300	4	20
NY-Long Isl.	Oyster Bay	23.9	38.5	13	5,000	1,000	2	11
NY-Long Isl.	Penn Terminal	9.3	15.0	6		41,500	38	380
NY-Long Isl.	Port Jefferson	57.9	93.1	22	51,400	11,000	12	109
NY-Long Isl.	Port Washington	18.4	29.6	13	41,400	9,100	8	76
NY-Long Isl.	Ronkonkoma	94.3	151.8	22	39,100	8,700	6	68
NY-Long Isl.	West Hempstead	13.1	21.1	11	3,600	1,300	3	20

Table continues on the next page.

Exhibit 5-83 (cont'd.)
Commuter Rail Route Characteristics and Ridership (2002)

Region	Route	Length mi	Length km	Stations	Weekday Ridership	Peak Hour Pass.	Peak Hour Trains	Peak Hour Cars
NY-Metro N.	Harlem	77.4	124.5	36	85,500	12,300	17	134
NY-Metro N.	Hudson	75.8	122.0	29	48,000	8,300	13	94
NY-Metro N.	New Haven	60.7	97.7	26	104,400	15,700	20	157
NY-Metro N.	New Canaan Branch	7.9	12.7	4	5,000			
NY-Metro N.	Danbury Branch	24.2	38.9	7	2,600		1	2
NY-Metro N.	Waterbury Branch	27.1	43.6	6	600			
Philadelphia	R1	29.6	47.7	16	5,000	1,100	13	29
Philadelphia	R2	57.1	75.7	35	13,700	9,000	26	93
Philadelphia	R3	48.0	77.3	36	18,300	13,400	37	143
Philadelphia	R5	70	127.0	49	36,100	20,100	53	214
Philadelphia	R6	24.7	39.8	19	7,700	4,400	22	62
Philadelphia	R7	45.1	73.7	26	15,200	9,100	29	101
Philadelphia	R8	23.7	38.5	20	10,600	6,800	27	78
Philadelphia	PennDOT	72.2	116.2	12	700			
San Diego	Coaster	41.1	66.1	8	5,000		4	
San Francisco	CalTrain	76.8	123.6	33	29,000			
San Jose	Altamont Comm. Exp.	86.0	138.4	10	2,800		2	12
Seattle	Sounder*	39.3	63.2	8	2,900	1,500	3	
Syracuse	City Express	3.5	5.6	4	100			
Toronto	Bradford	41.5	66.8	6	1,600	800	1	7
Toronto	Georgetown	29.4	47.3	8	8,700	3,300	3	24
Toronto	Lakeshore East	31.6	50.9	10	30,000	7,500	5	51
Toronto	Lakeshore West	39.3	63.3	12	37,200	10,100	6	62
Toronto	Milton	31.2	50.2	8	13,200	4,000	3	27
Toronto	Richmond Hill	21.0	33.8	5	4,800	1,800	3	18
Toronto	Stouffville	29.0	46.7	8	2,000	1,200	2	12
Vancouver	West Coast Express	43	65	8	7,600	2,500	3	22
Washington	Fredericksburg	53.8	86.5	11	6,300	1,300	2	11
Washington	Manassas	35.8	57.6	10	5,300	1,200	2	10

*Extension of existing line underway in 2002.
**Additional infill station under construction in 2002.
†Data include all branches of the route.

SOURCE: Operator survey, APTA (R5)

NOTES: Because of overlapping routes, the sum of individual route lengths and stations may be greater than the actual system totals. Some systems included overlaps in length totals; others did not. Lengths are for a single direction of a route.

Burlington's Champlain Flyer ceased operations in March 2003. Syracuse's OnTrack City Express operates 11:15 a.m. to 6:30 p.m. Wednesday through Sunday.

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