# 6. Operating Issues

### **6.1 INTRODUCTION**

The previous three chapters have introduced the three major components that control rail transit capacity. Chapter Three, *Train Control and Signaling*, describes the capabilities—and determination of separation—for a range of train control systems. The minimum separation of the train control system can be calculated with some precision once the weak link has been determined—usually the maximum load point station. Whether a train will achieve this minimum separation is an operating issue. Is the equipment performing to specification? On manual systems, is the train driven at or close to the optimal envelope? The answer to both questions is not always yes. To operate a rail transit at its maximum achievable capacity without interference between trains, an allowance has to be made for these operating variables.

Chapter Four, *Station Dwells*, analyzed and developed alternate methodologies to estimate dwells. Dwells cannot be estimated with precision. They are affected by many day-to-day circumstances. While some variables are accommodated in the methodology it is not possible to make allowances for all. An additional allowance is required to handle some of the day-today irregularities. This is an operating issue. Dwells can also be optimized by the design of stations, vehicle interiors and scheduling—another operating issue.

Chapter Five, *Passenger Loading Levels*, offered two routes to estimate the number of passengers. One is how many passengers will physically crowd onto a train—providing the maximum achievable capacity. The other requires a policy decision to establish a more comfortable peak-within-the-peak loading level, appropriate to today's modern rail transit and attractive to passengers. Either level is capable of handling an overload of passengers when situations dictate. This again is an operating issue.

Each of these operating issues will be discussed in this chapter, concluding with recommendations on the range of operating margins that should be included in the minimum headway that, in turn, produces the maximum achievable capacity that is the goal of this project.

### **6.2 TRAIN PERFORMANCE**

Much has been made of the uniformity of performance of the electrical multiple-unit trains that handle over 90% of all North American rail transit. There is indeed a remarkable uniformity in the rates of braking and acceleration due to the dictates of passenger comfort. Variations in the reduction of acceleration with speed increase and different maximum or balancing speeds have been accommodated in the calculations of minimum train control system separation in Chapter Three, *Train Control and Signaling*. These calculations also accommodate fluctuations in line voltage.

Although the wide spread introduction of electronic controls has improved the uniformity of actual to specified performance, there still can be differences between individual cars and trains due to manufacturing tolerances, aging of components and variance in set-up parameters.

The result can be up to a 10% difference in performance between otherwise identical cars. Any impact is diluted when the under-performing car is coupled in a train. One such car in a ten-car consist will make a negligible difference. In a two-car train the results are noticeable. In many systems, underperforming cars or trains are colloquially called *dogs*. Often such trains cannot keep schedule and become progressively late. As discussed later in this chapter, this situation can reduce system capacity. This is a sufficiently common situation that an allowance should be made in determining achievable capacity and under-performing trains are one component, albeit minor, in determining an appropriate operating margin.

There is a trend to design rail equipment not only to fail safe but also to fail *soft*. Certain electronic-monitored rail transit cars are designed to drop to lower performance rates if motor or control equipment exceeds a set temperature, or if the line voltage drops below a certain level. This performance drop may be sudden or can be progressive but has to be significant, typically 25% to 50%, to achieve the desired effect. Once a single car on a train has reduced performance, the remaining cars become overloaded and it is easy for an avalanche effect to disable the entire train. This level of performance reduction cannot reasonably be compensated for in the operating margin. Automatic warning of the reduction is usually provided and rapid removal of the equipment by train or control room operators is needed to avoid service disruptions.

Lower braking performance will also affect capacity. However the minimum train separation calculations, for safety reasons, have already compensated for this by assuming a braking performance set at a proportion of the normal specification of  $1.3 \text{ m/s}^2$ . The equations of Chapter Three allow a user-specified value to be inserted for this percentage. The recommended value is 75%.

Brake system failures are not regarded as a capacity issue. Trains with one or more sets of cut-out brakes are invariably immediately removed from service.

Performance differences are minor compared to the effect of component failures. Failure management procedures have been a feature of the industry from the earliest days—usually allowing a defective motor to be cut-out so that the affected car or train can continue in-service, or if significantly crippled, limp home. This practice can also extend to motor control equipment and other subsystems. Air and low voltage power are invariably train-lined—that is, shared between coupled cars—so that the failure of a compressor, battery, motor-generator set or inverter should have no effect on performance.

Redundant components are also becoming more common for motor and train control equipment. These features, combined with automated, and sometimes remote, diagnostics, and effective preventive maintenance programs have resulted in increases in the mean distance traveled between disruptive inservice failures. It is not uncommon for many classes of modern rail equipment to achieve 100,000 km (60,000 mi) between inservice failures and a few car series on a handful of systems have reached double this level.

The typical rail transit car travels 80,000 km (50,000 mi) each year—somewhat less for light rail vehicles. Some 20% of this travel occurs during the peak hours. Each car therefore has a potentially disruptive peak-hour failure approximately once every 5 years. With multiple-unit trains the chance of a failure is proportionate to the number of cars. Counteracting this is the fact that a failure that could be chronic for a single car is rarely so on longer trains. It is not uncommon for an eight- or ten-car train to include one car with a totally inactive propulsion system.

Consequently, it is neither appropriate nor practical to compensate for major equipment failures in determining the achievable capacity of a rail transit line. Operations planning should ensure that such failures can be managed with the least disruption. Unfortunately, operations planning is often given scant attention in the initial design of a rail transit system. Thus senior operating staff arrive to find many operating failure management options have not been provided. These include periodic pocket or spur tracks to accommodate bad-order equipment, or spare equipment to plug gaps in service; frequent cross-overs and bidirectional signaling to permit operating around failed or derailed trains, failed switches, line-side fires and suicides; and terminal station layout allowing forward and rear train reversals and storage of spare or bad-order equipment.

Poor or nonexistent operations planning may result in a system that is unable to reach its achievable capacity or to sustain this capacity reliably. This is an important issue as this project has striven to determine a rail transit capacity that is both achievable and sustainable. Attempting to quantify the impacts of the more significant equipment failures on capacity is beyond the scope of the study. Eleven references in Appendix One, *Literature Summaries*, discuss operations simulation and modeling that allow some failure scenarios to be considered and the temporary reduction in capacity determined.

Abramovici<sup>(R01)</sup>, in *Optimization of Emergency Crossovers* and Signals for Emergency Operations in Rail Rapid Transit Systems, calculates the impact of forced single track working on capacity for a typical rail rapid transit system with crossovers approximately 3 km (2 mi) apart. Achievable capacity is reduced to 33% of normal with uni-directional signaling and 60% of normal with bi-directional signaling. However, with optimized cross-overs and bi-directional signaling, emergency operation at 80-90% of normal capacity can be obtained.

Retaining so high a proportion of capacity during a serious failure carries a price—but a price that is reducing as the industry moves to train control systems with inherent bidirectional capability. New systems that are being designed for high capacity or have links that preclude rerouting passengers on other routes, should examine the cost effectiveness of retaining an emergency situation capacity that is a high proportion of normal achievable capacity.

### **6.3 OPERATING VARIATIONS**

Differences among train operators can have an effect on capacity because of operating below the maximum equipment performance envelope and civil speed restrictions; an understandable situation, particularly with inexperienced operators who want to avoid triggering the automatic overspeed emergency brake.

The result is twofold. The signaling system minimum train separation will be increased and the train will fall behind schedule. As discussed in Chapter Three, other workers have suggested that automatically driven trains can achieve a throughput—and so achievable capacity —that is 5 to 15% higher than manually driven trains. The project has been unable to obtain any data to support this, and the station dwell field survey suggests that any such gain is more than lost in the relatively slow station-door opening and departure procedures that were noted, predominantly on automatically driven systems.

A train that is late due to operator performance is no different from one that is late due to equipment under-performance, as discussed in the previous section. At close headways, passengers tend to arrive uniformly on station platforms with surges at interchange stations due to the arrival of connecting buses or trains. The result is that a late train will have additional passenger movement, will have a longer station dwell and will become progressively later until it interferes with the schedule of the following train.

The same situation occurs if the train ahead runs fast—termed running *sharp* on many systems. More passengers accumulate on the platforms and the following train has longer dwells.

To accommodate these routine irregularities, two allowances are made in operations planning and scheduling. An operating margin is added to the minimum train separation time and maximum load point station dwell 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 and an analysis of existing margins and recommendations for estimating margins are the subjects of the next section in this chapter.

The second allowance is schedule recovery, an amount of time added to the terminal turn-around time and dwell that allows for recovery from the accumulated delays on the preceding oneway 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 carry a given volume of passengers. The methodology for calculating turn-around times was presented in Chapter Three. The amount of schedule recovery time needed to avoid constraining capacity cannot be calculated. The best guidelines are that it should be at least half a headway at headways below every 5 min moving toward a full headway as frequency drops toward the minimum train separation. Chapter Three discussed ways to provide schedule recovery at terminal station by turning on-time trains behind the station. Late trains can then be turned in front of the station gaining 90 to 120 sec but an at economic cost.

Experience on some rail rapid transit systems, operating at their closest design headway, has shown that removing one train from service, that is, running 29 trains an hour instead of the rated capability of 30 trains an hour, can sufficiently reduce accumulated delays such that the 29 trains run closer to schedule and actually carry more passengers—and at a lower cost.

Due to equipment unavailability or failure early in the peak period, or to staff absenteeism that cannot be made up from the spare board, runs are periodically missed on rail transit systems—particularly the larger ones. This situation creates a gap in service. Dispatchers or supervisors—and certain automatic train supervision systems—will strive to close the gap or at least arrange for it to fall outside the peak-within-the-peak at the maximum load point station. Nevertheless the remaining trains must handle the passengers from the missing train(s). Their dwells will increase and the achievable capacity will be reduced.

There is no way to determine the probability or quantity of missed runs—or their effect on achievable capacity. Such irregularities can only be accommodated in the conservative assignment of loading levels and operating margins. Where achievable capacity has been based on the bare minimum of these discretionary components then missed runs will create significant peak-period perturbations.

### 6.4 OPERATING MARGINS

As a starting point for recommending suitable operating margins to incorporate into the determination of the maximum achievable capacity, an attempt was made to survey existing operating margins.

In general operating agencies were unable to quote specific data. Rail transit planners and schedulers discuss the desirability of both operating margins and schedule recovery but generally operating margin is as much accidental as planned. It is the amount of time between the closest headway and the sum of the minimum train separation and the maximum load point station dwell. As headways widen, operating margin increases. When headways are pushed to their limit it diminishes, sometimes almost to zero. As a result service irregularities increase. Some operators accept this as the price of obtaining maximum capacity and will even push a train into service on a line that is theoretically at capacity—and then usually remove it immediately after a single one-way peak-direction trip. More passengers have indeed been carried and line staff are left to sort

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out any erratic performance at the end of the peak period when a few gaps or bunching in service are less critical.

This approach is counter to the suggestion of the previous section that capacity could be increased by removing a peakhour train. This is very much a system-specific operating issue. It involves minutiae that cannot easily be simulated and is beyond the scope of this study. On a system that is at or close to capacity, the only realistic way to find out if adding or subtracting a train will increase capacity, and/or improve headway regularity, is to try it for a period of time.

To determine operating margins on existing systems, maximum-load-point station dwell and headways were recorded during both morning and afternoon peak periods on 10 North American systems. The results are shown graphically on the following page. This is truly a case where a picture—or chart tells a thousand words. There are many possible reasons for irregular headways (shown as spikes), where known, for example a passenger holding a door, these are tabulated in the main data spreadsheet, provided on disk with this report. Unknown reasons can include technical failures, trains holding for a meet or trains coming into or going out-of-service.

Light rail headways on observed systems were generally sufficiently long that any irregularities reflected problems other than schedule interference between trains. The closest observed on-street headway was in Calgary, shown in Figures 6.1 through Figure 6.3 Note that the headways are all multiples of the 80-sec traffic light cycle. This multiple of light cycles is pursued in Chapter Eight, *Light Rail Capacity Determination*. Although one train per cycle is often possible, the recommendation is that achievable capacity should be based on one train every other 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 other light rail representative in the headway regularity charts on the following pageis San Francisco Muni operating in the Market Street subway—Figure 6.8. This operation is effectively high-level rail rapid transit with the complication that individual cars on trains from five surface routes are coupled into longer trains for operation in the subway after lengthy sections of on-street operation. Regularity of arrival at the coupling points is difficult to achieve and, with different cars of the same train

Figure 6.1 CTS 3rd St. SW E/B

450

400



Figure 6.2 CTS 1st St. SW W/B



Figure 6.3 CTS City Hall E/B















Figure 6.14 TTC King S/B



Figure 6.15 TTC Bloor N/B



Figure 6.5 BC Transit Burrard W/B



Figure 6.6 BC Transit Broadway E/B



Figure 6.7 BC Transit Metrotown E/B





Figure 6.10 NYCT Grand Cen. N/B Exp.



Figure 6.11 NYCT Queens Plaza W/B

Figure 6.12 PATH Journal Square W/B



Feb. 8, 1995, 7:48-9:27



System	Station Direction	Average Station Dwell	Dwell Std. Dev.	Average Headway	Headway Std. Dev.	Dwell as % of Headway	Headway Coeff. of Variation	Train Control Separation	Dwell +2 SD	Estimated Operating Residual
PATH1	Exchange Place E/B	23.3	7.4	115.8	35.8	20.1	0.309	55.0	38.2	22.6
NYCT1	Queens Plaza W/B	40.7	17.3	134.7	36.9	30.2	0.274	53.0	75.3	6.4
BCT1	Broadway E/B	30.2	2.6	145.6	37.9	20.7	0.260	40.0	35.3	70.2
MUNI	Montgomery W/B	34.4	11.0	146.0	51.7	23.6	0.354	60.0	56.4	29.6
BCT2	Burrard W/B	26.7	2.5	150.7	31.0	17.7	0.206	40.0	31.7	79.0
TTC1	<sup>1</sup> Bloor N/B	43.0	15.3	145.5	65.1	29.4	0.50	55.0	73.5	17.0
NYCT2	Grand Central S/B	64.3	16.7	164.7	57.8	39.0	0.351	53.0	97.6	14.1
TTC2	King S/B	28.1	5.9	168.3	76.8	16.7	0.456	55.0	39.9	73.4
CTS1	1st St. SW W/B	34.6	11.1	176.6	83.4	19.6	0.472	80.0	56.8	39.9
CTS2	3rd St. SW E/B	40.0	16.2	181.4	89.4	22.1	0.493	80.0	72.5	28.9
NYCT3	Grand Central N/B	53.9	14.8	184.1	47.4	29.3	0.257	53.0	83.6	47.5
CTS3	City Hall E/B	36.8	20.6	191.4	102.8	19.2	0.537	80.0	78.0	33.4
PATH2	Journal Square W/B	47.3	23.4	199.7	51.1	23.7	0.256	55.0	94.1	50.6
BART	Embarcadero W/B	49.9	15.7	201.7	95.6	24.7	0.474	90.0	81.3	30.4
<sup>2</sup> BCT3	Metrotown E/B Off-peak	37.8	10.4	241.3	74.0	15.7	0.307	40.0	58.5	142.8

Table 6.1 Data summary of surveyed North American rail rapid transit lines at or close to capacity (seconds)

<sup>1</sup> Adjusted to remove long delay at beginning of peak-period.

<sup>2</sup> Only off-peak data. Included for comparison. Excluded from averages.

going to different destinations, dwells can be extended when passengers must move around a crowded platform to locate their specific car—a relatively rare occurrence as the trains are usually made up in the same order. Destination signs at each platform berth, and on the side of each car, assist passengers in finding their specific car or train.

Figures 6.1 to 6.15 are shown in small scale allowing them to fit on a single page for easy visual comparison. The overall impression is of many irregularities in operation. The data is from a random sample of normal days, or a consolidation of 2 adjacent days. Only when there were major service disruptions was the data survey abandoned and rescheduled for another peak period.

Although much has been made of the uniformity of rail rapid transit operation that allows generic calculations of minimum train separation and dwell times, headway irregularities are a factor of life and must be accommodated in estimating the achievable capacity of a line through use of conservative loading levels, realistic dwells and the addition of an operating margin.

Data are summarized in Table 6.1 with calculations of dwell and headway means and standard deviation.

The operating residual is the result of removing the minimum train separation and the mean dwell plus two standard deviations (see section 4.5.7) from each mean headway. Minimum train separation is estimated at 50 to 55 sec for three aspect signaling system, 40 sec for BC Transit's moving-block signaling system and 80 sec for Calgary— based on the traffic light cycle times along the downtown mall. BART has regulatory and powersupply constraints that limit the number of trains simultaneously in the Trans-bay tunnel. A nominal minimum headway of 90 sec is used. This should be possible with the planned future train control improvements.

The results are shown in the last column and in Figure 6.16 with the operating residual as the top component of each bar. The bars are arranged in order of increasing headway. Note that the bar furthest to the right is the only off-peak data set. It is included only for comparison and shows the large operating residual available when a system is not at capacity.

The operating residuals range widely and bear little relationship to system, technology or loading levels. They indicate whether adequate operating margin can be accommodated. The most generous ones are on BC Transit's SkyTrain due to the closer minimum train separation of the moving-block signaling system. Toronto's King station has a higher operating margin than expected due, in great part, to the very short dwell with all alighting passengers. At Bloor station on the same line, larger volumes of mixed-flow passengers almost double the dwell time reducing the operating residual to 17 sec. Bloor station is the constraint on the line. At one time, the Toronto Transit Commission had planed to rebuild Bloor Station with dual platforms.

A proxy for service reliability is the headway coefficient of variation—the standard deviation divided by the mean. Discounting the high values for Calgary's light rail caused by traffic light cycles, this ranges from a high of some 0.5 on the TTC and BART to approximately half this on and NYCT and PATH. BC Transit's sophisticated automatic train supervision and driverless trains show their capability and produce the lowest and best figure. These results are somewhat incongruous as there are automated and traditional, manual operations at both the top and bottom of the listing. Ideally there should be a relationship between the operating residual and the headway coefficient of variation. However, as shown in Figure 6.17, there is no reasonable relationship.



Figure 6.16 Headway components of surveyed North American rail rapid transit lines at or close to capacity (seconds)



Figure 6.17 Relationship between operating residual and the headway coefficient of variation

### **6.5 ESTIMATING MARGINS**

Although there is no clear relationship between existing operating margins and other operating criteria, this does not allow this important factor, and the related terminal recovery or layover time, to 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.

Taking the operating residual as a surrogate for operating margin, the average of the near capacity systems, discounting Calgary and off-peak data, is 39 sec. The lower quartile is 25 sec and the lower half is 32 sec.

Selecting a recommended operating margin is a dilemma; too much reduces achievable capacity, too little will incur sufficient irregularity that it may also serve to reduce capacity. Yet, when necessary to provide higher capacity, a handful of rail transit lines in New York and Mexico City all but eliminate the operating margin with times below 10 sec.

It is recommended that a range be considered for an operating margin. A reasonable level for a system with more relaxed loading levels, where the last ounce of capacity is not needed, should be 35 sec. Where that last margin is needed then a minimum level of 10 sec can be used in the clear understanding that headway interference is likely.

In between these extremes is a tighter range of 15-20-25 sec that is recommended. This range is used in estimating achievable capacity with the simple procedures and recommended as a default value in the computer spreadsheet.

# 6.6 OPERATING WITHOUT MARGINS

It is reasonable to ask how several rail transit lines in other countries operate at much closer headways than in North America and yet achieve substantially higher capacities with excellent on-time performance and reliability.

The four highest capacity double-track rail transit lines in the world are believed to be Tokyo's Yamanote line; sections of the Moscow and St. Petersburg metros that operate at 90-sec headways; and Hong Kong's Mass Transit Railway Corporation which carries 75,000 passengers per peak-hour direction in 32 trains on the lower Kowloon section of the Tsuen Wan line.<sup>3</sup>

All systems have been visited by the Principal Investigator. The Russian<sup>4</sup> systems appear to have a high level of staff

<sup>&</sup>lt;sup>3</sup> The MTRC has a capacity constraint where the Kwun Tong subway terminates so as to deposit entire train loads at the peak point of another line. MTRC is presently installing the SACEM quasi moving-block signaling system to increase the system capability from 32 to 34 trains an hour. Only so small an increment is needed as the capacity constraint will be relieved by the new airport subway line presently under construction.

<sup>&</sup>lt;sup>4</sup> Similar operating arrangements occur on the Russian-designed metros in Warsaw and Prague.



Figure 6.18 JR East high capacity car with six double doors and longitudinal seats that are locked up against the wall in the morning peak. The small number of seats are automatically unlocked at about 10.00h.

discipline and surprising equipment reliability. The close headways are maintained by strict control of dwell times. Each station headwall has a clock showing the time from the departure of the previous train. As the 90-sec headway time approaches the doors are closed—often irrespective of whether passenger movement had finished.—and the train departs precisely 90 sec behind the previous train. Any delay to a train consequently rebounds down the line—but trains behind the delay remain perfectly spaced. This approach is also partially responsible for the high capacity of many double-track lines in Japan but here other factors play a role.

The Japanese systems maintain the world's highest passenger throughput despite an intricate combination of through worked services combining trains from different companies—both public and private—in multiple operating patterns: non-stop, express, limited express, skip-stop and local.

Six factors<sup>5</sup> combined to maintain these high capacities. First is the very high loading levels that would not be acceptable in the west (these levels are increasingly a concern in Japan as an affluent population demands better commuting quality). Despite this concern, the JR East has just introduced a high capacity car with almost no seats, illustrated in Figure 6.18.<sup>6</sup> Second is an aggressive management of station dwells using more or wider doors, large interior off-sets, and clearly marked door positions and queuing areas on each platform. A trial car with wide doors and platform markings is shown in Figure 4.12.

This dwell management is completed by familiar platform managers and their white-gloved assistants. Contrary to popular belief, the manager will rarely handle a passenger; the assistants are not trying to push more passengers onto the train but to close the doors and avoid delays.<sup>7</sup>

The third factor is the precision of driving. Most drivers are recruited to this prestigious job from railway high schools where they have already been indoctrinated. Driver training can take six months at special schools before the recruit gets extensive line experience under the supervision of a senior operator. Some schools have simulators with every meter of each line videotaped—particularly important as even some of the high capacity lines have grade crossings. Many grade crossings are protected by a criss-cross array of infra-red presence detectors that control an approach signal. The nerve and precision to drive at these, still red, signals at maximum line speed is remarkable.

Equivalent discipline applies to vehicle and system maintenance. Federally enforced levels of inspection and preventive maintenance ensure exceptionally high equipment availability. These levels would be uneconomic in North America and the cost is being questioned by some Japanese rail transit operators.

The fifth factor is the extensive use of off-line stations, intermediate stations with four tracks, and terminal stations with multiple tracks.

The final factor is the reliability built into the equipment through redundancy and use of over-designed components. Japanese urban rail rolling stock is heavy, in part due to these design practices and in part due to government buffing strength regulations. This also carries a high price and one Japanese railway has recently specified a series of *throw-away* cars. Vehicles are designed and built to have half the life of conventional stock, thus avoiding the cost of the exceptionally thorough and expensive rebuilds periodically required on conventional equipment by central government regulations.

Hong Kong's high capacity MTR shares only a few of the Japanese features—mainly very high levels of crowding. Coincidentally, Hong Kong handles the same number of peakhour passengers on two tracks as NYCT does on its busiest four-track Manhattan trunk.

Dwell control is a feature of other systems, but its methods would not be acceptable in North America and are steadily falling out of use elsewhere. The omission of doortraction/brake interlocks allows train doors to open before a train has stopped and to close as the train is moving away from the platform. If this feature is cautiously employed—as once common in Paris and Berlin—dwells can be reduced. On the Buenos Aires metro the practice extended to doors that might not close at all between stations.

### 6.7 SKIP-STOP OPERATION

Certain high-capacity operations in Japan use skip-stop service, as employed in Philadelphia and New York, and until recently, in Chicago. Skip stops, in themselves, provide faster travel times for the majority of passengers with less equipment and staff. In themselves skip stops rarely increase capacity as the constraint remains the dwell at the maximum load point station at which, by definition, all trains must stop. In fact capacity can be slightly reduced as the extra passengers transferring between *A* and *B* 

<sup>&</sup>lt;sup>5</sup> Based on discussions held by the Principal Investigator with executives from several Japanese subway and suburban railway companies on an October 1994 transit study tour.

<sup>&</sup>lt;sup>6</sup> The significant use of urban rail transit in Japan can be put in context with the 1993 daily rail ridership in the greater Tokyo region of 35.96 million passengers, about double the total daily ridership in all three North American countries. Tokyo is served by the partly privatized JR East railway; two subway companies, one public and one private; and seven private suburban railways—the largest two of which, Odakyû. and Tôbu together carry 50% more passengers a day than the NYCT.

<sup>&</sup>lt;sup>7</sup> Platform attendants/managers also exist on North American systems.

trains at common stations, can increase dwells. Conversely a balanced skip-stop operation can equalize train loadings and reduce extreme dwells.

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.

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.

Light rail operations may also skip stations when an ondemand operating policy is adopted. This requires on-board passenger stop signals that can range from the traditional pullcords to use of the passenger-actuated door controls on stanchions at each doorway. Drivers must observe whether there are any intending 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 the practice has no effect on achievable capacity.

Demand stops are common on the eastern light rail operations that have evolved from traditional streetcar services but are surprisingly rare elsewhere, even where there are clearly lowvolume stations and quiet times which could contribute to lower energy, lower maintenance costs and a faster, more attractive service.

Off-line stations can greatly increase capacity. They are used in other countries but are unknown in North America except on AGT systems. AGT off-line capacity is discussed in Chapter Ten.

## 6.8 PASSENGER-ACTUATED DOORS

The majority of new North American light rail systems have elected to use passenger-actuated doors. The rationale is increased comfort as interior heat or air conditioning is retained, and wear and tear on door mechanisms is reduced. The practice can extend dwells but is of little value at higher capacities or busy stations where all doors are generally required. Consequently some systems use the feature selectively and allow the train operator to override and control all doors as appropriate.

A typical rail rapid transit car door will cycle in 5 sec. Certain doors on light rail systems, associated with folding or sliding steps, can take double this time. Obviously a cycle initiated at the end of the dwell will extend the dwell by this cycle time plus the passenger movement time.

The problem is a contrariety as a system approaching achievable capacity could not tolerate such dwell extensions but would, in any event, be using all doors which might just as well be under driver control—avoiding any last minute door cycling.

### 6.9 OTHER STATION CONSTRAINTS

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

or poorly located kiss-and-ride or park-and-ride facilities may deter usage. Inadequacies in passenger access to a station may reduce demand but not capacity. The only factor that has a potential effect on the achievable capacity of a system is the ease 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.

Station exiting requirements are specified by the National Fire Prevention Association 130 rapid transit standards. Exits, emergency exits and places of refuge must be adequate to allow a platform with one headway's worth of passengers plus the entire complement of a full-length fully loaded train to be able to be evacuated to a safe location within four minutes—without using elevators and treating escalators as a single-width stairway.

These regulations ensure that, in all but the most unusual circumstances, where there is a disproportionate reliance on emergency exits, full capacity loads can leave the platform before the next train arrives.

On older systems NFPA 130 requirements may not be met. Additional exits must be provided to ensure that achievable capacity is not constrained by platform back-ups. Rates of flow are established for passageways, 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 and adequate exit-fare control must be provided. The nominal rate for a single-coin or magnetic-ticket-actuated fare gate or turnstile is 60 passengers per minute. This is an optimistic rate. Actual usage will range between 30 and 40 passengers per minute, possibly longer at stations with a large proportion of tourists or other non-regular transit users. The exit-fare gate rate is also reduced by failure rates and, on systems with distancerelated fares, by tickets with inadequate stored value. Typically 10% of fare gates should be assumed to be out-of-service at any time. About one in 4000 transactions will fail with magnetic tickets. Proximity cards are reported to have failure rates two to three times better but there is insufficient use to confirm this. Add-fare requirements can be as low as one in a 100 depending on operator policy-several systems allow a passenger to underpay, on the final ride on higher value stored value tickets, as a form of random discount.

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

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

Fare payment is a particular factor on the few light rail systems that still use on-board payment and checks. The flow rate analysis showed that flat fare payments added almost exactly 1 sec per boarding passenger, about 25% to an upstairs board, 50% to a level board. This can significantly impact running time over many stations. These factors however cannot be applied to the dwell time calculations of Chapter Four, *Station Dwells*, as the



Figure 6.19 Wheelchair loading platform and ramp

far more drastic impact is the restriction of boarding to the manned door, rather than spread along all doors of the train.

The Toronto Transit Commission has recently followed the practice of most new light rail systems and introduced a proof of payment fare collection system on its Queen St. streetcars. San Francisco and Philadelphia have station collection in the subway portion of their lines. MUNI has long term plans to move its entire light rail fare collection to the faster and less expensive proof of payment system—two surface stations have already been converted.

If on-board manual fare collection is used, dwells must be increased by the above percentages to arrive at achievable capacity. The computer spreadsheet does not compensate for this.

### 6.10 IMPACT OF AMERICANS WITH DISABILITIES ACT (ADA)

With dwell times being one of the most important components of headway, the time impact of persons using wheelchairs was examined. In addition to the modest number of field observations that could be timed, data were obtained from those systems that have actual rather than anecdotal movement and delay times. The facts to date, while sparse, do tell a coherent story. Actual measured lift times are shorter than anecdotal claims, running 2-3 min with some as low as 60 sec. Level wheelchair movements are generally faster than walking passengers except where the car or platform is crowded. One movement at a new San Francisco loading platform on the K line was measured at 13 sec from doors fully opened to train moving.<sup>8</sup> An example of this mini-high or high-block loading arrangement is shown in Figure 6.19.



Figure 6.20 Tri-Met's Siemens-Düwag partial low-floor car



Figure 6.21 Profiled light rail platform showing slide out or fold down step that avoids any internal steps



**Figure 6.22 Profiled light rail platform** Provides two steps into all doors, except the front door which is wheelchair accessible. All slopes are a maximum of 8.5° to meet ADA requirements. Most of the platform is only slightly higher than a sidewalk. Additional details on light rail wheelchair facilities with city specific information are contained in Chapter Eight, Light Rail Capacity Determination.

San Francisco has one of the best of the high-block loading arrangements although requiring a second stop. The loading takes place at the parallel second, rather than tapered first door. An elastic filler covers most of the gap between the platform and door threshold. No bridge is required, the driver does not have to leave the cab, relying on wayside markings to position the train with the second door at the wheelchair loading platform.

Most rail transit wheelchair users are very agile. These are the people who want the "mainstream" option and use it. They seem to be particularly sensitive to not causing delays.

As well as being the preferred arrangement for meeting ADA regulations, high-platform loading also provides the maximum capacity. Dwells are reduced and no interior car capacity is lost to the stepwells or to interior steps—a feature of high-floor cars with low-level boarding and some low-floor cars. Low-floor cars will offer much of the speed and easy access of high-platform loading. The first low-floor car to be introduced in the United States (Figure 6.20) will be running in 1997 in Portland.

Level high-floor loading may be problematic in many systems. The options range from the interior folding steps used in San Francisco to the outboard folding steps used in San Diego or the Manchester style profiled platform, shown in Figures 6.21 and 6.22. Such a platform has an intermediate height and is

<sup>&</sup>lt;sup>8</sup> However, this is one of the arrangements where the car/train must stop twice, once for physically challenged passengers, then again for regular passengers.

profiled up to a short stretch that is level with one doorway for wheelchair use. Where the street arrangement permits, the profiled platform can be raised so that its mid-section-taking up most of the length—is raised one step providing a single-step entry to most doors.

Another option to meet the ADA requirements is the separate wheelchair ramps that are used in Baltimore, Sacramento and San Francisco, among others. In this arrangement, shown in Figure 6.19, a car-floor-level platform, sized for one wheelchair, is accessed by a ramp at one end, preferably the front end of each light rail stop. This arrangement is often termed high-block or *mini-high* loading. These are less popular with the physically challenged community and present a greater physical and visual intrusion into the street scene. However there are numerous examples, particularly in Sacramento, of carefully integrated and relatively unobtrusive arrangements. These high-block platforms have advantages over car- or platform-mounted lifts in reducing delays. The platforms also save the need for maintenance and repair of mechanical lift equipment.

One of the most salient issues is the number of persons using wheelchairs that will elect to use mainstream rail transit when all ADA measures have been implemented. In the project survey over 25,000 passengers were counted at one doorway out of the eight to 40 doorways on each monitored train. Out of an estimated 100,000 peak-period passenger movements observed on those systems that are fully wheelchair accessible, five wheelchairs were seen and timed. This represents one wheelchair per 20,000 passengers. Other systems have estimated ratios that range from one in 5,000 to one in 10,000. However the usage of lifts is some three to five times higher than this due to use by passengers other than those in wheelchairs.

During the survey, doorway delays were observed quite frequently due to passengers, not in wheelchairs, who were otherwise physically or mentally challenged; elderly; with children; carrying packages; or accompanied with push-chairs, shopping trolleys, crutches and walking frames. Most of the latter, on light rail with steps declined to use the lift and created the longest doorway times for a single passenger. ADA requirements will reduce such delays as systems move away from mechanical lifts at single doors to multiple door level loading-whether high or low floor.

Many delays were also due to passengers hesitating at a doorway, possibly uncertain that this was the correct train to board-or the right station to exit. The ADA requirement to clearly delineate the platform edge, and to visually and aurally indicate the train arriving at a platform and, once on-board, the next station should reduce delays due to such confusion.

Others have raised the potential problem of a wheelchair user attempting to board a heavily loaded train or light rail car. In theory operating staff should ask standing passengers to vacate the car to accommodate the wheelchair. This obviously has the potential for lengthy dwell extensions.

However, very few such situations occur. The average rail transit car loading in North America through the peak hour is  $0.5 \text{ m}^2$  per passenger (5.4 sq ft) At this loading a wheelchair could be accommodated in any vestibule, on any train, without impeding other passengers or delaying the train. Passengers not



Figure 6.23 Wheelchair user in designated space — BC

only move aside to accommodate a boarding wheelchair but often will assist the wheelchair user reaching a designated space.

Transit

Once on-board there is the issue of any capacity reduction due to the space taken by the wheelchair-equivalent to three to six standing passengers, depending on the loading density. Given the average peak-period space occupancy cited in the last paragraph, there is clearly no impact on most systems, although NYCT and the San Francisco Muni, for example, might be affected. It is possible that the location of designated spaces relative to doorways and the positioning of wheelchairs could disrupt interior passenger circulation on narrow rail transit cars.

However, Figure 6.23 shows a wheelchair user on a BC Transit car, one of the narrowest rail rapid transit car designs on the continent. The wheelchair user's legs extend slightly into the aisle but are less of an obstruction than the other passengers sitting on the longitudinal seats in the foreground of the photograph. On these cars the wheelchair-designated space is immediately adjacent to and parallel to the door. There are no restraints. Special handholds are provided and an interior wall-on the far side of the wheelchair-prevents wheelchair movement in the event of emergency braking. A seat folds down when the space

is not occupied. The only non-standard feature of the location are a lower height passenger intercom and the omission of the dual stanchion in the center of the vestibule that would interfere with wheelchair maneuverability.

There was insufficient information obtained from operating agencies or the survey to quantify any impact of ADA on the achievable capacity of rail transit systems. There were sufficient numbers and varieties of boardings and alightings observed for the study team to conclude that, with full implementation of ADA, and the elimination of lifts on close headway rail systems, wheelchairs generally will have no or little impact on capacity—even allowing for substantial increase in use and for rare incidents, such as one observation, where the front wheels were briefly stuck in the platform-door gap.

In the interim, wheelchair-lift use may cause delays but these are generally on systems with long headways (6 min and above) and have minimal impact at these levels. In the longer term other requirements of ADA may sufficiently improve boarding and alighting movements to off-set any negative impact of wheelchair use—if indeed there is such an impact.

## 7. Grade Separated Rail Capacity Determination

### 7.1 INTRODUCTION

The preceding four chapters developed the methodologies for each of the components in calculating capacity. This chapter brings these methodologies together for the principal category of grade separated rail, which includes over 90% of rail transit in North America:

grade separated rail transit is operated by electrically propelled multiple-unit trains on fully segregated, signaled, double-track right-of-way.

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

AGT systems use proprietary technology and often have train control separation times and vehicle loading levels that are atypical of conventional rail transit. These atypical situations and the capacity of AGT with off-line stations are dealt with in Chapter Ten, AGT Capacity Determination.

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

This is due to two reasons. Several light rail systems converge surface routes into a signaled grade separated section operating at, or close to, capacity. Other, less busy systems, have the signaled grade separated sections designed economically—not for minimum headways down to 2 min. Typically this signaling is designed for 3- to 4-min headways—more restrictive than the headway limitations of on-street operation, with or without varying forms of pre-emption. However signaled grade separated sections may not always be the prime headway limitation. Chapter Eight explains how to calculate and determine the weak link in the capacity chain for light rail.

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

### 7.2 THE WEAKEST LINK

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

- 1. The close-in time at the busiest station,
- 2. Junctions, and
- 3. Turn-backs.

In new systems it is poor design that capacity should be limited by junctions or turn-backs. Both can be designed to avoid constraints. Chapter Three, section 3.10, shows that a flat junction can handle 200-m (660-ft) trains with standard rail transit performance, under fixed-block train control, on noninterference headways down to 102 sec plus an operating margin. The equivalent time for the same length trains with a moving-block signaling system is 63 sec plus an operating margin. Chapter Three recommends that junctions controlled by a three aspect signaling system should be grade separated where trains combine to a joint headway below 3 min. Only where there are flat junctions with headways for their respective train control systems below these levels, plus a 20-sec operating margin, is it necessary to utilize Equation 3-26 to determine the junction throughput limitation.

Section 3.9 of Chapter Three similarly shows that a two-track terminal station can turnback 200-m trains every 120 sec with a terminal time of 175 sec—that is the time for passenger flows and for the driver to change ends. Section 3.9 and Chapter Six, *Operating Issues*, suggest that where passenger flows are heavy, dual-faced platforms be provided; where changing ends is a limitation that crew set-backs be used; that 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 bad-order rolling stock; and, finally, that a three-track terminal station can handle exceptional passenger flows from trains on headways below 90 sec.

On new systems, turn-backs can be disregarded as a capacity constraint unless economic circumstances or labor practices prevent an optimal terminal design. Only in such exceptional circumstances is it necessary—after determining the minimum headway from this chapter—to apply Equations 3-21 and 3-25 to ensure that adequate terminal time is provided to allow for the anticipated passenger flows and changing ends.

On older systems, terminal station design may be sub-optimal and Equation 3-25 should be checked with the actual station cross-over geometrics to ensure there is adequate terminal time. This calculation should then be cross-checked with actual field experience.

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 system's capacity limitation can be assumed to be the closein movement at the busiest station.

### 7.3 GROWTH AND ACHIEVABLE CAPACITY

The achievable capacity as defined in this report is not the capacity at which a rail transit will open—or reach after a decade. It is the maximum achievable capacity when the system is saturated and provided with a full complement of rolling stock. It can be looked at as the long-range design capacity after decades of growth.

A difficult question is what ultimate capacity a system should be designed for. With good data, a constancy of historical trends some transportation models can be calibrated to predict passenger demand with reasonable accuracy. However predictions beyond 10 to 15 years are of decreasing accuracy particularly in areas without an existing rail transit system or good transit usage which makes the modal split component of the model difficult to calibrate.

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

### 7.4 SIMPLE PROCEDURE

Taking advantage of the relative performance uniformity of electric multiple-unit trains in urban rail transit service allows the use of this simple procedure to estimate a range of achiev able peak hour passenger capacities for grade separated lines at their maximum capacity.

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

This simple procedure assumes system and vehicle characteristics that are close to the industry norms listed in Table 7.1. It also assumes that there are no speed restrictive curves or grades over 2% on the maximum load point station approach and that the power supply voltage is regulated within 15% of specifica-

Table 7.1 Simple method performance assumptions

TERM	DESCRIPTION	DEFAULT	UNIT
Gi	Grade into headway critical station	< ± 2	%
D	distance from front of train to exit block	<10	m
K	% service braking rate	75	%
t <sub>os</sub>	time for overspeed governor to operate	3	secs
t <sub>il</sub>	time lost to braking jerk limitation	0.5	secs
a,	service acceleration rate	1.3	m/s <sup>2</sup>
d <sub>s</sub>	service deceleration rate	1.3	m/s <sup>2</sup>
t <sub>br.</sub>	brake system reaction time	1.5	secs
V <sub>max</sub>	maximum line velocity	100	km/h
t <sub>d</sub>	dwell time	35-45	secs
tom	operating margin	20-25	secs
l <sub>v</sub>	line voltage as % of normal	>85	%
S <sub>mb</sub>	moving block safety distance	50	m

tions. The procedure, as does the study as a whole, assumes an adequate supply of rolling stock. If any of these assumptions are not met then the simple procedure may be used only as a guideline and the complete procedure of section should be used. This procedure does not apply to locomotive-hauled commuter rail or to automated guideway transit using a proprietary system with small, narrow vehicles.

This simple procedure is contained on the computer disk but a computer is not required. The result can be calculated in the time it takes to load the spreadsheet program or, if the recommended medium-comfort loading levels are accepted, directly and simply from Figure 7.5 (cab control signaling) or Figure 7.6 (moving-block signaling) at the end of this section.

The range of trains per hour are shown in Figure 7.1 for the above assumptions for cab control systems and in Figure 7.2. for moving-block signaling systems. New systems that are designed for maximum capacity would not use the more limited and more expensive three-aspect signaling system. Such a system may be used for systems designed for less than maximum throughput— in which case this procedure is not applicable. Consequently the choice of train control system is limited to cab control and moving-block.

This is a method to determine the maximum capacity of a rail transit system. Consequently, train lengths are shown for typical maximum lengths of 200 and 150 m (trains of 8 and 6 heavy rail cars) and 120, 90 and 60 m (trains of 4, 3 and 2 articulated light rail vehicles respectively). The maximum number of trains per hour can be selected from Figures 7.1 and 7.2, rounded down and multiplied by the selected train loading level obtained from Chapter Five, *Passenger Loading Levels*, section 5.5. Figure 5.8, reproduced again as Figure 7.3, shows a range of linear loading for heavy rail cars from  $7^{1}$  to 11 passengers per meter of length. Figure 5.7, reproduced again as Figure 7.4, shows a range of linear loading levels for light rail cars from 5 to 9 passengers per meter of length. These linear loading levels represent the peak-within-the-peak and a loading diversity factor should be

<sup>&</sup>lt;sup>1</sup> The lower ranges for the short cars in Vancouver and Chicago should not be used in the simple procedure method. This is based on 6 to 8 car trains of 23-m-long cars.



**Figure 7.1 Cab control throughput** in trains per hour with a range of dwell times plus an operating margin from 45 sec (lower bound) to 70 sec (upper bound)



**Figure 7.2 Moving-block throughput** in trains per hour with a range of dwell times plus an operating margin of 45 sec (lower bound) to 70 sec (upper bound)

applied if loading levels in the upper ranges of these charts are selected. When calculating diversity on the capacity of a line in a city with existing rail transit—of the same mode—the existing loading diversity factor or near equivalents should be obtained from Chapter Five, *Passenger Loading Levels*, section 5.6. For new systems, a loading diversity factor of 0.8 should be used for heavy rail and 0.7 for light rail. For example the typical median light rail level of 6 passengers per meter of car length would reduce to 4.2 applying the suggested loading diversity factor of 0.7.

Applying these loading levels to the throughput ranges above provides a direct range of passengers per peak hour direction per track versus train length, shown in Figures 7.5 and 7.6.



Chicago 14.6m car, 2 doors transverse seating Vancouver 12.5m car, 2 doors mixed seating





Figure 7.4 Linear passenger loading of articulated light rail cars

### 7.5 COMPLETE PROCEDURE

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

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

In all but the most exceptional situation, the limitation will be the close-in, dwell and operating margin time at the maximum



Figure 7.5 Achievable capacity with multiple command cabcontrol signaling system and peak-hour average loading of two passengers per square meter for one track of a grade separated rail transit line



Figure 7.6 Achievable capacity with moving-block signaling system and peak-hour average loading of two passengers per square meter for one track of a grade separated rail transit line Note: The number of trains per hour vary with train length, refer to Figures 7.1 and 7.2. 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 Figure 7.5 and

Figure 7.6. load point station. The complete procedure requires that the following values be calculated:

- 1. the close-in time at the maximum load point station
- 2. the dwell time at this station
- 3. a suitable operating margin
- 4. the peak-within-the peak train passenger load
- 5. the loading diversity factor to translate from peak-withinthe peak to peak hour.

These procedures can be calculated manually, or by experienced users developing their own computer spreadsheet. The spreadsheet on the computer disk allows the many variables to be inserted to produce passengers per peak hour direction per track. However this spreadsheet cannot and does not assist in determining the weakest link or the maximum load point station. Nor does it solve the issue of how much operating margin should be provided or the appropriate loading level.

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

### 7.5.1 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. This is not always the case. With increasingly dispersed urban travel patterns some rail transit lines do not serve the downtown. Los Angeles' Green Line and Vancouver's proposed Broadway-Lougheed line are examples.

The 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 peak hour and rarely for the preferable 15 min peak-within-the-peak. Depending on the number of zones and nodes in the model, data accuracy at 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 for new systems.

### 7.5.2 DETERMINING THE CONTROL SYSTEM'S MINIMUM TRAIN SEPARATION

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

Table 7.2 Minimum train separation parameters

	a a wf = 1.f S	BECODIDITION
VALUE	IEnw	DESCRIPTION
calculated	T(a)	train control separation in seconds
200 meters	I (3)	length of the longest train
10 meters		distance from front of stonned train to start of station
To motors	D	exit block in meters
calculated	V <sub>a</sub>	station approach speed in m/s
29.2 m/s	V <sub>max</sub>	maximum line speed in m/s (29.2 m/s=100 km/h)
75%	K	braking safety factor —worst case service braking is
		K% of specified normal rate — typically 75%
2.4 - 3 aspect	B	separation safety factor — equivalent to number of
1.2-cab cont		braking distances (surrogate for blocks) that separate
1 — mov block		trains
3.0 seconds	t.,	time for overspeed governor to operate on automatic
	-os	systems - to be replaced with driver sighting and
		reaction times on manual systems
0.5 seconds	t <sub>il</sub>	time lost to braking jerk limitation
1.5 seconds	t <sub>br</sub>	brake system reaction time
1.3 m/s <sup>2</sup>	as	initial service acceleration rate
1.3 m/s <sup>2</sup>	d <sub>s</sub>	service deceleration rate
0%	Gi	grade into station, downgrade = negative
0%	Go	grade out of station, downgrade = negative
90%	l <sub>v</sub>	line voltage as percentage of specification
6.25 meters	Pe	positioning error — moving block only
50 meters	S <sub>mb</sub>	moving-block safety distance moving block only

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

Although the equations appear long, the arithmetic is simple and can be implemented in a spreadsheet with basic functions if the report's computer disk is not available. Before going to this effort, check the availability of the required input parameters in Table 7.2. Parameters can be adjusted for system specific values or left at their default value. Train length is the most important variable. However if most parameters are left at their default values then it would be simpler to refer to Figure 7.7 which shows the minimum train control separation against length for the three types of train control system. The equation for threeaspect and cab-control signaling systems, derived from Equation 3-15 of Chapter Three with dwell and operating margin components removed and grade and voltage factors added, is

$$T(s) = \sqrt{\frac{2(L+D)}{a_s(1-0.1G_o)}} + \frac{L}{v_a} + \left(\frac{100}{K} + B\right) \left(\frac{v_a}{2d_s}\right) + \frac{a_s(1-0.1G_i)l_v^2 t_{os}^2}{20,000v_a} \left(1 - \frac{v_a}{v_{max}}\right) + t_{os} + t_{jl} + t_{br}$$
Equation 7-1

The equation for moving-block signaling systems with a fixed safety-separation distance, derived from Equation 3-18 of Chapter Three with dwell and operating margin components removed is

$$T(s) = \frac{L - S_{mb}}{v_a} + \frac{100}{K} \left(\frac{v_a}{2d_s}\right) + t_{jl} + t_{br}$$
 Equation 7-2

#### Minimum train separation seconds



Figure 7.7 Minimum train separation versus length

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 suboptimal minimum train separation.

Higher throughput is usually obtained with a moving-block signaling system with a variable safety distance comprised of the braking distance at the particular speed plus a runaway propulsion allowance. The equation for such a system, derived from Equation 3-20 of Chapter Three with dwell and operating margin components removed and a line voltage factor added, is

$$T(s) = \frac{L+P_e}{v_a} + \left(\frac{100}{K} + B\right) \left(\frac{v_a}{2d_s}\right) + \frac{a_s (1-0.1G_i) l_v^2 t_{os}^2}{20,000 v_a} \left(1 - \frac{v_a}{v_{max}}\right) + t_{os} + t_{jl} + t_{br}$$
Equation 7-3

The appropriate one of these equations must be solved for the minimum value of T(s). The approach speed  $v_a$  that produces this minimum value must then be checked against any speed restrictions approaching the station from Figure 7.8. The dotted line example in Figure 7.8 shows that at 120 m<sup>2</sup> from a station, the approaching train will have a speed of 64 km/h. If there is a speed limit at this point that is lower than 64 km/h then the minimum train separation T(s) must be calculated with the approach speed  $v_a$  set to that limit.

Finally, whether using the spreadsheet or individual calculations, check the results with Figure 7.7. The minimum train

<sup>&</sup>lt;sup>2</sup> Distance from the front of the approaching train to the stopping point.



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

#### 7.5.3 DETERMINING THE DWELL TIME

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

The train close-in time at the headway critical station, being dependent on the physical performance and length of a train and other fixed system characteristics, can be calculated with some precision. Station dwell time cannot be determined with the same exactitude. All but one of literature references to dwell assigned a set time to dwell. Many simulations do likewise using typical figures of 15-20 sec for lesser stations and 30-45 sec for major stations. The one methodology to determine *controlling dwell*—dwell plus operating margin—requires knowledge of dwell times over the peak hour—information only available for existing systems or new lines in areas where a station with similar passenger volumes can be analyzed.<sup>3</sup>

Chapter Four, *Station Dwells*, describes the main constituents of dwell:

- Passenger flow time at the busiest door
- Remaining (unused) door open time
- Waiting to depart time (with doors closed)

Three methods of estimating dwell or controlling dwell are provided in this section. The first method is the one used in the simple procedure of this chapter and by most of the literature references—simply assigning a reasonable figure to the headway critical station. The second method uses field data from this study allowing the selection of a controlling dwell (mean dwell plus 2 standard deviations) from the headway critical station of systems with similarities to the one being analyzed.

The fourth and final method uses the statistical approach of Chapter Four of determining dwells 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. It is regrettable that the study failed to find a better method of estimating dwell or controlling dwell times and explains why other practitioners over a period of three decades have resorted to simply assigning a *reasonable value* to dwell.

#### **METHOD ONE Assigning a Value**

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

#### **METHOD TWO Using Existing Dwell Data**

Dwell data from the project's field survey are summarized in Table 7.3. Data were usually collected at the highest use station of lines that were at or close to capacity. As none of the newer light rail systems are approaching capacity<sup>4</sup> the busiest systems

System	Location	Total	Time/Date	Mean	Mean
		Pass	1995	Dwell	Headway
BART	Embarcadero	2298	am Feb. 8,	48.0	155.0
BCT	Broadway	257	pm Apr. 5,	30.0	166.0
BCT	Metrotown (off-peak)	263	pm Apr. 5	34.0	271.5
CTS	1st St. SW (LRT)	298	am Apr. 25	33.0	143.0
CTS	3rd St. SW (LRT)	339	pm Apr. 25	38.0	159.0
CTS	City Hall (LRT)	201	pm Apr. 26	34.0	161.0
NYCT	Grand Central (4&5) S/B	3488	am Feb. 8	61.5	142.5
NYCT	Queens Plaza (E&F)	634	am Feb. 9	36.0	121.0
PATH	Journal Square	478	am Feb. 10	37.0	204.0
SF Muni	Montgomery (LRT)	2748	pm Feb. 21	32.0	129.0
ПС	King	1602	am Feb. 6	27.5	129.5
πс	Bloor	4907	pm Feb. 7	44.0	135.0

#### Table 7.3 Peak-period dwells for heavily used systems

<sup>&</sup>lt;sup>3</sup> ALLE, P., *Improving Rail Transit Line Capacity Using Computer Graphics*. The methodology for calculating controlling dwell is contained in full in Appendix One and can be used in the rare case that the dwell determination can be based on existing dwell time data. No operating margin should be added when controlling dwell is calculated.

<sup>&</sup>lt;sup>4</sup> Maximum design capacity—that is without limitations of single-track sections or line sections signaled for lower throughput than the maximum capabilities of the signaling system.

were surveyed. Selection of a dwell from this table is less arbitrary than method one 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 dwells range from 27.5 sec to 61.5 sec. The highest data, with the exception of the TTC's King Station, are mainly alighting and mixed flow records from manually operated systems with two-person crews. Most dwells in Table 7.3 fit into the 35 to 45 sec range suggested in the previous method.

Where comparable field data also allows the calculation of standard deviation the controlling dwell can be selected as the mean dwell plus two standard deviations. Refer to Table 4.17 for examples. When the controlling dwell is so estimated any additional operating margin (section 7.5.4) can be reduced or eliminated. Alternately the greatest of the *mean dwell plus two standard deviations* or the *mean dwell plus the operating margin* (from section 7.5.4) can be used.

#### METHOD THREE Calculating Dwells from Station Hourly Passenger Flows

This method involves complex mathematics. It is applicable to new systems<sup>5</sup> where Method two is not appropriate and where data on hourly, directional flow at each station is available from a regional transportation model. Use of the Excel version of the spreadsheet is recommended for this method and a simplified guide is contained in the spreadsheet. Other readers may wish to skip this section and jump to 7.5.4.

Chapter Four developed regression equations to relate passenger flow times to the number of boarding, alighting or mixed flow passengers, and, in turn, to convert this flow time to dwell time. These regression equations can be used to estimate the dwell time from hourly passenger flows into the maximum load point station. However the best regression fit involves logarithmic functions and the estimation of a constant for the ratio between the highest doorway and the average doorway passenger flow rate.

The mathematics are complex and it is uncertain if the results provide any additional accuracy that merits this complexity particularly if the hourly station passenger volumes by direction are themselves somewhat uncertain. This method is best suited to new lines in locations without rail transit and with a sufficiently refined and calibrated regional transportation model that can assign hourly passenger flow, by direction, to individual stations.

The first step in the process is to obtain the hourly passenger flow from the regional transportation model. Many models produce 2-hour am peak flows. In this case, use either the model's peak-hour conversion factor or a typical value of 60% to arrive at an approximate peak-hour passenger figure.

Then, from the model select the station with the highest passenger volume, either into or out of the station, and classify the flow as, *mainly boarding, mainly alighting* or *mixed*. Most models deal with the morning peak period. If the maximum load point station is downtown it is likely that the flow will be primarily alighting. If the station is also an interchange with another rail transit line then flows could also be mixed.

Unless station flows are also available for the afternoon rush this process assumes that the morning peak defines limiting head-way—and so maximum capacity. This is usually the case. Morning peaks tend to be sharper, afternoon peaks more dispersed as a proportion of passengers pursue diversions shopping, banking, visiting a bar, restaurantor theater—between work and the trip home. This more spread peak should override the fact that boarding is slightly slower than alighting.

As the controlling dwell time will occur during the peakwithin-the-peak, the next step is to adjust the flow to the peakwithin-the-peak 15 min rate using a loading diversity factor.

$$D_{ph} = \frac{R_{hour}}{4R_{15\text{min}}}$$
Equation 7-4

where  $D_{ph}$  = diversity factor—peak hour  $R_{hour}$  = ridership in peak hour  $R_{15min}$  = ridership in peak 15 min

The factor should be selected based on the rail mode and the type of system. Section 7.5.6, later in this chapter, describes how to select an appropriate diversity factor.

The peak 15-min movement of passengers on a single-station platform,  $P_{15\text{min}}$ , can be expressed as

$$P_{15\min} = \frac{P_{hour}}{4D_{ph}}$$
 Equation 7-5

where  $P_{hour}$  = peak-hour movement of passengers on a single station platform (*obtained from* regional transportation model)

The number of double-stream train doors available in that 15-min period,  $D_{15}$ , is

$$D_{15} = \frac{900D_nN_c}{T(s) + t_d + t_{om}}$$
 Equation 7-6

where T(s) = train control separation in seconds

 $t_d$  = dwell time in seconds

- $t_{om}$  = operating margin in seconds
- $D_n$  = number of double stream doors per car

 $N_c$  = number of cars per train

The passenger flow at the busiest, i.e., controlling, door of the train in the peak-within-the-peak,  $F_{\text{max}}$  is

$$F_{\max} = \frac{RP_{15\min}}{D_{15}} = \frac{RP_{hour} (T(s) + t_d + t_{om})}{3,600D_n N_c D_{ph}}$$
 Equation 7-7

where R = Ratio of busiest door usage to average door usage

This ratio is close to unity for heavily loaded rail transit lines operating at capacity as passengers are forced to spread themselves relatively evenly along the platform. Under lighter conditions the ratio will increase. As capacity is being calculated at the maximum load point station during the peak-within-thepeak, a ratio of 1.2 is recommended for heavy rail and 1.5 for light rail.

The regression equations of Chapter Four, Station Dwells,

<sup>&</sup>lt;sup>5</sup> This method can also be used on existing systems to estimate the change (increase) in the controlling dwell at stations where new development, or interchange with a new rail transit line, significantly increases the station's passenger volume.

section 4.6.4, can be simplified by omitting the reverse flow terms and are expressed for all alighting, all boarding or mixed flow as: $^{6}$ 

Equation 7-9

$$\ln(FT_{\max}^{mixed}) = 1.368 + 0.0948F_{\max}^{alight} - 0.112F_{\max}^{board} - 0.00184(F_{\max}^{alight})^2 - 0.00225(F_{\max}^{board})^2$$

Equation 7-10

where  $FT_{max}$  = Flow time for the respective type of flow, alighting, boarding or mixed, at the maximum use door (*seconds*)

Section 4.6.6 determined dwell time relative to the respective maximum doorway flow time as:

 $\ln(t_d) = 3.168 + 0.0254FT_{max}^{(mode)}$  Equation 7-11

Substituting in Equation 1-11 for  $FT_{\text{max}}$  and Equation 1-8 for  $F_{\text{max}}$  produces:

$$\begin{aligned} \ln(t_d) &= 3.168 \\ &1.440 + 0.0922 \left( \frac{RP_{hour}(T(s) + t_d + t_{om})}{3,600D_n N_c D_{ph}} \right) - 0.00116 \left( \frac{RP_{hour}(T(s) + t_d + t_{om})}{3,600D_n N_c D_{ph}} \right)^2 \\ &+ 0.0254e \end{aligned}$$
Equation 7-12

Equation 7-12 is solely for the expected dominant am peak and mainly alighting case. Similar expressions can be derived for mainly boarding flows and for mixed flows.

These equations have to be solved for the value of the dwell time  $t_d$ , contained as both a natural logarithm and as an exponential. The equations are not solvable in closed form and the preferred solution is the simplest, using recursive numeric assumptions.

The recursive numeric assumption approach is carried out in the spreadsheet on the computer disk. The dwell is shown to the nearest integer. This seeming accuracy should not be allowed to conceal the uncertainties of some of the equation components. At best the ensuing accuracy should be in the range of  $\pm$  3-4 seconds, not necessarily better than the alternative, simpler methods of estimating or assigning a dwell time—but the only method that relates dwell time to the hourly, directional station passenger volumes. The results for all alighting passengers based on the values of Table 7.4 are shown in Figure 7.9.

#### The Excel version of the spreadsheet contains a simplified stepby-step guide to utilize this method of estimating dwell times.

The results show the expected trend. Dwell time increases with the hourly passenger movement. The resultant achievable capacTable 7.4 Values used to compute Figure 7.9

Unit	Value	Description
D <sub>ph</sub>	0.8	Diversity factor peak hour
T(s)	55	Train Control Separation in seconds
t <sub>om</sub>	20	Operating margin in seconds
D <sub>n</sub>	4	Number of double stream doors per car
N <sub>c</sub>	8	Number of cars per train
R	1.2	Ratio busiest/average door usage
L	184	Train Length, meters
Pm	7.5	Loading Level, passengers per meter



Figure 7.9 Dwell time and achievable capacity at a maximum load point station versus hourly alighting passengers at a single platform—unit values from Table 7.4.

ity decreases at a lesser rate. Capacity is reduced by a comparable amount if either the number of doors per car is reduced from four to three or an uneven spread of passengers along the platform results in the ratio of the maximum to average door flow increasing from 1.2 to 1.5.

Although the regression analysis is based on data from heavy volume stations, the results become increasingly inaccurate at extremes. Neither equation 7-12, nor its implementation on the computer spreadsheet, should be used with the maximum doorway flow greater than 25-30 passengers—equivalent to approximately 20,000 passengers per peak-hour direction per platform with the default values of Table 7.4. It is unlikely that a single station would handle half the total capacity of a line. Where this

<sup>&</sup>lt;sup>6</sup> Chapter 4, section 4.6.4, also developed regression equations with slightly improved explanation of variance by including the number of passengers standing—a surrogate for impedance to passengers when boarding or alighting from the car. As the number of standing passengers cannot be reasonably known when estimating achievable capacity, these slightly improved equations are not used.

does happen—such as a single downtown terminal station multiple platforms or dual-faced platforms will be required. Although the analysis can be adjusted for the number of provided platform *faces* at through stations, the estimation of dwell times based on hourly passenger flow is not applicable to terminal stations where other factors dictate the layover time.

This method is particularly valuable to estimate the changes in headway—and capacity—from increased passenger volumes at an existing station. If land use changes or area growth increase the estimated hourly usage of a station significantly, for example, an additional 5,000 passengers per peak hour direction—then the value of *R* (the ratio of busiest door usage to average door usage) can be calculated rather than estimated from the current dwell time. The difference between the calculated dwell before and after the passenger growth can be added to the existing peak dwell with potential accuracy within  $\pm 2$  seconds.

#### 7.5.4 SELECTING AN OPERATING MARGIN

Chapter Six, *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.

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 dwell, 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.<sup>7</sup> A very small number of rail transit lines in North America are operating at capacity and can accommodate little or no operating margin. On such lines operations planners face a dilemma of scheduling too few trains to meet the demand, resulting in extended dwells 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 more 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 sec—remains the best guide. The recommended procedure is to aim for 25 sec and back down to 20 or even to 15 sec if necessary to provide sufficient service to meet the estimated demand. Where demand is unknown or uncertain in the long term future—when a system in planning reaches maximum capacity—then 25 sec, or more, should be used.

When the controlling dwell has been estimated as the *mean dwell plus two standard deviations* the operating margin can be reduced to 10 seconds or less, or eliminated. Alternately the greatest of *mean dwell plus two standard deviations* or *mean dwell plus operating margin* can be used.

### 7.5.5 SELECTING A PASSENGER LOADING LEVEL

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

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-within-the-peak loading levels from line to line. Mexico City is probably the most extreme example in North America. Where this variety exists then the loading level should be selected based on the closest matching line—for example, a heavy trunk serving downtown or a cross-town feeder line.

Figure 7.3 and Figure 7.4 provide a range of loading levels from 5 to 9 passengers per meter of car length for light rail and from 7 to 11 for heavy rail. For new systems where attempts are being made to offer a higher quality of service, the recommended approach is to base the loading level on the commonly suggested medium comfort level for new rail transit systems of  $0.5 \text{ m}^2$  per passenger, averaged over the peak hour—that is, no loading diversity factor is required. This provides a recommended linear loading level of 6 passengers per meter of train length for heavy rail and 5 for light rail.

An alternative approach is to base the loading levels on either the nominal capacity of a vehicle or the actual peak-hour use.

The nominal capacity of a range of vehicles is shown in Table 7.5. Note that as previously discussed in this report the nominal rated capacity can be an artificial and impractical "crush" level. Table 7.5 is sorted in descending order of loading level. The upper range should be discounted. A tone is applied over those data that may be applicable for use in the complete method of determining capacity. Note that the upper ranges of these levels are still relatively high and the comfort accordingly low.

Table 7.5 also demonstrates the difficulty in determining capacity when five essentially identical Siemens-Düwag light rail vehicles from four different operators are examined. The nominal capacities of these cars, highlighted with boxes, range from 6.9 to 3.9 passenger per meter. This is a ratio of 1.8:1 despite the cars having almost the same dimensions and the same number of seats.

Table 7.6 shows the actual peak-within-the-peak linear loading levels for major North American trunks, again in ascending 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.

It is interesting to note the difference between the actual levels in Table 7.6 and the nominal (published car capacity) levels for those systems represented in both tables. These are shown in Table 7.7. The similarities (CTS-Calgary) and the variances (all other systems) are a cautionary exercise in the acceptance and use of published data. However in fairness to certain systems it

<sup>&</sup>lt;sup>7</sup> The principal investigator has discussed the concept of a goal with rail transit planners based on an average of one *disturbed* peak period per ten weekdays (two weeks) but has never seen such goals documented.

Table 7.5 Nominal agency or manufacturer's car capacity for heavy and light rail vehicles

System, Car Type		Seats	Total	Passengers
			Pax	per meter
CTA 2000 B 1981-87	HH	49	150	10.3
CTA 3200 (A&B) 1992	HH	39	150	10.3
11C H6 1986-89	нн	/6	226	9.9
NFTA BUTAIO LHV 1983-84		51	180	8.8
NJ1 PCC 1946-49	LH	55	125	8.8
SEPTA Single End: B-IV 1982	HH	65	180	8.8
PATH PA-4 1986-88	HR	31	130	8.4
NYCI H32 1964-65	HR	50	145	7.9
NYCT H68 1986-88	HR	70	175	7.7
MBTA 01400 Red 1962	HR	54	160	7.6
WMATA B3000 Chopper 1984	HR	68	170	7.4
Metro-Dade Heavy Rail 1984	HR	76	166	7.3
MTA Married Pair 1984-86	HR	76	166	7.3
TTC A-15 (PCC) 1951	LR	45	103	7.3
NYCT R62 1984-85	HR	44	110	7.1
MTA LRV 1991-93	LR	85	201	6.9
TTC L-3 (ALRV) 1987-89	LR	61	155	6.7
MBTA 01200 Orange 1980	HR	58	132	6.7
TTC L-1/2 (CLRV) 1977-81	LR	46	102	6.6
Calgary U2, U2AC 1980-84, 86	LR	64	158	6.5
MBTA 00600 Blue 1979	HR	42	94	6.4
Tri-Met LRV 1983-86	LR	76	166	6.3
SCCTA SCLRV 1987	LR	76	167	6.2
MARTA CQ 310 1979	HR	68	136	5.9
SRTD U2A 1986-91	LR	60	144	5.9
Edmonton U2 1978-83	LR	64	140	5.8
GCRTA Cleveland RT 84-85	HR	80	128	5.6
GCRTA Cleveland 800 1981	LR	84	126	5.2
MBTA LRV Green 1986-88	LR	50	112	5.1
LACMTA LRV 1989-94	LR	76	137	5.0
PAT Pittsburgh U3 1986	LR	63	125	4.9
PATCO PATCO II 1980-81	HR	80	96	4.6
SEPTA N-5 1993	LR	60	90	4.5
San Diego U2 1980-89	LR	64	96	4.0
San Diego U2A 1993	LR	64	96	3.9

<sup>8</sup> Stated maximum or crush load passenger capacity per vehicle from the operator or manufacturer. Schedules maximum loads for NYCT. Some stated values for total passengers are well below realistic crush loading reflecting an agency's desire to maintain comfortable loading levels.

should be pointed out that the official (nominal) car capacity could be based on previous decades when higher loading levels were expected and achieved on heavy rail systems.

### 7.5.6 DETERMINING AN APPROPRIATE LOADING DIVERSITY FACTOR

The next step is to adjust the hourly capacity from the peakwithin-the-peak 15-min rate to a peak-hour rate using a loading diversity factor from Chapter Five, *Passenger Loading Levels*. The diversity factor is calculated according to Equation 7-4. The diversity factor was used in Method 4 for calculating the dwell time. If this method was used then obviously the same diversity factor must be used. Otherwise the factor should be selected based on the rail mode and the type of system. Table 7.8

 Table 7.6 Passengers per unit train length, major North

 American trunks, 15-min peak-within-the-peak

System	Trunk Name		Length	Seats	Avg./ Car	Pass./m
NYCT	53rd Street Tunnel	HR	see <sup>g</sup>	50/70	197/227	10.4 <sup>9</sup>
NYCT	Lexington Ave. Loca	IHR	15.56	44	144	9.3
NYCT	Steinway Tunnel	HR	15.56	44	144	9.3
NYCT	Broadway Local	HR	15.56	44	135	8.7
TTC	Yonge Subway	HR	22.7	80	197	8.7
NYCT	Lexington Ave. Ex.	HR	15.56	44	123	7.9
NYCT	Joralemon St. Tun.	HR	15.56	44	122	7.8
NYCT	Broadway Express	HR	15.56	44	119	7.6
NYCT	Manhattan Bridge	HR	22.77	74	162	7.1
NYCT	Clark Street	HR	15.56	44	102	6.6
CTS	South Line	LR	24.28	64	153	6.3
GO Transit	Lakeshore East	CR	25.91	162	152	5.9
BCT	SkyTrain	HR	12.4	36	73	5.9
PATH	World Trade Center	HR	15.54	31	92	5.9
PATH	33rd St.	HR	15.54	31	88	5.7
CTA	Dearborn Subway	HR	14.63	46	82	5.6
NYCT	60th Street Tunnel	HR	22.77	74	126	5.5
NYCT	Rutgers St. Tunnel	HR	22.77	74	123	5.4
CTS	Northeast Line	LR	24.28	64	125	5.1
CTA	State Subway	HR	14.63	46	75	5.1
CalTrain	CalTrain	CR	25.91	146	117	4.5
LIRR	Jamaica - Penn Sta.	CR	25.91	120	117	4.5
Metra	Metra Electric	CR	25.91	156	113	4.4
MARTA	North/South	HR	22.86	68	82	3.6
MARTA	East/West	HR	22.86	68	77	3.4

<sup>9</sup> Service through NYCT's 53rd St. Tunnel is provided by line E, operating 18.35-m cars, and line F, operating 22.77-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 10.7 for the E and 10.0 for the F.

Table 7.7 Passengers per unit train length, 15 min peak-within-the-peak, nominal versus actual values (only thebusiest NYCT lines using each car type included)

System Location			Pass	√m
			Nominal	Actual
NYCT	53rd St. Tunnel	HR	7.8 <sup>10</sup>	10.4
NYCT	Lexington Ave. Loc.	HR	7.1	9.3
ΠΟ	Yonge Subway	HR	6.6	8.7
NYCT	Manhattan Bridge	HR	7.7	7.1
CTS	South Line	LR	6.5	6.3
CTS	Northeast Line	LR	6.5	5.1
PATH	World Trade Center	HR	8.4	5.9
CTA	Dearborn Subway	HR	10.3	5.6
CTA	State Subway	HR	10.3	5.1
MARTA	North/South	HR	5.9	3.6
MARTA	East/West	HR	5.9	3.4

<sup>10</sup> This is the weighted average for scheduled loadings of both car types used on this trunk. See also note 9.

provides existing examples. Unless there is sufficient similarity with an existing operation to use that specific figure, the recommended loading diversity factors are 0.80 for heavy rail, 0.75 for light rail and 0.60 for commuter rail operated by electric multiple-unit trains.

Type	System	Routes	Diversity factor
CR	LIRR	13	0.56
CR	Metra <sup>11</sup>	11	0.63
CR	Metro-North	4	0.75
CR	NJT <sup>11</sup>	9	0.57
CR	SEPTA	7	0.57
CR	Average		0.60
LRT	CTS	2	0.62
LRT	Denver. RTD	1	0.75
LRT	SEPTA	8	0.75
LRT	Tri-Met	1	0.80
LRT	Average		0.73
RT	BCT	1	0.84
RT	CTA	7	0.81
RT	MARTA	2	0.76
RT	MDTA	1	0.63
RT	NYCT	23	0.81
RT	PATCO	1	0.97 <sup>12</sup>
RT	PATH	4	0.79
RT	STCUM	4	0.71
RT	TTC	3	0.79
RT	Average		0.79

Table 7.8 Diversity of peak-hour and peak 15-min loading

<sup>11</sup> Mainly diesel hauled—not EMU.

<sup>12</sup> These data are suspicious.

#### 7.5.7 PUTTING IT ALL TOGETHER

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

$$H_{\min} = T(s) + t_d + t_{om}$$
 Equation 7-13

The maximum number of trains per hour T<sub>max</sub> then is

$$T_{\max} = \frac{3,600}{H_{\min}} = \frac{3,600}{T(s) + t_d + t_{om}}$$
 Equation 7-14

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

$$C_{\max} = T_{\max} L P_m D_{ph} = \frac{3,600 L P_m D_{ph}}{T(s) + t_d + t_{om}}$$
 Equation 7-15

where

$$H_{\min}$$
 = minimum headway in seconds  
 $T(s)$  = minimum train separation in seconds

 $t_d$  = dwell time in seconds

$$\tilde{t_{om}}$$
 = operating margin in seconds

$$T_{\rm max}$$
 = train throughput per hour

$$C_{max}$$
 = maximum single track capacity in passengers per peak hour direction

L =train length in meters

 $P_m$  = loading level in passengers per meter of train length

 $D_{ph}$  = loading diversity factor

The spreadsheet contains this calculation. Given the range of values that can be calculated, estimated or assigned for certain of the components in Equation 7-15, it is appropriate that the results be expressed as a range.

The results should be checked for reasonableness against typical capacities in Figure 7.10, which is based on the simple procedure loading levels of 5 passengers per meter for light rail and 6 passengers per meter for heavy rail—approximately 0.5  $m^2$  per passenger. Higher levels are possible only if less comfortable loading levels have been used. Lower levels imply either errors or that all seated passengers have been assumed or an excessive operating margin has been included.

This chart is not an appropriate check for electric multipleunit (emu) commuter rail whose signaling systems are usually designed for lower throughput with loading levels based on all seated passengers. Commuter rail capacity based on train length is also affected by the common use of bi-level cars, although few such trains currently fit into the applicable category of electric multiple-unit operation. Figure 7.10 and an approach to *Grade Separated Rail Capacity Determination* are contained in the Excel version of the spreadsheet. The simplified step-by-step approach, without charts and equations is also in the generic version of the spreadsheet. Refer to the spreadsheet user guide at the front of this report.



Figure 7.10 Typical maximum passenger capacities of grade separated rail transit—excluding all-seated commuter rail.

# 8. Light Rail Capacity Determination

### 8.1 INTRODUCTION

This chapter covers methods for determining the capacity of light rail transit lines. While the approach used in Chapter Seven, *Grade Separated Rail Capacity Determination*, will work in most situations, light rail transit lines often have characteristics such as street running, grade crossings and single track, 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.

#### 8.1.1 SELECTING THE WEAKEST LINK

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 also include on-street operation (often in reserved lanes) and private right-of-way with grade crossings. Other limitations can be imposed by single-track sections and the street block lengths. The line capacity is determined by the weakest link; this could be a traffic signal with a long phase length, but is more commonly the minimum headway possible on a block signaled section. The first portion of this chapter discusses the capacity limitations imposed by right-of-way characteristics.

The capacity constraints are grouped in sections to in order of decreasing relative importance for most systems. (See Table 8.1). This order is not definitive for all systems, but it is appropriate for many. System-specific differences, such as short block lengths on signaled sections, will change the relative importance of each item.

#### 8.1.2 OTHER CAPACITY ISSUES

Car loading levels for light rail transit for use in the equations in this chapter should be determined with reference to the passenger

Table 8.1 Light rail capacity constraints

Section	Constraint
8.2	Single track
8.3	Signaled sections
8.4	On-street operation
8.5	Private right-of-way with grade crossings

loading standards for light rail transit in Chapter Five, *Passenger Loading Levels*. Light rail loading levels are generally lighter than those for rail rapid transit but not as generous as the one seat per passenger policy common on commuter rail.

Light rail train lengths are more restricted than for rail rapid transit or commuter rail because of lower car and coupler strengths, and street block and station platform lengths. These issues are considered in section of this chapter.

One additional issue which is of particular importance to light rail operations and capacity is the method of access for mobility impaired passengers. While the speed of each access method varies, all can have an effect where close headways and tight scheduling occur. The overall discussion of the impact of the Americans with Disabilities Act (ADA) is contained in Chapter Six, *Operating Issues*. More specific light rail accessibility issues are dealt with in section of this chapter.

### 8.2 SINGLE TRACK

Single track is the greatest capacity constraint on light rail lines where it is used extensively. Single-track sections are used primarily to reduce construction costs. Some lines have been built with single track as a cost-saving measure where the rightof-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 by-pass a particular obstacle; for example, the San Diego Trolley had a short single-track segment<sup>1</sup> on the East Line in order to save the cost of building a second overpass over an Interstate highway. This segment has since been replaced with double track as part of the double-tracking of the majority of the San Diego Trolley system. When this program is complete, single track will be used only on the East Line extension to Santee.

The Sacramento light rail line, like San Diego's, featured substantial single-track construction as a way to keep initial costs low. However, the extensive use of single track has limited operational flexibility and mandated a minimum headway of 15 min. This long headway has necessitated the use of 4-car trains to meet the peak-period ridership demand. The length of these trains is such that they block intersections while stopping at the downtown stations. As in San Diego, much of the Sacramento line is in the process of being double-tracked to remove these constraints.

Tri-Met of Portland is also removing its single-track constraint at the eastern end of its light rail line in Gresham. A second

<sup>&</sup>lt;sup>*T*</sup> Actually a gauntlet track with the four rails interlaced, but with the same operational implications as single track.

track is being added on the existing right-of-way in order to increase operational flexibility and reduce the anxiety train operators have about arriving late at the single-track meet point. The latter problem is caused by delays elsewhere on the line, particularly wheelchair boardings and alightings.

Baltimore's light rail transit line includes substantial singletrack construction but ridership demand has not yet been strong enough to require double-tracking in the existing right-of-way.

While most of these newer light rail lines are moving away from single-track operation, SEPTA depends on large sections of single track on its much older Media and Sharon Hill lines. Careful scheduling is used to allow an approximately 10-min peak headway of mixed local and express services to operate on each line. The common eastern portion of these lines is doubletracked.

While determining the extent of single track possible on a system is possible, the exact layout is highly system specific. Estimates can be made of the number of track kilometers required for a certain number of route kilometers once the intended headway is known.<sup>2</sup> 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.

### 8.2.1 CALCULATING SINGLE-TRACK HEADWAY RESTRICTIONS

Single-track sections greater than 400-500 m are potentially the most restrictive capacity constraint for light rail. The headway limitation is very simply TWICE the time taken to traverse the single-track section, plus an allowance for switch throw and lock—unnecessary for spring switches or gauntlet track<sup>3</sup>—plus an operating margin to minimize the potential wait of a train in the opposite direction.

This is a very site-specific time; however, a reasonable approximation can be calculated from the length and maximum speed on the section, based on the similar performance of modern light rail vehicles.

The time to brake from the maximum line speed to a stop can be expressed as

$$t_{bs} = \frac{v_{\max}}{d_s} + t_{jl} + t_{br}$$
 Equation 8-1

where

 $t_{bs}$  = time to brake to stop (s)

$$v_{max}$$
 = maximum speed reached (*m/s*)

$$d_s$$
 = deceleration & acceleration rate ( $m/s^2$ )

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

 $t_{br}$  = operator and braking system reaction time

The distance covered in this time is

$$S_{bs} = \frac{v_{\max}t_{bs}}{2} = \frac{v_{\max}^2}{2d_s} + \frac{v_{\max}(t_{jl} + t_{br})}{2}$$
 Equation 8-2

where  $s_{bs}$  = braking distance to stop

The distance and time covered to reach the maximum singletrack section speed involves specific vehicle characteristics as the nominal acceleration rate—usually identical to the braking rate—decreases with speed. A reasonable approximation is to assume that the average acceleration rate to the maximum section speed is half the braking rate. The total time and distance from start to stop then become

$$t_{ss} = \frac{3v_{\max}}{d_s} + t_{jl} + t_{br}$$
Equation 8-3

where  $t_{ss}$  = time from start to stop

$$S_{ss} = \frac{3v_{\max}^2}{2d_s} = \frac{v_{\max}(t_{jl} + t_{br})}{2}$$
 Equation 8-4

where  $s_{ss}$  = distance covered start to stop

The time to cover a single-track section becomes

$$T_{st} = (N_s + 1) \left( \frac{3v_{\max}}{d_s} + t_{jl} + t_{br} \right) + \frac{(L_{st} - (N_s + 1)s_{ss})}{v_{\max}} + N_s t_d$$
  
Equation 8-5

where  $T_{st}$  = time to cover single track section (s)  $L_{st}$  = length of single track section (m  $N_s$  = number of stations on single track section  $t_d$  = average station dwell time on section (s)

Substituting for  $S_{ss}$  from Equation 8-4, adding a speed margin to compensate for the difference between actual and theoretical performance on a manually driven system, adding the train length to the section length and adding an operating margin produces

$$T_{st} = SM\left(\frac{(N_s+1)}{2}\left(\frac{3\nu_{\max}}{d_s} + t_{jl} + t_{br}\right) + \frac{L_{st} + L}{\nu_{\max}}\right) + N_s t_d + t_{om}$$
  
Equation 8-6

where 
$$T_{st}$$
 = time to cover single track section (s)  
 $L_{st}$  = length of single track section (m)  
 $L$  = train length (m)  
 $N_s$  = number of stations on single track  
section  
 $t_d$  = station dwell time (s)  
 $v_{max}$  = maximum speed reached (m/s)  
 $d_s$  = deceleration<sup>4</sup> rate (m/s<sup>2</sup>)  
 $t_{jl}$  = jerk limiting time (s)  
 $t_{br}$  = operator and braking system reaction  
time  
 $SM$  = speed margin<sup>5</sup> (constant)  
 $t_{om}$  = operating margin (s)

<sup>&</sup>lt;sup>2</sup> See Allen, Duncan W., *Practical Limits of Single-Track Light Rail Transit Operation* in Appendix One.

<sup>&</sup>lt;sup>3</sup> Gauntlet track interlaces the four rails without needing switches, saving capital and maintenance costs and potential operating problems due to frozen or clogged switch points. The disadvantage is that the single-track section cannot be used as an emergency turn-back (reversing) location.

<sup>&</sup>lt;sup>4</sup> Also used as a surrogate for twice the average acceleration from 0 to v<sub>max</sub>.

<sup>&</sup>lt;sup>5</sup> An allowance to adjust for out of specification equipment and train operators that do not push to the edge of the operating envelope, i.e., maximum permitted speed. Typically 1.08 to 1.2, 1.1 is used in the results.

This equation can be readily solved using typical values from Table 8.2

The value of the maximum single-track section speed should be the appropriate speed limit for that section. 55 km/h (35 mph) is a suitable value for most protected, grade separated lines. If the single-track section is on-street then a speed below the traffic speed limit should be used. If there are signaled 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 pre-emption.

This equation is included on the computer spreadsheet. A selection of results is shown in Figure 8.1.

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

Lengthy single-track sections can severely limit headways and capacity and may require one or more double-track passing

Table 8.2 Data values for single-track travel time

TERM	VALUE
jerk limitation time	0.5 seconds
brake system reaction time	1.5 seconds
dwell time	15-25 seconds
service braking rate <sup>4</sup>	1.3 m/s <sup>2</sup>
speed margin	1.1 to 1.2
operating margin time	10-30 seconds

Time to Traverse (seconds)



Figure 8.1 Light Rail travel time over single-track section with speed limit of 55 km/h and various numbers of stations train length 56 m, dwell time 20 sec, operating margin 20 sec, other data as per Table 8.2. The closest headway with a single-track section is TWICE the above traverse plus operating margin time.

sections in the single-track section. These should, wherever possible, be of sufficient length to allow opposing trains to *pass on-the-fly* and to allow some margin for off-schedule trains. Obviously trains should be scheduled to pass at this location.

### **8.3 SIGNALED SECTIONS**

Restrictions due to signaled sections are largely covered in Chapter Seven, *Grade Separated Rail Capacity Determination*. 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 dominant capacity constraint.

For example the Edmonton light rail line has a peak headway of 5 min with this also being the minimum headway possible based on the signaling. At the other extreme is New Jersey Transit's Newark city subway with a peak headway of 2 min and a minimum headway of 15 sec being permitted by the signaling. This is made possible with very short *advisory* signal blocks, single car trains (PCC's) and multiple-berth platforms at the terminals. Now only a single route, the city subway no longer requires the capacity provided by such close blocks except in unusual circumstances, however, similar arrangements in Philadelphia are used much closer to capacity.

SEPTA currently schedules trains in the Market Street light rail subway as close as 60 sec. The closely spaced two-aspect color-light signaling is for spacing purposes only, that is it is advisory. A driver can see several signals ahead. A range of green allows full speed operation with the driver using judgment to slow down as a red signal approaches. There are no train stops and the car may pass a red signal and approach the car ahead on line-of-sight to permit multiple berthing in a single station.

Equally high capacity is provided at the City Hall terminal, which is a large loop containing the multiple-berth Juniper Street station. In past decades as many as 120 streetcars per hour passed through the tunnel.

These arrangements are not fail-safe and collisions have occasionally occurred. Multiple-berth stations can be confusing to passengers but will improve with the ADA-required information signage. However, with reasonable driver discipline, these arrangements provide the highest light rail capacity—potentially over 20,000 passengers per peak-hour direction per track—and have provided it safely, economically and at relatively high speeds for over half a century.

### **8.4 ON-STREET OPERATION**

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-within-the peak rate of over 60 cars an hour on Queen Street East where several car lines share a four block stretch.

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 center reservation 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 where congestion is severe; Toronto's King Street is an example.

Even with these improvements in segregating transit from other traffic, light rail trains must still contend with traffic lights, 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 below.

#### 8.4.1 EMPIRICAL APPROACH

Capacity is the product of train frequency and train capacity. This can be given as

$$\frac{Passengers}{Hour} = \frac{Trains}{Hour} \times \frac{Cars}{Train} \times \frac{Passengers}{Car}$$
Equation 8-7

The maximum number of trains per hour can be determined from Equation 8.2. Note that this should be applied for the intersection with the longest traffic signal cycle or train dwell time.

$$C_p = \frac{(g/C)3600R}{(g/C)D + t_c} \qquad \text{Equation 8-8}^6$$

where

 $C_p$  = trains per hour per track

- $t_c$  = clearance time between trains is defined as the sum of the minimum clear spacing between trains plus the time for a train to clear a station, with typical values of 25 to 35 sec. (Some transit agencies use the signal cycle time as the minimum clearance time.)
- D = dwell time at stop under consideration, typically ranging from 30 to 40 sec, sometimes to 60 sec.
- R = reductive factor to compensate for dwell time variations and/or uncontrolled variable associated with transit operations. R values are tabulated from 1.0 in perfect conditions with level of service "E", to 0.634 with level of service "A", assuming a 25% coefficient of variation in dwell times. Maximum capacity under actual operating conditions would be about 89% of that under ideal conditions—resulting in about 3,200 effective sec of green per hour.
- g = effective green time in sec, reflecting the reductive effects of on-street parking and pedestrian movements as well as any impacts of pre-emption.

C = cycle length in sec. (Cycle lengths should be divisible into 3600 to allow consistent train scheduling with headways a multiple of the cycle length, preferably no less than two cycles, see tabular example below.)

Cycle Length	60	72	75	80 90	100	120	sec	
Cycles per hour	60	50	48	45 40	36	30		
Minimum headway	120	144	150	160180	200	240	sec	

This empirical approach is often not appropriate for light rail systems but may have value for traditional streetcar operation. Note that on-street parking and pedestrian movements can impact capacity. More details and examples can be found in the Highway Capacity Manual <sup>(R67)</sup> and the ITE Transportation Planning Handbook<sup>(R42)(R43)</sup>.

#### **8.4.2 PRACTICAL ISSUES**

It is hard to encompass all the variables which affect on-street light rail transit operation in a single formula. Note, for example, the vagueness of the definitions of the R and g variables in Equation 8.8 as a way to accommodate the less concrete aspects of on-street operation. Even with these vagaries, the capacity of on-street light rail is often greater than on grade-separated, signaled rights of way where higher speeds and block signals force the separation between trains to be increased.

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 variability 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.

Traffic signals can be a major impediment to light rail transit operation where they are not designed with the needs of light rail trains in mind. Poor traffic signaling can make train operation slow, unreliable and unattractive to potential passengers. These problems can be addressed through the use of signal pre-emption and progression.

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

There is often a misconception of the impact of pre-emption. At the modest headways typical of new light rail systems, where trains operate only every few traffic light cycles, the green time advanced or held for a light rail trains can be restored in the following cycles with no net loss of cross-street capacity. Edmonton demonstrated that by tying area traffic signals and the light rail signaling system into a computer the introduction of light rail actually increased capacity on both cross-streets and parallel streets.

<sup>&</sup>lt;sup>6</sup> LEVINSON, HERBERT S., Capacity Concepts for Street-Running Light Rail Transit, Australian Road Capacity Conference, 1994.

Signal pre-emption, linked to a central traffic control computer, is being implemented extensively on the Toronto streetcar system. Close stop spacing on the streetcar lines gives pre-emption an edge over progression because of the limited number of traffic signals between streetcar stops.

The San Diego Trolley originally used signal pre-emption on its "C" Street downtown mall but has since switched to signal progression. Increased light rail service on the mall had exposed the inadequacy of the pre-emption controllers to deal with high volumes of bi-directional traffic and resulted in failures. Table 8.3 contains some representative phase lengths for light rail transit signal pre-emption and 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 light 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 light cycle and proceeding on the next. Ideally the cycle length will be slightly longer than a long average dwell in order to allow the majority of trains to leave shortly after passenger activity has ended. Note that the Calgary timings for progression in Table 8.3 were measured on the 7<sup>th</sup> Avenue Mall which is shared with buses; the phases must therefore be longer to accommodate both transit modes in the same phase.

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

Operating heritage streetcars—vintage trolleys—in conjunction with light rail service can constrain capacity unless operated over sections of the light rail (such as downtown San Jose) where light rail speeds are already low. Figure 8.2 shows a heritage streetcar on the downtown tracks of Portland's LRT.

Table 8.3 Average phase lengths at light rail transitcrossings (number of crossings observed in parentheses)7

City	Progression	Pre-emption	Railway Gates
Calgary	43.2 (3)	N/A	41.7 (3)
Portland	N/A	17.2 (4)	46.8 (2)
San Diego	19.6 (2)	25.9 (2)	41.9 (3)

<sup>7</sup>Each crossing was usually monitored for four or more train movements or until a consistent phase time had been established. Cycle times vary.



Figure 8.2 Heritage streetcar service in Portland. These cars are accurate reconstruction's of the historic *Council Crest* series cars. They are built on relatively modern (PCC) trucks and provide the acceleration, braking and safety features—but not top speeds—of modern light rail cars. Equipped with radio and inductive communications, they operate the pre-emption in the same manner as the light rail service cars. Even so, operation is limited to outside weekday peak periods. If necessary to take a heritage service into account in determining capacity, cars with modern performance can be treated as the equivalent of a light rail vehicle. Dwells, particularly with tourists and wheelchairs can be extended and off-line stations may be necessary, as provided by Tri-Met at Lloyd Center. The vintage cars may require specific arrangements that are beyond the scope of this project.

#### 8.4.3 DETERMINING ON-STREET CAPACITY

Capacity can be estimated by using Equation 8-8 where blocks are long and trains are short—for example a classic streetcar operation. Where, as is often the case, light rail train lengths approach the downtown block lengths then the throughput is simply one train per traffic light cycle, provided the track area is restricted from other traffic. When other traffic, for example, left-turn lanes, may prevent a train from occupying a full block throughput drops as not every train can proceed on receiving a green light. 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.

### 8.5 PRIVATE RIGHT-OF-WAY WITH GRADE CROSSINGS

Private right-of-way with grade crossings is the predominant type of right-of-way for many light rail transit systems. This can take the form of a route which does not follow existing streets or one which runs in the median of a road physically separated from other traffic except at crossings. Capacity on lines with full 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 pre-emption is not available, Equation 8.8 for street running should be used to determine line capacity since it incorporates the cycle length of traffic signals, pre-empted or not.

#### 8.5.1 PRE-EMPTION

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. As shown in Table 8.3, 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 is removed as a factor.

Portland's Eastside MAX line offers an excellent example of pre-emption. This line features a long section of median running on a minor arterial street (Burnside Street). Train speed is limited to the speed limit of the street and signal pre-emption is used to allow trains to maintain this speed on the line segment. Traffic signal phase time lost to the cross streets when lights are pre-empted is returned in subsequent phases. Towards the eastern end of this line segment the light rail tracks make a very long, low-angle crossing, of a major arterial with the only protection being the pre-empted traffic lights. (Figure 8.3) All pre-empted crossings on the Tri-Met light rail line have signals in advance to notify the train operator that the train has been detected and that the signal will become permissive. As can be seen in Table 8.3, the pre-emption system employed in Portland is very effective in minimizing the delay to cross traffic while giving light rail trains almost complete priority.

The SCCTA light rail line in San Jose also uses median running an arterial street but local traffic engineers have only given the light rail minimal priority over other traffic, particularly during rush hours. Where the line runs through the city of Santa Clara the light rail line has no priority over other traffic and suffers substantial delays. Similar delays due to a lack of priority face the Los Angeles Blue Line over the route section between the end of the downtown subway and the start of the old interurban right-of-way at the Washington Boulevard station.

### 8.5.2 GRADE CROSSINGS AND STATION DWELL TIMES

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 Figure 8.4. Using farside 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.

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 start the crossing cycle before leaving the station or by an automatic method. The San Diego Trolley shares some of its trackage with freight trains and uses a communication device that identifies light rail trains to crossing circuits 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 is added before the crossing is activated. This ensures that the



**Figure 8.3 Tri-Met light rail train approaching an angled gated crossing** (*Note the gate is across the highway*). The potential delay to cross traffic at these crossings is almost three times longer than with the 100% pre-empted signalized intersections closer to downtown. At higher train frequencies these occupancy times will become unacceptable and signalized intersections would be required—potentially reducing light rail speeds—but not the light rail capacity as the crossing occupancy time is well within a normal green phase.



Figure 8.4 Light rail platform options at a crossing

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.

Other systems use an inductive link between the light rail train and wayside to activate pre-emption, switches and, in the future, ADA-mandated information requirements. 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 North America.

This arrangement can permit one light rail train per traffic signal cycle. However, the possibility of interference with buses held at a red light suggests the previously referenced maximum throughput of one train per two signal cycles.

# 8.6 TRAIN LENGTH AND STATION LIMITATIONS

#### 8.6.1 STREET BLOCK LENGTH

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

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

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

#### **8.6.2 STATION LIMITATIONS**

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

A more important restriction can be in the design of terminal stations. 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 following streetcars while passengers board and alight from the preceding car. Any scheduled recovery time for the streetcar operator is hard to accommodate in these conditions since the volume of following cars will practically force cars ahead out of the loop.

The Baltimore light rail line also uses single-track termini but the level of service (15-min headway) is not high enough for these to be a capacity limitation. However, the terminals are designed to allow an arriving train to unload passengers before the departing train ahead leaves through the use of an extra platform as shown in Figure 8.5. 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. Note that single-track termini, while inexpensive, have limited flexibility and should generally be avoided.

### 8.7 WHEELCHAIR ACCESSIBILITY EFFECTS

#### 8.7.1 INTRODUCTION

The accessibility of light rail transit to wheelchairs and other mobility devices (considered together with wheelchairs in this section) is a major issue for light rail transit systems. The relative rarity of level loading with high-level platforms on light rail has resulted in a variety of methods having been devised to allow wheelchair access to light rail vehicles. Each of the methods is outlined in the sections which follow. Chapter Six, *Operating Issues*, has discussed general capacity issues related to the ADA, including typical light rail provisions. This section expands the discussion and adds specific arrangements of individual operators. The illustrations of wheelchair loading options, Figures 6.19 through 6.23, are not repeated.

Boarding and alighting times with non-level loading of wheelchairs tend to be highly variable depending on the skill of the passenger. Experienced users can be remarkably quick. Passenger movement times are often lower than for lift-equipped buses



Figure 8.5 Single-track terminus with separate unloading platform (Baltimore)

as there is more room to maneuver wheelchairs, walkers and scooters in light rail vehicles. Off-vehicle fare collection also helps to speed loading for mobility impaired and able-bodied passengers alike. Some agencies require the passenger and wheelchair to be strapped in, a time consuming process which is becoming less common. Some systems have experienced passenger conflicts over mobility device seating priority when other passengers occupy the folding seats provided to create space for wheelchairs and other mobility devices.

It should be noted that both mobility impaired passengers and transit agencies prefer access methods that do not single out the mobility impaired passengers for special treatment. Lifts and special ramps cause delays which reduce the reliability of the service while isolating those users 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 mobility impaired passengers will likely decrease in favor of more reliable and less exclusionary methods such as low-floor cars.

Reducing the delays associated with wheelchair boardings and alightings is an important issue where capacity is constrained. This is of particular concern on lines with single track.

#### 8.7.2 HIGH PLATFORMS

High-level 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. Unfortunately this is not an ideal access method for light rail as high-platform stations are bulky and costly to construct on in-street sections—defeating two of the major benefits of light rail, low costs and community friendly design. Nevertheless high platforms are used exclusively on a number of systems including Los Angeles, St. Louis and Calgary.

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

The profiled platform shown in Figures 6.21 and 6.22 has not been used in North America but has proved effective in Manchester offering low cost, low intrusion, fast passenger movements and mainstream wheelchair loading.

#### 8.7.3 LOW-PLATFORM METHODS

#### **Car-Mounted Lifts**

Car-mounted lifts are used only on the San Diego Trolley, one of the first light rail transit systems to be wheelchair accessible.

Lifts are mounted in the cars so that the first door on the right side of every train is lift-equipped. When not in use, the lift is stored in a vertical position which completely blocks the doorway to use by other passengers. While the lift initially was prone to failure, the current installation is quite reliable with a failure rate of about one-quarter of a percent.<sup>8</sup>

Boarding and alighting times with the car-mounted lifts are around 1 min 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 dwell time extends to  $1\frac{1}{2}$  or 2 min when the lift is used.

#### **Platform-Mounted Lifts**

Platform-mounted lifts are used by the Portland and San Jose light rail systems. 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 the precise stopping requirements, increased susceptibility to vandalism and an increase in the distance that the train operator must walk to operate the lift.

For the SCCTA in San Jose, wheelchair handling is slow because of their wayside lift arrangement. The lift is stored vertically in an enclosed housing at the front of each platform. To operate the lift, the train operator must raise sliding steel doors on each side of the lift housing, lower the car side of the lift to floor level, lower the platform side to ground level, have the passenger board the lift, raise the lift and board the passenger, store the lift and secure the housing. This procedure takes 2 to 3 min giving a total train delay (including loading and unloading) of 4 to 6 min per passenger requiring the lift. These delays can easily consume the train's scheduled terminal recovery time. An average of 25 wheelchairs and scooters are carried each weekday on the SCCTA light rail line but this has increased to as many as 50 a day for special events.

Tri-Met in Portland uses a different type of wayside lift. Under normal circumstances the lift is at ground level ready to receive intending passengers. The presence of the passenger on the lift signals the passenger's intention to board to the train operator. The train operator then aligns the first door of the train with the lift and boards the passenger. The car's steps are bridged by a folding plate on the lift. This configuration speeds the use of the lift somewhat but does not prevent it from having an effect on punctuality. The average time required for each mobility device movement was given as 1 min 50 sec by Tri-Met staff but this could increase to 4 or 5 min in a worst case scenario with an inexperienced user. The determination of the train operator in minimizing dwell in the use of the lift also varies.

Tri-Met expects to be able to remove the wayside wheelchair lifts by September 1997 when all trains will include an accessible low-floor car. Section 6.10 of Chapter Six, *Operating Issues*, suggests that other operators will follow Portland's lead, greatly reducing the potential for wheelchair-related delays in the future.

<sup>&</sup>lt;sup>8</sup> Based on San Diego Trolley data for May 1994. Out of 1,069 lift passengers carried (2,138 lift cycles) only six failures were recorded giving a failure rate of 0.28%.

#### **Mini-High Platforms**

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

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

#### 8.7.4 LOW-FLOOR CARS

Low-floor cars<sup>9</sup> offer a straightforward solution to the need for universal access to light rail vehicles. By bringing the floor height down to just above the railhead, boarding is simplified for all passengers as steps are no longer required. Small, extendible ramps and slight increases in platform edge height allow passengers in wheelchairs and other mobility devices to board without the aid of lifts or special platforms<sup>10</sup>. Low-floor cars provide much of the benefit of level loading without the need for high platforms. Typical floor height is 350 mm<sup>11</sup> (14 in.), about double the height of a normal curb. Medium or intermediate height platforms are therefore still required for no step boarding. Bridging plates with staff attendance are still required on most designs although it appears that passengers with pushchairs and many wheelchair users elect to navigate the gap without this assistance. While low-floor cars have operated in Europe for over a decade, the first North American operation will begin in Portland in 1997. The use of at least one low-floor car in every train will allow Tri-Met's existing platform mounted wheelchair lifts to be removed. Boston has also ordered low-floor cars to make its Green Line subway-surface routes accessible. As in Portland, the cars will be compatible with the agency's existing fleet to allow mixed-train operation. Toronto is also expected to acquire low-floor cars for use on the Spadina LRT line under construction but purchase has been postponed because of a surplus of existing streetcars.

Low-floor cars have some drawbacks which have yet to be fully resolved. Cost is a problem with any new technology, lowfloor cars included. Cars with a 100% low floor can cost up to double those with a 70% low-floor design, such as in Portland which in turn carry a 25-30% cost premium over conventional high-floor light rail vehicles. With a partial low-floor, the ends of the car and the driving (end) trucks, and sometimes the articulation, can be of conventional construction and can retain component and maintenance commonality with existing light rail equipment.

Steps inside the car provide access to the high-floor sections. 100% low-floor designs require the use of stub axles, hub motors and other space-saving components. These items add to costs and have not yet been satisfactorily proven for high-speed use or on the tracks typical of North America. As a result, the cars on order for Portland and Boston will be 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 and broader North American use will likely follow for those systems with on-street low level loading.

A published Transit Cooperative Research Program report, Applicability of Low-Floor Light Rail Vehicles in North America, deals extensively with this issue.

### 8.8 CAPACITY DETERMINATION SUMMARY

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 streetrunning 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 as follows:

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

<sup>&</sup>lt;sup>9</sup> Note the difference between the terms low-floor car and low-level loading. The former states that the majority of the floor of the car is slightly above curb height; the latter describes cars (low-floor cars included) where passengers can enter from street level, without the need for platforms. <sup>10</sup> Some low-floor car/station platform arrangements require a manually

<sup>&</sup>lt;sup>10</sup> Some low-floor car/station platform arrangements require a manually positioned bridging plate that can extend dwell times.

<sup>&</sup>lt;sup>11</sup> Certain low-floor designs ramp down the doorways to achieve a 280-300mm floor height.

The first step in the process is to check the headway capabilities of any single-track section over 500 m (1600 ft) in length from the procedure in section 1.2 of this chapter. Then compare this with the design headway of the signaling system and with twice the longest traffic signal phase of any on-street section. Select the most restrictive headway in seconds and convert into trains per hour by dividing into 3600. The simple procedure provides a reasonable estimate of capacity by using the range of loading levels shown in Figure 8.6, derived from Figure 5.7 of Chapter Five, Passenger Loading Levels, with the incorporation of a loading diversity factor range from 0.70 to 0.90. An example for a typical medium capacity light rail system has a 400-m single-track section without a station. Figure 8.1 shows this limits headway to  $2 \times 80$  sec including an operating margin-a total of 160 sec. The system operates fourcar trains on-street. As these are the length of the shortest city block headway is limited to twice the traffic signal cycle of 80 sec, or 160 sec. Sections of right-of-way are signaled for 3-min headway-180 sec.

Typical of such systems, the right-of-way signaling becomes the limitation allowing a maximum of 20 trains per hour. Four car trains of 25-m articulated light rail vehicles at the midpoint loading of 5 passengers per meter produces an hourly capacity, inclusive of a loading diversity factor, of  $4 \times 25 \times 5 \times 20$ — 10,000 passengers per peak-hour direction. Note that at this frequency the ability to schedule trains to avoid delays on the single-track section is unlikely. This will not reduce capacity but add delays that require more vehicles and crew to carry that capacity.

Where there are no single-track or on-street constraints and the signaling system is designed for maximum throughput, the

Passengers/Unit Length meters

8.0

7.5

7.0

6.5

6.0

5.5

5.0

4.5

4.0

3.5

3.0

0.2



Standing Space m<sup>2</sup>

0.4

0.3

Passengers per peak-hour/direction per track



Figure 8.7 Light rail capacity on segregated right-of-way with maximum cab-control signaling system throughput based on range of dwell time plus operating margin of 45 to 70 sec. (headway varies with train length, refer to Fig. 7.1)

maximum capacity can be determined through the procedures of Chapter Seven, *Grade Separated Rail Capacity Determination*, summarized for shorter light rail trains in Figure 8.7. At the upper end of these levels the system has become a segregated rail rapid transit system using light rail technology.

No allowance is contained in Figure 8.7 for extended dwells due to low-level (step) loading, wheelchairs or on-board fare collection. At minimum headways with cab-control better than 120 sec it is reasonable to expect level loading—whether high or low—and off-vehicle fare collection.

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

Predominantly segregated and signaled light rail can reach the achievable capacity of some rail rapid transit systems. At this upper end of the light rail spectrum achievable capacity calculations should follow those of rail rapid transit.

Note that no light rail lines in North America exceed a capacity of 10,000 passengers per peak-hour direction per track. The exception is Mexico City's Line A—really a steel-wheeled metro line with six-car trains on entirely segregated right-of-way. MBTA's Green line trunk is the closest system to 10,000 passengers per peak-hour direction. Achievable capacities to and above 20,000 passengers per peak-hour direction are reported in Europe, however, at these levels, the lines, often called premetro or U-bahn, have many or all of the characteristics of rail rapid transit operated by light rail equipment.

# 9. Commuter Rail Capacity Determination

### 9.1 INTRODUCTION

Commuter rail 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. Annual ridership is shown in Figure 9.1. The capacity of such systems can best be determined from the procedures of Chapter Seven, Grade Separated Rail Capacity Determination. Care must be taken to take into account the sometimes lower vehicle performance and lower throughput of signaling systems where these are based on railroad rather than rapid transit practices. Elsewhere, with the exception of SEPTA's Philadelphia lines, Chicago's Metra Electric and South Shore lines, and the Mont-Royal tunnel line in Montréal, commuter rail uses diesel locomotive-hauled coaches and follows railroad practices. Electric locomotive-hauled coaches are also being used by SEPTA and New Jersey Transit (NJT) on routes which also see 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 most commuter rail lines the determination of capacity is at once both simple and inexact. Unlike the grade separated rail capacity determination, there are no reasonable methodologies that allow the calculation of the train control throughput and controlling dwell times to produce the achievable passenger capacity of a line.

The number of trains that can be operated in the peak hour is dependent on negotiations with the owning railroad. Many factors are involved, single or double (or more) track, the signal-



Figure 9.1 Commuter rail ridership (millions per year)

ing or train control system, grade crossings, speed limits, freight service, switching services—and the priorities to be accorded to these. Although railroads are becoming more conducive to accommodating commuter rail services—and the revenue and capital upgrading they produce—they have the upper hand and obtaining slots (alternately called paths or windows) for commuter trains at a reasonable cost is often a difficult and protracted business.

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

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

### 9.2 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 Three, *Train Control and Signaling*, will not enter into the picture.

A definitive answer may not always be obtained, particularly with single-track sections that are shared with freight. Freight traffic can vary and available commuter rail paths can vary. Usually the agreement will ensure a minimum number of commuter rail slots 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. Indeed, Chicago's Metra is planning new services aimed specifically at the reverse commuter.

The number of slots available per hour may range from one upwards into the double digits. Ten or more trains per hour is at the upper range of traditional railroad signaling and will exceed it if long, slow freights must be accommodated. At the upper end of this range, commuter rail is effectively in sole occupancy of the line for the peak period and can approach 20 trains per track per hour—a 3 min headway.<sup>1</sup> When electric multiple-unit commuter trains have similar performance to rail rapid transit, the capacity calculations of Chapter Seven, *Grade Separated Rail Capacity Determination*, can be used as a rough approximation of railroad signaling throughput by using the longer train length and adjusting the separation safety factor B from the suggested value of 2.4 for a rapid transit three-aspect signaling system to 3 or 4.

However caution should be exercised as some multiple-unit trains may not have all axles or cars powered; that is, the consist may be made up of motored and trailer cars. Locomotive-hauled commuter trains vary in power, length and gearing ratios making it difficult to cite typical acceleration rates and impractical to adapt the general calculations used in Chapter 7. 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 blocks.

Additional complications are raised by the variety of services operated and the number of tracks available. The busier commuter rail lines tend to offer a substantial number of stopping patterns to minimize journey times and maximize equipment utilization. A common practice is to divide the line into zones with trains serving the stations in a zone then running express to the station(s) in the central business district. Through local trains provide connections between the zones. A number of lines in the Chicago and New York areas are operated this way-Metra's Burlington Northern line to Aurora operates with five zones in the morning peak; Metro-North's New Haven line (including the New Canaan Branch) operates with seven zones. Such operating practices are made possible with three or more tracks over much of the route and the generous provision of interlockings to allow switching between tracks. Grade separated junctions are also common where busy lines cross or converge. Commuter rail throughput at complex interlockings associated with some stations and junctions, for example Harold Junction on the LIRR, requires specialized analysis that is beyond the scope of this report.

#### 9.2.1 STATION CONSTRAINTS

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, with  $46^2$  platform tracks at Grand Central Terminal, is thus able to use three of its four Park Avenue tunnel tracks in the peak direction. Even when one of the tunnel tracks was

closed for reconstruction, 23 trains per hour were handled on the remaining two peak-direction tracks.

The situation at New York's Penn Station is less relaxed where the LIRR has exclusive use of five tracks and shares four more with Amtrak and NJT. Currently the LIRR operates the East River tunnels with two tracks inbound and two tracks outbound with a peak headway of 3 min 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<sup>1</sup>/<sub>2</sub> min in a rush but 5 min is the minimum scheduled. Capacity into the station could be increased by improving track connections to the West Side Yard and so further reducing the number of trains which must be turned in Penn Station; this change would permit the East River tunnels to be operated with three tracks in the peak direction and allow the operation of additional trains.

#### 9.2.2 STATION DWELLS

Station dwell times on commuter rail lines are generally not as critical as they are on rapid transit and light rail lines as frequencies are lower and major stations have multiple platforms. In most cases the longest dwells are at the downtown terminals where the train is not blocking others while passenger activity takes place. Passenger flows are generally unidirectional 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 an example.

SEPTA's four track regional rail tunnel through Center City Philadelphia is one of the few locations where commuter trains run through from one line to another without terminating downtown. SEPTA schedules provide a very generous time of 10 min for trains to make two station stops over this 2.3 km-line segment.<sup>3</sup>

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 NJT, 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 min. Gallery cars usually feature one exceptionally wide door (2-m wide) at the center of each side to allow rapid boarding and alighting with multiple passenger streams.

<sup>&</sup>lt;sup>1</sup> Other typical commuter rail headways can be found in the ITE Transportation Planning Handbook (R42 and R43).

<sup>&</sup>lt;sup>2</sup> 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.

<sup>&</sup>lt;sup>3</sup> While there are three stations on this segment, the timetables only provide departure times and so do not include the dwell time at the first Center City station. Go Transit is the other agency that through routes commuter trains.

The estimation process for dwell times in Chapter Four, *Station Dwells*, should not be used for other than multiple-unit equipment with power operated sliding doors. Generally locomotive-hauled commuter rail equipment (and in some cases EMUs) have fewer doors, not all of which may be in use. Dwell times can be extended when passengers have longer to move within a car or train to an open door.

### 9.3 TRAIN CAPACITY

Except for a few situations where standing passengers are accepted for short distances into the city center, commuter rail train capacity is based solely on the number of seats provided on each train. A loading diversity allowance of 0.9 or 0.95 is used.

Where the equipment 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:

#### (trains per hour) $\times$ (seats per train) $\times$ 0.90

In many cases train length is adjusted according to demand. The longest train will be the one arriving just before the main business start time—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 loading diversity factor applied.

Where the commuter rail rolling stock is unknown the number of seats per unit length of train can be used, based on the shortest platform that the service will stop at. A number of systems, particularly older ones, operate trains which exceed the platform length at a number of stations. This situation is particularly common where platforms are constrained by physical and builtup features. Passengers must take care to be in the correct car(s) if alighting at a station with short platforms.<sup>4</sup> Train length on electric lines can also be limited by the amount of current the overhead or third-rail is able to supply.

Table 9.1 shows the seats and seats per meter length of all existing North American commuter rail cars, in descending order. All cars have substantially the same dimensions—the AAR passenger car maximums of 25.2-m long (82.7 ft) and 3.2-m wide (10.5 ft). A complete table of car dimensions, doors and ADA accessibility types is provided in Appendix Three and on the computer disk.

Passengers per meter of car range from over 7 to below 2. At the high end are the double-deck car types, bi-levels<sup>5</sup> and gallery cars. 3+2 seating is needed to reach 7 passengers per meter (7/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 7/m can be used as a maximum. A range of 5/m is the upper end for single level cars. with 4/m preferred. These preferred and recommended

#### Table 9.1 Commuter rail car capacity

Suctom	Designation	Builder	Date Built	Seats	Seate/m
LIRR	C-1	Tokyu Car	1990	190	73
MBTA	BTC	Kawasaki	1991	185	7.1
LIBR	C-1	Tokyu Car	1990	181	70
MRTA	CTC	Kawasaki	1991	180	6.9
Metra	TASA, TBSA	St. Louis	1955	169	6.5
STCUM	Gallery Trailer	Cdn. Vickers	1970	168	6.5
GO Transit	Bi-Level Trail.	H-S/UTDC	1977-91	162	6.3
Metra	TA2A, B, C	Budd	1961-65	162	6.3
Tri-Rail	Bi-Level	UTDC	1988-91	162	6.3
GO Transit	Bi-Level Cab	H-S/UTDC	1983-90	161	6.2
Metra	TA3B. C. D. E. F	Pullman	1956-65	161	6.2
Metra	TA3G. H. I. J. K	Pullman	1966-70	161	6.2
Metra	TA3L	Pullman	1958	161	6.2
Tri-Rail	Bi-Level III	UTDC	1988	159	6.1
Metra	TA2D, E, F	Budd	1974-80	157	6.1
Metra	CA2A, B, C	Budd	1961-65	156	6.0
Metra	MA3A (emu)	St. Louis	1971-72	156	6.0
Metra	MA3B (emu)	Bombardier	1978-79	156	6.0
Metra	CA3A. B	Pullman	1959-60	155	6.0
Metra	CA3C, D, E, F	Pullman	1965-68	155	6.0
STCUM	Gallery Cab	Cdn. Vickers	1970	154	5.9
Metra	CA2D	Budd	1974	149	5.8
CalTrain	Gallery Coach	Sumitomo	1985-87	148	5.7
Metra	Gallery	Nippon Sharyo	1995	148	5.7
Metra	TN1A, D, F	Budd	1950-55	148	5.7
SCRRA	Bi-Level V Mod.	UTDC/Bombardier	1992-93	148	5.7
Metra	CA2E	Budd	1978	147	5.7
Metra	CA2F	Budd	1980	147	5.7
Metra	CA2G	Budd	1980	147	5.7
Metra	TN1B,C,E,G H,I	Budd	1951-73	145	5.6
Metra	TN2A	Budd	1978	145	5.6
SCRRA	Bi-Level V Mod.	UTDC/Bombardier	1992-93	145	5. <b>6</b>
Metra	Gallery	Nippon Sharyo	1994	140	5.4
CalTrain	Gallery Cab	Sumitomo	1985	139	5.4
Metra	CN1A, B	Budd	1965, 74	139	5.4
LIRR	PT-75	Pullman Standard	1963	133	5.3
Metra	TA3L	Pullman	1966-70	136	5.2
CalTrain	California	Morrison Knudsen	1993	135	5.2
SEPTA	JW2-T	Bombardier	1987	133	5.1
Conn DoT	Comet II Mod	Bombardier	1991	131	5.1
Metro-North	Shoreliner	Bombardier	1986	131	5.1
NJT	Comet I	Pullman Standard	1971	131	5.1
NJT	Comet II/IIA	Bombardier	1982-83	131	5.1
NJT	Comet IIB	Bombardier	1987-88	131	5.1
CalTrain	California (Cab)	Morrison Knudsen	1993	130	5.0
Conn DoT	Comet II Mod	Bombardier	1991	130	5.0
Metro-North	ACMU	Pullman Standard	1962	130	5.0
NICTD	TMU-1	Sumitomo	1992	130	5.0
SICUM	Sing, Lev./00	Bombardier	1989	130	5.0
MBIA	BIC-1A	Bombardier	1987	12/	4.9
SEPIA	ISL II	Buda	1964	127	4.9
ISEP IA		General Electric	19/3-//	12/	4.9
	17-72 DT 70	Pullman Standard	1955-56	123	4.9
LIHH	111-12	Fullman Standard	1955-56	123	4.9
Metro-North	M-4 D	TOKYU Car	1988	126	4.9
Metro-North	M-6 U	Morrison Knudsen	1993	126	4.9
NJI	Comet IIB	Bombardier	198/-88	126	4.9
		Pute Standard	19/1	125	4.8
SEPIA	IOL II		1903	125	4.8
			19/1, 02	123	4.1
LINN	[ IVI- I	וסטטם	1900-11	1 122	4./

<sup>&</sup>lt;sup>4</sup> Another common station limitation, lack of park and ride capacity, is considered in Chapter Six, *Operating Issues*.

<sup>&</sup>lt;sup>5</sup> Also called tri-levels on certain systems as there is an intermediate level at each end over the trucks.

Table 9.1 Commuter rail car capacity continued

System	Designation	Builder	Date Built	Seats	Seats/m	System	Designation	Builder	Date Built	Seate	3
LIRR	M-1	GE	1972	122	4.7	Metro-North	M-4 B	Tokyu Car	1988	114	1
MBTA	BTC-1B	Bombardier	1989-90	122	4.7	NJT	Arrow III	GE	1977-78	113	+
MBTA	CTC-1A	Bombardier	1989-90	122	4.7	N.JT	Comet II/IIA	Bombardier	1982-83	113	+
Metro-North	M-1A B	Budd	1971	122	4.7	VRE	Cab	Mafersa	1992	112	╈
LIRR	P-72	Pullman Standard	1955-56	118	4.7	SEPTA	ISI III	St Louis	1967	111	┢
LIRR	PT-72	Pullman Standard	1955-56	118	4.7	STCUM	Class B	CC&F	1953-54	109	╈
NJT	Comet IB	Pullman Standard	1968	121	4.7	NICTD	FMU-2	Sumitomo	1992	110	╈
LIRR	M-3	Budd	1985	120	4.6	Metro-North	SPV 2000	Budd	1081	100	╈
MARC	Coach	Sumitomo	1992-3	120	4.6	N.IT	Comet III	Bombardier	1001-01	103	+
Metro-North	M-3A A	Budd	1984	120	4.6	Metro-North	M-6 B	Morrison Knudsen	1000 01	100	╈
VRE	Trailer	Mafersa	1992	120	4.6	MARC	F/H Cab	Nippon Shanyo	1085-87	104	╈
NJT	Arrow II	GE	1974-75	119	4.6	NIT	Comet III	Bombardier	1000-01	103	┢
NJT	Arrow III	GE	1977-78	119	4.6	Conn DoT	C&O 1600	Pullman Standard	1050 01	102	+
Conn DoT	Cornet II Mod	Bombardier	1991	118	4.6	STCLIM	MLL (emu)	CC&F	1052	9/	╈
LIRR	M-1	GE	1972	118	4.6	STCUM	Mil (trailer)	CC&F	1052	84	╋
LIRR	M-1	Budd	1968-71	118	4.6	MRTA	BTC-1	Pullman Standard	1070	07	┢
MARC	E/H Toilet	Nippon Sharvo	1991	118	4.6	VBE	BTC-2	Budd	1055	00	╈
Metro-North	M-1A A	Budd	1971	118	4.6	MARC	Coach	Budd	10/0	06	╈
Metro-North	M-2 A	GE	1973	118	4.6	MRTA	BTC-3	MBB	1097-89	06	+
Metro-North	M-4 A	Tokyu Car	1988	118	4.6	MARC	Coach	Budd	10/0	05	╈
Metro-North	M-6 A	Morrison Knudsen	1993	118	4.6	MBTA	CTC-1	Pullman Standard	1070	05	╈
Metro-North	Shoreliner	Bombardier	1986-91	118	4.6	STCUM	MB90 (emu)	Romhardier	1004	05	┢
NJT	Comet III	Bombardier	1990-91	118	4.6	STCUM	MR90 (trailer)	Bombardier	100/	05	+
SEPTA	JW2-C	Bombardier	1987	118	4.6	MRTA	CTC-3	MRR	1097-99	04	┢
NJT	Cornet IIB	Bombardier	1987-88	117	4.5	NICTO	EMU-1	Sumitomo	1082	03	┢
NJT	Arrow II	GE	1974-75	115	4.4	NICTD	FMII-1A	Sumitomo	1083	03	┢
NJT	Arrow III	GE	1977-78	115	4.4	VBF	CTC-2	Budd	1055	30	╈
NJT	Comet I	Pullman Standard	1971	115	4.4	MARC	Toilet Coach	Budd	10/0	92	╈
NJT	Cornet IB	Pullman Standard	1968	115	4.4	MARC	Toilet Coach	Budd	10/0	00	+
LIRR	M-3	Budd	1985	114	4.4	NIT	Comet IIB	Bombardior	1007 00	00	┢
MARC	Coach	Nippon Sharyo	1985-87	114	4.4	STCHM	Coach	COLE	1042	00	┝
MARC	E/H Cab	Nippon Sharyo	1991	114	4.4	Conn DOT	SBV 2000	Budd	1070	- 03	-
MARC	E/H Coach	Nippon Sharyo	1991	114	4.4	MARC	Coach	Budd	10/0	04	╋
Metro-North	M-2 B	GE	1973	114	4.4	MARC	Toilet Coach	Budd	1040		╋
Metro-North	M-3A B	Budd	1984	114	4.4		C&O 1600	Dudu Dullman Standard	1949		╋
<b></b>			******	******			000 1000	Dullman Standard	1055 56	00	╋

levels allow some space for toilets, wheelchairs and bicycles. If these provisions are extensive then the car capacity should be reduced accordingly.

Obviously the train length should exclude the length of the locomotive(s) and any service cars, if any, 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 type standing densities from Chapter Five, *Passenger Loading Levels*, are not appropriate for commuter rail and should not be used.