Report 13

Rail Transit Capacity

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Under TCRP Project A-8, research was undertaken by Transport Consulting Limited to (1) obtain current information on rail transit capacity, including a) factors affecting capacity; b) current values for parameters affecting capacity under a range of operating conditions; and c) current values for maximum passenger and vehicle capacities achieved under various operating practices and loading standards and (2) provide appropriate methodologies for estimating the capacity of future rail transit systems and modifications to existing systems. The scope included investigation, evaluation, and documentation of current North American experience in rail transit capacity for light rail transit, rapid rail transit, commuter rail, and automated guideway transit.

To accomplish this effort, the researchers conducted a comprehensive survey of existing literature on rail transit capacity experience and capacity analysis methodologies. In addition, a survey of 63 rail transit operators in the United States, Canada, and Mexico was performed to determine actual line-by-line capacity and capacity constraints of each system. Extensive field surveys were also conducted to determine passenger boarding rates and dwell times for different rail transit modes, platform heights, and fare collection methods. Quantitative analyses then produced easy-to-use procedures for estimating achievable rail transit capacity. Thus, the report is a valuable resource for transportation and rail transit planners, designers, and operators.

CONTENTS

ACKNOWLEDGMENTS

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The report was written by Tom Parkinson, president of TCL, the principal investigator, and Ian Fisher of the University of British Columbia, the research associate with contributions from the associate investigator Ian Graham, operations planner for the British Columbia Rapid Transit Company and Dr. Jonathan Berkowitz the project's statistical advisor. Murray McMillan of the Vancouver Sun assisted in editing the report.

The research team acknowledge with thanks the time and effort of numerous people in rail transit operating agencies who provided information for the rail transit survey and assisted the team in the field data collection. TCRP Program Officer Christopher Jenks deserves many thanks for his help and support throughout this project.

Inside the Report

This report has three main sections. This introductory section, paginated with roman numerals, contains the *Problem Statement, Research Objectives* and *Research Approach* of the project, followed by the *Summary* and a *User Guide.*

In the main section, the first two chapters, *Rail Transit In North America* and *Capacity Basics*, describe the industry and capacity issues. The following four chapters: *Train Control and Signaling, Station Dwells, Passenger Loading Levels*, and *Operating Issues* develop the methodology. These are followed by chapters seven through ten, which present capacity calculation methods for the four rail transit groups, respectively: *Grade Separated Rail, Light Rail, Commuter Rail* and *AGT.* The final chapters present recommendations and suggestions for *Future Research* followed by a *Bibliography* and *Glossary.*

In the third and final section, three *appendices* summarize the *Literature Reviewed* and the *Data Survey*, and *Tabulate the Data* used in the project. In particular Table A 3.3 provides a detailed listing of all North American individual transit routes and ridership.

Problem Statement

In the past several decades, many developments have taken place that directly affect North American rail transit performance, vehicles, operations, and systems technologies. These developments include the extension and modernization of rail rapid transit and commuter rail systems, the introduction of the proof of payment fare collection system, the requirements of the Americans with Disabilities Act (ADA), and the construction of new light rail, automated guideway transit (AGT), rail rapid transit, and commuter rail systems. Consequently, data and procedures related to estimating rail transit capacity need updating to take these developments into account.

Rail transit capacity information available in the 1985 *Highway Capacity Manual* is based on operating experiences from the prior two decades. While providing broad guidelines and general approaches to determining rail transit capacity, it does not fully reflect current experience.

There is a need to identify and document the factors affecting rail transit capacity and collect data on current values of these factors in order to update and expand the range of applications for this information. The research must take into account vehicles, station designs, fare policies, train control technologies, and operating practices that better reflect North American rail transit experience. There is also a need for information and procedures for estimating transit capacity. Rail transit capacity, as defined for this project, includes both the number of people and the number of vehicles past a point per unit of time, and it relates to stations, routes, junctions, and other controlling transit system features.

Examples of applications for new rail transit capacity information include the following:

- project planning and operations analysis for new starts and extensions,
- evaluating transit line performance,
- establishing and updating service standards,
- studying environmental impacts,
- assessing the capacities of new signaling and control technologies,
- estimating changes in system capacity and operations over time, and
- assessing capacity impacts in land-development studies where transit is expected to provide a significant role in site access.

Research Objectives

The objectives of this research have been to obtain current information on rail transit capacity and to provide appropriate methodologies for estimating the capacity of future rail transit systems and of modifications to existing systems, taking into account generally accepted theory and observed operating practices.

Effort has been divided among the four rail modes:

Light Rail Transit (LRT)
Rail Rapid Transit (Heavy Rail) (RT)
Commuter Rail (Regional Rail) (CR)
Automated Guideway Transit (AGT)

Research Approach

The study has taken a structured and methodical approach that makes maximum use of previous work and existing data. The North American rail transit industry monitors ridership carefully, usually as part of the Federal Transit Administration (FTA) (UMTA) Section 15[1] reporting. Annual summary reports are also prepared by American Public Transit Association (APTA), Canadian Urban Transit Association (CUTA), and individual rail operators. Less frequently published reports summarize rail equipment rosters with quantities, dimensions and other information.

These data have been augmented by direct contacts with each agency to determine peak-point ridership, theoretical and actual minimum headways, limitations on headways, individual car loadings, locations and frequencies of pass-ups, and other relevant factors.

The initial data collection was used as an input into an analytic framework containing the above capacity influencing factors with particular emphasis on achieving accurate real-life calibration for each factor.

Additional data needs were identified—concentrating on systems with heavily used rail lines. The only accurate way to determine the true maximum capacity of a car is when there are pass-ups. That is when passengers wait for the next train on a routine day-by-day basis. There are only an estimated six locations in the United States and Canada where pass-ups occur on rapid transit, all were visited.

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[1] FTA—Federal Transit Administration. Section 15 of the Urban Mass Transportation Act of 1964, as amended. *Uniform System of Accounts and Records and Reporting System.*

Based on the analytic framework and data collected, quantitative analysis was carried out and calibrated, with formulae and constants determined to provide a comprehensive method for determining rail transit capacity over a wide range of variants for each of the four rail modes.

A practical method of using the data and determining capacity has been developed in two categories. The first category is a simple method containing basic parameters with constants for major variables that reflect typical or *average* conditions. The second category is more complete, adding further variants, including capacity adjustments for grade and line voltage.

To assist in using the results of this research, a computer disk has been prepared containing spreadsheets into which system variables can be inserted. (See Summary for availability.)

Footnotes and References

To avoid duplication, references are shown as (R23) and refer to the bibliography in Chapter Twelve and the literature review item of the same number in Appendix One. Footnotes are shown by an italicized superscript number[8] referenced to the bottom of each page.

Summary

S1 INTRODUCTION

Rail transit systems in North America carry 5 billion passengers each year. Fifty-three agencies operate 207 routes of the four rail transit modes with a total length of 8,200 km (5,100 mi), providing 29 billion passenger-kilometers of service annually.

Two systems dominate. The largest operator, Sistema de Transporte Colectiva (STC) in Mexico City, has recently overtaken MTA New York City Transit in ridership. STC carries 1,436 million passengers annually, 29% of the continent's total. MTA-NYCT carries 1,326 million passengers annually, 27% of the continent's total, 50% of the United States' total. Adding all New York City area rail operators makes the New York area the continent's largest user of rail transit with 1,585 million passengers annually, 32% of the continent's total, 59% of the United States' total. Together the rail transit systems in the New York area and in Mexico City account for 61% of all unlinked rail passenger trips in North America. Summary data is shown in Tables S.1 and S.2.

Rail transit plays a vital role in five metropolitan areas carrying over 50% of all work trips and, in three regions, over 80% of all central business district (CBD)-oriented work trips. Rail transit plays an important but lesser role in another six regions. Other rail transit systems carry a smaller proportion of all regional trips but fill other functions—defining corridors, encouraging densification and positive land-use development, reducing congestion and providing reliable, economic and environmentally responsible capacity in overloaded corridors.

S2 CAPACITY

This study has concentrated on the achievable capacity of the four rail transit modes: rail rapid transit, light rail, commuter rail and automated guideway transit.

Table S.1 North American rail ridership by mode

MODE	Annual Unlinked Trips	%
Rail Rapid Transit	4,137,377,073	80.8%
Light Rapid Transit	473,778,608	9.2%
Commuter Rail	333,692,317	6.5%
Automated Guideway	175,034,327	3.4%
TOTAL	5,119,882,325	100%

Table S.2 Transit ridership summary (million)

	All Transit	Rail Transit	% by rail
USA	8,643	2,671	31%
Canada	2,001	770	38%
Mexico	n/a	1,503	n/a

Achievable Capacity

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

The basics of rail transit capacity are very simple—the product of how many trains can be operated in the peak hour and by the number of passengers that will fit on those trains. However, as many contributors to this field have pointed out, some of the factors in this seemingly simple calculation vary widely, none more so than the density of loading. Leroy Demery(R22) states this succinctly in reference to new rail transit lines in the USA:

> *. . . long before crowding levels. . . . . . reached New York levels, prospective passengers would choose to travel by a different route, by a different mode, at a different time, or not at all. . . . . . . .outside the largest, most congested urban areas, the level of crowding that transit passengers appear willing to tolerate falls well short of theoretical "design" or "maximum" vehicle capacity. . .*

Determining how many passengers will fit on a train is a policy issue subject to significant economic constraints. The actual levels in North America vary by a factor of six to one from Mexico City's Line 2 to most commuter rail systems where universal policies provide a seat for all longer distance passengers. The range on rail rapid transit in the United States is less at approximately three to one. The project has reduced this range further with recommended loading ranges for rail rapid transit and light rail of two to one.

The other largest variable in the determination of achievable capacity is the operating margin. An *operating margin* must be added to the *minimum train separation time* plus *maximum station dwell* to arrive at the closest practical train headway—and so maximum throughput. Although rail transit is noted for reliable and regular operation, minor delays are routine and an operating margin—and the associated end-of-line schedule recovery time—are essential to prevent delays from compounding. Service designed so that routine irregularities do not spread from one train to another is desirable and is said to be operating with a *noninterference headway.*

The range of operating margins on close headway rail rapid transit in North America exceeds four to one. After analyzing this range, the project recommends a range of 15 to 25 sec—just less than two to one.

At the maximum load point station it is possible to calculate the minimum train separation possible with a given train control system with some precision, and the portion of station dwell

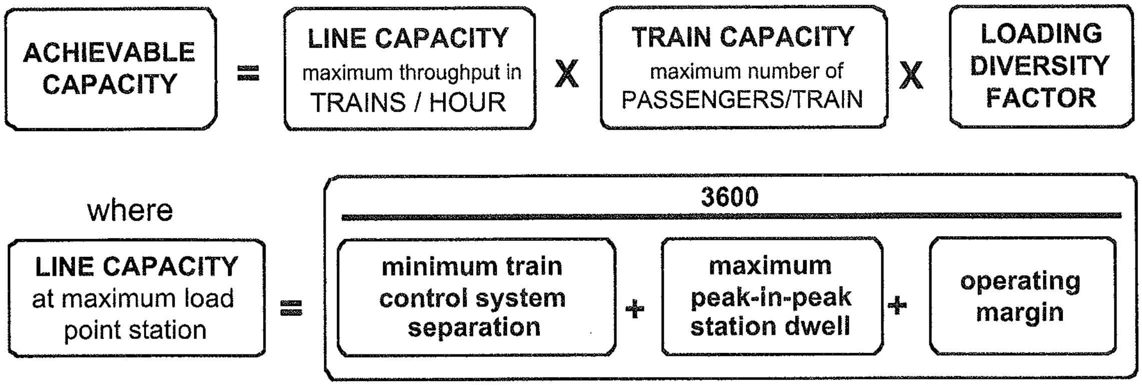

Figure S.1 Basic capacity calculation (all line capacity components in seconds)

related to passenger flow with reasonable accuracy. It is, however, a classic case of statistical *spurious accuracy* to pursue these definable elements with too much rigor when other factors vary so widely. The well-stated caution from Richard Soberman, one of the earlier workers in this field, should always be kept in mind:

> *The capacity of transit service is at best an elusive figure because of the large number of qualifications that must be attached to any measure of capacity that is adopted.*

S3 GROUPING

For the purpose of capacity analysis and determination, the four modes of rail transit in this study can be grouped into specific categories based on the type of alignment and rolling stock.

The first category is fully segregated, signaled, double-track right-of-way, operated by electrically propelled multiple-unit trains. This is the largest category encompassing all rail rapid transit, all non-institutional automated guideway transit,[1] several light rail sections—for example, the Market Street subway in San Francisco, and several commuter rail lines on the East Coast. This category represents 94% of all rail transit ridership on the continent.

The second category is light rail without fully segregated tracks, divided into on-street operations and private right-of-way with grade crossings. The third category is commuter rail other than services included in category one. In each of these categories the basic capacity analysis is determined by the flow chart shown in Figure S.1.

Occasionally the throughput bottleneck is not the maximum load point station but a junction, a heavy-use station with an entry speed restriction or a turn-back movement. Generally these constraints can be avoided by good design and should not be accepted on new systems.

S4 TRAIN CONTROL

The three major designs of train control system offer progressive increases in capacity. By far the most common constraint is the close-in movement at the maximum load point station. Occasionally another heavy-use station with mixed flow may require longer dwells and become the constraint. The minimum headway can be readily calculated with the only uncertainty being the safety separation factor. Logical safety separation factors were developed for each generic type of train control and showed close correlation to field experience. A summary of the results is shown in Figure S.2 and Table S.3.

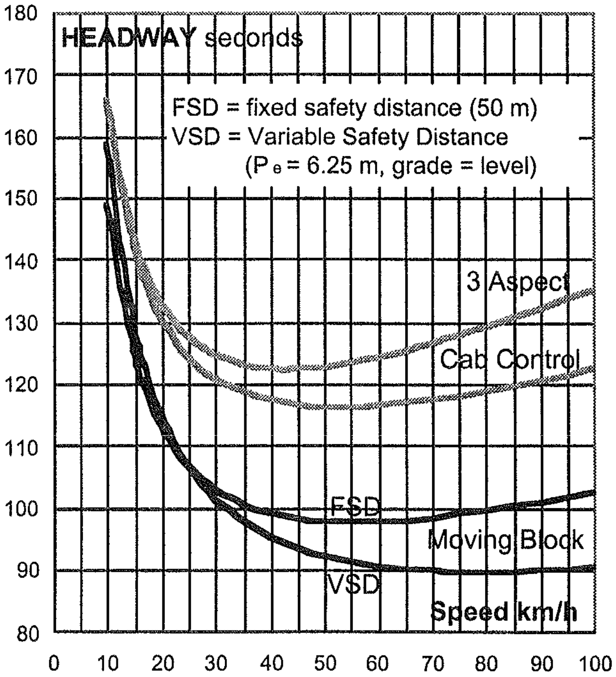

Figure S.2 Moving block headways with 45 sec dwell and 25-sec operating margin compared with conventional fixed block systems

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[1] The Morgantown Automated Guideway Transit system, with off-line stations, is not classed as a public operation by APTA, but is included as a *transit* operation in this report.

Table S.3 Headway result summary in seconds with 200-m (660-ft) trains (8-10 cars) VSD = variable safety distance

Station dwell	0	30	45
Operating margin	0	15	25
3 aspect system	57	102	122
Cab controls	51	96	116
Moving Block-VSD	32	77	102

The minimum train separation is based on systems designed for the greatest throughput with typical equipment performance. Many systems are not designed for this maximum throughput but use a more economical train control system with lower capabilities. In this case the design capabilities of the train control system must be obtained and used in the achievable capacity calculation.

The headway calculations can make allowances for grades into and out of stations and reductions in line voltage. Adjustments for speed restrictions on the approach to the maximum load point station are also accommodated with a distance-speed chart that permits a manual adjustment to the approach speed. Where available, or on systems with unusual circumstances, the use of a comprehensive suite of simulation programs is recommended.

The components of a typical rail rapid transit system with full length trains, a 45-sec station dwell and the recommended mid-range operating margin are shown in Figure S.3.

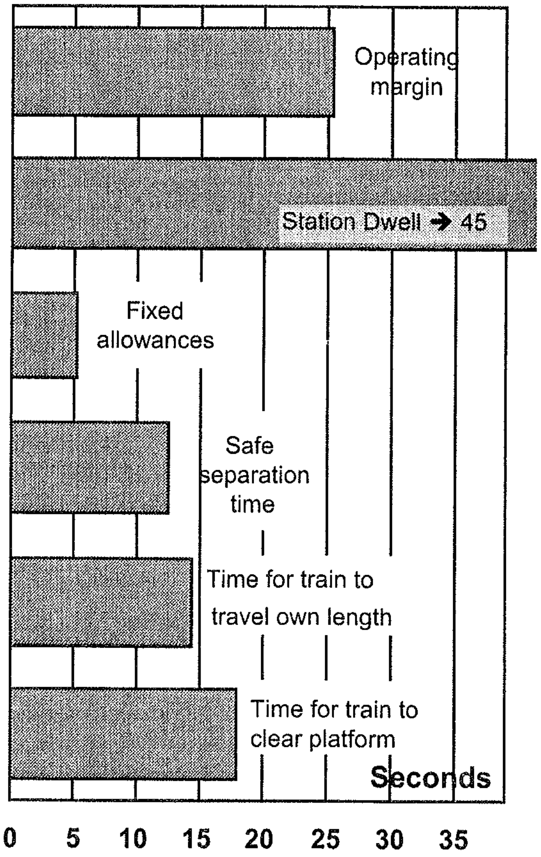

Figure S.3 Headway components for cab-control signaling that compose the typical North American minimum headway of 120 sec

S5 STATION DWELLS

As Figure S.3 shows, the station dwells are the largest component of the minimum headway, and they are also a partly controllable item. One disconcerting result of the field survey, which concentrated on lines at or close to capacity, is the relatively small proportion of dwell time productively used for passenger flow—shown in Figure S.4. This is discussed as a potential area for future research in Chapter Eleven.

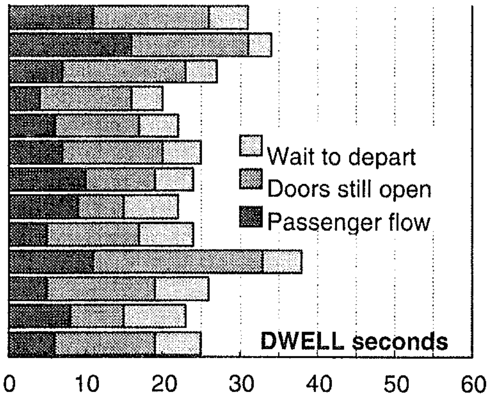

Figure S.4 Toronto Transit Commission King Station S/B dwell time components: am peak period (part) (flow time averages 31% of total dwell)

Although it was not possible to equate flow times with door width, statistical analysis produced a good fit between passenger volumes and dwells for all level loading situations, independent of mode and system. This result avoided having separate equations for a variety of situations.

The majority of the field data collection involved doorway flow time. The results are summarized in Figure S.5. The most surprising result was the consistently faster loading rate up light rail steps compared to alighting down the steps.

A special survey of passenger flows at special events— a football game and a rock concert—disproved the theory that flows would be faster. In the limited sample observed they were slightly slower than in normal peak periods. This can be attributed to the many riders to special events not accustomed to transit use.

On the few light rail systems with on-board fare collection, boarding time was 31% slower. The exact-fare collection process added one second per passenger on average. Light rail with low-level loading—with steps on the car as distinct from low-floor cars—produced times per passenger that averaged exactly double those for level loading, an additional 2.05 sec per passenger.

Flow rates—and the resultant dwell times—for light rail with on-board fare collection or low-level loading were not used in

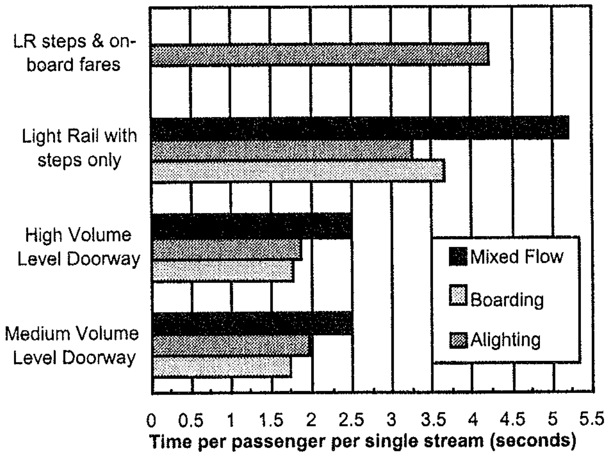

Figure S.5 Summary of rail transit doorway average flow times

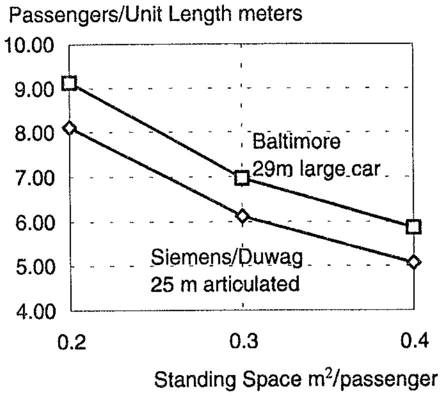

Figure S.6 Linear passenger loading of articulated LRVs.

the calculation of maximum achievable capacity. On-board fare collection through a single door is not possible at significant passenger volumes. All North American light rail systems with on-board fares use station fare collection at busy trunk stations. Maximum achievable capacity with steps is an oxymoron. The busiest light rail trunk, San Francisco's Market Street subway, uses cars equipped with folding steps to provide level loading. The other heavy trunk light rail line, in Boston, also operates at less than half the maximum achievable capacity of three-car articulated light rail trains operating close to the minimum headway—primarily because of the level of demand but also, in part, because of longer dwells caused by the low-level loading.

S6 LOADING LEVELS

A comprehensive survey of theoretical and actual car capacity resulted in a detailed methodology to select seating arrangements and standing densities that produce car and train loading levels. The recommended result to base loading on the linear length of a car or train is summarized in Figures S.6 and S.7 and Table S.4.

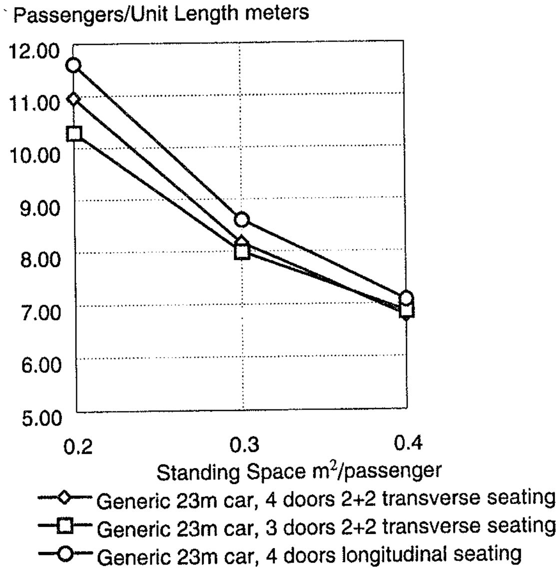

Figure S.7 linear passenger loading heavy rail cars

Table S.4 Linear load summary—passengers per meter

	Average	Median	Std. Dev
All Systems	6.4	5.9	2.0
Commuter Rail	4.8	4.5	0.7
Heavy Rail	6.8	6.3	2.0
Heavy Rail less NYCT	5.5	5.6	1.5
NYCT alone	7.9	7.8	1.8

Three levels of loading diversity were reviewed. The diversity of loading within a car and between cars of a train was incorporated in the recommended linear loading levels. The more important diversity between the peak-within-the-peak and the full peak hour is shown in Table S.5. The recommended loading diversity factors based on actual North American experience are

- **0.80—rail rapid transit**
- **0.75—light rail**
- **0.60—commuter rail**

S7 OPERATING ISSUES

The field survey, plus data provided by several operators, showed a surprising amount of headway irregularities. An index was developed—the coefficient of variation of headways—but no relationship could be found between this and headway, dwell or train control separation. The potential savings from controlling dwell were demonstrated by a few operators who combined close headways with brisk operation. This topic is suggested as an area for future research in Chapter Eleven.

A wide range of data was compiled to determine actual operating margins. A selection is shown in Figure S.8. The recom-

Table S.5 Diversity of peak hour and peak 15 min

Type	System	Routes	Diversity factor
CR	CalTrain	1	0.64
CR	GO Transit	7	0.49
CR	LIRR	13	0.56
CR	MARC	3	0.60
CR	MBTA	9	0.53
CR	Metra	11	0.63
CR	Metro-North	4	0.75
CR	NICTD	1	0.46
CR	NJT	9	0.57
CR	SCRRA	5	0.44
CR	SEPTA	7	0.57
CR	STCUM	2	0.71
CR	Tri-Rail	1	0.25[2]
CR	VRE	2	0.35
CR	**Sum/Average**	**74**	**0.56**
LRT	CTS	2	0.62
LRT	Denv. RTD	1	0.75
LRT	SEPTA	8	0.75
LRT	Tri-Met	1	0.80
LRT	**Sum/Average**	**12**	**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
RT	PATH	4	0.79
RT	STCUM	4	0.71
RT	TTC	3	0.79
RT	**Sum/Average**	**46**	**0.79**
All	**Sum/Average**	**133**	**0.67**

[2] Service is only one train per hour and is not included in the average.

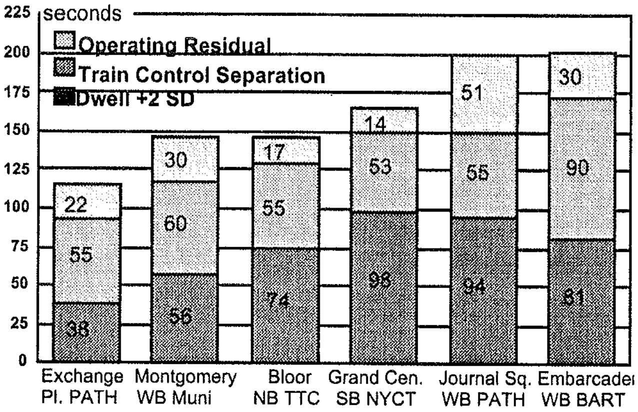

Figure S.8 Headway components of selected North American rail rapid transit systems (in seconds)

mended range to be applied in capacity determination is 15 to 25 sec.

Other operating issues were reviewed. Skip-stop operation and passenger-actuated doors were found not to influence maximum achievable capacity. Skip-stop operation still requires all trains to stop at the maximum load point station. Passenger transfers between A and B trains could extend dwells slightly. Passenger-actuated doors, a common light rail feature, have no effect at systems close to capacity as at heavy volumes train operators control the doors—disabling the passenger actuation.

The Americans with Disabilities Act (ADA), timing wheelchair boarding and alighting movements, and agency plans to meet ADA requirements were reviewed. This led to the conclusion that ADA would probably have no negative consequences on maximum achievable capacity but possibly positive ones as better visual but audio messaging could reduce doorway delays from passengers who are uncertain what train to board or alight from. All heavy volume rail transit will adopt level loading where wheelchair movements can be as fast as those of other passengers—sometimes faster.

S8 CAPACITY DETERMINATION

Capacity determination was broken down into the four modes and into simple and complete methods. Over 90% of North American rail transit fits into the main category of Chapter Seven, *Grade Separated Rail Capacity Determination,* and in reality any rail transit system intending to offer the maximum achievable capacity will be in this category.

The simple methodology uses two charts that provide a modest range for rail transit with typical parameters. The charts (Figures S.11 and S.12) offer variants for heavy rail and light rail with either cab-control or moving-block signaling systems.

The complete method takes the user through a series of steps that require some judgment. The first call is to determine the weakest link in the capacity chain, then calculate or pick a dwell time—three methods are given. Other calls include the operating margin and the passenger loading level.

Three subsequent chapters deal with the specifics of light rail, commuter rail and automated guideway transit. Equations to determine the headway constraints of light rail single-track sections are developed. The results for selected parameters are shown in Figure S.9. Commuter rail is unique in that train capacity is the total number of seats in the train less an allowance of 5-10%. Commuter rail throughput — outside the main category of electric multiple-unit operation on dedicated tracks —cannot be calculated but must be obtained from the capabilities of the specific signaling system, or more commonly from the number of trains contracted with the owning railroad.

S9 THE RESULTS

Figure S.10 shows the capability of various train control systems with trains of different length. Figure S.11 shows the dwell time and achievable capacity relative to hourly, directional platform volumes at the maximum load point station. Figure S.10 contributes to the main results shown in Figure S.11 and Figure S.12. These latter two figures together constitute the simple method of capacity determination based on the assumptions of Table S.6.

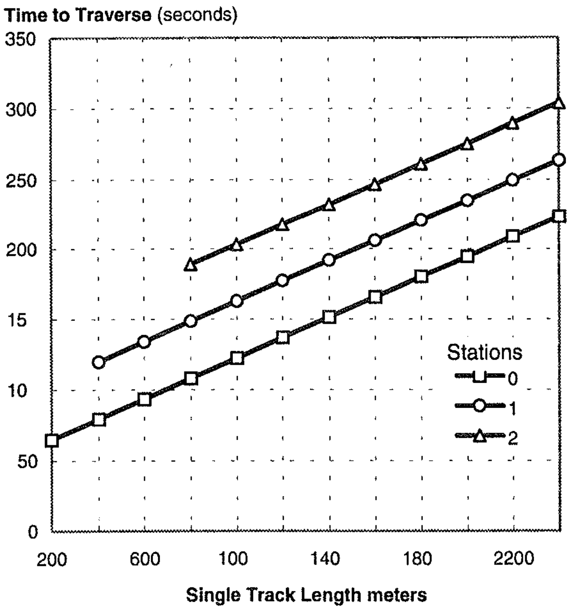

Figure S.9 Light rail travel time over single-track section. (with a speed limit of 55 km/h and various numbers of stations train length 56 m, dwell time 20 sec, operating margin 20 sec, other data as per Table 8.2.)

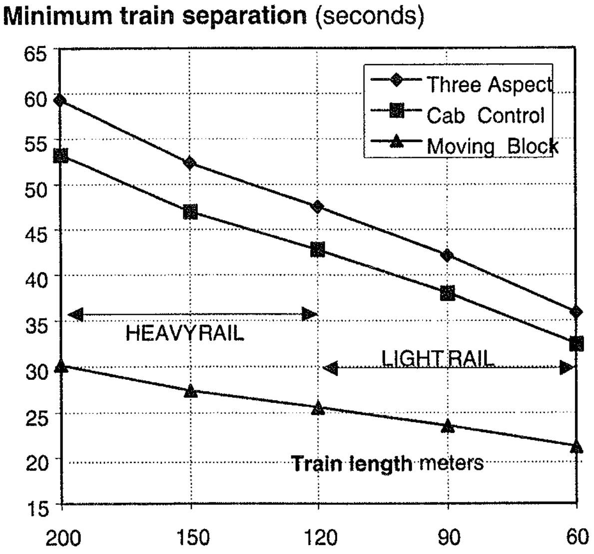

Figure S.10 Minimum train separation versus length

Table S.6 Simple method performance assumptions

TERM	DESCRIPTION	DEFAULT	UNIT
G_i	Grade into headway critical station	< ± 2	%
D	distance from front of train to exit block	<10	m
K	% service braking rate	75	%
t_{os}	time for overspeed governor to operate	3	secs
t_{jl}	time lost to braking jerk limitation	0.5	secs
a_s	service acceleration rate	1.3	m/s²
d_s	service deceleration rate	1.3	m/s²
t_{br}	brake system reaction time	1.5	secs
v_{max}	maximum line velocity	100	km/h
t_d	dwell time	35-45	secs
t_{om}	operating margin	20-25	secs
l_v	line voltage as % of normal	>85	%
S_{mb}	moving block safety distance	50	m

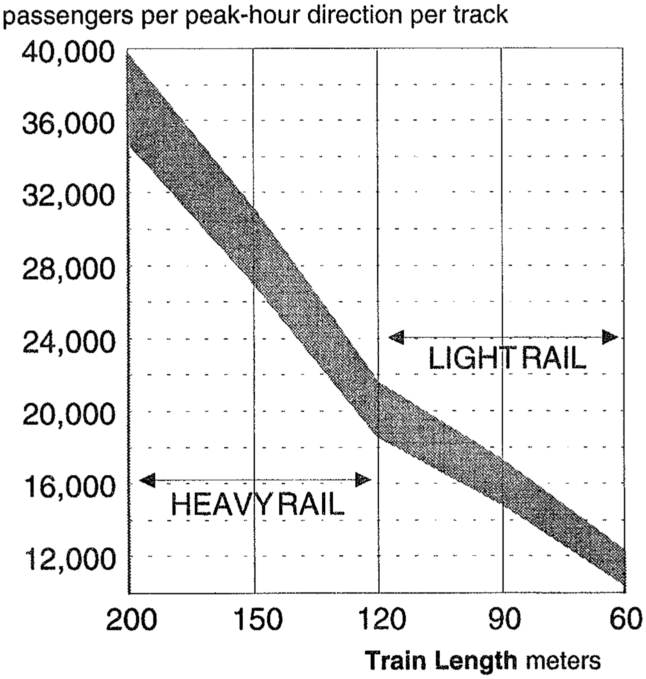

Figure S.11 Achievable capacity with a multiple-command cab-control signaling system and peak-hour average loading of two passengers per square meter for one track of a grade separated rail transit line

S10 COMPARISONS

The highest capacity double-track rail rapid transit is believed to be the Yamanote line in Tokyo reaching 100,000 passengers per peak-hour direction. Hong Kong's busiest line carries 75,000 and some European lines reach 60,000. In past eras high ridership was sustained on rail rapid transit and light rail or streetcar lines in several North American cities. This is no longer the case.

In North America, Mexico City's Line 2 with 75,000 passengers per peak-hour direction is the heaviest. In the United States and Canada, no lines exceed 50,000. NYCT's two-track trunk combining lines E and F (Queens Blvd. Express) carries 49,800 while the busiest four-track trunk is the Lexington Avenue line used by the 4, 5 and 6 services with 63,200 passengers per peak-hour direction.

In theory a four-track line could carry double the capacity of two tracks if the services were independent. However, where local and express services are inter-worked, the New York ratio of up to 50% additional capacity is modest and for maximum capacity determination four tracks of local and express service can be considered capable of carrying 180% of the passengers per peak hour on two tracks.

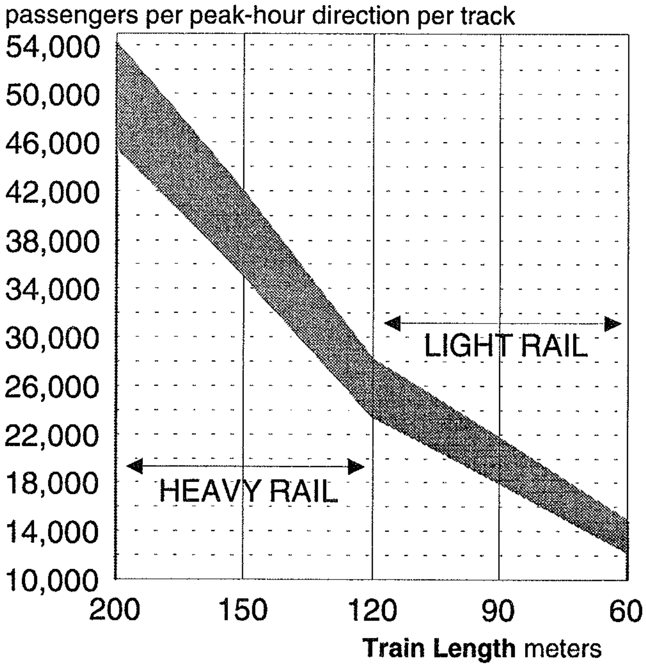

Figure S.12 Achievable capacity with a moving-block signaling system and peak-hour average loading of two passengers per square meter for one track of a grade separated rail transit line Caution: With the exception of San Francisco's Muni metro, signaled grade separated light rail lines are rarely provided with the minimum headway capabilities represented by the capacity ranges in Figure S.11 and Figure S.12.

Outside New York and Mexico City the heaviest rail rapid transit lines are Toronto's Yonge subway with 26,900 passengers per peak-hour direction, Montreal's Orange line with 24,400, followed by WMATA with 15,300 and BART with 14,900.

With the exception of New York and Mexico City, none of the existing rail rapid transit trunks are close to the maximum achievable capacity range with conventional train control of 34,000 to 40,000 as shown in Figure S.11.

The story with light rail is similar. The busiest trunks appear to be Boston's Green Line subway with the Massachusetts Bay Transportation Authority (MBTA) giving a rough estimate of 10,000 passengers per peak-hour direction. San Francisco's Market Street subway is estimated to be carrying 7,000 to 8,000, with the third busiest trunk in Philadelphia handling 4,100 in the peak hour. These usage figures are well below the maximum achievable capacity range for light rail of 19,000 to 21,000 from Figure S.12.

The heaviest commuter rail ridership is on the LIRR into Manhattan with 41,500 passengers per peak-hour direction, followed by Metro North into Grand Central with 36,000 and the C&NW in Chicago with 22,300—all multiple-rack trunks which exceed all but the four busiest rail rapid transit lines on the continent, three of which are in Mexico City.

All line and trunk ridership data are tabulated in Appendix Three (A3) and summarized in Table S.7.

The achievable capacity data developed in this report are a measure of the supply of service given an adequate supply of rolling stock, staff and operating funds. There are few urban corridors in North America where demand requires this maximum achievable capacity.

Table S.7 Peak-hour ridership summary 1993

	Maximum	Minimum	Average
CR lines	41,480	103	4,374
LRT lines	4,950	268	1,390
RT lines	29,175	1,200	10,626
CR trunks	41,480	601	11,373
LRT trunks	10,000	477	3,469
RT trunks	49,829	2,331	16,020

S11 INCREASING CAPACITY

Where higher capacity is required there are the obvious steps of running longer trains and increasing loading levels. However, the commonly operated rail rapid transit train length of 180 m (600 ft) is regarded as close to a practical maximum, and increasing loading levels is contrary to the need to make rail transit more attractive with higher quality service.

The two most appropriate ways to increase achievable capacity are through advanced train control systems and shorter station dwells. Processor-based train control systems have now gained acceptance and will become standard in the future. They offer a 20 to 30% increase in throughput and the possibility, through sophisticated automatic train supervision components, of better service regulation. They also make more efficient operation possible. Driverless operation has accumulated 10 years of safe experience in Vancouver and Miami and 30 years on some automated guideway transit systems. Acceptance elsewhere is slow but the advantages are considerable, not only in operating economies but in the ability to operate shorter trains more frequently throughout the service day — a feature highly appreciated by users and a contributor to ridership growth. Potentially some of these economies can be translated into less crowded conditions for future generations of passengers.

Capacity can be maximized by avoiding junctions near heavy stations and ensuring that terminal and turn-back locations do not have constraints—providing multiple platforms when necessary.

Inefficient use of station dwell time is common on several North American systems. Improvements not only have the potential to increase capacity in the order of 5 to 20% — with the existing number of cars—but also to reduce costs, reduce travel times and attract more passengers.

This is an area suggested for future research in the next chapter. While much of the dwell time relates to operating practices, improvements in signage, platform markings and interior car design can all contribute to shorter dwells.

S12 ECONOMIC ISSUES

This project has not dealt with economic issues where limitations in the size of the car fleet or the operating budget restrict the number of trains operated. While this is one possible topic for future research, it is relatively straightforward to estimate the capacity given a set number of trains.

The throughput in trains per hour can be estimated by determining the round-trip time plus layover time and any terminal operating margin in minutes and dividing this into 60. The result is then multiplied in turn by the number of trains for throughput in trains by hour. Multiplying again by the passenger loading on a train (see Chapter Five, *Passenger Loading Levels,* or Figures S.6 and S.7) gives a maximum hourly capacity. Multiplying this again by the loading diversity factor, 0.6, is recommended for commuter rail with an increase to 0.9 possible, by 0.8 for rail rapid transit, and by 0.75 for light rail to produce an achievable capacity in passengers per peak-hour direction per track.

S13 CONCLUSIONS

The study has achieved its goals of surveying the North American rail transit industry and providing a complete range of information to determine the maximum achievable capacity of each mode.

The principal methodology can be found on an easy-to-use but comprehensive computer spreadsheet. Although few new rail transit lines will be concerned with the upper range of achievable capacity, the methods are applicable to existing systems and allow an examination of the impact of many variables on capacity.

This approach is particularly valuable in analyzing the impact of single high-use stations. The changes in capacity—and so the cost to provide that capacity—can be compared by examining alternates such as double-faced platforms or spreading the load between two closely spaced stations.

The results of this project show maximum achievable capacities, based on reasonable loading levels, that are more conservative than earlier work in this field. As demands for improved standards grow, loading levels will likely decrease and the achievable capacity shown in this study will not only be appropriate but may have to be further reduced.

Computer Disk

A 1.44 MB, 3.5" IBM-formatted high-density disk is available on request, containing spreadsheet and database files from the project. The spreadsheet files are designed to allow users to input basic system parameters from which the maximum achievable capacity will be calculated and presented as a single estimate in passengers per peak-hour direction. Suggested default parameters are provided for all entry areas.

Apple Macintosh users with compatible programs should be able to read and use some of these files using their Apple File Exchange program. Transport Consulting Limited regrets that it cannot provide the disk or files in formats other than those described below.

THE DISK IS NOT REQUIRED TO CALCULATE CAPACITY. BOTH THE SIMPLE AND MORE COMPREHENSIVE METHODS DOCUMENTED IN THIS REPORT CAN BE CARRIED OUT USING EITHER MANUAL OR COMPUTER TECHNIQUES.[3]

The disk contains the following capacity calculation files which are also available to download from the Internet at APTA's dissemination site on the World Wide Web: http://www.apta.com/tcrp

A8 DATA DISK	FILE NAME
Rail Capacity (Excel)	RAILCAP.XLS
Rail Capacity (Generic)	RAILCAP.WK1
LRT Single Track Time (Excel)	LRSINGLE.XLS
LRT Single TT (Generic)	LRSINGLE.WK1

All project spreadsheet work has been carried out in Microsoft Excel 5.0 for Windows. The generic Lotus 1-2-3, and Quattro Pro files are suitable for either the DOS or Windows version of these programs. However they do not contain the charts, equations, color and user-friendly formatting of the Excel version, nor the component that estimates dwell from hourly station passenger volumes. This latter process, described in Chapter Four, *Station Dwells,* would not translate to a generic version. Use of the Excel version is recommended whenever possible.

USING THE SPREADSHEETS Instructions, together with a printout of sections of the capacity spreadsheet are contained in the next section—*User Guide.*

ADDITIONAL DATA FILES The project's database file is included as TCRPA-8.MDB, and a selection of the field data collection as a spreadsheet, A8DATASS.EXE.

TCRPA-8.MDB is in Microsoft Access®$^{(TM)}$ 2.0 format. Note that this format cannot be read by Access version 1.0 or 1.1. The file A8DATASS.EXE, when executed, expands to the spreadsheet field data file A8DATASS.XLS in Microsoft Excel 5.0 format. TCL regrets that disk space prevents including other formats. Both files require their respective programs running under Microsoft Windows®$^{(TM)}$ and should be possible to import into other database or spreadsheet programs.

CAUTION Reasonable care has been taken in obtaining and transcribing data. However the data is from various sources and for different years—1992 through 1995. The accuracy of the originating agency's data cannot be verified. In particular ridership data may only be accurate within ± 10%. The capacity calculation spreadsheets are intended to assist in the estimation of capacity under a variety of normal conditions. Not all variables or system specific conditions can be accounted for. Consequently Transport Consulting Limited can provide no assurance or warrantee of the suitability or accuracy of these programs for any

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[3] The process that estimates dwell from hourly station passenger volumes calculations has compound logarithmic functions and should only be attempted by experienced spreadsheet users.

specific purpose. The disks by request have been checked to be free from common known viruses. No such assurances can be given for copies of the programs obtained from other sources.

LIMITATION of LIABILITY In no event will Transport Consulting Limited, the Federal Transit Administration, the Transit Cooperative Research Program, the Transportation Research Board, or the National Research Council be liable for direct, indirect, special, incidental or consequential damages arising out of the use or inability to use these computer files and their documentation, even if advised of the possibility of such damages.

ORDERING The disk is available on request to
American Public Transit Association
c/o TCRP Dissemination
1201 New York Ave., N.W.
Washington, D.C. 20005
FAX (202) 898-4019
e-mail: tcrp@apta.com
Include name and mailing address on request.

Internet
The spreadsheets can be downloaded from APTA's TCRP Dissemination site on the World Wide Web.
http://www.apta.com/tcrp

CORRECTIONS Transport Consulting Limited would appreciate notification of any errors or problems with the disk and will make reasonable attempts to prepare a corrected version. e-mail Tom_Parkinson@mindlink.bc.ca.

The contractor regrets that it otherwise cannot enter into correspondence regarding use of, or problems with, the programs on the disk, or the conversion for use in other programs or with other operating systems.

The spreadsheet files will operate reasonably on any IBM compatible computer with a 386 or higher CPU running Windows and 4MB of RAM. Microsoft Access 2 requires a minimum of 6MB of RAM to run reasonably. When expanded, the total files require less than 3 MB of hard disk space.

User Guide

THE REPORT

The basics of rail transit capacity are straightforward. The hourly throughput of trains is determined, multiplied by the number of passengers per train, then adjusted by a loading diversity factor that compensates for the fact that trains are not evenly loaded over a peak hour.

However there are many nuances to these basics that can become complex resulting in this report having several sections with complicated mathematics. For ease of use, capacity calculation methods are divided into two: a simple method and a complete method. Spreadsheets are available on request to perform the math for the complete method. This user guide provides assistance in obtaining an understanding of rail transit capacity and performing either the simple or complete calculations.

STARTING OUT

The preceding summary, this user guide, and the first two chapters—Chapter One, *Rail Transit In North America* and Chapter Two, *Capacity Basics*—should be read by all users. Readers wanting to use the simple method of capacity estimation can use the preceding summary section or jump to the beginning of the appropriate application chapter. Chapter Seven, *Grade Separated Rail Capacity Determination* covers the majority of North American rail transit —fully segregated, signaled, double track right-of-way, operated by electrically propelled multiple-unit trains; Chapter Eight, *Light Rail Capacity Determination* for light rail; Chapter Nine, *Commuter Rail Capacity Determination* for commuter rail and Chapter Ten, *AGT Capacity Determination* for automated guideway transit.

More details of capacity nuances and methodology development can be consulted as needed in Chapter Three, *Train Control and Signaling;* Chapter Four, *Station Dwells;* Chapter Five, *Passenger Loading Levels* and Chapter Six, *Operating Issues.* To avoid the details on train control systems and the more complex mathematics, start Chapter Three at section 3.6.4 and in Chapter Five omit section 5.5.

These last two chapters are also of value to the general reader as they deal with factors that can greatly effect capacity. Loading levels can make a greater than three to one difference between policies that provide a seat for most passengers to ones that allow high levels of standing. Operations and reliability go hand in hand and there can be almost a 50% difference in capacity between a system incorporating a substantial operating margin to achieve good reliability and one where the need for capacity reduces the operating margin almost to nothing.

THE SPREADSHEET

Whether you can use the spreadsheet or not, this section provides a step-by-step guide to capacity calculation and should be read by all users. This section is abstracted from the Excel version of the spreadsheet but, like the generic version of the spreadsheet, necessarily omits the user-friendly color coding and the embedded charts and equations, instead referring to specific sections of the report. If you can run Excel do so and omit this section. The Excel spreadsheet is self-explanatory. It is based on TCRP Report A-8 and is applicable to all grade separated electric multiple-unit rail transit with level loading.

CAUTION This capacity calculation spreadsheet is intended to assist in the estimation of rail transit capacity under a variety of normal conditions. Not all variables or system specific conditions can be accounted for. Consequently Transport Con Consulting Ltd can provide no assurance or warrantee of the suitability or accuracy of these programs for any specific purpose.

LIMITATION of LIABILITY In no event will Transport Consulting Ltd., the Federal Transit Administration, the Transit Cooperative Research Program, the Transportation Research Board or the National Research Council be liable for direct, indirect, special, incidental or consequential damages arising out of the use or inability to use these computer files and documentation, even if advised of the possibility of such damages.

THE SPREADSHEET IS NOT INTENDED TO STAND ALONE AND SHOULD BE USED ONLY IN CONJUNCTION WITH THE REPORT AND THE EXAMPLES AND EXPLANATIONS THEREIN

CONVERSION Do not import the Excel 5.0 file into another spreadsheet. Certain functions do not translate. Instead use the generic version of the spreadsheet RAILCAP.WK1 specifically converted for DOS or windows versions of Lotus 1-2-3, Quattro Pro, or other spreadsheets. When opening the file always check to ensure correct values are obtained by comparing the results in the default column with the adjacent entry column. Excel users must install the solver add-in.

SIMPLE ACHIEVABLE CAPACITY ESTIMATION The report contains simple methods to estimate achievable capacity of rail transit that does not require use of the spreadsheet. Refer to Figures S.11 and S.12 in the report, also reproduced on line 390 of the Excel spreadsheet. This is the preferred method rather than using this spreadsheet with default values. It provides faster results and a reasonable range of values with less chance of error.

COMPLETE METHOD OF CAPACITY ESTIMATION Achievable capacity is the maximum number of passengers that can be carried in an hour, in one direction, on a single rail transit track, allowing for the diversity of demand. There is no precise value. The density of passengers on a car—the loading level—can vary from system to system by up to a factor of three. Similarly an allowance for irregularities, the operating margin, can range widely depending on priorities—maximum capacity or the most reliable operation. Values for the loading level and operating margin are inputs into this methodology. The default values can be used but reference to the report is recommended to select an appropriate value for each specific system.

The best method to estimate capacity is with a complete system simulation involving models of the signaling system, power supply system and train performance. The following methodology involves simplifications and approximations. Correctly applied with reasonable input values, it should estimate capacity within ±10%. Incorrectly used it can produce erroneous values.

ALWAYS CHECK THE RESULTS WITH THE RANGES IN THE REPORT, AND FIGURES S.11 AND S.12, TO ENSURE THEY ARE REASONABLE. IF IN DOUBT USE THE RANGES FROM THE REPORT.

step 1 DETERMINING THE WEAK LINK

Rail transit capacity is set by the weakest link or bottle-neck on a system. This may be at a flat junction or at the terminal turnback. Such constraints should not be tolerated on a new system. Where they may exist on an existing system, Chapter Seven of the report shows methods to calculate such headway restrictions and in turn, the achievable capacity. By far the most common bottle-neck is the time for one train to replace another at the busiest—maximum load point—station.

On light rail systems a possible weak link is any single-track section over 400 to 600 m long. A separate spreadsheet LRSINGLE.XLS or WK1 contains the equation to calculate the headway restrictions due to single track. Light rail may also be limited by on-street operation or by grade crossings, as discussed in Chapter Eight. However the most common limitation is that of any signaled section. The methodology of Chapter Three (step 2) can be used for light rail when the signaling is designed for maximum throughput. Otherwise, the design headway of the system should be used.

If you are sure that the weak link is the time for one train to replace another at the busiest station, then proceed to the next step that is applicable to rail rapid transit (heavy rail), light rail with segregated right-of-way signaled for maximum throughput, all automated guideway transit with on-line stations and commuter rail with electric multiple-unit equipment using rapid transit type signaling. For other capacity determination refer to the report.

step 2 CALCULATING SIGNALING SYSTEM THROUGHPUT AT THE PEAK-POINT STATION

The minimum train separation includes any safety distances or times, the time to brake into a station and to accelerate out until the platform is clear for the next train to enter. Refer to Equation 3-15, the station minimum headway formula, for conventional signaling.

The spreadsheet applies this equation for conventional three aspect, cab control and moving-block signaling. Insert your system and train values in the blue column[4] or use the defaults (red column). The results are shown in the yellow cells.

RESULTS

Three aspect	Cab control	Moving block		
57	51	32	H(s)	seconds
43	52	55	V_a	km/h

where **H(s)** = Station minimum train separation without dwell or operating margin, and

$\mathbf{v_a}$= Optimum approach speed to maximum load point station

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[4] The spreadsheet BLUE for *values* is shown as a light tone, RED, *default* values as a dark tone, YELLOW for *results* as a heavy border.

Spreadsheet (part) RAILCAP.XLS showing default data

VALUE	DEFAULT	TERM	SI	DESCRIPTION
200	200	L	metres	length of the longest train
10	10	D	metres	distance— train front to exit block
75	75	K	constant	% service braking rate
2.4	2.4	B 3 aspect sig		train detection uncertainty constant
1.2	1.2	B cab control sig.		train detection uncertainty constant
1	1	B moving block sig.		train detection uncertainty constant
3	3	t_{os}	seconds	overspeed governor operating time
0.5	0.5	t_{jl}	seconds	time lost to braking jerk limitation
1.3	1.3	a_s	m/s²	service acceleration rate
1.3	1.3	d_s	m/s²	service deceleration rate
1.5	1.5	t_{br}	seconds	brake system reaction time
100	100	v_{max}	km/h	maximum line velocity
6.25	6.25	P_e	metres	Positioning error (mov. block only)
100	100	v_l	%	% of normal line voltage
0.0	0	G	%	Grade into headway critical station

If your system is not designed for minimum train separation insert the value of H(s) obtained from a simulation or specification in the above results box and transfer to Step 7.

NOW check that there are no speed restrictions on the maximum load point station approach that would prohibit a train operating at the optimal approach speed v_a in the above results boxes. Refer to Figure 3.5 which shows the distance a train would be from the station platform stopping point at the respective speeds. If there are no speed restrictions (due to curves or switches or safety speed limits) then proceed to the next step.

IF there are speed restrictions within this distance then manually type in the restriction in the respective result boxes above in kilometers per hour. The station minimum train separation in the cell above will automatically increase from the calculated level.

step 3

ESTIMATING OR CALCULATING THE DWELL TIME

Refer to Chapter Four, *Station Dwells*, for a detailed discussion. Dwells cannot be determined precisely. You have two choices.
1) Select a reasonable value from the table below.

Peak-period dwells for heavily used systems

System	Location	Total Pass	Time/Date 1995	Mean Dwell	Mean 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
TTC	King	1602	am Feb. 6	27.5	129.5
TTC	Bloor	4907	pm Feb. 7	44.0	135.0

This table lists mean dwells at the maximum load point station of several systems. Your choice should be from 30 to 60 sec. The high value would be for a rail rapid transit system with heavy mixed flows, the lower value for uni-directional flows under optimal conditions. A default of 45 sec is recommended where a specific value is not self evident.

2) Use the methodology of Chapter Four to estimate a dwell based on the hourly flow, by direction, at the maximum load point station. This methodology is calculated in the Excel spreadsheet but omitted from the generic spreadsheet.

step 4

OPERATING MARGIN SELECTION

Refer to Chapter Six, *Operating Issues,* for a detailed discussion. An operating margin is essential for regular running. If the minimum headway consisted only of the minimum train control separation plus the maximum dwell, any minor incident, delay or extended dwell would result in interference between trains.

The more operating margin that is allowed then the lower the line capacity and the greater the probability of even performance. Determining an operating margin requires a balancing act between these two desires. The table below (Table 4.17 in the report) offers guidance based on the project's field survey. For maximum capacity, a range of 15 to 25 sec is recommended. A default value of 20 sec is used in the spreadsheet. If your priorities are to avoid irregular running at the expense of maximum passenger capacity then a higher operating margin could be appropriate.

Alternately from this table you can select a controlling dwell consisting of the mean dwell plus two standard deviations and omit or minimize any operating margin. One approach is to use the higher of this or dwell plus operating margin.

Controlling dwell examples (seconds)

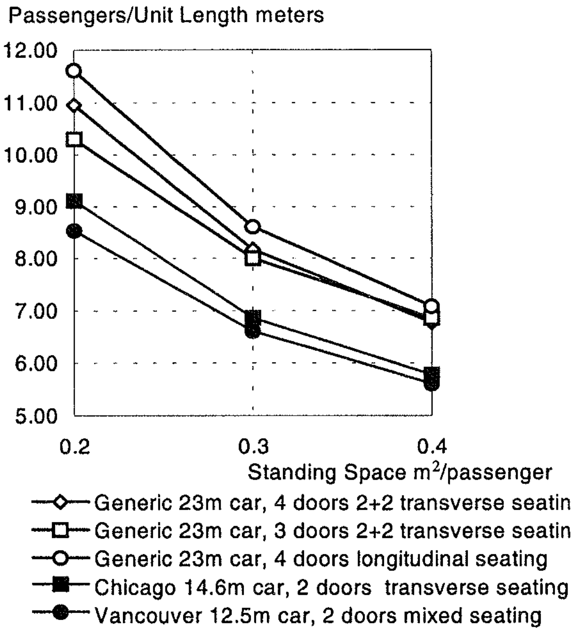
System	mean	SD	n	m+SD		Operational	
	secs	secs	no. of samples	upper limit ONE SD	TWO SD	Margin +15 sec	+25 sec
BART	46.3	12.0	290	58.3	70.2	61.3	71.3
CTS	35.7	15.7	91	51.5	67.0	50.7	60.7
ETS	24.7	8.8	18	33.6	42.3	39.7	49.7
NYCT	30.7	20.9	380	51.6	72.6	45.7	55.7
PATH	51.3	23.0	252	64.3	97.3	66.3	76.3
Portland	32.0	19.4	118	51.4	70.8	47.0	57.0
S. Diego	51.1	17.9	34	69.1	86.8	66.1	76.1
MUNI	50.4	21.8	75	72.2	93.9	65.4	75.4
TTC	36.6	23.2	322	59.8	83.0	51.6	61.6
Vanc'ver	30.7	7.2	82	37.9	45.1	45.7	55.7

step 5 SELECTING THE LOADING LEVEL

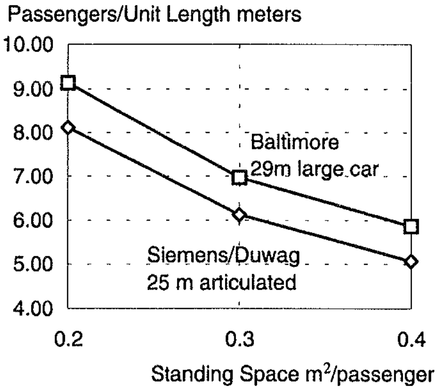
Refer to Chapter Five, *Passenger Loading Levels,* for a detailed discussion. Levels vary widely across North America from the loaded conditions on certain New York trunks and on Mexico City meter lines to the more relaxed levels that provide almost a seat for every passenger. In fact, a seat for every passenger is the common standard on all commuter rail lines.

There are two approaches. 1) Select a loading level, in passengers per meter of car or train length, from the heavy rail figure below (Figure 7.3 in the report), 7.0 passengers per meter of train length is recommended, or from the figure for articulated light rail below (Figure 7.4 in the report), 6.0 passengers per meter of train length is recommended.

2) Calculate the capacity of a specific car by entering the dimensions, the type of seating and the standing density in Equation 5-2. This calculation is contained in the spreadsheets.



Linear passenger loading of heavy rail cars



Linear passenger loading of articulated light rail cars

step 6 SELECTING THE LOADING DIVERSITY FACTOR

Refer to Chapter Five, *Passenger Loading Levels,* and Chapter Seven, *Grade Separated Rail Capacity Determination,* for detailed discussion. The next step is to select a loading diversity factor based on the rail mode and the type of system. Consult the table below (Table 5.14) for actual diversity factors of various systems. Unless there is sufficient similarity with an existing operation to use a 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.

Diversity of peak hour and peak 15 minutes[5]

Type	System	Routes	Diversity factor
CR	CalTrain	1	0.64
CR	GO Transit	7	0.49
CR	LIRR	13	0.56
CR	MARC	3	0.60
CR	MBTA	9	0.53
CR	Metra	11	0.63
CR	Metro-North	4	0.75
CR	NICTD	1	0.46
CR	NJT	9	0.57
CR	SCRRA	5	0.44
CR	SEPTA	7	0.57
CR	STCUM	2	0.71
CR	Tri-Rail	1	0.25[6]
CR	VRE	2	0.35
CR	**Sum/Average**	**74**	**0.56**
LRT	CTS	2	0.62
LRT	Denv. RTD	1	0.75
LRT	SEPTA	8	0.75
LRT	Tri-Met	1	0.80
LRT	**Sum/Average**	**12**	**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
RT	PATH	4	0.79
RT	STCUM	4	0.71
RT	TTC	3	0.79
RT	**Sum/Average**	**46**	**0.79**
All	**Sum/Average**	**133**	**0.67**

[5] This peak hour diversity factor is the same as the peak-hour factor (phf) in the *Highway Capacity Manual*(R47)

[6] Service is only one train per hour and is not included in the average.

step 7

THE FINAL STEP— CALCULATING THE ACHIEVABLE CAPACITY OF A RAIL RAPID TRANSIT SYSTEM ON SEGREGATED TRACK WITH TRAINS OPERATING AT THE CLOSEST SPACING PERMITTED BY THE SIGNALING

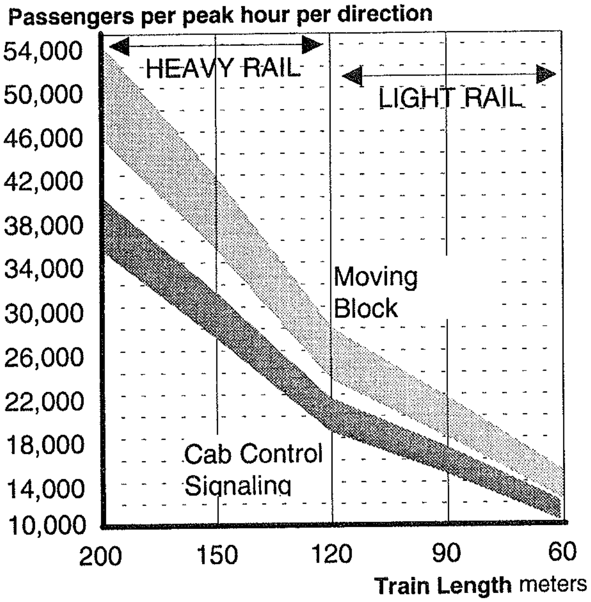
In this final step, the results of the preceding steps are brought together and multiplied to produce the estimated achievable capacity of the system.

Total headway is the sum of the signaling minimum headway plus dwell time and operating margin or dwell time plus two standard deviations. Dividing this sum into 3600 produces the number of trains per hour, which must then be multiplied by the passengers per meter, the train length and the loading diversity factor to produced the achievable capacity in passengers per peak-hour direction per track.

Data from preceding steps (default values shown)

FROM	3 aspect	cab-control	moving block	Type of train control system
Step 2	57	51	32	Signaling minimum headway
Step 3	32	32	32	Dwell Time seconds
Step 4	20	20	20	Operating Margin seconds
	110	103	85	TOTAL HEADWAY seconds
	32.9	34.8	42.5	TRAINS PER HOUR
Step 5	5.8	5.8	5.8	Passenger per metre
Step 6	0.8	0.8	0.8	Loading Diversity
Step 2	200	200	200	Train Length metres
	30,700	32,500	39,600	ACHIEVABLE CAPACITY in passengers per peak hour direction per track

ALWAYS CHECKTHAT THE FINAL RESULT IS REALISTIC BY REFERRING TO THE FOLLOWING FIGURE. IF THE RESULTS ARE ABOVE THESE LEVELS THEN YOU HAVE EITHER SELECTED UNREALISTIC INPUT DATA OR MADE AN ERROR. IF IN DOUBT USE THE DEFAULT VALUES FROM FIGURES S.11 AND S.12.



Typical maximum passenger capacities of grade-separated rail transit — exlcuding all-seated commuter rail.

CAUTION Light rail signaling is rarely designed for minimum headway. No light rail line in the United States and Canada carries more than 10,000 passengers per peak-hour direction.

1. Rail Transit in North America

1.1 INTRODUCTION

Rail transit plays a significant role in moving people in North American cities. In U.S. urbanized areas exceeding 200,000 in population, 35% of all transit trips in 1993 took place on one of the four rail modes with rail rapid transit alone accounting for 28% of these trips.

The four rail modes consist of Automated Guideway Transit (AGT), Commuter Rail (CR), Light Rail Transit (LRT) and Rail Rapid Transit (RT), often called Heavy Rail. Table 1.1 and Figures 1.1 and 1.2 give a condensed look at some of the key North American statistics for each mode.

Table 1.1 Comparison of key modal statistics

Type	Routes	Average Line Length (km)	Total Length (km)	Average Station Spacing (km)	Average Line Speed (km/h)
AGT	3	6.3	19.0	0.70	24.3
CR	77	73.7	5672.1	5.71	52.7
LRT	51	13.9	708.5	0.83	22.1
RT	76	25.3	1868.6	1.47	36.2

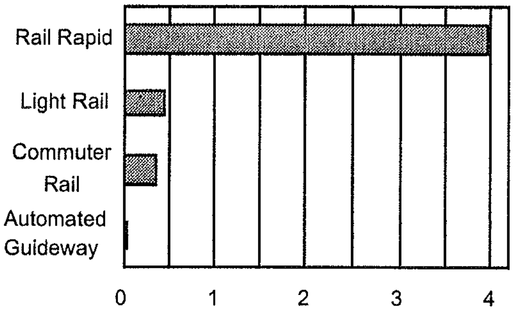


Figure 1.1 Rail transit annual passenger trips by mode (billions, Fiscal Year 1993)

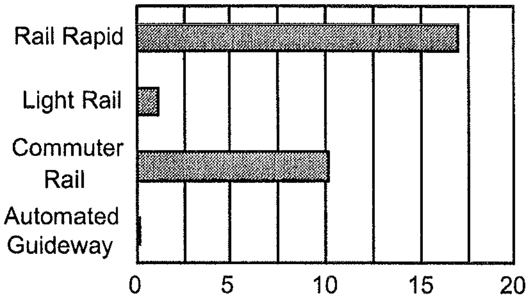


Figure 1.2 Rail transit annual passenger-kilometers by mode (billions, Fiscal Year 1993)

1.2 LIGHT RAIL TRANSIT

1.2.1 INTRODUCTION

Light rail transit (LRT) started as a modification of streetcar operation to allow higher speeds by separating it from street traffic. LRT is characterized by its versatility of operation as it can operate separated from other traffic below grade, at-grade, on an elevated structure, or together with road vehicles on the surface. Service can be operated with single-car or multiple-car trains. Electric traction power is taken from an overhead wire, thus eliminating the restrictions imposed by having a live third-rail at ground level. (An exception is Southeastern Pennsylvania Transportation Authority's [SEPTA] grade-separated Norristown high-speed line which uses third-rail current collection.) This flexibility helps to keep construction costs moderate and explains the popularity this mode has experienced since 1978 when the first of 14 new North American light rail transit systems was opened in Edmonton, Alberta.

These newer light rail transit systems have adopted a much higher level of segregation from other traffic than earlier systems enjoyed. Boston opened a downtown streetcar subway in 1897 with Philadelphia and Newark following later. New Jersey Transit's (NJT) Newark City Subway, opened in 1935, also benefits from extensive surface private right-of-way. Segregation from motor traffic permits higher speeds, greater schedule reliability and improved safety. Modern signal pre-emption and progression methods have also made on-street operation faster and more reliable.

Passenger loading can be accomplished at street level with steps on the cars, or at car floor level with high-level platforms. The lines in Calgary, Edmonton, Los Angeles and St. Louis operate entirely with high-platform access. The San Francisco Municipal Railway uses moveable steps on its cars to allow them to use both high-platform stations and simple street stops. Pittsburgh takes a different approach and has two sets of doors on its light rail vehicles, one for high platforms the other for low-level loading. Most other systems use low-level loading with steps. Low-floor cars, already popular in Europe, have been ordered for Portland and Boston to provide floor-level loading without the need for steps or high platforms. Wheelchair access also benefits because lifts are not required with low-floor cars.

1.2.2 STATUS

There are currently 23 light rail transit systems in operation in North America (Table 1.2). This total includes the traditional streetcar lines in Toronto and New Orleans. Lines that are primarily operated for heritage and tourist purposes, such as those in Memphis and Seattle, are not included in this study.

The recent popularity of light rail transit is apparent in that 12 of the surveyed light rail systems have opened since 1980.

Older streetcar systems in Boston and Philadelphia survived the widespread replacement of streetcars with buses following the two world wars thanks to city center tunnels that gave them rapid access to downtown. San Francisco's streetcars benefited from two tunnels that provide strategic routes under major hills in that city. Pittsburgh's streetcars survived for similar reasons. These older systems have been modernized with new cars, and, in the cases of Pittsburgh and San Francisco, with tunnels penetrating the downtowns of their respective cities.

Toronto is the last city to operate a largely conventional streetcar network. Toronto's streetcars must share most their routes with vehicular traffic, a condition which leads to relatively low speed service. Many of the other older streetcar systems with light rail characteristics must also operate with general traffic on substantial portions of their routes. Such is the case in San Francisco and Philadelphia where tunnels bypass downtown traffic congestion and surface in outlying areas.

1.2.3 RIDERSHIP

Ridership information collected by light rail transit systems is not as comprehensive as for the other modes with many systems only reporting the total number of passengers carried on an average weekday. Peak-hour and peak-15-min flows were obtained for a number of systems but this important data was not available for some of the major light rail transit systems. As a result, average weekday ridership for major routes is shown in Figure 1.3 with the available peak flows shown in Figure 1.4. Data for the TTC's traditional streetcar lines are not included but may be found in Appendix (A3). Few light rail lines operate near capacity, with the exception of the trunk portions of San Francisco's Muni Metro and Boston's Green Line.

Table 1.2 North American light rail transit systems

Abbreviation	System Name
Bi-State	Bi-State Development Agency (St. Louis)
CTS	Calgary Transit
Denv. RTD	Denver Regional Transportation District
ETS	Edmonton Transit
GCRTA	Greater Cleveland RTA
LACMTA	Los Angeles County MTA
MBTA	Massachusetts Bay Transportation Authority
Metrorrey	Metrorrey (Monterrey, Mexico)
MTA	Mass Transit Administration of Maryland
NFTA	Niagara Frontier TA (Buffalo)
NJT	New Jersey Transit Corporation
PAT	Port Authority of Allegheny County (Pittsburgh)
RTA - N.O.	Regional Transit Authority - New Orleans[1]
SCCTA	Santa Clara County Transportation Authority
SDT	San Diego Trolley Inc.
SDTEO	Sistema del Tren Electrica Urbana (Guadalajara, Mexico)
SEPTA	Southeastern Pennsylvania Transportation Authority (Philadelphia)
SF Muni	San Francisco Municipal Railway
SRTD	Sacramento Regional Transit District
STC	Sistema de Transporte Colectiva (Mexico City)
STE	Servicio de Transportes Eléctricos del DF (Mexico City)
Tri-Met	Tri-County Metropolitan Transportation District of Oregon (Portland)
TTC	Toronto Transit Commission[2]

[1] Historic, conventional street car line.

[2] Conventional streetcar network with little segregation of tracks.

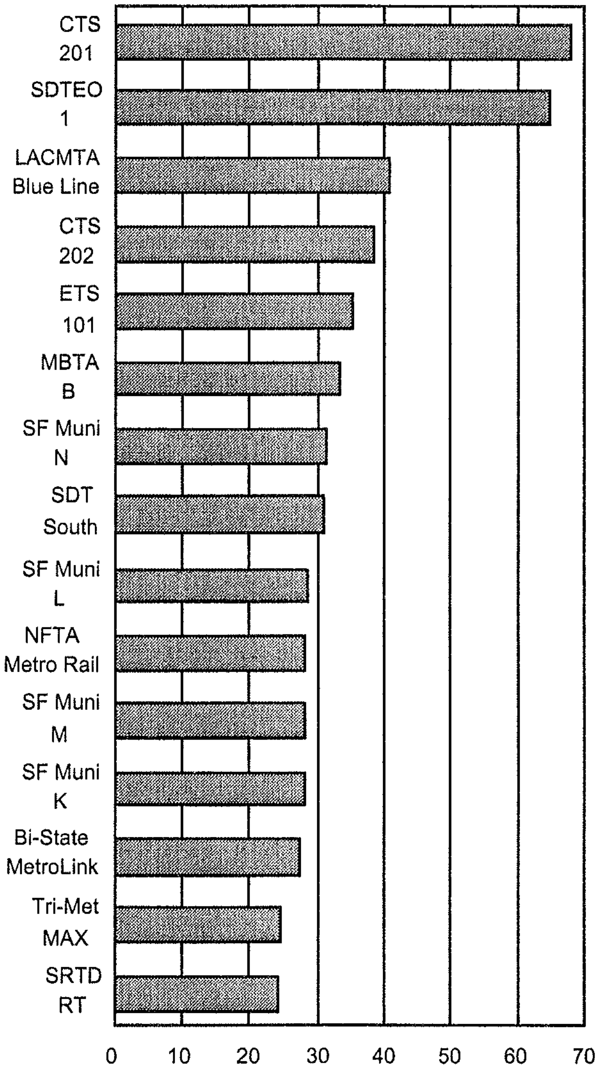


Figure 1.3 Weekday ridership for the 15 busiest North American LRT lines (thousands, Fiscal 1993)

It is worth noting that the first and fourth busiest light rail transit lines in North America, Calgary Transit's South (201) and Northeast (202) lines, operate mostly at-grade; downtown operation is on a transit mall shared with buses.

1.3 RAIL RAPID TRANSIT

1.3.1 INTRODUCTION

Rail rapid transit (heavy rail) is by far the predominant urban rail travel mode in North America. Systems are listed in Table

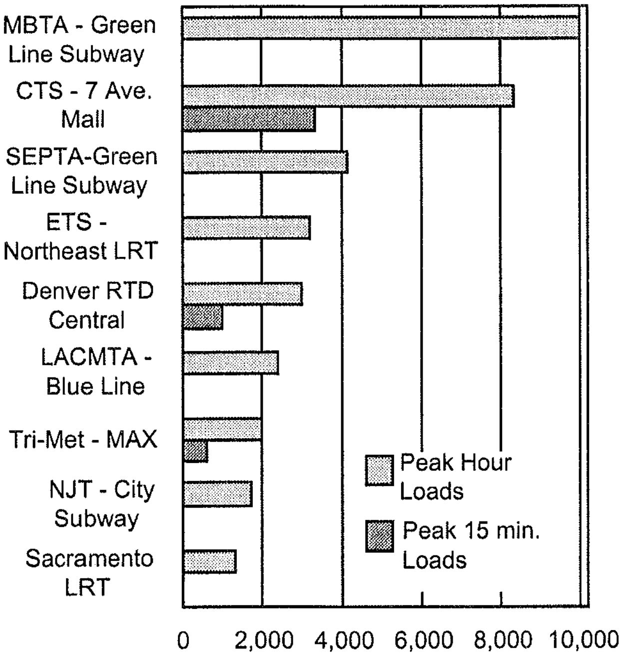


Figure 1.4 Peak-hour and peak-15-min directional flows for light rail transit trunks (passengers per hour per direction, Fiscal 1993)[3]

1.3. Figures 1.1 and 1.2 illustrate the lead rail rapid transit has over the other rail modes in both annual passenger trips and annual passenger kilometers. Rail rapid transit is characterized by fully grade-separated rights-of-way, high-level platforms and high-performance, electric multiple-unit (EMU) cars.

The expeditious handling of passengers is enabled through the use of long trains of up to 11 cars running a frequent service. Loading and unloading of passengers at stations is rapid due to level access and multiple double-stream doors.

Power is generally collected from a third-rail but can also be received from overhead wires as in Cleveland, Boston's Blue Line and Chicago's SkokieSwift.[4] Third-rail power collection, frequent service and high operating speeds generally necessitate the use of grade-separated pedestrian and vehicular crossings. Grade crossings are an exceptional feature on third rail systems in Chicago and New York.

1.3.2 STATUS

A distinction can be made between the generally older systems where high passenger densities are routine and stations are spaced closely together, and newer systems that tend to place a higher value on passenger comfort and operating speed.

BART in the San Francisco Bay area is a prime example of the latter category with fast trains where most of the passengers have upholstered seats. BART station spacing outside downtown San Francisco and Oakland is wide to allow the high overall speed required to compete with the automobile. The Canadian and Mexican systems are exceptions. Despite being of relatively recent construction, they have loading and station spacing standards similar to older lines in the United States. BC Transit's SkyTrain is included in the rail rapid transit category rather than light rail or automated guideway categories. It most closely resembles rail rapid transit system in operating practices and right-of-way characteristics.

Table 1.3 North American Rail rapid transit systems

Abbreviation	System Name
BART	San Francisco Bay Area Rapid Transit Dist.
BCT	BC Transit (Vancouver, BC)
CTA	Chicago Transit Authority
GCRTA	Greater Cleveland Regional Transit Authority
LACMTA	Los Angeles County MTA
MARTA	Metropolitan Atlanta Rapid Transit Authority
MBTA	Massachusetts Bay Transportation Authority
MDTA	Metro-Dade Transit Agency (Miami)
MTA	Mass Transit Administration of Maryland
NYCT	MTA - New York City Transit
PATCO	Port Authority Transit Corp. (Philadelphia)
PATH	Port Authority Trans-Hudson Corp. (New York)
SEPTA	Southeastern Pennsylvania Transportation Authority (Philadelphia)
SIR	MTA - Staten Island Railway (New York)
STC	Sistema de Transporte Colectiva (Mexico City)
STCUM	Société de transport de la Communauté urbaine de Montréal
TTC	Toronto Transit Commission
WMATA	Washington Metropolitan Area Transit Authority

The costs of constructing fully grade-separated rights-of-way (subway or elevated) for rail rapid transit have limited new systems in recent years although extensions are being planned or built in several cities.

1.3.3 RIDERSHIP

Two of the 18 rail rapid transit systems operating in North America, the Sistema de Transporte Colectiva in Mexico City and MTA - New York City Transit, carry two-thirds of all riders using this mode. Figure 1.5 shows the dominance of these two

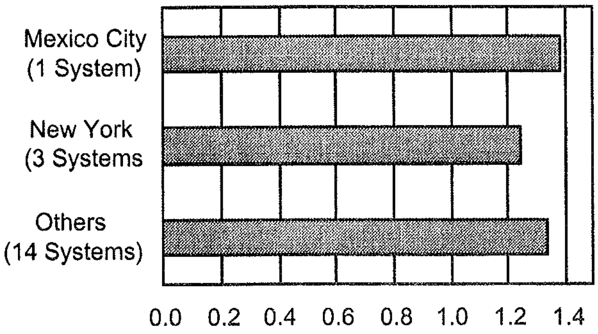


Figure 1.5 Concentration of rail rapid transit ridership (billions of annual riders, 1993 data)

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[3] 15-minute data not available for most light rail lines. MBTA Green line trunk data estimated by MBTA staff.

[4] Skokie Swift has light rail characteristics. The CTA defines it as rail rapid.

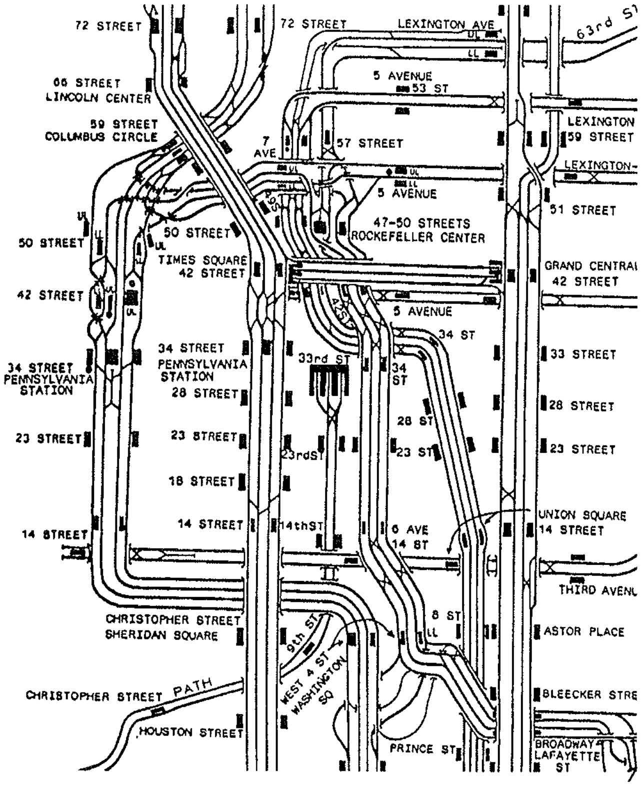

Figure 1.6 MTA-NYCT subway tracks in Midtown Manhattan[7]

regions relative to the rest of the continent.[5] Rail rapid transit's efficiency in moving large volumes of passengers in densely populated areas is evident in these, the two largest metropolitan areas in North America. Rail rapid transit plays a key role in enabling such concentrated settlements to exist. In 1992, 50.9% of business day travel into the Lower Manhattan hub was by rail rapid transit. In the 7 - 10 am time period this share increases to 62.2%.[6]

The 794-km route New York subway system is one of the largest and most complex in the world. This extensive subway system carries almost twice as many riders as does the local bus system. Most lines are triple or quadruple tracked to allow the operation of express services. A large number of junctions permit trains to be operated on a variety of combinations of line segments to provide an extensive network of service. Figure 1.6 shows the complexity of subway tracks in Midtown Manhattan.

Figure 1.7 illustrates the peak-hour and peak-15-min passenger flow rates for the 15 busiest rail rapid transit trunk lines in North America outside Mexico City.[8] The STC in Mexico City is not included because passenger crowding up to 6 passengers per m^2 — is beyond what is acceptable elsewhere in North America. For comparison, the peak hourly flow on the STC's busiest line (Line 2) is 75,300 with nine car trains every 115 sec. The graph uses trunks rather than routes in order to group those services sharing tracks together. All the trunks listed are double tracked and have at least one station used by all routes serving the trunk.

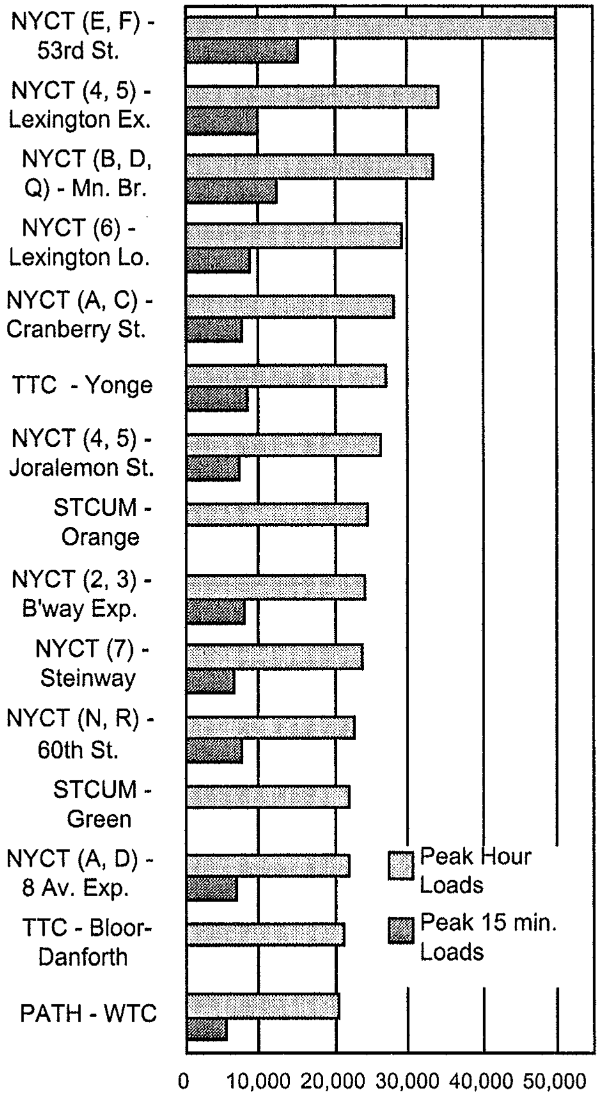

Figure 1.7 Peak-hour and peak-15-min flows for the busiest 15 North American rail rapid transit trunks[8]

When four track lines in New York are taken into consideration, the maximum load is a combination of the Lexington Avenue Express and Local at 63,200 passengers per peak-hour direction with almost comparable volumes on the combined Queens Boulevard lines at Queens Plaza. Detailed rail rapid transit ridership data can be found in the tables of Appendix Three.

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[5] The New York data used in the chart also includes the relatively small contributions of the Port Authority Trans-Hudson (PATH) and the MTA - Staten Island Railway.

[6] New York Metropolitan Transportation Council, Hub-Bound Travel 1992, December 1993.

[7] From *New York Railway Map*, courtesy John Yonge, © 1993 Quail Map Company, 31 Lincoln Road, Exeter, England

[8] Peak 15-min flow data were not available for all lines for which peak-hour data were available.

1.4 COMMUTER RAIL

1.4.1 INTRODUCTION

Commuter rail is generally a long distance transit mode using trackage that is a part of the general railroad system, some of which is used exclusively for passengers. Track may be owned by the transit system or access may be by agreement with a freight railroad. Similarly train operation may be by the transit agency, the track owner or a third-party contractor.

Service is heavily oriented toward the peak commuting hours, particularly on the smaller systems. All-day service is operated on many of the mainlines of the larger commuter rail systems and the term *regional rail* is more appropriate in these cases.

Commuter rail scheduling is often tailored to the peak travel demand rather than operating a consistent service throughout the peak period. Where track arrangements and signaling permit, operations can be complex with the use of local trains, limited stop expresses and zoned expresses. Zoned expresses are commonly used on busy lines with many stations where express trains serve a group of stations then run nonstop to the major destination station(s).

Diesel and electric power are both used for traction on commuter rail lines. Electric traction is capital intensive but permits faster acceleration while reducing noise and air pollution. It is used mainly on busy routes, particularly where stops are spaced closely together or where long tunnels are encountered. Both power sources can be used for locomotive or multiple-unit operation. All cars in a multiple-unit train can be powered or some can be unpowered *trailer* cars, which must be operated in combination with powered cars. Electric multiple-unit (EMU) cars are used extensively in the New York, Philadelphia and Chicago regions with the entire SEPTA regional rail system in Philadelphia being electrified. SEPTA and GO Transit (Toronto) are the only systems with lines routed through the center city. There are currently no diesel multiple-unit commuter trains in North America although this will change once commuter rail service begins in Dallas.

Locomotive-hauled commuter trains are standard for diesel operation and are becoming more common on electrified lines as a way to avoid the high costs of multiple-unit cars. New Jersey Transit and SEPTA have both purchased electric locomotives as an economical alternative to buying multiple-unit cars. Other systems place a high value on the flexibility of multiple-unit cars in varying train length. The STCUM in Montréal is replacing a mixed fleet of multiple-units and electric locomotives with a standard new multiple-unit design.

Commuter rail train length can be tailored to demand with cars added and removed as ridership dictates. This is particularly easy with multiple-unit equipment and can result in trains of anywhere from 2 to 12 cars in length. Where train length is constant all day, unneeded cars can be closed to passengers to reduce staffing needs and the risk of equipment damage.

Commuter rail is unique among the transit modes in that a high priority is placed on passenger comfort as journeys are long and the main source of competition is the automobile. All lines operate with the goal of a seat for every passenger except for the busy inner portions of routes where many lines funnel together and a frequent service is provided. Such is the case for the 20-min journey on the Long Island Rail Road (LIRR) between Jamaica and Penn Stations. Service between these points is very frequent (trains on this four-track corridor operate as close as 1 min apart in the peak hours) as trains from multiple branches converge at Jamaica to continue to Manhattan.

Commuter rail cars are generally designed with the maximum number of seats possible, although this tradition is changing somewhat where wheelchairs and bicycles must be accommodated. A number of common approaches are taken to achieve maximum seating over the car length. The simplest is the use of "2+3" seating where five seats are placed in each row as opposed to the usual four. This can be done quite easily in wide railroad-type cars and brings the number of seats per car to around 120. It is not especially popular with passengers. 2+3 seating is used by many operators including the LIRR and the MBTA in Boston. However, 2+3 seating places a constraint on aisle width, which may be problematical with increasing demands for wheelchair movement.

The other main approach to increasing car capacity is to add additional seating levels to the car, subject to any height restrictions, such as tunnels and underpasses, on the rail lines. The gallery type car is one example and adds an upper seating level to the car with an open well to the lower level. The well serves to permit ticket collection and inspection from the lower level but does limit the upper level to single seats on each side. Gallery cars can typically seat 150 to 160 passengers and are used most extensively by Chicago's Metra. A more recent development is the so-called bi-level car,[9] which has upper and lower levels over the center of the car with an intermediate level at each end over the trucks. Toronto's GO Transit popularized this design with relatively spacious seating for 160. It is now also being used by Metrolink in Los Angeles, the Coaster in San Diego and BC Transit's West Coast Express.

Passenger access to commuter rail trains can be from platforms at floor level or ground level with the former commonly used on busy lines or at major stations to speed passenger movements. Standard railway type "traps" in the stepwells allow cars to use both types of platform but require the train crew to raise and lower the trap door above the steps. The EMU cars used by the Northern Indiana Commuter Transportation District on the South Shore line out of Chicago and some New Jersey Transit cars employ an extra set of doors at the center of the car that are used exclusively at high platform stations, while the end doors are fitted with traps in the conventional manner for use at high- and low-platform stations. This arrangement is also being used on the new EMU cars being delivered to the STCUM for use on Montreal's Mount Royal tunnel line.

1.4.2 STATUS

Commuter rail services operate in 13 North American metropolitan regions. These include the recently started Coaster service between San Diego and Oceanside, California. There has been rapid growth in this mode as a result of the availability of government funding and the relatively low capital costs of the mode.

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[9] Less commonly known as tri-level cars as there are technically three floor levels.

Table 1.4 North American commuter rail systems

Abbreviation	System Name
CalTrain	San Mateo County Transit Dist. (San Francisco)
Coaster	North County Transit District (San Diego)
Conn. DoT	Connecticut Department of Transportation
GO Transit	GO Transit (Toronto)
LIRR	MTA - Long Island Railroad (New York)
MARC	Mass Transit Administration of Maryland
MBTA	Massachusetts Bay Transportation Authority
Metra	Metropolitan Rail (Chicago)
Metro-North	MTA - Metro-North Railroad (New York)
NICTD	Northern Indiana Commuter Transportation District.
NJT	New Jersey Transit Corporation
SCRRA	Southern California Regional Rail Authority (Metrolink)
SEPTA	Southeastern Pennsylvania Transportation Authority
STCUM	Société de transport de la Communauté urbaine de Montréal
Tri-Rail	Tri-County Commuter Rail Authority (Miami)
VRE	Virginia Railway Express

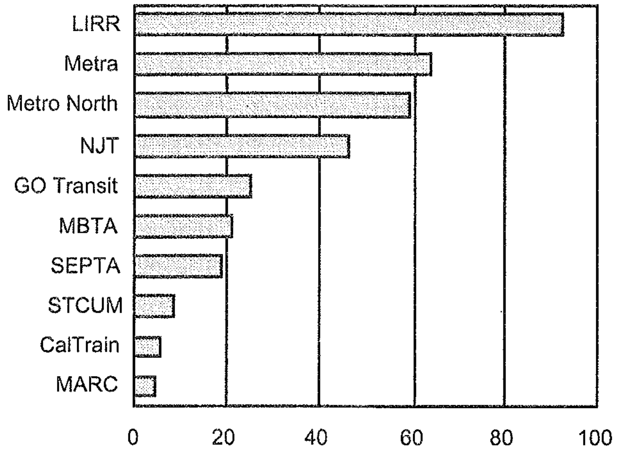

Figure 1.8 Annual ridership for the 10 busiest North American commuter rail systems (millions, Fiscal Year 1993)

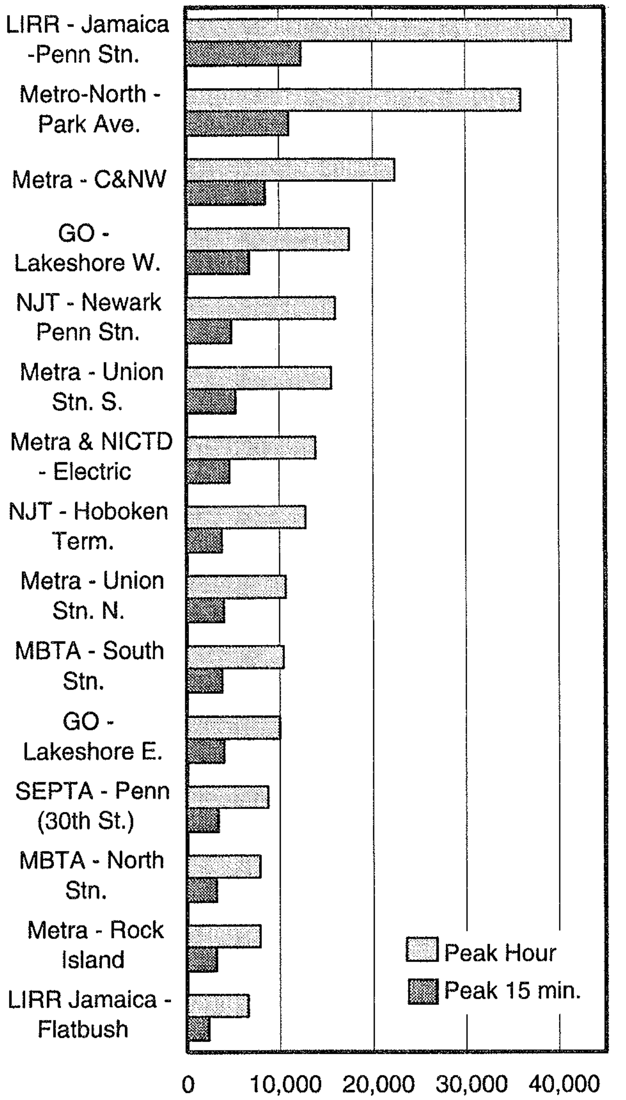

Figure 1.9 Peak-hour and peak-15-min flows for the busiest 15 commuter rail trunks [10] (Fiscal Year 1993)

Dallas's DART is expected to start commuter rail service in fall 1996.

Extensions and expansions are planned on other systems to enlarge the service area and provide additional parking for patrons. With many commuter rail lines serving low-density suburban areas, the provision of adequate customer parking is a key to maximizing ridership. To meet this need, some agencies, such as Metra, are building stations whose primary purpose is to allow parking capacity to be expanded at low cost in relatively undeveloped areas. (See Table 1.4.)

1.4.3 RIDERSHIP

Ridership is highly concentrated — New York(3) and Chicago(1) metropolitan systems are the four busiest on the continent, as shown in Figure 1.8. GO Transit in Toronto, one of the first of the new generation of commuter rail systems, ranks fifth. Boston's MBTA has had ridership double over the last decade thanks to extensive capital investment. Expansion plans should mean continued ridership growth for MBTA service in the future. Figure 1.9 shows the hourly and 15-min-peak riderships for the 15 busiest commuter rail lines in North America. Although the New York area is dominant in total commuter rail ridership, it is interesting that 10 of the 15 busiest individual routes are outside the New York area.

1.5 AUTOMATED GUIDEWAY TRANSIT

1.5.1 INTRODUCTION

Automated guideway transit (AGT) is the newest of the rail transit modes and has played a relatively minor role in North

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[10] Ridership data for SEPTA is from Regional Rail Ridership Census, 1993-94, copyright Southeastern Pennsylvania Transportation Authority, July 1994.

Table 1.5 North American automated guideway transit systems (surveyed systems)

Abbreviation	System Name
DTC	Detroit Transportation Corp.
JTA	Jacksonville Transportation Authority
MDTA	Metro-Dade Transit Agency
Morg. PRT	West Virginia University

American transit. As the name suggests, the operation of these systems is completely automated with personnel limited to a supervisory role. Inherent in the definition of this mode is the need for guideways to be fully separated from other traffic. Cars are generally small and service frequent—the name people mover is often applied to these systems, which can take on the role of horizontal elevators.

1.5.2 STATUS

Automated guideway transit systems operate in regular transit service in three U.S. cities plus the AGT system at the West Virginia University campus in Morgantown, WV. This 5-km line features off-line stations that enable close headways, down to 15 sec, and permit cars to by-pass intermediate stations. The cars are small, accommodating only 23 passengers, and are operated singly. On-demand service is possible at off-peak hours.

The transit operations surveyed (Table 1.5) include the Detroit People Mover, Miami MetroMover and the VAL line in Jacksonville, FL. The latter line, at less than a kilometer in length, is to be replaced with a more extensive automated monorail. The Detroit line has remained unchanged from opening in 1987 while the Miami MetroMover added two extensions in 1994.

The vast majority of AGT systems are, however, not operated by transit systems. Many lines serve institutions (such as the Morgantown line), airports and recreational facilities. The ridership table in the following section shows the dominance of these *nontransit* systems.

1.5.3 RIDERSHIP

Given the small number of transit agencies operating AGT, the amount of transit ridership data is limited. Even among the transit agencies, ridership data collection is limited to all-day ridership counts. Data from West Virginia University in Morgantown show their line carries 16,000 riders per day with a peak one-way hourly flow of 2,800.

Daily ridership data are shown in Table 1.6. Caution should be exercised with many of these figures as the non-transit systems are not required to provide the reporting accuracy mandated by the Federal Transit Administration (FTA). Ridership on many systems is also likely affected by seasonal patterns and less pronounced peaking than occurs on transit systems. Regardless of these qualifications, the total daily ridership on the 37 nontransit systems amounts to almost 670,000 compared to just over 40,000 on the three public AGT lines.

Table 1.6 Daily ridership for North American automated guideway transit systems (source: *Transit Pulse*[11] and database, various years, 1992-1994)

Category	Location	Ridership
Airport	Atlanta, GA	109,000
Airport	Chicago-O'Hare, IL	12,000
Airport	Cincinnati, OH	30,000
Airport	Dallas-Fort Worth, TX	50,000
Airport	Denver, CO	50,000
Airport	Houston, TX	8,500
Airport	Las Vegas, NV	15,000
Airport	Miami, FL	15,000
Airport	Orlando, FL	49,000
Airport	Pittsburgh, PA	50,000
Airport	Seattle-Tacoma, WA	43,000
Airport	Tampa, FL	71,000
Airport	Tampa-parking, FL	8,000
Institutional	Duke Univ. Hospital, NC	2,000
Institutional	Harbour Is., Tampa, FL	2,000
Institutional	Pearlridge Mall, HI	4,000
Institutional	Senate Subway, DC	10,000
Leisure	Bronx Zoo, NY	2,000
Leisure	Busch Garden, VA	6,000
Leisure	CalExpo, CA	4,000
Leisure	Carowinds, NC	7,000
Leisure	Circus-C., Las Vegas, NV	11,000
Leisure	Circus-C., Reno, NV	6,000
Leisure	Circus-Water Pk, Las Vegas, NV	2,000
Leisure	Disneyland, CA	15,000
Leisure	Disneyworld, FL	20,000
Leisure	Hersheypark, PA	8,000
Leisure	Kings Dominion, VA	5,000
Leisure	Kings Island, OH	7,000
Leisure	Lux-Excal, Las Vegas, NV	10,000
Leisure	Magic Mountain, CA	8,000
Leisure	Memphis/Mudd Is., TN	2,000
Leisure	Miami Zoo, FL	1,200
Leisure	Minnesota Zoo, MN	1,000
Leisure	Mirage, Treas Is., Las Vegas, NV	8,000
Leisure	Toronto Zoo, ON	2,000
Transit	Detroit Mover, MI	9,000
Transit	Jacksonville, FL	1,100
Transit	Miami Metromover, FL	12,000
Transit	Morgantown, Univ. of WV	16,000
All	***Total***	***691,800***

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[11] Transit Pulse, PO Box 249, Fields Corner Station, Boston, MA 02122.

2. Capacity Basics

2.1 INTRODUCTION

Capacity is an important measure of a rail transit system's passenger-handling capability. It is determined to ensure that a line is built, expanded or re-equipped with adequate facilities to handle the peak-hour passenger demands both in the near and long term, comfortably and safely. Other applications for capacity information are as follows:

- project planning and operations analysis for new starts and extensions,
- evaluating transit line performance,
- establishing and updating service standards,
- studying environmental impacts,
- assessing the capacities of new signaling and control technologies,
- estimating changes in system capacity and operations over time, and
- assessing capacity impacts in land-development studies where transit is expected to provide a significant role in site access.

This chapter defines capacity and develops an initial framework to analyze and determine the capacity of rail transit modes in North America.

2.2 TERMINOLOGY

2.2.1 DEFINITIONS

The North American rail transit industry is inconsistent in its use of terminology. Numerous reviewed reports use the same term to mean different things. Several reports develop their own definitions.

Chapter 13 provides a project glossary derived from the TRB and APTA transit glossaries. These definitions are used consistently throughout the report. Where reference must be made to an alternative definition, the variation is clearly noted in the text or via an accompanying footnote.

Note that headway and capacity are inversely related and this can be a source of confusion. The *minimum* or *closest* headway delivers the *maximum* capacity.

2.2.2 FOOTNOTES AND REFERENCES

To avoid duplication, references are shown as (R23) and refer to the Bibliography of Chapter 12 and the literature review item of the same number in Appendix One. Footnotes are shown by an italicized superscript number[8] referenced to the bottom of each page.

2.3 GROUPING

Following the extensive literature review and data collection, for the purpose of capacity analysis, the four modes of rail transit in this study have been grouped into categories based on alignment, equipment, train control and operating practices.

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

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

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

The fourth category is automated guideway transit (AGT). Although most AGT is a sub-set of the main category, *Grade Separated Rail* with very short trains, the use of off-line stations—on certain systems—is unique to this mode and requires separate examination. Off-line stations can also increase the capacity of more conventional rail transit as discussed in Chapter Six, *Operating Issues.*

Each of these categories is provided with its own chapter with the procedures for determining capacity.

- Chapter 7 *Grade Separated Rail Capacity Determination*
- Chapter 8 *Light Rail Capacity Determination*
- Chapter 9 *Commuter Rail Capacity Determination*
- Chapter 10 *AGT Capacity Determination*

2.4 THE BASICS

Professor Richard Soberman in the *Canadian Transit Handbook*(R19) states:

> *The capacity of transit service is at best an elusive*

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

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

> *figure because of the large number of qualifications that must be attached to any measure of capacity that is adopted.*

Most of the capacity calculations in the literature add constants, multipliers, reductive factors or other methods to correlate theory with practice.

In this study emphasis has been placed on reducing the number of qualifications and quantifying, describing and explaining adjustments between theory and practice in determining rail transit capacity.

The literature is in general agreement on a definition of rail transit capacity as:

> *The maximum number of passengers that can be carried in an hour, in one direction on a single track.*

Several papers add refinement to compensate for diversity of loading within the maximum peak hour. This compensated definition was referred to in some cases as the *practical maximum rail transit capacity.* Other definitions added qualifiers such as: *sustainable over a peak hour without impedance* (to other trains) or the less restrictive *without unrecoverable delays to trains.*

This study is oriented to practical results and it would be logical to include peak-hour diversity in the definition of maximum capacity. In North America the diversity factor of total peak-hour capacity to peak-within-the peak capacity ranges from 0.70 to 0.95. The latter high factor, relates only to a few lines in New York and Mexico City. Most rail transit fits into the range of 0.75 to 0.90.

However, in practice it is correct, if somewhat misleading, to quote a maximum hourly capacity of 60,000 passengers, or passenger spaces, per peak-hour direction when, as passengers do not arrive evenly over the peak hour to fill this capacity, the actual number of passengers carried in one hour is 45,000.

This introduces the issue of supply and demand. This study determines supply—the number of passenger spaces per peak hour per track that is provided—not the number of passengers actually carried. Although demand is not within the scope of the study, a secondary issue has been added to examine demand with particular respect to station constraints—inadequate platform size, number of exits, ticketing throughput and parking limitations—discussed in Chapter Six, *Operating Issues.*

To avoid any confusion between supply and demand, and to avoid confusion with other work, the study uses two definitions of capacity.

Design Capacity

The maximum number of passenger spaces past a single point in an hour, in one direction on a single track.

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

Achievable Capacity

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

Unless otherwise stated, reference in the study to passenger capacity means the achievable capacity of a single line.

Reference to single track is necessary as most rail rapid trunk routes in New York[3] have three or four tracks while the Broad Street subway in Philadelphia and the North Side L in Chicago have four tracks. The capacity of four-track lines is not a simple multiple of two single tracks and varies widely with operating practices—the merging and dividing of local and express services and train holding at stations for local-express transfers. The result is that, given adequate demand, four tracks can theoretically increase capacity by 80% over a double-track line—although 50% is more typical. A third express track does not necessarily increase capacity at all when restricted to the same *close-in* limitations at stations with two platform faces.

Design capacity has two factors, line capacity and train capacity, and can be expressed as shown in Figure 2.1. In turn the achievable capacity can be expressed as shown in Figure 2.2. The basic capacity expression can be expanded as shown in Figure 2.3. This expression of Figure 2.4 determines the number of trains per hour and is the inverse of the closest or minimum headway. The relevant minimum train separation in seconds is the minimum time to approach and leave a station, i.e., the time from when a train starts to leave a station until the following train can berth at that station. This is referred to as the *close-in* time.

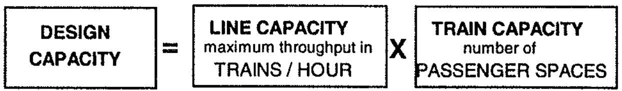

Figure 2.1 Basic design capacity expression

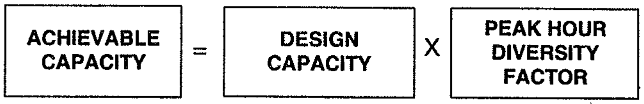

Figure 2.2 Basic achievable capacity expression

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[3] All New York four-track trunks merge into double-track sections, tunnels or bridges, crossing the Harlem and East Rivers.

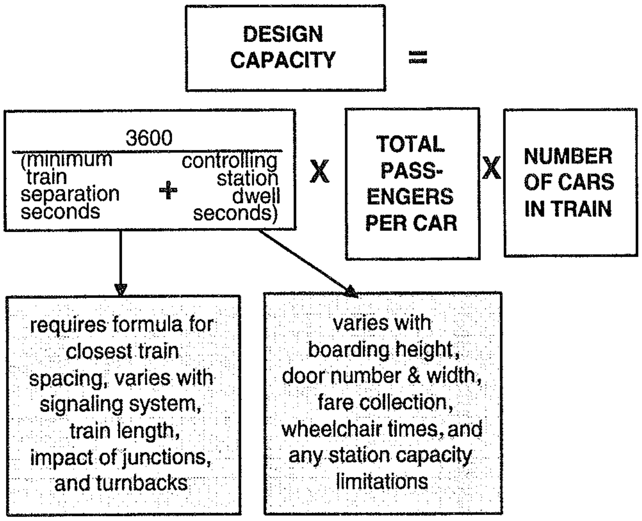

Figure 2.3 Expanded design capacity expression

$$\boxed{\frac{3600}{\left(\begin{array}{l}\text{minimum}\\ \text{train}\\ \text{separation}\\ \text{seconds}\end{array} + \begin{array}{r}\text{controlling}\\ \text{station}\\ \text{dwell}\\ \text{seconds}\end{array}\right)}}$$

Figure 2.4 Line capacity expression (train throughput/hour)

In determining this minimum headway, the train separation is based on *line clear close-in*, with successive green signals governing the following train. Such a headway is termed *noninterference*. The minimum line headway is determined by the critical line condition, usually the close-in at the maximum load point station.

The entire stretch of a line between junctions and turnbacks, where train density is physically constant, is governed by this one critical close-in. In a small number of cases the critical governor of headway is the terminal maneuver. In the *Rail Transit Survey* nine[4] out of 58 responding systems cited turn backs as a constraint — two light rail, five rail rapid transit and two commuter rail operators. In comparison, 34 operators cited train control limitations as a capacity constraint.

Junctions are not usually headway constraints. In the project's *Rail Transit Survey*, only four out of 58 responding systems cited junctions as a constraint — two commuter rail and two heavy rail operators. This reflects the good design of the busiest systems in the survey where potential junction constraints are minimized by grade separation. Chapter 3, *Train Control and Signaling*, develops analytic methods for determining the close-in time at stations, or headway limitations at junctions and turnbacks, for a variety of train control systems.

The other factor in the expression "controlling dwell" is based on actual station dwell time adjusted to a controlling value over the peak hour. The controlling dwell may contain an operating margin or a margin can be added separately to the denominator of the expression. Chapter Four, *Station Dwells*, develops the methodology and analysis of dwells. Chapter Six, *Operating Issues*, discusses and develops operating margins.

The expression of Figure 2.4 determines train throughput at the controlling station—usually the maximum load point station. In rare cases speed restrictions or heavy mixed passenger flows may dictate that other than the maximum load point station controls the closest achievable and repeatable headway.

From the above expressions the framework can be expanded to include other variables. Figure 2.5 outlines the project.

The next section in this chapter discusses the relationship between design and achievable capacity, followed by sections expanding and explaining the components of the project flow chart.

2.5 DESIGN VERSUS ACHIEVABLE CAPACITY

The objective of this project is to provide guidelines and methods that can be used for real-world evaluation of rail transit capacities. As such it is appropriate to consider the difference between *design* and *achievable* capacity.

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

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

Such an approach, however, does not incorporate many real-world factors that may reduce the *actual* number of regular riders that the system can or could sustain.

- Standing densities are not as absolute as the typical four passengers per square meter implies; people will crowd in more tightly in some situations than in others.
- It is rarely possible to equalize loading densities perfectly in a multi-car train; some car positions invariably carry more passengers on average than others.
- Many factors can reduce train performance (propulsion faults or differences, door problems, operator variation), which may not only increase the sustainable average headway, but will increase the variation in headway, and consequently the passenger load waiting for that train.
- *Minimum headway*, by definition, leaves no margin for schedule recovery from even minor delays, leaving the system susceptible to more variation in service.
- Passenger demand is usually distributed unevenly within the peak; there may be predictable "waves" of demand, corresponding to specific work start and finish times. Since passengers are essentially a "perishable" commodity (i.e., may not tolerate being forced to wait for later departures),

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[4] A closer examination of turnback constraints shows that many are due to operating practices—not physical constraints.

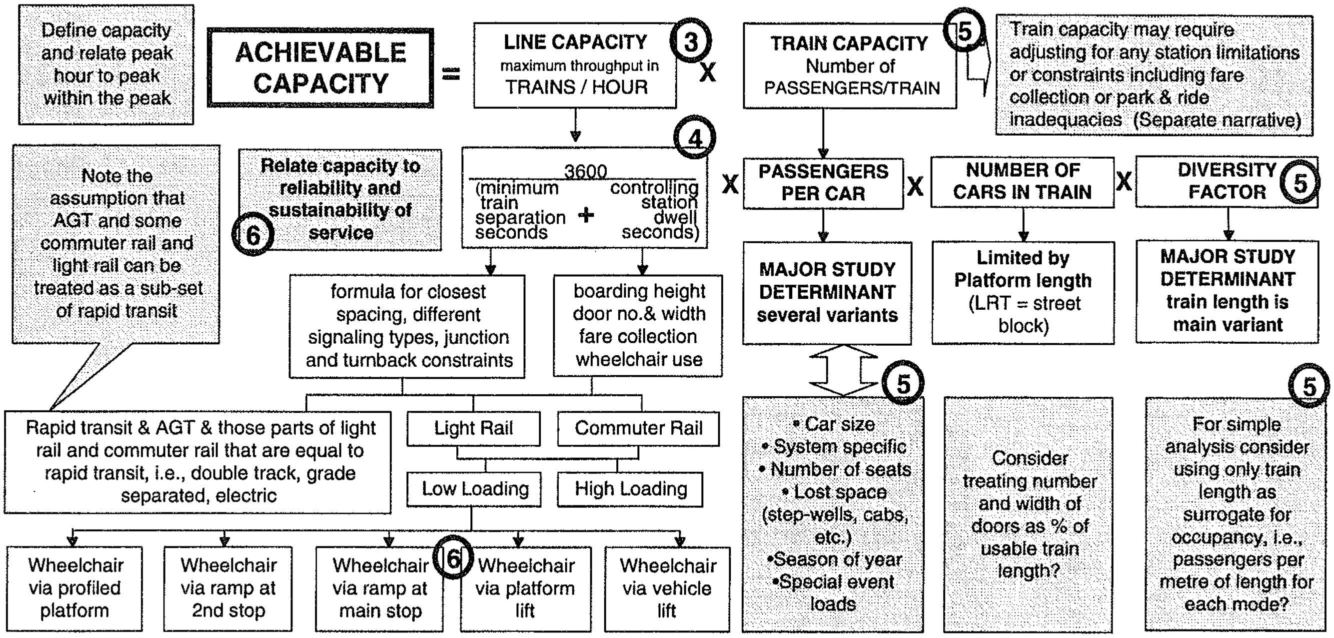

Figure 2.5 Project outline—analytic framework flowchart (Circled numbers denote the relevant report chapter)

the capacity rate requirement for the peak 10 to 15 min may have to be significantly higher than the average for the peak 1 or 2 hr.

- There is day-to-day fluctuation in demand. Some may be associated with the day of the week (peaks have become lighter on Mondays and Fridays as more people move into shorter or flexible work weeks), seasonally (lighter in the summer and at Christmas time), weather and special events. Beyond those identifiable factors, which may be at least partially anticipated, are essentially unpredictable, random variations in demand.
- Passengers are resilient to a degree, and will tolerate overcrowding or delay on occasion. This is an important safety valve that permits *at capacity* systems to accommodate special events or recover from service delays, with perhaps less difficulty than would be predicted.

Achievable capacity is the product of the *design* (maximum) capacity and a series of "reality" factors, most of which downrate the ideal. These factors are not absolutes, since they reflect human perception and behavior, as well as site-specific differences (expectations, cultural attitudes and the transportation alternatives). This study has endeavored to derive these factors from observation and understanding of existing North American rail rapid transit operations and combine them into a single *diversity factor*. Chapter Five, *Passenger Loading Levels*, details existing diversity factors and recommends factors for new systems.

2.5.1 SERVICE HEADWAY

Design (minimum) train operating headway is a function of

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

A review and comparison of signaling and train control systems is included in Chapter Three, *Train Control and Signaling*. Table 2.1 presents minimum headway constraints under current conditions on 53 of the systems surveyed. (Six operators stated there were no constraints, three did not respond.) These stated constraints are not necessarily absolute; many systems are not operating at or close to capacity and have therefore not exercised all of the relatively easy improvements that could be made within their existing plant and technology. In particular several of the turn-back constraints relate more to operating practices than physical limitations.

Achievable headway must account for additional factors that can affect the separation of individual trains:

- **Operator performance:** Differences among operators can

Table 2.1 Headway constraints by mode

Constraint	Light rail transit	Rapid transit	Commuter rail	Total
Signaling	11	12	10	33
Turnbacks	2	5	2	9
Junctions	0	2	2	4
Station approach	0	1	2	3
Single track	5	1	3	9
Station dwells	5	5	3	13
Other constraints	2	0	7	9
No of systems	18	17	15	52

have a significant effect, depending on the number of variables under direct operator control:
  - delay in initiating station departure (even if signaled by an automatic dispatching system);
  - acceleration and deceleration rates (especially the latter for manual positioning of trains at station stops);
  - maximum speed (particularly where an automatic emergency brake may be imposed for overspeed); and
  - train separation (anticipation of signals, or following distance in purely manual operation).
- **Vehicle performance:** Primarily the performance of propulsion; weak trains can impose a constraint on the entire line.
- **External interference:** A shared operating environment (street-running, grade crossings, lift or swing bridges) can impose delays that affect headways, both in a predictable pattern (e.g., *average* street congestion, traffic light timing) as well as randomly (grade crossing incidents, exceptional traffic congestion due to traffic incidents elsewhere, bridge operation).
- **Schedule recovery:** Systems that attempt to operate at the absolute minimum headway have no margin for schedule recovery in the event of a delay. When operating at the short headways implied in most high-volume situations, delays of even a couple of minutes will have some effect on passenger loading. If there is no allowance for the above variations, then the gap, and delays to all following trips, will be perpetuated until the end of the peak period. Schedule recovery (over and above any labor contractual requirements for operator layover) is essentially a judgment call, based on probabilities and consequences of delays, but ultimately determined by assessment of the passenger market.

The methodology for determining service headway with most of the above variables is developed in Chapter Three, *Train Control and Signaling.* Operating margins and schedule recovery allowances are developed in Chapter Six, *Operating Issues.*

2.5.2 STATION DWELLS—PRACTICAL ISSUES

Station dwells affect the overall round-trip time, and thus can affect the productivity of a given fleet if multiple trips are being made. (This is of virtually no consequence for *trippers*, including many commuter rail operations, which make only one trip in each peak period.) Mid-route station dwells also affect the in-service speed, and thus the service attractiveness. Round-trip time and fleet size issues are not necessarily related to *maximum capacity*, and are therefore not directly addressed by this study.

However, station dwells *do* become a factor in capacity when they combine with minimum operating headway to create a constraining headway bottleneck in the system. Typically this is a concern on fully segregated systems that are operating long trains on close headways; busy stations, especially major passenger interchanges, can produce block occupancy times that limit the entire system.

Station dwells are governed by the following:

- **Propulsion and door interlocking:** delay before the train stops, or after the doors close.
- **Door operation:** actual opening and closing time, plus door warning time and any other fixed system constraints on door operation.
- **Passenger volume:** average number of passengers boarding and alighting. In unconstrained, uni-directional situations, passengers can board or alight at a rate of better than 2 sec per passenger per single-stream doorway width.
- **Passenger crowding:** Efficiency of pedestrian movement is very sensitive to crowding; in the densities that are of concern to systems that are near capacity, movement is reduced to a slow shuffle as passengers vie for space either in the car or on the platform. The rate is further slowed when there is a mix of boarding and alighting.
- **Number, width and spacing of vehicle doors.**
- **Platform circulation:** If platforms are too narrow, or exit paths limited, congestion on the platform can cause delays in unloading a train; this can affect the overall station dwell.
- **Single/dual platform loading/unloading:** Door operation on a single side of a train is the norm; however, some systems configure busy stations with platforms on both sides of a train, to allow either for segregation (off-loading one side; loading on the other), or to split the combined passenger movement.
- **High or low level platform loading/unloading.**

The methodology for determining station dwells is developed in Chapter Four, *Station Dwells.*

2.6 LINE CAPACITY

Line capacity is the maximum number of trains that can be operated over a line in a peak hour. As shown in Figure 2.6, there are two principal factors in determining line capacity which are almost equal in weight. First is the capability or throughput

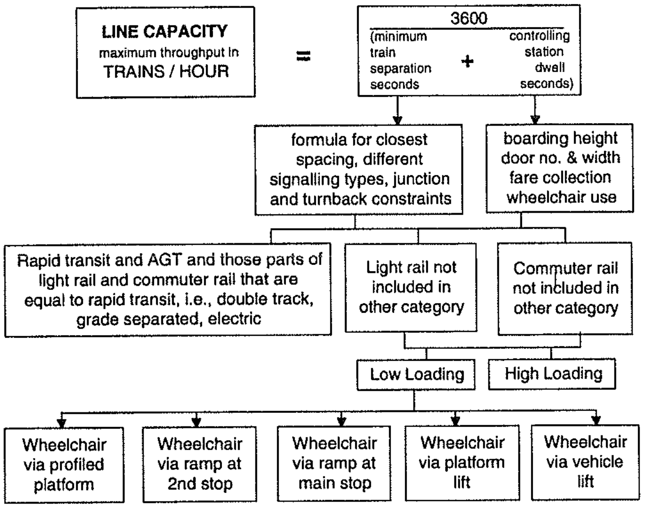

Figure 2.6 Line capacity flowchart (Not all wheelchair options apply to commuter rail)

of the train control system, adjusted for various constraints, principally those at terminals and at any junctions or single track sections. Second is the dwell time at stations.

Both factors can be further subdivided into the three categories based on alignment, equipment, train control and operating practices. In turn, light rail and commuter rail lines that are not in the principal segregated double-track category, must be divided by high- or low-level loading and by the method of handling wheelchairs.

2.6.1 TRAIN CONTROL THROUGHPUT

The number of trains per hour that is theoretically possible is dependent on the different signaling systems including conventional block signaling, cab signaling, and communication- or transmission-based signaling systems with moving blocks. Chapter Three, *Train Control and Signaling,* describes different signaling systems and develops empirical methods to estimate their throughput. More precise throughput determination requires the use of computer simulations.

2.6.2 COMMUTER RAIL THROUGHPUT

Certain line capacity issues are specific to commuter rail operation. Commuter rail signaling generally must accommodate trains of different lengths and speeds, and contract operations may set limits on the number of trains per hour.

Earlier in this chapter, commuter rail was divided into two classes: those lines that emulate rapid transit with electric multiple-unit operation on dedicated tracks (mainly in the New York City area) and all others. Both classes need special treatment for line capacity as they use railroad type signaling or train control, different operating practices, and trains with widely varying length and performance.

2.6.3 STATION DWELLS

Station dwells and train control system minimum separation are the two major factors in determining line capacity. In many circumstances dwells are the dominant factor. The third factor in headway is any operational allowance or margin. In some cases this margin can be added to the dwell time to create a *controlling dwell* time. An example of this is the dwell component of headways at one of the small number of rail transit lines in North America that are at capacity—lines 4 and 5 at Grand Central Station in New York.

The average dwell is 64 seconds—39% of the average head way of 165 sec. The minimum train separation at this location is 55 sec. The residual of headway minus dwell and train separation is 46 sec. This can be regarded as a surrogate for the operating margin. The need for a suitable margin is clearly shown in Figure 2.7 with the wide variation in dwells and individual train headways.

The three constituents of dwell in this example are shown in Figure 2.8, using NYCT Grand Central data from Figure 2.7. The three main components of dwell are

- Passenger flow time,
- Door open time after flow ceases, and
- Waiting to depart time after doors close.

These components vary widely from system to system. One example, with a high ratio of dwell time used for passenger

NYCT Grand Central 4& 5 Southbound Feb. 8, 1995, 7:48—9:27	
Average Dwell:	64
Average Headway:	165
Median Headway:	142.5
Headway Std. Dev.:	57.8
Dwell/Headway %	39.0

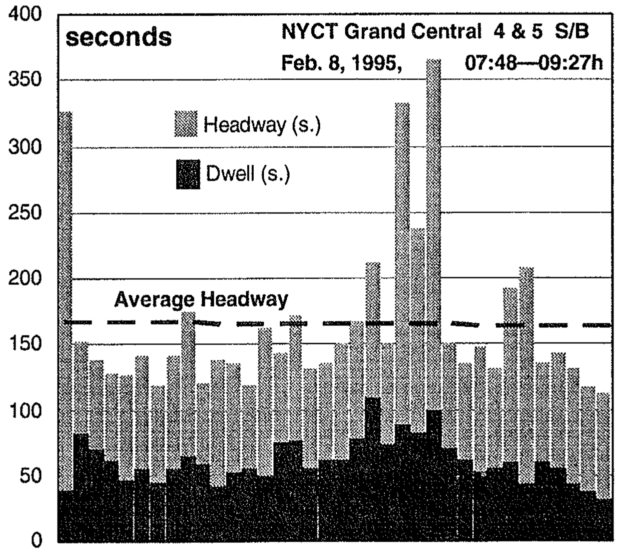

Figure 2.7 Dwell component of headway

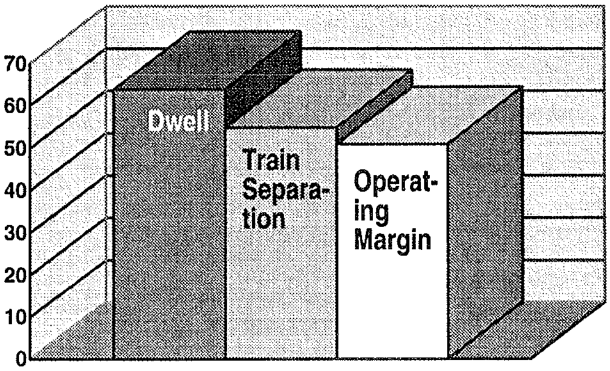

Figure 2.8 Average headway components in seconds

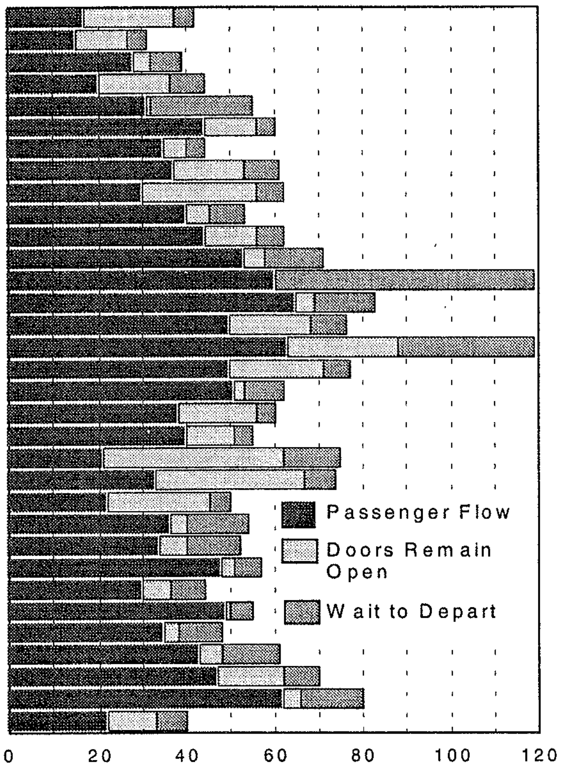

Figure 2.9 Station dwell components in seconds
NYCT Grand Central February 8, 1995 (NOTE some dwell times may have been extended due to local and express trains waiting for each other)

flow, is shown in Figure 2.9 The importance of station dwells is clear from these three figures. The methodology to determine dwell times is contained in Chapter Four, *Station Dwells*, and their associated operating margin in Chapter Six, *Operating Issues*.

Commuter Rail Dwells Dwells on many commuter rail lines are set by schedule or policy and can be relatively independent of passenger flows; consequently, they have a lesser effect on capacity than occurs on other modes. In these cases, the lower commuter rail deceleration and acceleration rates become more significant, particularly on busy lines such as Chicago's Aurora service where a wide range of express services is offered. The exceptions where dwell times are more significant are the high-volume, high-platform operations using electric multiple-unit operation on dedicated tracks. These lines, which are mostly in the New York City area, are included in the *Grade Separated Rail* category described in section of this chapter.

2.7 TRAIN/CAR CAPACITY

2.7.1 INTRODUCTION

Train capacity is the product of passengers per car and the number of cars, adjusted to achievable capacity case using a diversity factor to compensate for uneven car loadings over multiple-car trains (see Figure 2.10). Car capacity is often quoted at the crush loading level. This is inappropriate because such loading levels are rarely, if ever, achieved in practice. Rather, crush loading is a worst case level for which a car's structure, propulsion and braking systems are designed. Typically the North American crush level is based on 6 passengers per square meter (6/m^2) (1.8 sq ft per passenger), after making allowance for seated passengers and space lost to cabs and any equipment cabinets or stepwells. In reality, the typical maximum standing loads in North America range between four and five passengers per m^2 (2.2 to 2.7 sq ft per passenger) while the average over all systems through the peak period is only two passengers per square meter (5.4 sq ft per passenger).

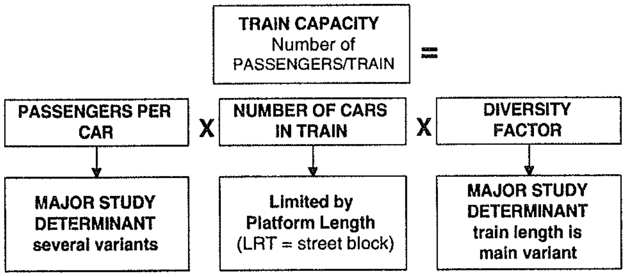

Figure 2.10 Train capacity flow chart

The only true means of measuring achievable car capacity is on those systems where pass-ups occur. That is where passengers wait for the next train rather than crowd onto the one in their station. Avoiding pass-ups is the goal of any transit system, so these are rare, but where they do occur, they provide hard data on achievable car capacity.

Determining full car capacity and pass-up capacity is discussed in the next sections relative to interior arrangements, type of system, old or new, and time of peak loading.

2.7.2 CAR CAPACITY

There are two approaches to the calculation and evaluation of car capacity — design-specific and dimensional average (generic).

2.7.3 DESIGN-SPECIFIC CAPACITY

If a specific car design has already been chosen, capacity calculation is relatively straightforward, as follows:

- Number of seats: Assume each seat occupied by one passenger.
- Standing area: Usable floor area (m^2 or ft^2), excluding an envelope of space for knees and feet of seated passengers, particularly in longitudinal (side-facing) seats.
- Standing density: A generally accepted average for short-distance sustainable *peak* loading is 4 passengers per square meter (2.6 sq ft per passenger), this may be reduced for longer distance trips, or where service policy or local conditions dictate otherwise.

- Standing efficiency: A factor that is used explicitly to increase or decrease the expected standing density, based on characteristics of the standing space.
- Wheelchair adjustment: With more and more rail systems becoming wheelchair accessible, and with an increasing number of wheelchair users being integrated into the regular transit system, a small adjustment may be required for wheelchair users. Typically a wheelchair occupies 1.2 to 1.5 m^2, or the equivalent of two to six standing passengers. The wheelchair adjustment factor is the average number of wheelchairs per car, times two to six. Typically wheelchairs represent such a small component of ridership that their overall effect on system capacity is negligible.
- Baggage adjustment: Similar to wheelchairs, some adjustment may be required if significant numbers of other large objects (bicycles, suitcases, etc.) are carried on board. On most systems the overall effect is negligible, but it could be a factor in lines that serve airports or recreational areas.[5]

2.7.4 CAR DIMENSIONS

If a specific car design has not been chosen, a "generic" car can be developed for capacity calculation. This approach avoids biases that may result from a somewhat arbitrary selection of existing transit systems. For example, a Portland LRT car with relatively generous seating and a New York MTA subway car designed primarily for standees may both be representative of their respective modes, but they do not indicate the range of possibilities for each.

The factors that control car capacity are as follows:

- **Car length:** Nominal length from center of couplers allows for calculation of multi-car train lengths.
- **Car width:** Car width at seat back height, typically 0.8 above the floor, is often 0.10 to 0.15 m wider than at floor/platform level), recognizing that passengers' hips and shoulders are wider than the space required for head and feet. Car width is usually described for exterior dimensions and can be converted to *interior* width by assuming a sidewall thickness of 0.05 to 0.10 m.
- **Nonpassenger space:** Out of the nominal rectangular envelope of the car, nonpassenger space must be deducted for driver's cabs (which can be omitted in a fully automated system), equipment lockers and bulkheads (if any), and the endwalls of the car (including a typical 300 mm distance to end of the coupler).
- **Seat density:** Seating density can range from a low of 1.5 pass/m^2, typical for commuter rail or long-distance suburban rapid transit, to a high of over 2.0 pass/m^2 on some heavy rapid transit lines that have put a premium on overall seating capacity. This is a service quality policy that is independent of other operating attributes.
- **Seating ratio:** As with seat density, the percentage of passengers to be seated is a site-specific design and policy decision.
- **Standing density:** Car floor space not occupied by seating, or designated for wheelchair, baggage or bicycle storage, can accommodate the typical 4 passengers per m^2, or may range widely (from 1.5 to7 passengers per m^2 in North America).

Long-established systems in large, older cities (New York, Philadelphia, Chicago, Toronto, etc.) sustain higher car loadings because people are used to it and because of limitations on the alternatives — high levels of traffic congestion, long driving times and high parking fees. Newer systems offer more space per passenger to be more attractive and competitive with alternative travel options.

2.7.5 CAR CAPACITY CALCULATION ALTERNATIVES

Three aspects of car capacity discussed above — *seat density, seating ratio* and *standing density* — are policy issues. Policy decisions on service levels and interior design can make a three to one difference between the capacities of two systems with the same given train length and the same minimum train control headway.

This suggests that for many capacity calculations, detailed determination of seating and standing space may be unnecessary, or, for new systems where vehicles have not been specified, not possible. There are two possible simplified methods for determining car capacity: the gross area alternative and the train length alternative. Both methods can still have a range of capacities as determined by the policies of a specific system.

2.7.6 TRAIN LENGTH ALTERNATIVE

This alternative offers the simplest method of establishing capacity based on policy decisions of seating type and quantity, and standing density. This method is developed in Chapter Five, *Passenger Loading Levels.*

2.7.7 TRAIN CAPACITY

Design train capacity is simply the product of car capacity and the number of cars per train. The latter in turn will be constrained largely by site-specific factors:

- platform length (especially on existing systems)
- on-street constraints (street-running light rail).

Achievable capacity is affected by systematic variation in loading within the train — train loading diversity. This can be significantly influenced by station design. The factor is closest to 1.0 if the majority of station entrances distribute passengers effectively along the length of the platform, or if biases in some locations are offset in others. In peak conditions, passengers will learn to spread out, but this process is rarely perfect, and pass-up conditions or excessive crowding will occur on some cars, while others are less heavily loaded. Existing loading diversities

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[5] Adjustments similar to those for wheelchairs and baggage can also be made for systems that allocate space for bicycles or strollers. Such space usage will be dealt with in narrative form.

are tabulated in Chapter Five, *Passenger Loading Levels*, and levels are recommended for use in calculating achievable capacity.

2.8 STATION CONSTRAINTS

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

- Station capacity—including occupancy limits imposed by the NFPA[6] 130 fire codes.
- Platform flow restrictions due to the number and width of exit and entry passageways and vertical circulation components.
- Parking space inadequacies at park and ride stations.
- Fare collection system capacity—fare collection arrangements are normally developed to match passenger demand, including the use of manual collection for special high demand events (football games, parades etc.) Only in unusual circumstances will fare collection restrictions limit capacity. One such circumstance is those few light rail systems that collect fares (at some or all stops) as passengers board. On-board fare collection on commuter rail services is not regarded as a capacity issue although it can be an operating problem on crowded trains.

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[6] National Fire Prevention Association

3. Train Control and Signaling

3.1 INTRODUCTION

Signaling has been a feature of urban rail transit from the earliest days. Its function is to safely separate trains from each other. This includes both a separation between following trains and the protection of specific paths through junctions and cross-overs. The facilities that create and protect these paths or routes are known as interlockings.

Additional functions have been added to basic signaling, starting, again from a very early date, with automatic train stops. These apply the brakes should a train run through a stop signal. Speed control can also be added, usually to protect approaches to junctions (turnouts), sharp curves between stations and approaches to terminal stations where tracks end at a solid wall. Automatic trains stops are in universal use. Speed control is a more recent and less common application, often introduced in conjunction with automatic train control or to meet specific safety concerns.

Rail transit signaling is a very conservative field maintaining high levels of safety based on brick-wall stops and fail-safe principles. A brick-wall stop means that the signaling separation protects a train even if it were to stop dead, an unlikely though possible event should a train derail and strike a structure. This protection allows for a) the following train's failure to observe a stop signal, b) driver and equipment reaction time, and c) some impairment in the braking rate.

Fail-safe design principles ensure that failure of single—and often multiple—components should never allow an unsafe event. Traditionally in North America this involves the use of heavy railroad style relays that open by gravity and have nonwelding carbon contacts. Compact, spring opening, European-style relays or solid state (electronic or computer controlled) interlockings are now being accepted. Here equivalent safety is provided by additional logic, duplicate contacts or multiple polling processors.

The rigor with which fail-safe principles have been applied to rail transit has resulted in an exceptional safety record. However, the safety principles do not protect against all possibilities—for example, a derailed train could interfere with the safe passage of a train on an adjacent parallel track. Nor do they protect against all possible human errors whether caused by a signal maintainer, dispatcher or train driver. An increasing inability to control the human element—responsible for three-quarters of rail transit accidents or incidents[1]—has resulted in new train control systems using technology or automation to reduce or remove the possibility of human error.

Train control, or more properly automatic train control, adds further features to basic signaling. Automatic train control is an ill-defined term but usually encompasses three levels:

- Automatic train protection (ATP)
- Automatic train control[2] (ATC or ATO)
- Automatic train supervision (ATS)

Automatic train protection is the basic separation of trains and protection at interlockings. In other words, the signaling system as described above.

Automatic train control adds speed control and often automatic train operation. This can extend to automatically driven trains but more commonly includes a driver, operator or attendant who controls the train doors and observes the track ahead.

Automatic train supervision attempts to regulate train service. It can be an integral feature of automatic train control or an add-on system. The capabilities of automatic train supervision vary widely from little more than a system that reports the location of trains to a central control office, to an intelligent system that automatically adjusts the performance and stop times of trains to maintain either a timetable or an even headway spacing.

Automatic train protection and automatic train control maintain the fail-safe principles of signaling and are referred to as *vital* or *safety critical* systems. Automatic train supervision cannot override the safety features of these two systems, and so it is not a vital system.

This chapter describes and compares the separation capabilities of various train control systems used on or being developed for rail transit. It is applicable to the main rail transit grouping of electrically propelled, multiple-unit, grade-separated systems. Specific details of train control for commuter rail and light rail modes are contained in the chapters dealing with these modes.

These descriptions cannot include all the complexities and nuances of train control and signaling but are limited to their effect on capacity. More details can be found in the references and in the bibliography. All urban rail transit train control systems are based on dividing the track into blocks and ensuring that trains are separated by a suitable and safe number of blocks. Train control systems are then broken down into fixed-block and moving-block signaling systems.

3.2 FIXED-BLOCK SYSTEMS

In a fixed-block system, trains are detected by the wheels and axles of a train shorting a low-voltage current inserted into the rails. The rails are electrically divided into blocks. Originally this required a rail to be cut and an insulating joint inserted. Only one rail is so divided. The other rail remains continuous to handle the traction power return.

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[1] PARKINSON, TOM, Safety Issues Associated with the Implementation of ATCS-Type Systems, *Transportation Development Centre, Transport Canada, August 1989.*

[2] Sometimes termed automatic train operation to avoid confusion with the overall term automatic train control.

By moving from direct current to alternating current circuits,[3] the blocks can be divided by an inductive shunt[4] connected across the rails, avoiding the need for insulated joints. These are called jointless track circuits and both rails are then available for traction power return. A track circuit can be any reasonable length. Each circuit is expensive so lines use the minimum required for appropriate headways. Circuits will be short where trains must be close together, for example in a station approach, and can be longer between stations where trains operate at speed.

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

In the simplest two-aspect block system, the signals display only stop (red) or go (green). A minimum of two empty blocks must separate trains, and these blocks must be long enough for the braking distance plus a safety distance. The safety distance can include several components, including sighting distances, driver and equipment reaction times, and an allowance for partial brake failure, i.e. a lower braking rate.

Automatic train stops have long been a feature of rail transit (almost from the turn of the century). These prevent a train running through a red signal by automatically applying the emergency brakes should the driver ignore a signal. Called a *trip stop,* the system consists of a short mechanical arm beside the outer running rail that is pneumatically or electrically raised when the adjacent signal shows a stop aspect. If a train runs through this signal, the raised arm strikes and actuates a trip cock on the train that evacuates the main air brake pipe. Full emergency braking is then applied along the length of the train. To reset the trip cock the driver must usually climb down to track side and manually close the air valve.[5]

A two-aspect signaling system does not provide the capacity normally required on busy rail transit lines—those with trains an hour or better. Increased capacity can be obtained from multiple aspects where intermediate signals advise the driver of the condition of the signal ahead, so allowing a speed reduction before approaching a stop signal. Block lengths can be reduced relative to the lower speed, providing increased capacity.

The increased number of blocks, and their associated relay controls and color-light signals, is expensive. There is a diminishing capacity return from increasing the number of blocks and aspects as shown in Figure 3.1. This figure also shows that there is an optimal speed to maximize capacity. Between stations the line capacity is greatest with maximum running speeds of between 40 km/h (25 mph) with three aspects to 55 km/h (34 mph) with 10 aspects. At the station entry — invariably the critical point for maximum throughput — optimal approach speeds are from 25 km/h (15 mph) to 35 km/h (22 mph).

In North America, the most common block signaling arrangement uses three aspects. In Europe and Japan, a small number of systems extend to four or five aspects.

Optimizing a fixed-block system is a fine art, with respect both to block lengths and to boundaries. Block lengths are also influenced by grades because a train's braking distance increases on a down grade and vice-versa. Grades down into a station and curves or special work with significant speed restrictions, below the optimal levels given above, will reduce throughput and so reduce capacity. Fortuitously, one useful design feature of below-grade systems is a gravity-assisted profile. Here the stations are higher than the general level of the running tunnel. Trains use gravity to reduce their braking requirements in the station approach and to assist them accelerating away from the stations. This not only reduces energy consumption, equipment wear and tear and tunnel heating, but also reduces station costs because they are closer to the surface, allowing escalators and elevators to be shorter. More important to this study, it increases train throughput — altogether a good thing.

Requiring a train operator to control a train's speed and commence braking according to multiple aspect color-light signaling requires considerable precision to maximize throughput. Coupled with the expense of increasing the number of aspects an improvement has been developed over the past three decades — cab signaling.

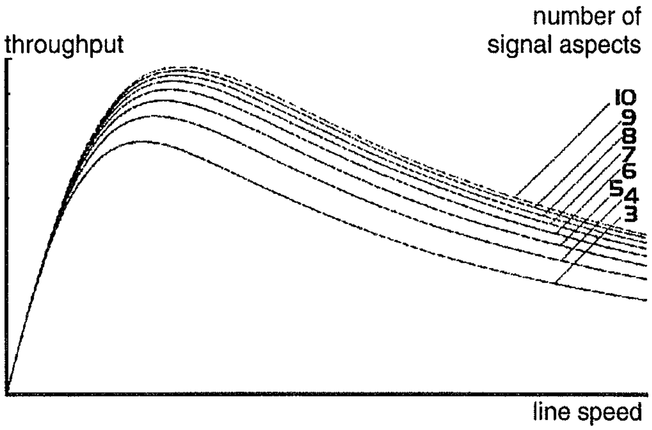

Figure 3.1 Throughput versus number of signal aspects[R26]

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[3] Alternating current track circuits use different frequencies, combinations of frequencies or modulated frequencies. In all cases care must be taken to avoid interference from on-board vehicle equipment. Modern high power chopper and VVVF (variable voltage, variable frequency) three phase ac motor control equipment can emit considerable levels of EMI (electro magnetic interference). The systems engineering to coordinate and avoid such interference is difficult and complex and is beyond the scope of this report.

[4] In essence, the shunt shorts the small alternating current track circuits while presenting a low resistance to the high direct currents.

[5] Resetting the trip cock is understandably an unpopular task and consumes time. Consequently drivers may approach a trip cock cautiously at less than the optimal speed, particularly when closely following another train. In this case they expect the signal aspect to change as they approach but cannot be certain. Automatically driven trains will typically operate closer to the optimal speeds and braking rates and so can increase throughput.

There are times when it is operationally desirable to operate through a stop signal and its associated automatic train stop, particularly when the train ahead is delayed in a station and following trains wish to close up to expedite their subsequent entry to the station. The process is commonly called *key by* from an arrangement where the driver must lean out of the cab and insert a key in an adjacent electrical switch. However, the most common arrangement no longer involves a key, merely a slow movement of the train into the next block, which lowers the trip stop before it is struck by the train. The train must then proceed on visual rules toward the train ahead. In recent years an increase in the number of incidents caused by this useful, time saving, but not fail-safe, procedure has caused several systems to prohibit or restrict its use.

3.2.1 CAB SIGNALING

Cab signaling uses a.c. track circuits such that a code is inserted into each circuit and detected by an antenna on each train. The code specifies the maximum allowable speed for the block occupied and may be termed the *reference* or *authorized* speed. This speed is displayed in the driver's cab—typically on a dual concentric speedometer, or a bar graph where the authorized speed and actual speed can be seen together.

The authorized speed can change while a train is in a block as the train ahead proceeds. Compared to color-light signals, the driver can more easily adjust train speed close to the optimum and has less concern about overrunning a trip stop. Problems with signal visibility on curves and in inclement weather are reduced or eliminated.

Cab signaling avoids much of the high capital and maintenance costs of multiple-aspect color-light signals, although it is prudent and usual to leave signals at interlockings and occasionally on the final approach to and exit from each station. In some situations, dwarf color-light signals can be used. In this way trains or maintenance vehicles that are not equipped with cab signaling—or trains with defective cab signaling—can continue to operate, albeit at reduced throughput.

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

Signal engineers may argue over the merits of block-signaling and cab-signaling equipment from various manufacturers—particularly with respect to capital and maintenance costs, modular designs, plug versus hard-wired connections and the computer simulation available from each maker to optimize system design. However, for a given specification, the throughput capabilities vary little provided that—the signaling is optimized as to block length, boundary positioning and, when applicable, the selection of *reference* speeds. Consequently a listing or description of different systems is not relevant to capacity determination.

3.3 MOVING-BLOCK SIGNALING SYSTEMS

Moving-block signaling systems are also called transmission-based or communication-based signaling systems—potentially misleading because cab signaling is also transmission based.

A moving-block signaling system can be likened to a fixed-block system with very small blocks and a large number of aspects. Several analytic approaches to moving-block systems use this analogy. However a moving-block signaling system has neither blocks nor aspects. The system is based on a continuous or frequent calculation of the clear (safe) distance ahead of each train and then relaying the appropriate speed, braking or acceleration rate to each train.

This requires a continuous or frequent two-way communication with each train, and a precise knowledge of a train's location, speed and length; and fixed details of the line—curves, grades, interlockings and stations. These may be contained in a table that allows changes to be made without the normal full rigor required for changes to safety-critical software. Temporary changes can be easily made to add speed restrictions or close off a section of track for maintenance work.

Based on this information, a computer can calculate the next stopping point of each train—often referred to as the target point—and command the train to brake, accelerate or coast accordingly. The target point will be based on the normal braking distance for that train plus a safety distance.

Safety Distance Braking distance is a readily determined or calculated figure for any system. The safety distance is less tangible because it includes a calculated component adjusted by agency policy. In certain systems this distance is fixed; however, the maximum throughput is obtained by varying the safety distance with speed and location—and, where different types of equipment are operated, by equipment type.

In theory, the safety distance is the maximum distance a train can travel after it has failed to act on a brake command before automatic override (or overspeed) systems implement emergency braking. Factors in this calculation include

- system reaction time;
- brake actuation time;
- speed;
- train load (mass)—including any ice and snow load;
- grade;
- maximum tail winds (if applicable);
- emergency braking rate;
- normal braking rate;
- train to track adhesion; and
- an allowance for partial failure of the braking system.

The safety distance is frequently referred to as the "worst-case" braking distance, but this terminology is misleading. The truly worst case would be a total braking failure. Worst case implies reasonable failure situations, and total brake failure is not regarded as a realistic scenario on modern rail transit equipment that has multiple braking systems. A typical interpretation of the safety distance assumes that the braking system is three-quarters effective.

Train Position and Communication Without track circuits to determine block occupancy, a moving-block signaling system must have an independent method to accurately locate the position of the front of a train, then use look-up tables to calculate its end position from the length associated with that particular train's identification. The first moving-block systems, developed in Germany, France and the United States, all used the same principle—a wire laid alongside or between the running rails periodically transposed from side-to-side, the zigzag or Grecian square arrangement. The wire also serves to transmit signals to and from antennas on the train.

The wayside wires are arranged in loops so that each train entering a loop has a precise position. Within the loop, the control system counts the number of transpositions traversed, each a fixed distance apart— m (82 ft) is typical although much shorter distances have been used. Between the transpositions, distance is measured with a tachometer.[6]

The resultant positioning accuracy can be in the order of centimeters and with frequent braking rate feedback can result in station stop accuracy within ± 20 cm (8 in.) or better.

The use of exposed wayside wires is abhorred by maintenance-of-way engineers, and recent developments portend changes to existing systems and for the many moving-block signaling systems now under development. Inert transponders can be located periodically along the track. These require neither power nor communication wiring. They are interrogated by a radio signal from each train and return a discrete location code. Positioning between transponders again relies on the use of a tachometer. Moving-block signaling systems already have significantly lower costs for wayside equipment than do fixed-block systems, and this arrangement further reduces this cost as well as the occupancy time required to install or retrofit the equipment — an often critical factor in resignaling existing systems.

Removing the positioning and communicating wire from the wayside requires an alternate communication system. This can most economically be provided by a radio system using over-the-air transmission, wayside radiating cables, intermittent beacons or a combination thereof.

As with any radio system, interruption or interference with communications can occur and must be accommodated. After the central control computer has determined any control action, it will transmit instructions to a specific train using the identification number of the train's communication system. It is clearly vital that these instructions are received by and only by the train they were determined for.

There are numerous protocols and/or procedures that provide a high level of security on communication systems. The data transmission can contain both destination codes and error codes. A transmission can be received and repeated back to the source to verify both correct reception and correct destination, a similar process to radio train order dispatching. If a train does not receive a correctly coded confirmation or command within a set time, the emergency brakes will be automatically applied. The distance a train may travel in this time interval — typically less than 3 sec — is a factor in the safety distance.

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

The first moving-block signaling systems used mainframe computers with a complex interconnection system that provided high levels of reliability. There is now a move toward the use of much less expensive and space-consuming personal computers (PCs).

PCs and their local area networks (LANs) have been regarded as less robust than mainframe systems, and as suspect for use in safety-critical applications. The first major application occurred in Vancouver in 1994 when, after 10 years of mainframe operation, the entire SkyTrain train control system was changed to operating on PCs with Intel 486 CPUs. Reliability has increased in the subsequent 15 months of operation. However, it is not possible to attribute this improvement solely to the new hardware because new software was also required by the change in operating systems. The proprietary computers and software on each train were not changed.

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

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

Instead, an equivalent level of safety is provided on the basis of statistical failure modes of the equipment. Failure analysis is not an exact science. Although not all failure modes can be determined, the statistical probability of an unsafe event[7]can be predicted.

Determining failure probability is part of a safety assurance plan — a systematic and integrated series of performance, verification, audit, and review activities, including operations, maintenance and management activities that are implemented to assure safe and satisfactory performance. The plan can cover a specific area, such as software, or can encompass the entire system, where software would be but one aspect. Such a plan will usually include a fault tree analysis.

The typical goal in designing processor-based systems is a mean time between unsafe failures of 10^9 hours, or some 114,000 years.[8] After due allowance for statistical errors and the incorporation of a large safety margin, this is deemed to be equivalent to or better than the so-called fail-safe conventional equipment.

The possibility of even a low incidence of unsafe failure may give cause for concern and the acceptance of processor-based signaling, particularly moving-block systems, has been slow. However the safety of conventional rail transit signaling is not as absolute as is often made out. Minor maintenance errors can cause unsafe events. An estimated three-quarters of rail transit accidents are attributed to human error.[9]

Two methods are used to achieve the high levels of safety on processor-based control systems. One is based on redundancy, where two or more computers operate with the same software. The output of both or the output of at least two out of three

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[6] Tachometer accuracy is helped by the ability for continual on-the-fly calibrations as the distance between each transposition is fixed and known. This fully compensates for wheel wear but not for slip or slide. Errors so caused, while small, can be minimized by the use of current sophisticated slip-slide control or, where feasible, placing the tachometer on an unmotored axle.

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

[8] PARKINSON, TOM, Safety Issues Associated with the Implementation of ATCS-Type Systems, *Transportation Development Centre, Transport Canada August 1989.*

[9] Ibid.

must coincide before a comparator circuit transmits a command. Thereafter, the safety consequences of the output can be considered in a conventional fashion. This method is a hardware-intensive solution.

The other method is based on diversity. Two sets of software, created and verified by independent teams, are run on the same or separate computers. Again their output must agree before any commands are executed. This is a software-intensive solution.

Because software development can account for over half the cost of a moving-block signaling system, and with hardware costs declining — particularly with the use of PCs — the hardware-intensive approach to redundancy is invariably the most economic. However, the relative cost of software development, testing, commissioning and safety assessment is expected to drop with the introduction of modular code blocks — safety critical portions of software that remain unchanged from system to system.

In some regards, software-based systems, once fully tested and commissioned, are less prone to unsafe errors created during equipment installation and maintenance. However there are three major remaining areas of concern.

1. Revisions to software may be required from time to time and can escape the full rigor of a safety assurance plan.
2. Removing track circuits also removes broken rail detection. While no specific data for rail transit have been found, the Southern Pacific Railroad found that fewer than 2 percent[10] of broken rails were detected *in advance* by track circuits — it appears that most breaks occur from the stress of a train passing. Nevertheless, some moving-block signaling systems have long track circuits added to detect broken rails.
3. Removing track circuits also eliminates the detection of any and all vehicles whose wheels and axles short across the rails. A major hazard exists if maintenance vehicles, or a train with a defective train control system, enter into or remain in an area where automatically controlled trains are run. This requires a rigorous application of operating rules and requires the defect correction and reentry into the control system or removal of an automatic train protection failed train, before service can resume in the occupied area.

   This potential hazard can be reduced by adding axle counters at various locations. These count entry and exit into a specified track section. In conjunction with appropriate software, they will prevent an automated train from following an unequipped train at an unsafe distance. However, an unequipped train is not so protected but depends on the driver obeying rules, whether using line-of-sight operation, or depending on any remaining wayside signals.

Hybrid Systems There are times when an urban rail transit system shares tracks with other services, such as long distance trains, whose equipment is impractical or uneconomic to equip with the moving-block signaling system. Use of axle counters for the safety of unequipped rolling stock substantially reduces capacity. To avoid this reduction while still obtaining the close headway of the moving-block system for the urban or short distance trains requires a hybrid design.

The SACEM system developed by Matra is employed in Paris and Mexico City[11] The SACEM combines a fixed-block system with a transmission based system. Conventional blocks are subdivided into smaller increments that permit those trains, equipped with a continuous communication system, to operate on closer headways. Unequipped trains continue to be protected by the basic block system. As equipped trains operate through some signals displaying red an additional aspect must be added to such signals — indicating that the signal is not applicable to that specific train.

SACEM has a throughput capability between fixed-block and moving-block signaling systems that depends on the mix of equipped and unequipped trains. The manufacturer claims an increase in capacity up to 25%, which is comparable to the general 30% increase of moving-block over fixed-block signaling systems — all else being equal. The two equipped rail transit lines in Mexico City do not have any unequipped long distance trains with their longer braking distances and so should obtain the maximum capacity improvement.

While classed as a hybrid system, SACEM does not use moving-blocks and is really an overlay system. Shorter blocks — applicable to certain trains only — are overlaid onto a conventional fixed-block system.

Moving-block signaling systems have been installed by the SEL (Standard Electrik Lorenz) of Stuttgart, Germany, and its Canadian subsidiary SEL Canada. Both are now part of the Alcatel group, a French consortium.

The Alcatel SelTrac®™ system has evolved through five generations over two decades. There are some 20 worldwide installations of which five are in North America: Vancouver, Toronto, Detroit, San Francisco and Orlando (Disneyworld monorail).

The SelTrac system uses an inductive loop to both communicate with trains and, through the loop transpositions, to determine positioning. Processing power is centralized with the on-board computers limited to processing signals and controlling the vehicle subsystems. The use of Intel x86 processors to control critical train movements was introduced in 1994. Transponder positioning has been developed to reduce hardware costs and improve failure management. In addition, SelTrac includes an integrated automatic train supervision subsystem.

The second manufacturer with a system in service is also French. Service started on Line D of the Lyon metro in 1992 using Matra Transport's Maggaly®™ system. The Maggaly system uses inductive transmission with positioning transponders and places the bulk of the processing power on-board. Line data are stored on-board with the wayside equipment limited to system management and providing the location of a leading train to its immediate follower.

The advantages of moving-block signaling systems are considerable. Beyond the capacity increase of interest to this study, the concept offers the potential for lower capital and maintenance costs, flexibility, comprehensive system management capabilities and inherent bi-directional operation. The

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[10] Ibid.

[11] Line A and Line 8.

slow acceptance of processor based train control systems may explain why most conventional train control suppliers have stayed away from this concept until the recent selection of moving-block systems by London Transport and New York City Transit, together with several smaller systems. This selection is not necessarily based on the capacity increases but as much on the economics and relative ease of installing the system on top of a conventional signaling system on existing lines that must remain in operation throughout the conversion, modernization or replacement.

Subsequent to the London and New York decisions, many manufacturers have announced the development of moving-block signaling systems.

General Railway Signal is developing its ATLAS®™ system. This is a modular based concept that allows various forms of vehicle location and communication systems. A feature is a vital stored database and low requirements for the vehicle-wayside data communication flow.

Union Switch & Signal is developing its MicroBlok®™ which shares some similarity with Matra's SACEM, overlaying "virtual" software based blocks on a conventional fixed block system. With radio based communications and vital logic distributed on the wayside, the system uses some concepts developed for the Los Angeles Green Line which entered service in August 1995.

AEG Transportation System's Flexiblok®™ shares some features with MicroBlok and SACEM. It is a radio-based system designed for both standalone use and for incrementally adding capacity and features to traditional train control systems. Operational and safety responsibilities are distributed through the system, which incorporates nonproprietary interfaces conforming to Open System Interconnect protocol standards.[12] AEG's US division, previously Westinghouse Electric Transportation Systems, is developing a transmission-based train control system tailored to the North American market.

Harmon Industries' UltraBlock®™ system is radio based with transponder positioning technology. Line profile information is stored on-board. Vital processing is distributed along the wayside.

Siemens Transportation Systems is developing a moving-block system based on its Dortmund University people mover, an under-hanging cabin system that has been in service since 1984.

CMW (Odebretch Group, Brazil) is supplying a radio-based overlay system to the São Paulo metro with distributed processing. The system is claimed to reduce headways from 90 to 66 sec. As section 4.7 of this chapter shows, such close headways are only possible with tightly controlled station dwells which are rarely achievable at heavy volume stations.

Morrison Knudsen (with Hughes and BART) is developing a moving-block signaling system based on military communication technology. The system uses beacon-based, ranging spread spectrum, radio communications which are less susceptible to interference and can tolerate the failure or loss of one or more beacons.

NOTE: The above discussion represents the best information available to the researchers at the time this report was written. Other suppliers may exist and omissions were inadvertent. This discussion is not intended to endorse specific products or manufacturers.

> *All moving-block systems that base train separation on a continually adjusted distance to the next stop or train ahead (plus a safety distance) should have substantially similar train throughput capabilities. Capacity for a generic moving-block signaling system is developed in section 3.8 of this chapter, based on information from existing systems (Alcatel and Matra).*
>
> *Those systems under development (above) that succeed in the market can reasonably be expected to have comparable capacities. However, there is insufficient information to confirm this.*

3.4 AUTOMATIC TRAIN OPERATION

Automatic acceleration has long been a feature of rail transit. A driver no longer has to cautiously advance the control handle from notch to notch to avoid pulling too much current and so tripping the line breaker. Rather, relays, and more recently microprocessors, control the rate of acceleration smoothly from the initial start to maximum speed.

Cab signaling and moving-block signaling systems transfer speed commands to the train and it was a modest step to link these to the automatic acceleration features, and comparable controlled braking, to create full automatic train operation (ATO). The first North America application occurred in 1962 on NYCTA's Times Square Shuttle, followed in 1967 by Montreal's Expo Express, then, in short order by PATCO's Lindenwold line and San Francisco's BART. Most new rail transit systems have incorporated ATO since this innovative period.

The driver's or attendant's role is not necessarily limited to closing the doors, pressing a train start button and observing the line ahead. Drivers are usually trained in, and rolling stock is provided with, manual operating capabilities. PATCO pioneered the concept of having drivers take over manual control from time to time to retain familiarity with operations. Manual driving under cab controls, limited color-light signaling or radio dispatching is routine, if infrequent, on many ATO-equipped systems when there is a train control failure or to provide signaling maintenance time.

Dispensing entirely with a driver or attendant is controversial. In 1965 the driverless Transit Expressway was first operated in a controlled environment in Pittsburgh. This Automated Guideway Transit (AGT) system, and similar designs, have gained widespread acceptance in nontransit usage as driverless people movers in airports, amusement parks and institutional settings. Morgantown's AGT was the first public transit operation to gain acceptance for driverless operation when it opened in 1968. After a long gap Miami's downtown people mover opened in 1985 with the Detroit People Mover and the full-scale urban rail transit

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[12] The proprietary nature of many moving-block signaling systems is a concern to potential customers who are then captive to a particular supplier. Traditional train control systems in theory allow many components from different manufacturers to be mixed and matched. However, particularly with the introduction of solid state interlockings, this is not always feasible.

SkyTrain system in Vancouver starting the following year. Driverless public transport is now well established in these cities but no subsequent operations have chosen to follow, despite their record of safety, reliability and lower operating costs. Fundamental concerns with driverless automatic train operation clearly remain.

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

In the literature Klopotov(R32) makes claims of capacity improvements of up to 15% with ATO. Bardaji(R10) claims a 5% capacity increase with automatic regulation. Other reports allude to increases without specific figures. None of the reports substantiate any claims. Attempts to quantify time improvements between manual and automatic driving for this study were unsuccessful. Any differences were overshadowed by other variations between systems.

Intuitively there should be an improvement in the order of 5 to 10% in the station approach time. As this time represents approximately 40% of station headway, the increase in capacity should be from 2 to 4%.

The calculations used to determine the minimum station headway assume optimal driving but insert a time for a drivers sighting and reaction time — in addition to the equipment reaction time. The calculations in this report compensate for ATO by removing the reaction times associated with manual driving.

3.5 AUTOMATIC TRAIN SUPERVISION

Automatic Train Supervision (ATS) encompasses a wide variety of options. It is generally not a safety-critical aspect of the train control system and may not need the rigor of design and testing to its hardware and software that characterizes other areas of train control. At its simplest it does little more than display the location of trains on a mimic board or video screen in the central control or dispatcher's office.

One step up in sophistication provides an indication of on-time performance with varying degrees of lateness designated for each train, possibly grouped by a color code or with a digital display of the time a train is behind schedule. In either case corrective action is in the hands of the variously named controller, dispatcher or trainmaster.

Urban rail transit in North America is generally run to a timetable. Those systems in Europe that consistently operate at the closest headways (down to 90 sec) generally use headway regulation that attempts to ensure even spacing of trains rather than adhere strictly to a timetable. Although it appears that keeping even headways reliably provides more capacity, this is an issue of tradition, operating rules and safety[13] that is beyond the scope of this study.

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

Corrective action can include eliminating coasting, increasing line speed, moving to higher rates of acceleration and braking and adjusting dwell times — usually only where these are preprogrammed. Such corrective action supposes that the system does not normally work flat out.

The Vancouver system is an example of unusually comprehensive ATS strategies. Here trains have a normal maximum line speed of 80 km/h (50 mph) which ATS can increase to 90 km/h as a catch up measure — where civil speed restrictions so permit. Similarly acceleration and braking can be adjusted upwards[14] or downwards by 10%.

In normal operation trains use less than their full performance which reduces energy consumption and maintenance, and leaves a small leeway for on-time corrective action. Together, these strategies can pick up 2 to 3 min in an hour.

Correcting greater degrees of lateness or irregularity generally involves manual intervention using short turn strategies or removing slow-performing or defective trains from service.[15] This is difficult to implement in the peak period and common practice is to let the service run as best it can and wait to make corrections to the timetable until after the peak period.

A further level of ATS strategies is possible — predictive control. Although discussed as a possibility, this level is not known to be used in North America. In predictive control a computer looks ahead to possible conflicts, for example a merge of two branches at a junction. The computer can then adjust terminal departures, dwell times and train performance to ensure that trains merge evenly without holds, or are appropriately spaced to optimize turn-arounds at any common terminal.

The nonvital ATS system can also be the host for other features such as on-board system diagnostics and the control of station and on-board information through visual and audio messages — including those required by ADA.

Summary ATS has the potential to improve service regularity and so help maximize capacity. However, the strategies to correct irregular service on rail transit are limited unless there is close integration with ATO and the possibilities of adjusting train performance and station dwells. Without such strategies, ATS allows dispatchers to see problems but remain unable to address them until the peak period is over. In Chapter Six, *Operating*

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[13] Certain Russian systems that maintain remarkably even 90-sec headways require drivers to close doors and depart even if passenger flow is incomplete.

[14] A train's performance is limited by motor heating characteristics. Corrective actions that increase performance also increase heating. Depending on ambient temperature this can only be carried out for a limited period before the train's diagnostic equipment will detect over-heating and either cut one or more motors out or force a drop to a lower performance rate.

[15] One North American system is known to use a skip-stop strategy for seriously late trains, that is running through a station where the train would normally stop. Akin to the bus corrective strategy of "set downs only, no pick-ups," this is both unusual and can be difficult for passengers to accept.

Issues, an operational allowance to compensate for irregular operation is developed. A sophisticated ATS system in conjunction with a range of feasible corrective actions can reduce the desired amount of operating margin time.

3.6 FIXED-BLOCK THROUGHPUT

Determining the throughput of any rail transit train control system relies on the repetitive nature of rail transit operation. In normal operation trains follow each other at regular intervals traveling at the same speed over the same section of track.

All modern trains have very comparable performance. All low-performance equipment in North America is believed to have been retired. Should a line operate with equipment with different performance and/or trains of different length, then the maximum throughput rates developed in this section should be based on the longest train of the lowest performing rolling stock.

Trains operating on an open line with signaling protection but without station stops have a high throughput. This throughput is defined as *line* or *way capacity*. This capacity will be calculated later in this section although it has little relevance to achievable capacity except for systems with off-line stations. Only Automated Guideway Transit, or some very high capacity lines in Japan, can support off-line stations.

Stations are the principal limitation on the maximum train throughput — and hence maximum capacity — although limitations may also be due to turn-back and junction constraints. The project survey of operating agencies indicated that the station close-in plus dwell time was the capacity limitation in 79% of cases, turnback constraints in 15%, and junctions in 5% of cases. Further inquiry found that several turnback and junction constraints were self-imposed due to operating practices and that stations were by far the dominant limitation on throughput.

In a well-designed and operated system, junction or turnback constrictions or bottlenecks should not occur. A flat junction can theoretically handle trains with a consolidated headway approaching 2 min. However, delays may occur and systems designed for such close headways will invariably incorporate grade-separated (flying) junctions. Moving-block signaling systems provide even greater throughput at flat junctions as discussed in section 3.10.

A two-track terminal station with either a forward or rear scissors cross-over can also support headways below 2 min unless the cross-overs are long, spaced away from the terminal platform, or heavy passenger movements or operating practices when the train crew changes ends (reverses the train) result in long dwells. The latter two problems can be resolved by multiple-platform terminal stations, such as PATH's Manhattan and Hoboken terminals and Mexico City's Indios Verdes station, or by establishing set-back procedures for train crews.[16]

In this chapter the limitations on headway will be calculated for all three possible bottlenecks: station stops, junctions and turnbacks.

Nine reports in the literature survey provide detailed methods to calculate the throughput of fixed-block rail transit signaling systems:

- AUER, J.H., Rail-Transit People-Mover Headway Comparison(R9)
- BARWELL, F. T., Automation and Control in Transport(R11)
- BERGMANN, DIETRICH R., Generalized Expressions for the Minimum Time Interval between Consecutive Arrivals at an Idealized Railway Station(R13)
- DELAWARE RIVER PORT AUTHORITY, 90 Seconds Headway Feasibility Study, Lindenwold Line(R21)
- GILL, D.C., and GOODMAN C.J., Computer-based optimisation techniques for mass transit railway signalling design(R26)
- JANELLE, A., POLIS, M.P., Interactive Hybrid Computer Design of a Signaling System for a Metro Network(R31)
- LANG, A SCHEFFER, and SOBERMAN, RICHARD M., Urban Rail Transit Its Economics and Technology(R39)
- VUCHIC, VUKAN R., Urban Public Transportation Systems and Technology(R71)
- WEISS, DAVID M., and FIALKOFF, DAVID R., Analytic Approach to Railway Signal Block Design(R73)

All the reports deal with station stops as the principal limitations on capacity and use Newton's equations of motion to calculate the minimum train separation, adding a variety of nuances to accommodate safety distances, jerk limitations, braking system and drivers' reaction times plus any operating allowance or recovery margin. In the following section a classical approach is examined, followed by a recommended practical approach derived from the work of Auer(R09) in combination with information from several other authors. Then an examination is made of the sensitivity of the results to several system variables.

3.6.1 STATION CLOSE-IN TIME

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

When interference occurs, trains may be held at approaches to stations and interlockings. This requires the train to start from stop and so increases the close-in time, or time to traverse and clear an interlocking, reducing the throughput. With throughput decreased and headways becoming erratic, the number of passengers accumulated at a specific station will increase and so increase the dwell time. This is a classic example of the maxim that when things go wrong they get worse.

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[16] Set back procedures require the train crew or operator to leave the train at a terminal and walk to the end of the platform where they board the next entering train which can be immediately checked and made ready for departure. On a system with typical close headways of two minutes this requires an extra crew every 30 trains and increases crewing costs by some 3%—less if only needed in peak periods. The practice is unpopular with staff as they must carry their possessions with them and cannot enjoy settling into a single location for the duration of their shift.

The minimum headway is composed of three components:

- the safe separation (close-in time),
- the dwell time in the station, and
- an operating margin.

Station dwells are discussed in Chapter Four, *Station Dwells*, recovery margins are discussed in Chapter Six, *Operating Issues.*

3.6.2 COMPUTER SIMULATION

The best method to determine the close-in time is from the specifications of the system being considered[17], from existing experience of operating at or close to capacity or from a simulation. It is common in designing and specifying new rail transit systems, or modernizing existing systems, to run a variety of computer simulation models. These models are used to determine running times, to optimize the design of track work, of signaling systems and of the power supply system. Where the results of these models are available they can provide an accurate indication of the critical headway limitation—whether a station close-in maneuver, at a junction or at a turnback.

Such models can be calibrated to produce accurate results. In particular, many simulation models will adjust train performance for voltage fluctuations in the power supply—a variant that cannot be otherwise be easily calculated. However caution should be exercised in using the output from simulations. Simulations can be subject to poor design, poor execution or erroneous data entry. In particular, increments of analysis are important. The model will calculate the voltage, performance, movement and position of the front and rear of each train in small increments of time, and occasionally in increments of distance or speed. Such increments should approach one tenth of a second to produce accurate close-in times.

Simulation programs are also often proprietary to a specific consultant or train control, traction substation or vehicle supplier. They require considerable detailed site and equipment data. As such, they may not be practical or available for determining achievable capacity, making it necessary to calculate the throughput of the particular train control system by more general methods.

If the minimum headway is not available from the system designers or from a simulation, then straightforward methods are available to calculate the time. Here train separation is based on a *line clear* basis—successive green signals governing the following train. The minimum line headway is determined by the critical line condition, such as the close-in at the maximum load point station plus an operating margin. The entire stretch of line between junctions and turnbacks, where train density is physically constant, is controlled by this one critical time.

The classical expression for the minimum headway of the typical rail transit three-aspect block-signal system is

$$H(t) = \frac{\dfrac{2BL}{v_{ap}} + D_w + \sqrt{\dfrac{2L}{a}}}{1 - M} \qquad \text{Equation 3-1}$$

The block length must be greater than or equal to the service stopping distance.[18]

$$BL \geq SD = \frac{V_{ap}^2}{2d} \qquad \text{Equation 3-2}$$

where $H(t)$ = headway *in seconds*
BL = block length approaching station *(m)*
D_w = station dwell time *in seconds*
SD = service stopping distance *(m)*
L = length of the longest train *(m)*
v_{ap} = maximum approach speed *(m/s)*
a = average acceleration rate through the station platform clear-out *(m/s^2)*
d = braking rate *(m/s^2)*
M = headway adjustment combining operational tolerance and dwell time variance *(constant)*

Although the headway adjustment factor, M, can encompass a variety of items, it is difficult to encompass all the variables that can affect headway. These include

- any distance between the front of the train and the start of the station exit block,[19] particularly if the train is not berthed at the end of the platform;
- control system reaction time;
- on manually driven trains, the train operator sighting and reaction time;
- the brake system reaction time;[20]
- an allowance for jerk limitation;[21]
- speed restrictions on station approaches and exits whether due to speed control for special work or curves; and
- grades approaching and leaving a station.

In addition, the length of the approach block and the approach speed are not readily obtainable quantities. Consequently this traditional method is not recommended and an alternate approach will be developed, based, in part, on the work of Auer. This uses more readily available data accommodating many of the above variables. This approach encompasses both manually and automatically driven trains, multiple command cab controls, and, by decreasing block length, a moving-block system.

Even so, it should be borne in mind that not all variables can be included, and assumptions and approximations are still needed. This approach, while more comprehensive than many in the literature, is not as good as using information from signaling

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[17] The train control design engineers will be aiming to minimize the close-in time and information from this source, particularly if the result of an accurate simulation, is invariably the most accurate way to determine practical capacity.

[18] On close headway systems block lengths may be less than the service stopping distance. New York has approach blocks down to 60m (200′) and lengths as short as 15m (50′) occur on some systems—particularly automated guideway transit systems.

[19] This allows for blocks that do not start at the end of the platform—at the headwall—or shorter trains that are berthed away from the headwall.

[20] Older equipment may have air brakes applied by releasing air from a brake control pipe running the length of the train (train-lined). There is a considerable delay as this command passes down the train and brakes are applied sequentially on cars. Newer equipment uses electrical commands to control the air, hydraulic or electric brakes on each car and response is more rapid.

[21] Limitations applied to the start and end of braking and the start of acceleration to limit the rate of change of acceleration—commonly, if somewhat erroneously called jerk.

engineers, based on actual block positions, or from a comprehensive and well-calibrated simulation.

3.6.3 CALCULATING LINE HEADWAY

On a level, tangent (straight) section of track with no disturbances the line headway $H(l)$ is given by:

$$H(l) = \frac{L + S_{min}}{v_l} \qquad \text{Equation 3-3}$$

where $H(l)$ = line headway in seconds
S_{min} = minimum train separation in meters
L = length of the longest train in meters
v_l = line speed in m/s[22]

The minimum train separation corresponds to the sum of the operating margin and safe separation distance shown in Figure 3.2. It can therefore be further subdivided: *(all in meters)*

$$S_{min} = S_{sbd} + S_{td} + S_{om} \qquad \text{Equation 3-4}$$

where S_{min} = mininimum train separation distance
S_{sbd} = safe braking distance
S_{td} = train detection uncertainty distance
S_{om} = operating margin distance[23]

The safe braking distance is based on the rail transit assumption of brick-wall stops using a degraded service braking rate.[24] The train detection uncertainty reflects either the block length or the distance covered in the polling time increments of a moving-block signaling system. The operating margin distance is the distance covered in this time allowance. This will be omitted from further consideration in this section. It is developed in Chapter Six, *Operating Issues*, and added into the headway calculation by mode in Chapters Seven through Ten.

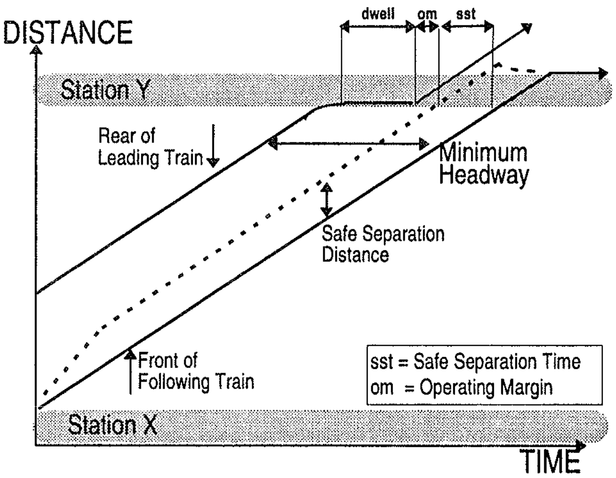

Figure 3.2 Distance-time plot of two consecutive trains (acceleration and braking curves omitted for clarity)

Substituting for S_{min} and removing S_{om} produces

$$H(l) = \frac{L + S_{td} + S_{sbd}}{v_l} \qquad \text{Equation 3-5}$$

There are several components in the safe braking time. The largest is the time to brake to a stop, using the service brake. A constant K is added to assume less than full braking efficiency or reduced adhesion—75% of the normal braking is an appropriate factor. There is also the distance covered during driver sighting and reaction time on manually driven trains, and on automatically driven trains brake equipment reaction time and a safety allowance for control failure. This overspeed allowance assumes a worst case situation whereby the failure occurs as the braking command is issued with the train in full acceleration mode. This is often termed *runaway propulsion*. The train continues to accelerate for a period of time t_{os} until a speed governor detects the overspeed and applies the brakes.[25]

$$S_{sbd} = \frac{100}{K} S_{bd} + S_{br} + S_{os} \qquad \text{Equation 3-6}$$

where S_{bd} = safe breaking distance *in meters*
S_{bd} = service braking distance *in meters*
K = braking safety factor
S_{br} = train operator sighting and reaction distance and/or braking system reaction distance *in meters*
S_{os} = overspeed travel distance *in meters*

The distance to a full stop from speed V_l at the constant service braking, deceleration or retardation rate is given by:

$$S_{bd} = \frac{v_l^2}{2d_s} \qquad \text{Equation 3-7}$$

where d_s = service deceleration rate *in m/s*^{2}

To be rigorous, the safe braking distance should also take into account grades, train load—passenger quantities and any snow and ice load and, in open line sections, any tail wind. These add complexities beyond the scope of this study and, except for downgrades, contribute a very minor increment to the result. Consequently they have been omitted. The effect of grades will be examined in the sensitivity analysis at the end of this section.

Modern rail transit equipment uses a combination of friction and electrical braking,[26] in combination with slip-slide controls, to maintain an even braking rate. An allowance can be added for the jerk limiting features that taper the braking rate at the beginning and end of the brake application.

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[22] Can be worked in feet with speed in feet per second. 10 mph=14.67 ft/sec, 10 km/h = 2.78 m/s

[23] Auer used the term *service control buffer distance*.

[24] Some workers use the emergency braking rate. As this is highly variable depending on location, equipment, and wheel to rail adhesion, it is not recommended.

[25] As the braking so applied is usually at the emergency rate, a case can be made that this component may be discounted or reduced.

[26] Electrical braking is both dynamic—with recovered energy burned by resistors on each car, or regenerative braking with recovered energy fed back into the line—here it feeds the hotel load of the braking train, adjacent trains, is fed back to the power utility via bi-directional substations or is burned by resistors in the substation. The latter two modes are rare. Regenerative braking was common in the early days of electric traction. It then fell out of use when the low cost of electricity failed to justify the additional equipment costs and maintenance. With increased energy costs and the ease of accommodating regeneration on modern electronic power conversion units, regeneration is now becoming a standard feature. Regeneration is sometimes termed recuperation.

The distance an automatically operated train moves until the overspeed governor operates can be expressed as

$$S_{os} = v_l t_{os} + \frac{a_l t_{os}^2}{2} \qquad \text{Equation 3-8}$$

where S_{os} = overspeed distance
t_s = time for overspeed governor to operate
a_l = line acceleration rate in m/s^2 at v_l
v_l = line speed

Substituting Equations 3-6, 3-7, and 3-8 in Equation 3-5 and adding a jerk limiting allowance produces

$$H(l) = \frac{L + S_{td}}{v_l} + \frac{100}{K}\left(\frac{v_l}{2d_s}\right) + \frac{a_l t_{os}^2}{2v_l} + t_{os} + t_{jl} + t_{br}$$

Equation 3-9

where t_{br} = train operator sighting and reaction time and/or braking system reaction time
t_{jl} = jerk limiting time allowance

Service acceleration is said to be following the motor curve as it reduces from the initial controlled rate to zero at the top, maximum, or balancing speed of the equipment. The acceleration rate at a specific speed may not be readily available and an approximation is appropriate for this item—a small component of the total line headway time. On equipment with a balancing speed of 80 km/h, the initial acceleration is maintained until speeds reach 10-20 km/h then tapers off, approximately linearly until speeds of 50-60 km/h, then approximately exponentially until it is zero. At line speeds appropriate to this analysis the line acceleration rate can be assumed to be approximate to the inverse of speed so that for intermediate speeds

$$a_l \cong a_s\left(1 - \frac{v_l}{v_{max}}\right) \qquad \text{Equation 3-10}$$

where v_l = line speed in m/s
v_{max} = maximum train speed in m/s
a_l = line acceleration rate in m/s^2
a_s = initial service acceleration rate in m/s^2

The train detection uncertainty distance is not readily available but can be approximated as either the block length(s)—again not easily obtained—or the braking distance plus some leeway as a surrogate for block lengths on a system designed for maximum throughput. This quantity is particularly useful as a simple method to adjust for the differences between the traditional three-aspect signaling system, cab controls with multiple aspects (command speeds) and moving-block signaling systems.

$$S_{td} \cong B\left(\frac{v_l^2}{2d_s}\right) \qquad \text{Equation 3-11}$$

where B is a constant representing the increments or percentage of the braking distance—or number of blocks—that must separate trains according to the type of train control system. A B-value of 1.2 is recommended for multiple command cab controls. A value of 2.4 is appropriate for three-aspect signaling systems where there is always a minimum of two clear blocks between trains.[27] The value of B for moving-block signaling systems can be equal to or less than unity and is developed in the next section.

Accepting these approximations and substituting Equations 3-10 and 3-11 in Equation 3-9 produces

$$H(l) = \frac{L}{v_l} + \left(\frac{100}{K} + B\right)\left(\frac{v_l}{2d_s}\right) + \frac{a_s t_{os}^2}{2v_l}\left(1 - \frac{v_l}{v_{max}}\right)$$
$$+ t_{os} + t_{jl} + t_{br}$$

Equation 3-12

where $H(l)$ = line headway *in seconds*
L = length of the longest train *in meters*
v_l = line speed in *m/s*
K = braking safety factor—worst case service braking is K% of specified normal rate—typically 75%
B = separation safety factor—equivalent to the number of braking distances (surrogate for blocks) that separate trains
t_{os} = overspeed governor operating time[28] *(s)*
t_{jl} = time lost to braking jerk limitation *(s)*
t_{br} = operator & brake system reaction time *(s)*
a_l = line acceleration rate *in m/s^2*
d_s = service deceleration rate *in m/s^2*

North American rail transit traction equipment tends to have very similar performance derived from the work of the Presidents' Conference Committee (PCC) in the mid 1930s. The chief engineer, Hirschfeld,[29] placed subjects on a moving platform and determined the acceleration rate at which they lost their balance or became uncomfortable. A wide variety of subjects were tested including people who were pregnant, inebriated or holding packages. From this pioneering work, the PCC streetcar evolved and with it rates of acceleration and deceleration (and associated jerk[30]) that have become industry standards. The recommended maximum rate is 3.0 mphps (1.3 m/s^2) for both acceleration and deceleration.

Attempts have been made to increase these rates, specifically on the rubber tired metros in Montreal and Mexico City, but subsequently these were reduced close to the industry standard. Except for locomotive hauled commuter rail, almost all rail transit in North America operates with these rates. The main difference in equipment performance is the maximum speed. Most urban rail systems with closer station spacing have a maximum speed of 50-60 mph (80-95 km/h), light rail typically has a maximum speed of 50 mph (80 km/h),[31] while streetcars have a maximum in the range of 40-50 mph (65-80 km/h). The few suburban type rail rapid transit systems have a higher maximum of 70-80 mph (110-130 km/h)—BART in San Francisco and PATCO in Philadelphia are the principal examples.

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[27] On existing systems the results can be calibrated to actual performance by adjusting the value of "*B*".

[28] t_{os}+ t_{jl}+ t_{br} may be simpified by treating as a single value—typically 5 sec for systems with ATO, slightly longer with manual driving.

[29] HIRSCHFELD, C.F., Bulletins Nos. 1-5, Electric Railway Presidents' Conference Committee (PCC), New York, 1931-1933.

[30] jerk—rate of change of acceleration.

[31] SEPTA's Norristown line is a higher speed exception.

The higher gearing rates required for these higher speeds result in either a reduced initial acceleration rate or, more typically, an acceleration rate that more rapidly reduces (follows the motor curve) as speed increases.

Braking rates are invariably uniform. Emergency braking rates vary widely and are significantly higher and more sustainable on equipment fitted with magnetic track brakes — all streetcars, most light rail and the urban rail transit systems in Chicago and Vancouver.

This relative uniformity of rates allows a typical solution of Equation 3.11 using the following data for a cab control system with electrically controlled braking and a train of the maximum length in North American rail transit.

The results of applying typical rail transit data to Equation 3-9 are shown in Figure 3.3 using the data values of Table 3.1.

Table 3.1 Data values for line headway

TERM	VALUE	
Train length	200 m	660 ft
Overspeed governor time[32]	3 sec	3 sec
Braking safety factor ***K***	75%	75%
Separation safety factor ***B***	1.2	1.2
Initial service acceleration rate	1.3 m/s^2	3.0 mphps
Service deceleration rate	1.3 m/s^2	3.0 mphps

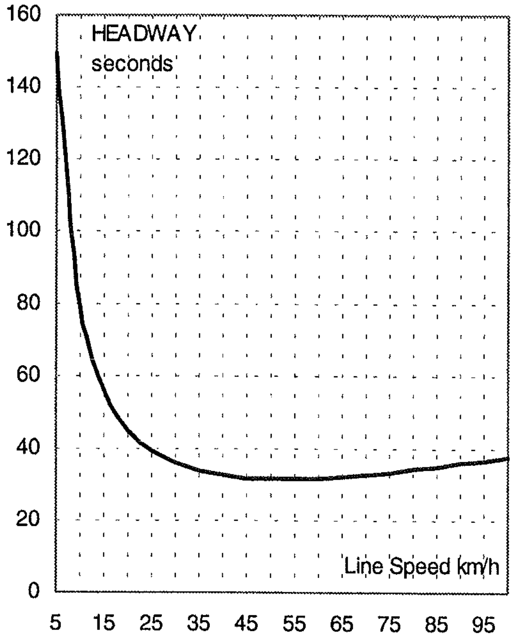

Figure 3.3 Line headway versus speed

Table 3.2 Breakdown of line headway time components

Speed km/h	Time to travel length	Time to brake x(100/*K*+*B*)	Over-speed accel. time	Over-speed time[33]	Jerk allow-ance	Line head-way
COLUMN	**1**	**2**	**3**	**4**	**5**	**6**
10	72.00	2.70	0.40	3	0.5	78.61
20	36.00	5.41	0.20	3	0.5	45.10
30	24.00	8.11	0.13	3	0.5	35.74
40	18.00	10.81	0.09	3	0.5	32.40
50	14.40	13.51	0.07	3	0.5	31.49
60	12.00	16.22	0.06	3	0.5	31.78
70	10.29	18.92	0.05	3	0.5	32.75
80	9.00	21.62	0.04	3	0.5	34.16
90	8.00	24.33	0.03	3	0.5	35.86
100	7.20	27.03	0.03	3	0.5	37.76

These are somewhat theoretical, showing headways down to 31.5 seconds — 120 trains per hour. There is a clear minimum at 50 km/h (31 mph). Obviously restricting train line speed to so low a value would be uneconomic, requiring a larger number of cars to meet a given demand — which would, in any event, diminish because of the slow travel times deterring passengers.

The equation and results will be applied in Chapter 10 for automated guideway transit with off-line stations and will be used as a basis for determining realistic headways with station stops.

To this end it is useful to examine the value of the components in the line headway, shown in Table 3.2 with all figures in seconds. Columns one through five in this table represent, consecutively, the first five terms of Equation 3-12. The time to travel the length of train and the factored braking time predominate. No value has been assigned to the brake system reaction time. The time associated with the runaway acceleration is small. Equation 3-12, adjusted to compensate for grades and line voltage variations, is included in the spreadsheet on the computer diskette. For manual calculations, the equation can be simplified to:

$$H(l) = 4 + \frac{L}{v_l} + 1.3\left(\frac{v_l}{d_s}\right) \qquad \text{Equation 3-13}$$

where the constant 4 is approximately the rounded up sum of columns 3, 4 and 5 plus a small allowance for brake reaction time. This should be increased to 7 for manually driven systems to add the train operator sighting and reaction time.

The next step is to accommodate station stops. Reference to the literature will show numerous ways to calculate the station headway. This approach is based on adapting the line headway equation.

3.6.4 CALCULATING STATION HEADWAY

Station headway, the time for one train to replace another at the maximum load point station, is by far the most common capacity

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[32] The 3-sec figure is conservative. For automatically driven trains, a time of 1 sec is appropriate and can drop as low as 0.2 sec on AGT systems. The higher figure is useful on cab control systems. When the overspeed detection occurs, and alarm is sounded in the cab to allow the driver to apply service braking and so cancel the automatic application of emergency brakes — avoiding wheel flats and passenger discomfort or loss of balance. The delay time is then based on typical manual reaction times of 2 to 3 sec. With entirely manual operation this term becomes a surrogate for driver sighting and reaction time. Values of 2 to 5 sec have been quoted in the literature. 3 sec is an appropriate value.

[33] Overspeed time is applicable to automatically driven trains.

limitation. Having derived an expression for line headway that uses readily available information with as few approximations as possible, it is possible to adapt this to station headway by

- changing line speed to approach speed and solving for this speed,
- adding a component for the time a train takes to clear the platform,
- adding the station dwell, and
- adding an operating margin.

The time for a train to clear the platform is

$$t_c = \sqrt{\frac{2(L + D)}{a_s}} \qquad \text{Equation 3-14}$$

Adding Equation 3-14 to 3-12 plus components for dwell and an operating margin produces the station headway

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

Equation 3-15

where
$H(s)$ = station headway *in seconds*
L = length of the longest train *in meters*
D = distance from front of stopped train to start of station exit block *in meters*
v_a = station approach speed *in m/s*
v_{max} = maximum line speed *in m/s*
K = braking safety factor—worst case service braking is K% of specified normal rate—typically 75%
B = separation safety factor—equivalent to number of braking distances plus a margin, (surrogate for blocks) that separate trains
t_{os} = time for overspeed governor to operate
t_{jl} = time lost to braking jerk limitation—(seconds) typically 0.5 seconds
t_{br} = operator and brake system reaction time
t_d = dwell time *(seconds)*
t_{om} = operating margin *(seconds)*
a_s = initial service acceleration rate *in m/s*^{2}
d_s = service deceleration rate *in m/s*^{2}

Typical values will be used and this equation solved for the approach speed under two circumstances:

1. three-aspect signaling system ($B = 2.4$)
2. multiple command speed cab controls ($B = 1.2$)

A 45-sec dwell time is used—typical of the busiest stations on rail transit lines operating at capacity—together with an operating margin time of 20 sec. The brake system reaction time will use a moderate level of 1.5 sec—this should be higher for old air brake equipment, lower for modern electronic control, particularly with hydraulically actuated disk brakes. Other factors remain at the levels used in the line headway analysis. (See Table 3.3.) The results of solving Equation 3.15 for minimum headway in Table 3.4 show a distinct optimum approach speed for fixed-block systems. Moving-block signaling systems, which adjust their separation according to speed, are discussed in the next section. The values are calculated in Table 3.5 with different values of dwell and operating margin times. Speeds are rounded to the nearest km/h or mph reflecting the approximations used in their derivation. As Figure 3.4 deals with maximum length trains, running at minimum headways, at the longest dwell[35] station, dwell times of 30 sec may not be possible and the lower values of H(s) are unlikely. The above calculations do not take into account any speed restriction in the station approach. Reference to Figure 3.4 shows a rapid fall off in throughput as the approach speed decreases. Speed restrictions may be due to curves, special work, or speed controls approaching a terminal station. The Figure 3.5 shows the speed of a braking train against

Table 3.3 Data values for station headway

TERM	VALUE
Train length	200 m (660')
Front of train distance	10 m (33')
Overspeed governor time	3 sec
Jerk limitation time	0.5 sec
Brake system reaction time	1.5 sec
Controlling dwell time	45 sec
Operating margin time	20 sec
Braking safety factor K	75%
Separation safety factor B	1.2 or 2.4[34]
Initial acceleration rate	1.3 m/s^2
Service braking rate	1.3 m/s^2

[34] $B = 1.2$ for cab control, 2.4 for 3 aspect signaling

Table 3.4 Optimum approach speeds

	Three-aspect signaling		Multi-code cab signaling	
Optimum approach speed	47 km/h	29 mph	52 km/h	32 mph

Table 3.5 Headways with dwell and operating margins

TIMES		MINIMUM HEADWAY	
Dwell time	Operating margin	Three-aspect signaling	Multi-code cab signaling
45 sec	25 sec	127 sec	121 sec
45 sec	15 sec	117 sec	111 sec
30 sec	25 sec	103 sec	96 sec
30 sec	15 sec	93 sec	86 sec

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[35] The longest dwell station is usually at the maximum load point station and is so assumed through this report. Reference to Chapter Four, *Station Dwells* shows that a high-volume mixed-flow station could have a longer dwell than the higher volume maximum load point station.

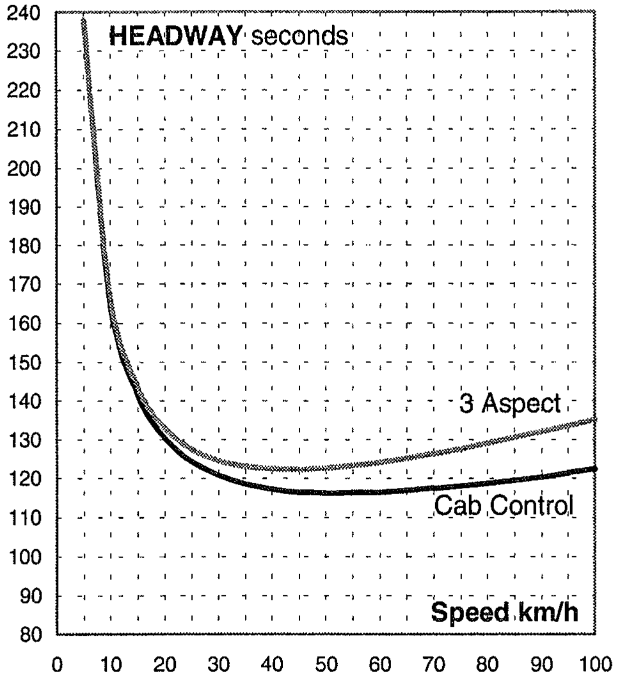

Figure 3.4 Station headway for lines at capacity

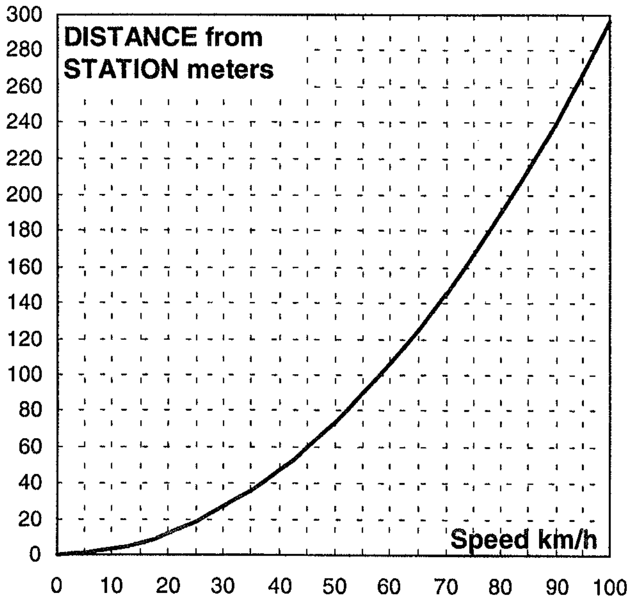

Figure 3.5 Distance — Speed chart

distance — using the performance data of Table 3.3. If a more restrictive speed limit is within the distance for a given approach speed — plus the length of the train — then that more restrictive limit should be used in Equation 3-15 to calculate the minimum headway.

On existing systems speed limits are usually posted on the wayside and included in the rule book. On new systems where speed limits are not known they can be approximated from

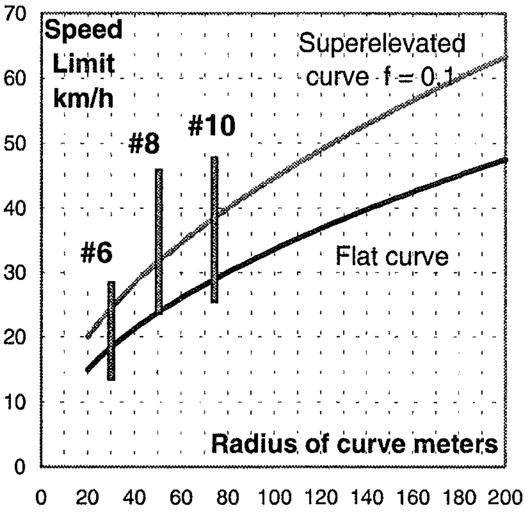

Figure 3.6 Speed limits on curves and switches

$$v_{sl} = (87R(e+f))^{1/2} \qquad \text{Equation 3-16}$$

where v_{sl} = speed limit in km/h
R = radius of curvature in meters
e = superelevation ratio (height the outer rail is raised divided by track gauge) usually not greater than 0.10
f = comfort factor (ratio of radial force to gravitational force — 0.13 is the maximum used in rail transit with some systems using as low as 0.05)

In U.S. customary units, mph and feet, the speed limit is

$$v_{sl} = (15R(e+f))^{1/2} \qquad \text{Equation 3-17}$$

The results of speed limits due to curves are plotted below for both flat curves and curves superelevated with the maximum radial force (e = 0.10). Transition spirals are not taken into account in Figure 3.6. The vertical bars show the AREA[36] recommended speed limit range for lateral and equilateral level turnouts of size #6, #8 and #10. Note that many operators have their own speed limits for turnouts that may differ from those shown.

3.7 SENSITIVITY

Two factors have not been taken into account in the determination of minimum headways in the preceding section — grades and fluctuations in traction voltage.

3.7.1 GRADES

The principal effect of grades is where downgrades into stations increase the braking distance[37] and the distance associated with

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[36] American Railway Engineering Association.

[37] Certain modern equipment uses accelerometers to adjust propulsion and braking to constant levels — independent of train load or grades. In this case grade need not be taken into account — up to the point that wheel-rail adhesion becomes inadequate — an unlikely event.

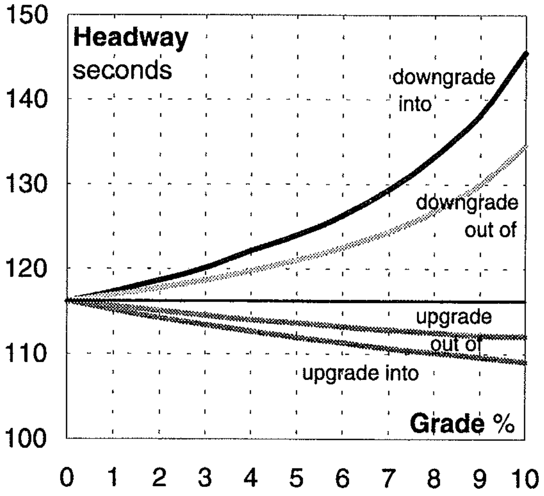

Figure 3.7 Effect of grade on station headway
(cab signals, dwell = 45, margin = 20 secs)

Table 3.6 Result of 4% station grades on headway
(cab signals, dwell = 45, margin = 20 secs)

4% grade	down in	up into	down out	up out
change	+5.9 secs	-3.6 secs	+3.5 secs	-2.2 secs
%	+7.3%	-3.1%	+3.0%	-1.9%

the runaway propulsion factor. A simple method to compensate for grades is to adjust the service braking and acceleration rates in Equation 3-15 while holding the component of the equation that relates to the time for a train to exit a platform constant. The acceleration due to gravity is 9.807 m/s^2. Thus each 1% in downgrade reduces the braking rate by 0.098 m/s^2. The results are shown in Figure 3.7. Note that most rail transit systems have design standards that limit grades to 3 or 4%, a few extend to 6% and the occasional light rail grade can extend to 10%. The impact of grades is greater into a station. The greatest impact is a downgrade into a station which increases the braking and so the safe separation distance. Block lengths must be longer to compensate for the longer braking distances. The absolute and percentage changes are tabulated in Table 3.6 for the typical heavy rail maximum grade of 4%.

3.7.2 LINE VOLTAGE

Rail transit in North America is supplied by direct current power at a potential of 600 to 750 volts with the occasional 1,500-volt system. As more power is drawn through the substations, feeders and third rail or overhead catenary, the voltage drops. Voltage is higher in the vicinity of substation feeders and drops off with distance. Voltage is said to be regulated within a system specification that is typically +20% to -30%.[38] The lowest voltage occurs at locations most remote from sub-stations in the peak hour when the maximum number of trains are in service. The lower voltage reduces train performance—at a time when the heavy passenger load is doing likewise. Both acceleration and balancing speed are reduced; braking is not affected.

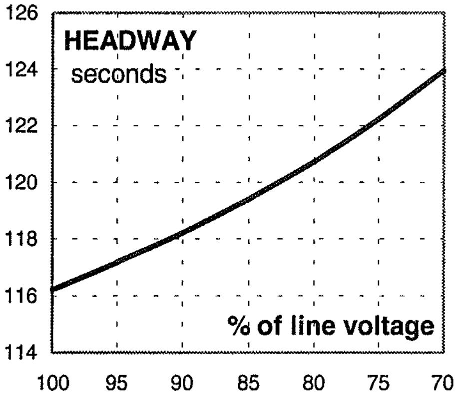

Figure 3.8 Headway changes with voltage

The acceleration of a train is approximately proportional to the power applied to the motors, which in turn is proportional to the square of the supply voltage. This is particularly true for older equipment with switched resistor controls[39], less so with modern electronically controlled equipment.[40] Consequently, for older equipment without on-board motor voltage feedback and control, the common 10% reduction in voltage will reduce acceleration to 81% of normal, the very rare 30% drop will reduce acceleration to 49% of normal.

Reduced acceleration affects the platform clear out component of the headway calculation. The resultant headway sensitivity to voltage is shown below. At a typical 15% drop in voltage (85% in Figure 3.8), headway increases by 3.2 seconds, a 2.7% change. It is not possible to calculate line voltage at any instance of time without a complete train performance and traction supply system simulation. This will automatically occur if a simulation is used to determine the minimum headway. Otherwise it is uncertain whether a manual adjustment should be made based on the above chart—with certain designs of modern rolling stock the effect of voltage drop can be less than shown.

3.7.3 ACCELERATION

Changes in acceleration affect the time required for a train to clear the platform and make minor adjustments to the runaway

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[38] Certain newer rail systems have purchased vehicles with electronic motor controls that are intolerant of voltage drops. Consequently the traction supply voltage has to be regulated to closer tolerances.

[39] Estimated to be used on about three quarters of the rolling stock in North America, including all NYCT cars except prototypes.

[40] Modern electronically controlled equipment may use accelerometers which will command the vehicle's power conversion unit to compensate for reduced voltage. Similar feedback systems may attempt to regulate motor voltage—ven with reduced line voltage. However such corrective action defeats the self regulating effect of the reduced line voltage—a rationing of power when demand from the trains exceeds the capability of the power supply — and so increases the likelihood that the power supply system will trip (disconnect) due to overload. On manually driven systems lower line voltage is immediately apparent to the driver and serves as an advisory to reduce demand or, when trains are lined up due to a delay, to start up in sequential order rather than simultaneously. Consequently, providing full correction for drops in line voltage is unwise.

propulsion safety factor. Headways for a cab signal train control system are shown with acceleration adjusted to 50%, 75% and 125% of the normal value—1.3 m/s^2(3.0 mphps). (See Figure 3.9).

3.7.4 BRAKING

Changes in braking rate affect both the braking time and the safe separation time. Headways for a cab signal train control system are shown with braking adjusted to 50%, 75% and 125% of the normal value in Figure 3.10. Changes in the braking rate have a greater effect on headway than those of acceleration. Note that the optimum approach speed increases with the braking rate. The normal rate (100%) is 1.3 m/s^2 (3.0 mphps).

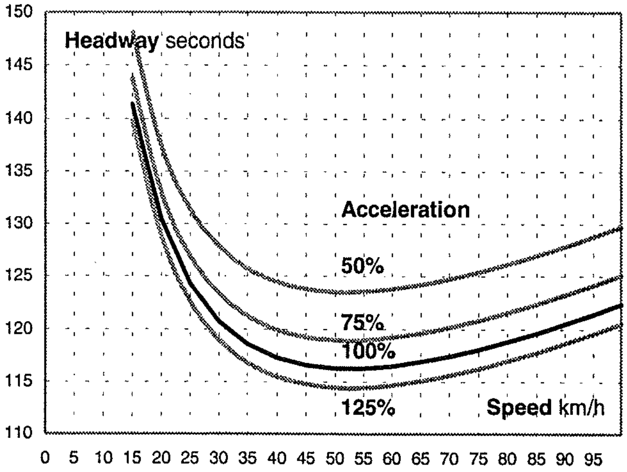

Figure 3.9 Headway changes with the acceleration rate

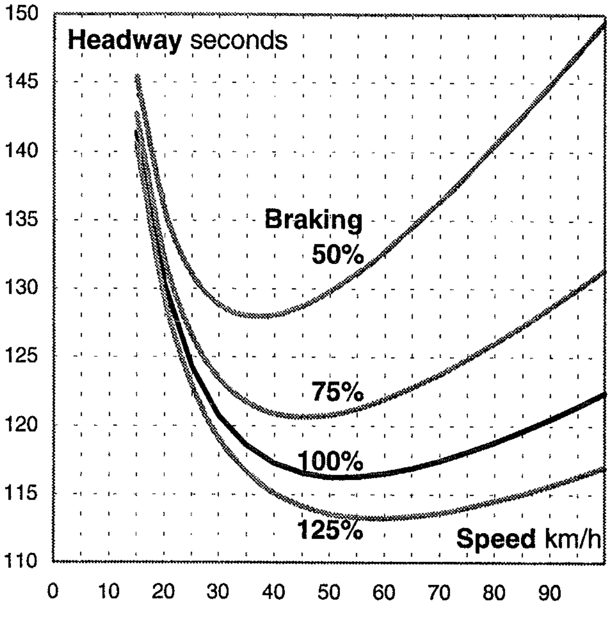

Figure 3.10 Headway changes with the braking rate

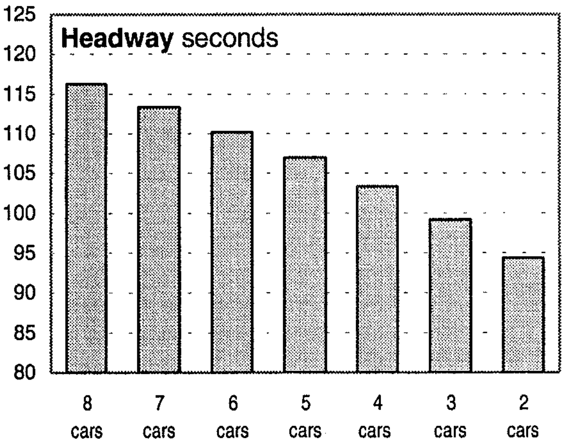

Figure 3.11 Headway changes with train length

3.7.5 TRAIN LENGTH

All previous work in this section has used a maximum train length of 200 m (660 ft). Shorter trains will permit closer train spacing as shown in Figure 3.11.

3.8 MOVING-BLOCK THROUGHPUT

Moving-block signaling systems can use a fixed safety separation distance, plus the calculated braking distance, to separate trains, or a safety distance that is continually adjusted with speed and grades. In this section both approaches will be developed and compared.

3.8.1 FIXED SAFETY DISTANCE

The minimum station headway for the close-in operation is expressed in Equation 3-15. For a moving-block signaling system there is no requirement for a train to travel its own length and vacate the station platform before freeing up a block for the following train. Rather, the moment a train starts from a platform the distance so freed is added to that available for the following train to proceed.

The term for the time to clear the platform block can be removed. The safety separation constant B—a surrogate for the number of blocks between trains can be set to zero. The fixed safety distance can be added to the train length to produce a term that represents the time to travel both the train length plus the fixed safety distance. The overspeed acceleration time equivalent and time constant terms can be removed—allowance for runaway propulsion is included in the fixed safety distance. The overspeed time can similarly be deleted.

The other factors in the equation should remain. The braking reaction time can be adjusted for the specific equipment. The station headway Equation 3-15 is shown below with the main components identified

$$\underbrace{H(s)}_{\text{Station close-in headway}} = \underbrace{\sqrt{\frac{2(L+D)}{a_s}}}_{\text{Time to vacate platform}} + \underbrace{\frac{L}{v_a}}_{\text{Time to travel own length}} + \left(\underbrace{\frac{100}{K}}_{\text{Brake system level \%}} + \underbrace{B}_{\text{Safe separa-tion factor}}\right)\underbrace{\left(\frac{v_a}{2d_s}\right)}_{\text{Brak-ing time}} + \underbrace{\frac{a_s t_{os}^2}{2v_a}\left(1-\frac{v_a}{v_{\max}}\right)}_{\text{Time equivalent of overspeed acceleration}} + \underbrace{t_{os}}_{\text{Over-speed time}} + \underbrace{t_{jl}}_{\text{Jerk limit time}} + \underbrace{t_{br}}_{\text{Brake system reac-tion time}} + \underbrace{t_d}_{\text{Station dwell time}} + \underbrace{t_{om}}_{\text{Operat-ing margin time}}$$

where $H(s)$ = station headway *in seconds*
L = length of the longest train *in meters*
D = distance from front of stopped train to start of station exit block in meters
v_a = station approach speed *in m/s*
v_{max} = maximum line speed *in m/s*
K = braking safety factor—worst case service braking is K% of specified normal rate—typically 75%
B = separation safety factor—equivalent to number of braking distances (surrogate for blocks) that separate trains
t_{os} = time for overspeed governor to operate on automatic systems—to be replaced with driver sighting and reaction times on manual systems (seconds)
t_{jl} = time lost to braking jerk limitation—typically 0.5 seconds
t_{br} = brake system reaction time—*older air brake equipment only (seconds)*
t_d = dwell time *(seconds)*
t_{om} = operating margin *(seconds)*
a_s = initial service acceleration rate *in* m/s^2
d_s = service deceleration rate *in* m/s^2

The final four time constants can be abbreviated so that

$$\sum t = t_{jl} + t_{br} + t_d + t_{om} \qquad \text{Equation 3-18}$$

The adaptation of Equation 3-15 for a moving-block signaling system with fixed safety separation becomes

$$H(s) = \frac{L + S_{mb}}{v_a} + \frac{100}{K}\left(\frac{v_a}{2d_s}\right) + \sum t \qquad \text{Equation 3-19}$$

where S_{mb} = moving-block safety distance

The calculation of the appropriate safety distance is described by Motz[R47]. The process is complicated and requires judgment calls on how to represent the worst case situation. The final figure may involve compromises involving decisions of the appropriate government regulatory body (if any) and/or the rail transit system executive.

The Vancouver SkyTrain moving-block signaling system uses a short safety distance of 50 m (165 ft), reflecting the short trains and high levels of assured braking from magnetic track brakes and motor braking—both independent of traction power. The resultant throughput is high and becomes limited by station dwells, junctions and issues of operational allowances.

Safety distances for more conventional equipment are triple or quadruple, particularly if there are significant grades. In these circumstances a variable safety distance will increase the throughput.

This alternate approach develops an approximation for a safety distance that adjusts with circumstances. In this case the assumption is made that the safety distance comprises the braking distance (i.e., $B = 1$) plus the runaway propulsion components and a positioning error distance—all adjusted for any downgrade into the *headway critical station.*

Discounting grades for the moment the station headway can be represented by:

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

Equation 3-20

where Pe = positioning error
B = 1

Adjusting for a the grade into a headway critical station, the service acceleration should be increased by one hundredth of the force of gravity for each percentage of grade, and the service braking rate reduced similarly. Thus the acceleration rate is multiplied by (1 - gG/100) where g is the acceleration due to gravity (9.807 m/s2) and G is the percentage grade—negative for downgrades. This adjustment approximates to (1 - 0.1G). The result becomes

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

Equation 3-21

The results of this equation are shown in Figure 3.12 using data from Table 3.3 with $B = 1$ and a positioning error of 6.25 m (21 ft). The resultant minimum headway of 97 sec occurs at an approach speed of 56 km/h (mph). The respective curves for a conventional three-aspect signaling system and a cab control system are included for comparison. As would be expected, a

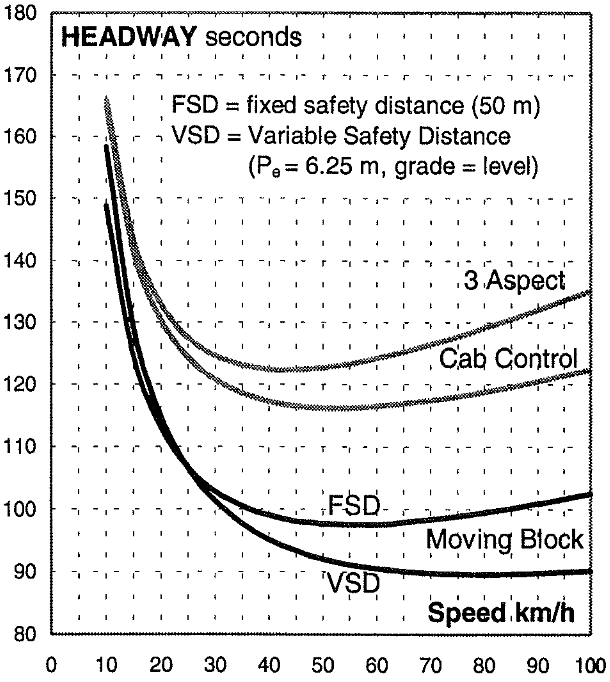

Figure 3.12 Moving-block headways with 45-sec dwell and 20-sec operating margin compared with conventional fixed-block systems

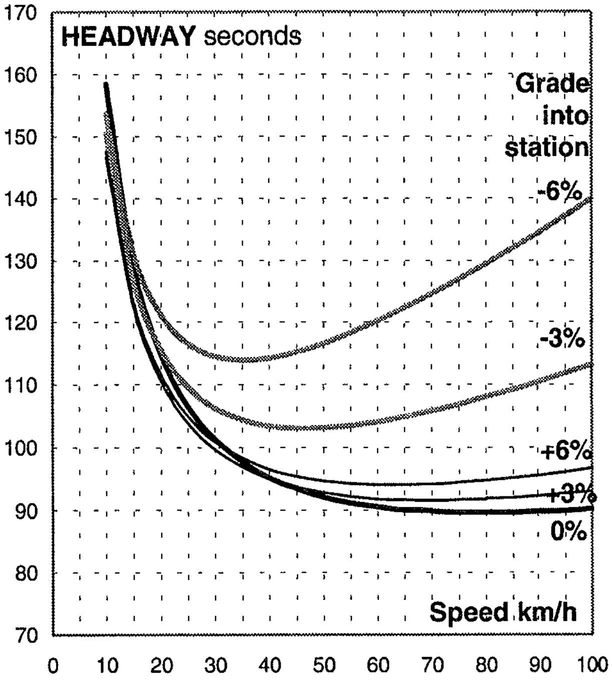

Figure 3.13 Effect of grades on a moving-block signaling system with variable safety distance

moving-block system with a speed variable safety distance shows the lowest overall headway. The difference between the two methods of determining the safety distance represents an eight second difference in the minimum headway—pointing out the importance of selecting the best method when a close headway is required.

The elasticity of moving-block headways with respect to voltage fluctuations will be negligible as the time to clear the platform is not a component in calculating the moving-block signaling system headway. The effect of grades is shown in Figure 3.13.

Downgrades (negative) into a station significantly reduce the minimum headway while positive grades have little effect.

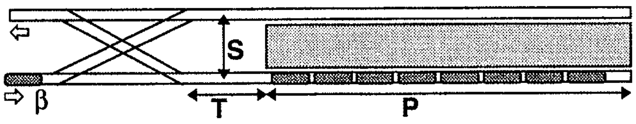

Figure 3.14 Terminal station track layout[42]

3.9 TURN-BACK THROUGHPUT

Correctly designed and operated turn-backs should not be a constraint on capacity. A typical minimal terminal station arrangement with the preferred[41] center (island) platform is shown in Figure 3.14. The worst case is based on the arriving train (lower left) being held at the cross-over approach signal while a train departs. It must, moving from a stop, traverse the cross-over and be fully berthed in the station before the next exiting train (lower right) can leave. The distance involved is

$$D_a = P + T + CS \qquad \text{Equation 3-22}$$

where D_a = approach distance
P = platform length
T = distance from cross-over to platform
S = track separation (≅ platform width +1.6m)
C = switch angle factor
5.77 for #6 switch
6.41 for #8 switch
9.62 for #10 switch

The time for this maneuver is expressed as

$$t_a = 2\sqrt{\frac{2D_a}{a_s + d_s}} = 2\sqrt{\frac{2(P + T + CS)}{a_s + d_s}} \qquad \text{Equation 3-23}$$

where t_a = approach time
a_s = initial service acceleration rate in m/s^2
d_s = service deceleration rate in m/s^2

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

[42] The diagram shows no run-on space beyond the station platform. Where there is little or no such space, mechanical or hydraulic bumpers should be provided.

The distance to exit the station, a straight run, is shorter but the initial acceleration rate will start to taper off. Leaving the travel distance the same to compensate for this, the time for the exiting train to clear the cross-over can be approximated as:

$$t_e = \sqrt{\frac{2(P + T + CS)}{a_s}} \qquad \text{Equation 3-24}$$

In between these two travel times is the terminal time that includes the dwell for alighting and boarding passengers, the time for the train operator to change ends and conduct any necessary inspections and brake tests, the time for the crossover switches to move and lock plus any desired schedule recovery time.

With two terminal tracks, the headway restriction is half the sum of these time components, expressed as:

$$H(t) \geq \frac{t_t + t_e + t_a}{2} + t_s \qquad \text{Equation 3-25}$$

where $H(t)$ = terminal headway time
t_a = terminal approach time
t_e = terminal exit time
t_t = terminal layover time
t_s = switch throw and lock time
(all in seconds)

Determining the terminal layover time is difficult. An approach is to look at the maximum terminal layover time for a given headway by transposing Equation 3-24.

$$t_t \leq 2(H(t) - t_s) - t_e - t_a \qquad \text{Equation 3-26}$$

The maximum terminal layover time can then be calculated. With the following typical *worst case* parameters:

where the headway = 120 sec
train length = 200 m
track separation = 10 m
distance from cross-over to platform = 20 m
initial service acceleration rate = 1.3 m/s^2
service deceleration rate = 1.3 m/s^2
switch is #10
switch throw and lock time is 6 sec

the terminal time $t_t \leq 175$ sec. This would increase by 9 sec if the incoming train did not stop before traversing the cross-over. While this is not a generous amount of time, particularly to contain a schedule recovery allowance, many systems maintain such close headways with minimal delays.

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

The full terminal layover time is available for station dwell. If passenger movement time is a limiting factor then this can be reduced with the use of dual-faced platforms. At terminals with exceptionally heavy passenger loading, multiple track layouts may be needed. An atypical alternative, used at SEPTA's 69th Street; PATH's World Trade Center termini; and the Howard, Desplaines, and 54th St. CTA Stations is the use of loops—with the exception of several examples in Paris this is rare for rail transit.

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

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

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

The above analysis has assumed that any speed restrictions in the terminal approach and exit are below the speed a train would reach in the calculated movements—approximately 21 km/h (13 mph) on a stop-to-stop approach, 29 km/h (18 mph) as the end of the train leaves the interlocking on exit. For safety reasons, some operators have imposed very low entry speeds, occasionally enforced with speed control signaling.

Slow terminal approaches are common on manually driven rail transit systems in the United States. In some cases this approach could be a greater restriction than the start from stop at the approach cross-over represented in Equation 3-24. If an approach speed restriction exists that is less than $(t_a \cdot a_s/2)$ *(m/sec)* then the above methodology should not be used.

3.10 JUNCTION THROUGHPUT

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

The capacity of a flat junction can be calculated in a similar manner to the terminal station approach. The junction

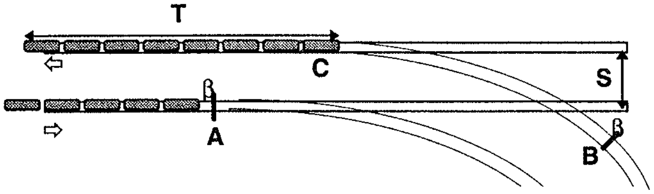

Figure 3.15 Flat junction track layout

arrangement is shown in Figure 3.15. The worst case is based on a train (lower left) held at signal "A" while a train of length "T" moves from signal "B" to clear the interlocking at "C". The minimum operable headway is the line headway of train "A" (from Figure 3.3) plus the time for the conflicting train to clear the interlocking plus the extra time for train "A" to brake to a stop and accelerate back to line speed. Ignoring specific block locations and transition spirals, this can be expressed approximately as:

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

Equation 3-27

where $H(j)$ = limiting headway at junction *(seconds)*
$H(l)$ = line headway (Figure 3.3) *(seconds)*
T = train length *in meters*
S = track separation *in meters*
C = switch angle factor
5.77 for #6 switch
6.41 for #8 switch
9.62 for #10 switch
a_s = initial service acceleration rate *in* m/s^2
d_s = service deceleration rate *in* m/s^2
v_l = line speed *in m/s*
t_s = switch throw and lock time *(seconds)*
t_{om} = operating margin time *(seconds)*

The limiting headway at the junction can then be calculated with the following typical parameters:

where line headway = 32 sec
line speed = 100 km/h
train length = 200 m
track separation = 10 m
initial service acceleration rate = 1.3 m/s^2
service deceleration rate = 1.3 m/s^2
switch is #10
switch throw and lock time is 6 sec

The result is a junction limiting headway of 102 sec plus an operating margin. While in theory this should allow a 120-sec headway with a flat junction, it does not leave a significant operating margin and there is a probability of interference headways. General guidance in rail transit design is that junctions should be grade separated for headways below 150 to 180 sec.

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

A real-life example of the restrictions created by junctions is contained in a NYCTA study.[43] This capacity analysis of NYCTA operations focused on the backbone of services in Queens—the Queens Boulevard line to 179th Street. The analysis determined headway constraints due to train performance, the signaling system, and station dwell times. An analysis of the partially flat junction at Nostrand Avenue indicated a throughput that was four trains per hour per single track lower than the 29 to 31 trains per hour that is typically the NYCTA maximum.

3.11 SUMMARY

Using as few approximations as possible, the minimum headway has been calculated for a range of train control systems with a wide number of variables. Table 3.7 summarizes the results including the raw minimum headway with the dwell and operating margin times stripped away.

The spreadsheets contained on the available disk allow the user to change most variables and obtain the minimum headway under a wide range of circumstances.

CAUTION This table and the spreadsheet make assumptions and approximations. The results are believed to be a reliable guide but are not a substitute for a full and careful simulation of the train control system in conjunction with a multiple train performance simulation. To these times approximately 6 seconds should be added for a 4% downgrade into the headway critical station. Three to four seconds can be added to allow for voltage drops at peak times on systems at full capacity—except for the moving-block signaling system.

The results of this chapter concur with field data and agree or are close to the calculations of most other headway determination

Table 3.7 Headway result summary in seconds with 200 m (660 ft) (8-10 cars) VSD = variable safety distance

Station dwell	0	30	45
Operating margin	0	15	25[44]
3 aspect system	57	102	122
Cab controls	51	96	116
Moving Block-VSD	32	77	102

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[43] As reported by panel member Herbert S. Levinson from the study: BOOZ ALLEN and HAMILTON INC., in association with Abrams-Cherwony; Ammann & Whitney; George Beetle: Merrill Stuart, Queens Transit Alternatives Technical Appendix, Part 5a, Operations/Capacity Analysis, NYCTA, New York, January 1981.

[44] Perversely, the operating margin should be increased as the dwell time increases

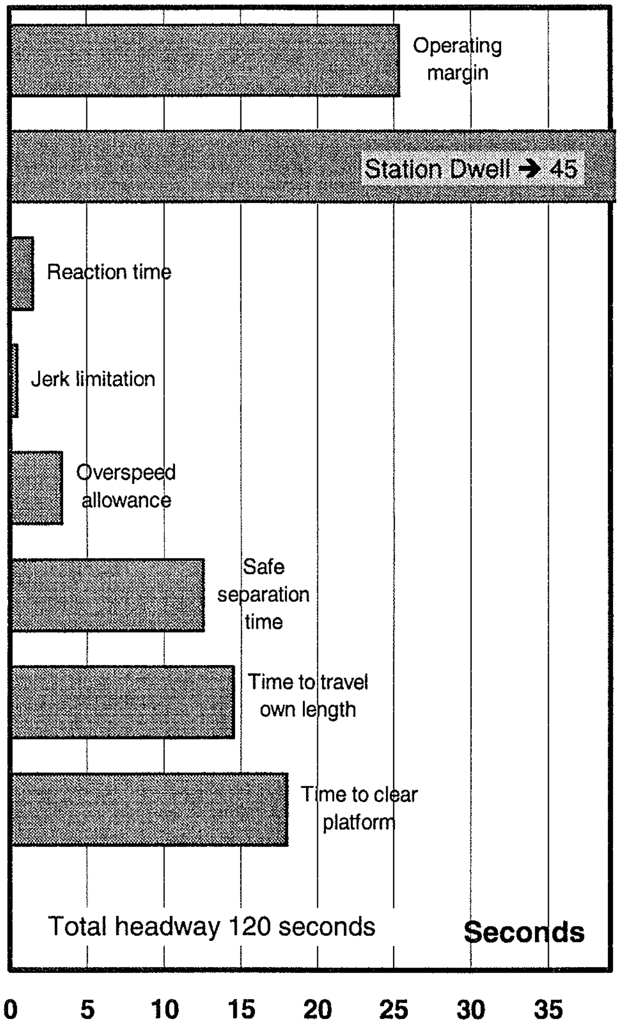

Figure 3.16 Headway components for cab control signaling that comprise the typical North American minimum headway of 120 sec

methods reviewed in Appendix One. Typical cited minimum headways, without dwell or operating margin times, are in the range of 50 to 60 sec for conventional train control—compared to the 51 to 57 sec in the above summary.

Auer(R09)estimates that a moving-block system should increase system capacity by 33% based on a 20-sec dwell[45] and 10-sec operating margin. With these quantities the headway of the VSD moving-block signaling systems is 62 sec—providing a capacity increase of 30% over the cab control signaling system value of 81 sec.

This reflects a slightly conservative approach in calculating the moving-block signaling system headway with the safety separation factor "B" set at a full braking distance. "B" can be reduced to less than one. Auer's capacity gain is achieved if "B" is set to 0.77.

The value of "B" can be adjusted for the three types of signaling to calibrate the equations of this chapter with actual field experience or system simulation.

The components of headway for the above mid range cab-control data are shown in the Figure 3.16 with a station dwell of 45 sec and operating margin of 25 sec.

The components are shown in the order of Equation 3.15 with terms running from the bottom upwards. Dwell is the dominant component and the subject of the next chapter.

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[45] Note that many of the referenced headway analyses use a fixed dwell of 20 or 30 sec. This is rarely adequate. On heavy rail transit systems with long trains running at or below headways of 120 sec the dwell at the headway controlling stations will often reach into the range of 40-50 sec—and so become the largest headway component.

4. Station Dwells

4.1 INTRODUCTION

In Chapter Two, *Capacity Basics,* station dwells were introduced as one of three components of headway. Dwells are the major component of headways at close frequencies as shown in Figure 4.1 — based on a heavy rail system at capacity, operating 180-m-long trains with a three-aspect signaling system. The best achievable headways under these circumstances are in the range of 110 to 125 sec.[1] In Chapter Two the concept of *controlling dwell* was also introduced. Controlling dwell is the combination of dwell time and a *reasonable* operating margin — the dwell time during a normal peak hour that controls the minimum regular headway. Controlling dwell takes into account routine perturbations in operations — but not major or irregular disruptions. The sum of controlling dwell and the train control system's *minimum train separation time* produces the maximum train throughput without headway interference.

In this chapter the components of dwell time are examined. The major component—passenger flow time—is analyzed. and methodologies developed for determining passenger flow times and dwell times.

4.2 LITERATURE REVIEW

The literature review produced 26 dwell time references listed in Table 4.1. The full listing is contained in Chapter Twelve, *Bibliography* and a summary of each reference is contained in Appendix One. These references can be divided into three categories. The largest category discussed dwell as a component in calculating train throughput.

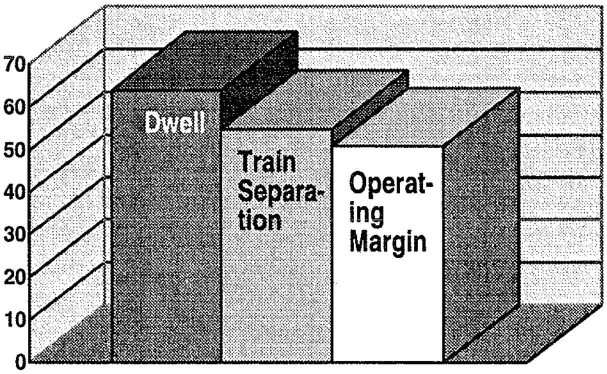

Figure 4.1 Typical headway components in seconds

The second category analyzed dwell time relative to the number of passengers boarding and alighting. This group concluded that linear regression provided the most suitable fit for both rapid transit and light rail with high- and low-level loading for specific systems.[2] Three references improved the data fit by including

Table 4.1 List of dwell time references

Alle, Improving Rail Transit Line Capacity Using Computer Graphics
Anderson, Transit Systems Theory
Auer, Rail-Transit People-Mover Headway Comparison
Barwell, Automation and Control in Transport
Canadian Urban Transit Association, Canadian Transit Handbook
Celniker, Trolley Priority on Signalized Arterials in San Diego
Chow, Hoboken Terminal: Pedestrian Planning
Gray, Public Transportation Planning, Operations and Management
Jacobs Transit Project— Estimate of Transit Supply Parameters
Janelle, Interactive Hybrid Computer Design of a Signaling System
Klopotov, Improving the Capacity of Metropolitan Railways
Koffman, Self-service Fare Collection on the San Diego Trolley
Kraft, Evaluation of Passenger Service Times
Levinson, Some Reflections on Transit Capacity
Levinson, ITE Transportation Planning Handbook ,Chapter 12
Levinson, Capacity Concepts for Street-Running Light Rail Transit
Lin, Dwell Time Relationships for Light Rail Systems
Miller, Simulation Model of Shared Streetcar Right-of-Way
Motz, Attainable Headways Using SELTRAC
Pushkarev, Urban Rail in America
Schumann, Status of North American LRT Systems
TRB, Collection and Application of Ridership Data on Rapid Transit
TRB, Highway Capacity Manual, Chapter 12
US DoT Characteristics of Urban Transportation Systems
Vuchic, Urban Public Transportation Systems and Technology
Walshaw, LRT On-Street Operations: The Calgary Experience

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[1] Some European systems operate three or more aspect signaling systems with headways down to 90 sec by strict control of dwells — on occasion, closing doors before all passenger movements are complete. This is not an acceptable practice in North America.

[2] Lin and Wilson (R44) indicate that crowding may cause a non-linear increase in dwell time during congested periods. Koffman, Rhyner and Trexler,(R33) after testing a variety of variables, including various powers, exponentials, logarithms and interaction terms, conclude that a linear model produced the best results for the specific system studied.

the number of passengers on-board a car as a variable. One paper, by Koffman, Rhyner and Trexler[R33], evaluated a variable to account for passenger-actuated doors on the San Diego trolley.

In the third category, a single paper (Alle[R02]) answered two key questions: "How many trains can realistically pass a point in one hour?" and "What is the impact of station dwell times on this throughput?"

Using an at-capacity section of the MTA-NYCT E & F lines, Alle analyzed the actual peak-hour dwells at Queens Plaza Station in New York by trapping 85% of the area under the normal distribution curve. The upper control limit becomes the mean plus one standard deviation with a 95% confidence interval. The results determined that this specific single track, with the given set of dwells, can support trains every 130 sec—almost identical to the actual throughput of 29 trains per hour (124 sec).

Alle's methodology is based on measurements of actual in-service dwell times, and so it is unsuitable for determining controlling dwells of new systems or new stations added to existing systems where such information would not be available.

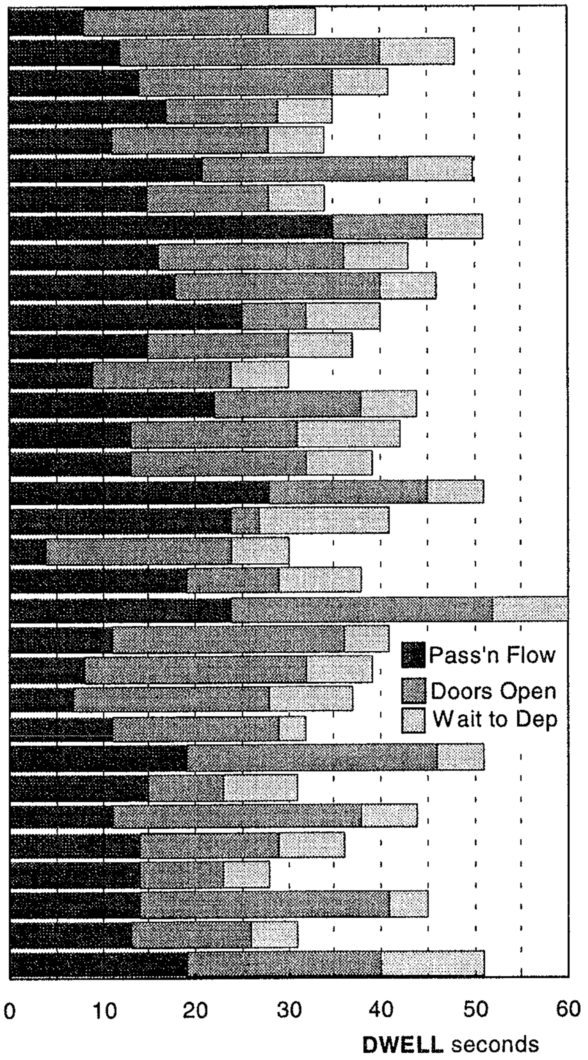
With the above exception, the literature offers only methods to determine passenger flow times; no material was found that adjusts these flow times to either the full station dwell time or a controlling dwell time. Many reports, and even some simulations, use a manually input average dwell time, a worst case dwell time, or merely a typical dwell time—often quoted at 15 to 20 sec per station with 30 sec or more for major stations. These gross approximations usually produce a throughput of 40 to 50 trains an hour and so require applying one or more factors to adjust the resultant throughput to the actual North American maximum of 30 to 32 trains an hour.

This situation required the authors to make a fresh start at developing a methodology for calculating dwells. Much of the field data collection involved timing dwells and passenger flows.

4.3 DWELL CONSTITUENTS

Dwell is made up of the time passenger flow occurs, a further time before the doors are closed and then a time while waiting to depart with the doors closed. Figures 4.2 through 4.5 show these dwell components for the peak period of four selected systems. Each of the systems has a different operating philosophy. BART is automatically driven with door closure and departure performed manually; the latter subject to override by the automatic train control. NYCT is entirely manual, subject only to a permissive departure signal. BC Transit is an entirely automatic system with unattended cars; door closing and departure times are preprogrammed. Station dwells are contained in a nonvital table of the train control system and are adjusted by station, destination, time-of-day and day-of-week. The Toronto Transit Commission is also entirely manual but, unlike New York, has recently implemented a safety delay between door closure and train departure on the Yonge subway.

The data collection did not time any delays between a train stopping in a station and the doors opening. Although there were such minor delays, few were long enough to possibly annoy passengers. Delays do occur with passenger-actuated doors used on many light rail systems. These are discussed separately in section 4.4.2 of this chapter.

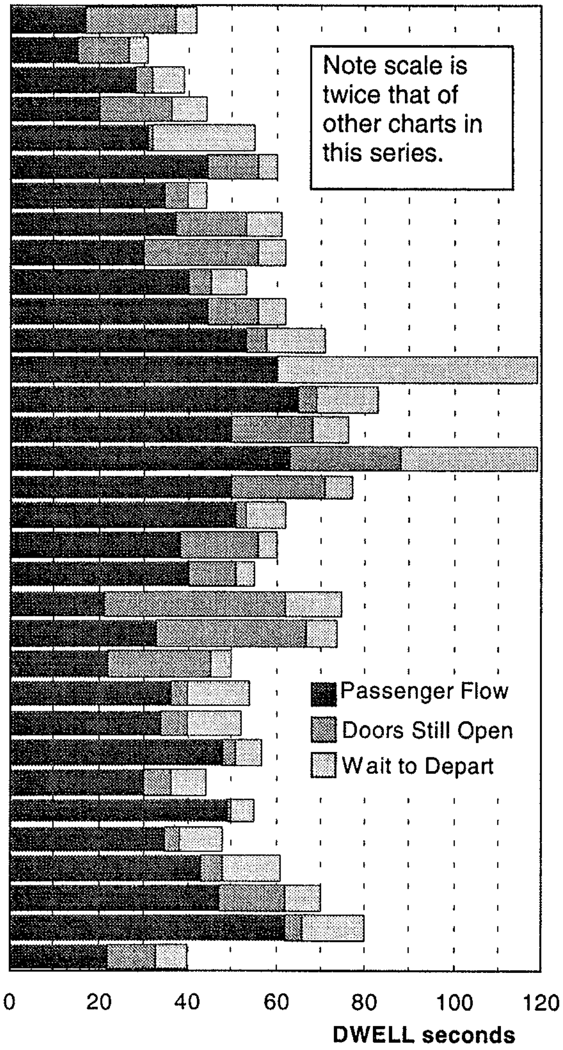


average headway — 153 seconds
number of passengers observed — 586
flow time averages 38% of total dwell

Figure 4.2 BART Montgomery Station dwell time components p.m. peak February 9, 1995

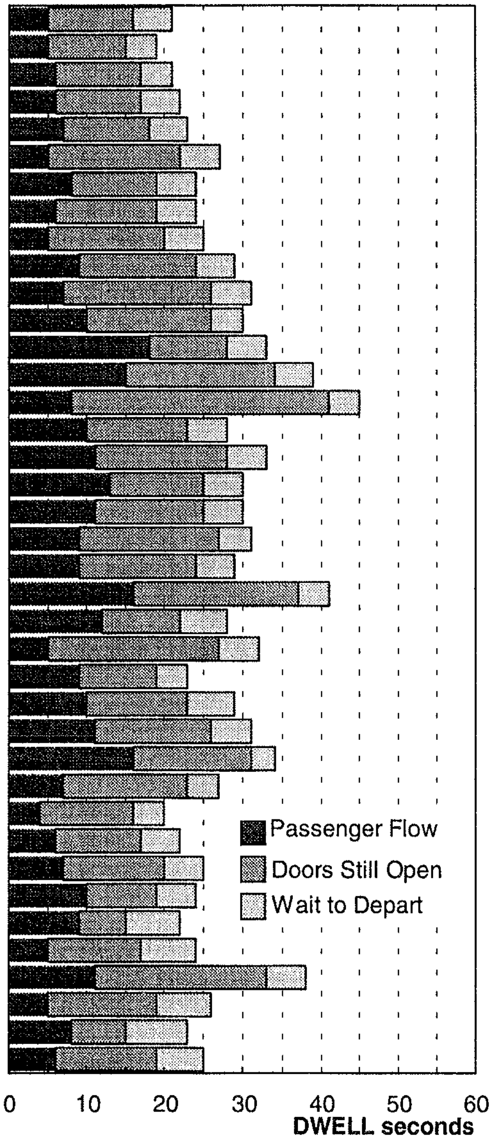
The preprogrammed nature of the BC Transit observations are very evident. There are two services in the data set. The short turn service has shorter dwells until it ends—just over halfway down the chart. Minor variants in the total dwell time for each service are due to observation errors. Data were collected at the heaviest used doorway(s) on the train. While it was not always possible to guarantee that this was selected, it is still surprising that the proportion of dwell time productively used for passenger movements is so small, ranging from 31 to 64% of the total dwell. Only New York fares well in this regard with a percentage of productive time double the other examples. However, there were major variations in the percentage of productive time between stations on the same system (See Table 4.3).

These four charts are representative of 61 data sets of door flows collected in early 1995 for those few systems operated at, or close to, the capacity of their respective train control systems.



average headway — 160 seconds
number of passengers observed — 1,143
flow time averages 64% of total dwell

Figure 4.3 NYCT Grand Central Station dwell time components a.m. peak February 8, 1995



average headway — 168 seconds
number of passengers observed — 428
flow time averages 31% of total dwell

Figure 4.4 Toronto Transit Commission King Station S/B dwell time components: am peak February 6, 1995

The data represent the movement of 25,154 passengers over 56 peak periods, two base (inter-peak) and three special event times, at 27 locations on 10 systems. All data sets are contained on the computer disk. Table 4.2 summarizes the results. The low percentage of dwell time used for passenger flow at the heaviest use door presents a challenge in determining dwell times from the passenger volumes in section of this chapter.

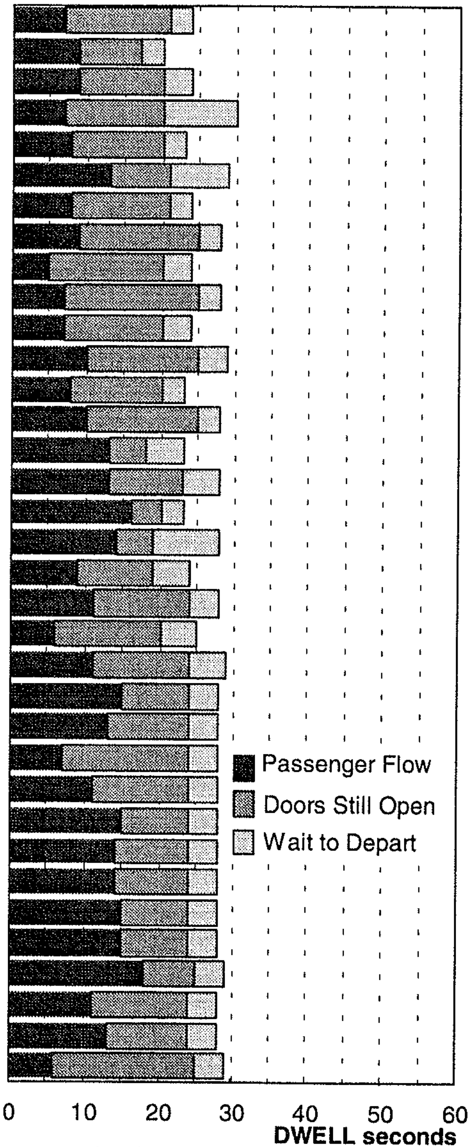
In Chapter Three, *Train Control and Signaling,* it was suggested that automatic driving—when compared with manual driving—should permit a train to run closer to civil speed limits and not commence braking until the last moment, thus reducing train separation by 5 to 15% and increasing capacity by a like amount and improving regularity.

There was insufficient data to confirm this, although Figure 4.5, shows BC Transit's automated operation with a short-turn service integrated into two other services at a very consistent 90-sec separation.

However, the project observers, timing dwells and counting a total of over 25,000 passengers at various locations on 10 systems noted a wide variation in operating practices that ranged from efficient to languid, with automatically driven systems predominantly in the latter group. It would appear that any operating gains from automatic driving may be more than offset by time lost in station dwell practices.

Several light rail and heavy rail systems were notably more expeditious at station dwells than their counterparts, contributing to a faster—and so more economic and attractive—operation. Most automatically driven systems had longer station dwells extending beyond the passenger movement time.

This inefficiency is extending to some manually driven systems where safety concerns have resulted in the addition of an



average headway — 151 seconds
number of passengers observed — 562
flow time averages 40% of total dwell

Figure 4.5 BC Transit SkyTrain Burrard Station inbound dwell time components am peak April 5, 1995

Table 4.2 Summary of door observations through one double-stream door during the peak period — four rail transit systems operating at or close to capacity (1995)

SYSTEM	Headway seconds	Total Pass.	% flow/ dwell
BART Montgomery	153	586	38%
NYCT Grand Central	160	1,143	64%
BC Transit Burrard	151	562	40%
TTC King Station	168	428	31%

Table 4.3 Summary of all door observations through a single double-stream door during the peak period (1995)

System Location	Pass.	Headway		% flow/ dwell	
		am	pm	am	pm
BART Montgomery	3400	02:43	02:43	38	37
BART Embarcadero	2298	03:22	02:50	58	43
BCT Burrard	562	02:31		40	
BCT Broadway	257		02:26		34
BCT Metrotown (off-peak)	263		04:01		35
CTS 1st St. SW	298	02:57		30	
CTS 3rd St. SW	339		03:01		26
CTS Heritage	100	05:54		38	
CTS City Hall	201		03:11		30
ETS Central	37	04:39		33	
ETS Churchill	103		04:53		33
NYCT Grand Central (4&5)[3]	3488	02:45	03:09	58	39
NYCT Queens Plaza (E&F)	401	02:15		34	
NYCT Queens Plaza (E&F)	634		02:37		25
PATH Journal Square	478	03:20		23	
PATH Exchange Place	525		01:56		36
Tri-Met 5th Ave. Mall	804	07:28		40	
Tri-Met Pioneer Sq. S.	471		08:22		28
SDT Civic Center	251	06:26		34	
SDT Imperial & 12th	20	07:31		20	
SDT City College	241	07:20	06:40	24	19
SF Muni Montgomery	2748	02:27	02:26	56	45
SF Muni Irving & Arguello	252	04:49		38	
SF Muni Duboce/Church	298		06:10		35
SF Muni 9th & Judah/Irving	176	04:32		37	
TTC King	1602	02:48	02:37	32	37
TTC Bloor	4907	02:42	02:38	52	58
TOTAL — AVERAGES	**25,154**			**43**	**35**

artificial delay between the time the doors have closed and the train starts to move from the platform.

A companion Transit Cooperative Research Program project A-3, TCRP Report 4, *Aids for Car Side Door Observation,* and its predecessor work, National Cooperative Transit Research & Development Program Report 13, *Conversion to One-Person Operation of Rapid-Transit Trains,* address some of these issues but do not examine overall door-platform interface safety or the wide differences in operating efficiency between various light and heavy rail systems. This issue is discussed further in Chapter Eleven, *Future Research.*[3]

4.4 DOORWAY FLOW TIMES

4.4.1 FLOW TIME HYPOTHESES

Flow time is the time in seconds for a single passenger to cross the threshold of the rail transit car doorway, entering or exiting, per single stream of doorway width.

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[3] Dwells may be intentionally extended to enable cross-platform connections between local and express trains.

In the course of conducting this study, several interesting conjectures and educated guesses were encountered relating to flow times and rail transit vehicle loading levels. Certain of these suggest the attractiveness of air-conditioned cars on hot days may decrease both doorway flow times and increase the loading level. Similarly with warm cars in cold weather—with loading levels offset by the bulk of winter clothing. While there is some intuitive support for these hypotheses no data were obtained to support them.

Other hypotheses related to different flow times between old and new rail transit systems, for example, that after delays and under emergency operation passengers will load faster and accept higher loading levels. Similar circumstances apply when rail transit is used to and from special events—such as sporting venues.

4.4.2 FLOW TIME RESULTS

Part of the dwell time determination process involves passenger flow times through a train doorway. Data were collected from a representative set of high-use systems and categorized by the type of entry—level being the most common, then light rail with door stairwells, with and without fare collection at the entrance. These data sets were then partitioned into mainly boarding, mainly alighting and mixed flows. The results are summarized in Figure 4.6. The most interesting component of these data is that passengers enter high-floor light rail vehicles faster from street level than they exit. This remained consistent through several full peak period observations on different systems. Hypotheses include brisker movement going home than going to work, entering a warm, dry car from a cold, wet street and, in the Portland light rail case, caution alighting onto icy sidewalks. Balance may also be better when ascending steps than when descending.

The fastest flow time, 1.11 sec per passenger per single stream, was observed on PATH boarding empty trains at Journal Square station in the morning peak. These flow data are consolidated and summarized by type of flow in Figure 4.7. The results show that, in these averages, there is little difference between the high-volume, older East Coast rail rapid transit systems, and the medium-volume systems—newer light rail and rail rapid transit. Doorway steps approximately double times for all three categories: mixed flow, boarding and alighting. Light rail boarding up steps, with exact fare collection, adds an average of almost exactly 1 sec per passenger.[4]

While most field data collection on doorway flow times is from the peak periods, the opportunity was taken on BC Transit's rail rapid transit system to compare peak-hour with off-peak and special event flows, as summarized in Figure 4.8. Project resources prohibited significant data collection at special events and outside peak periods. However, four field trips were made to survey flows and loading levels on BC Transit. One was before a football game, the second before a rock concert. In both cases a single station handled 10,000 to 15,000 enthusiasts in less than an hour. The other data collection trips surveyed a busy

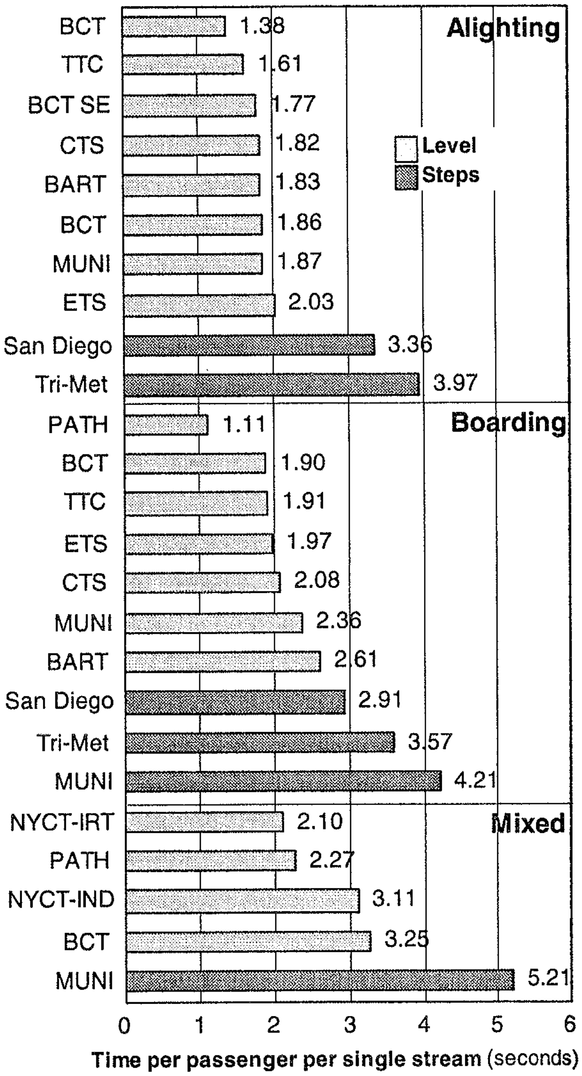

Figure 4.6 Selection of rail transit doorway flow times (1995)

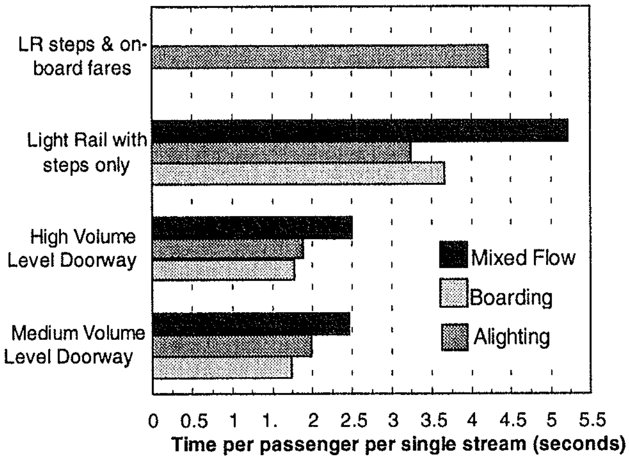

Figure 4.7 Summary of rail transit door average flow times

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[4] No data were collected for light rail fare payment alighting down steps—a situation unique to Pittsburgh.

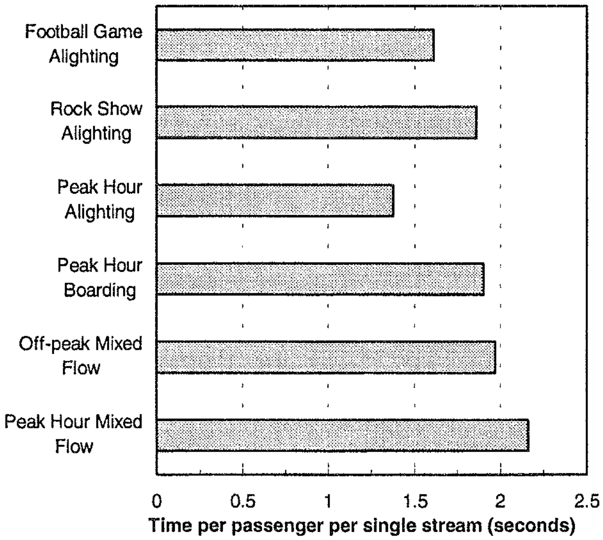

Figure 4.8 BC Transit doorway flow time comparisons (1994-5)

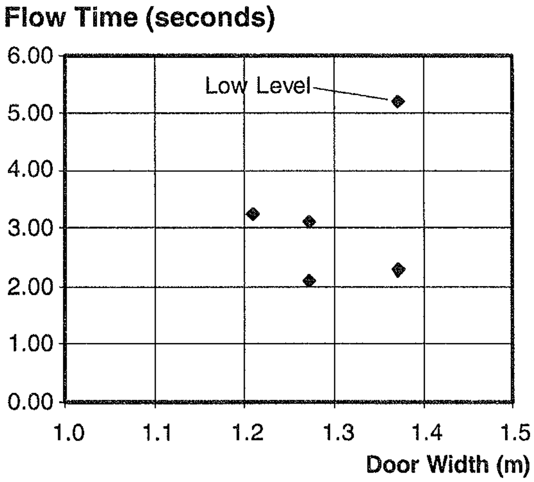

Figure 4.9 Mixed flow times versus door width

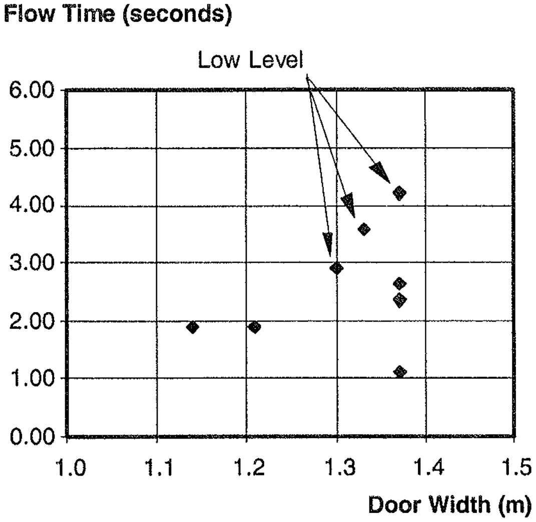

Figure 4.10 Boarding flow times versus door width

suburban station in the early afternoon base (inter-peak) period. The resultant data are contrary to the supposition that special event crowds move faster and that off-peak flows are slower than in the peak hour.

The results showed an increase in alighting flow times before special events. However, loading densities were 20 to 30% higher than during a normal peak hour. This higher level of crowding, together with the fact that many special event passengers are not regular riders, may account for the slower alighting time. Separate BC Transit analysis(R27) has measured car occupancy differences between normal peak-hour operation and after service delays. Standing density increased from a mean of 2.8 passengers per m^2 to 5 passengers per m^2. The equivalent standing space occupied declined from 0.36 m^2 per passenger to 0.2 m^2 per passenger (3.9 to 2.2 sq. ft. per passenger).

Off-peak flows are invariably mixed. The BC Transit off-peak data, an average of 21 trains over a 2-hour period, show faster movement than comparable peak hour mixed flows. However, these data are insufficient to draw firm conclusions.

4.4.3 EFFECT OF DOOR WIDTH ON PASSENGER FLOW TIMES

Figures 4.9, 4.10 and 4.11 plot the relationship between flow times in seconds per passenger per single stream against door width. A variety of statistical analyses failed to show any meaningful relationship between door width and flow time. The only conclusion can be that, within the range of door widths observed, all double-stream doors are essentially equal.

Field notes show that double-stream doors frequently revert to single-stream flows and very occasionally three passengers will move through the doorway simultaneously when one is in the middle and two move — essentially sideways — on either side. At some width below those surveyed a doorway will be effectively single stream. At a width above those surveyed a doorway will routinely handle triple streams. There are no single- or triple-stream doors on any modern North American rail transit vehicle although they exist on AGT and in other countries. JR East in Tokyo is experimenting with a quadruple-stream doorway — shown in Figure 4.12. Wide doors have been a characteristic of the AEG[5] C100 AGT used in many airports and on Miami's Metromover. This four-stream 2.4-m (8-ft) door is shown in Figure 4.13.

4.5 ANALYZING FLOW TIMES

Procedures must be developed that will translate station passenger volumes and flow times per passenger into total doorway use times and then into dwell times. Other work has developed

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[5] Previously Westinghouse Electric Corporation.

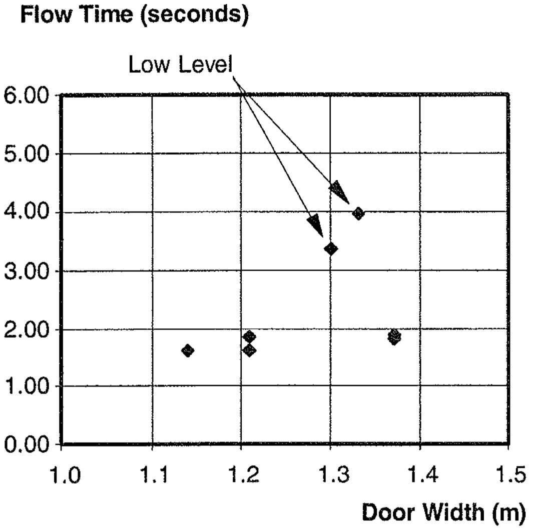

Figure 4.11 Alighting flow times versus door width

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Figure 4.12 Quadruple-stream doorway in Tokyo

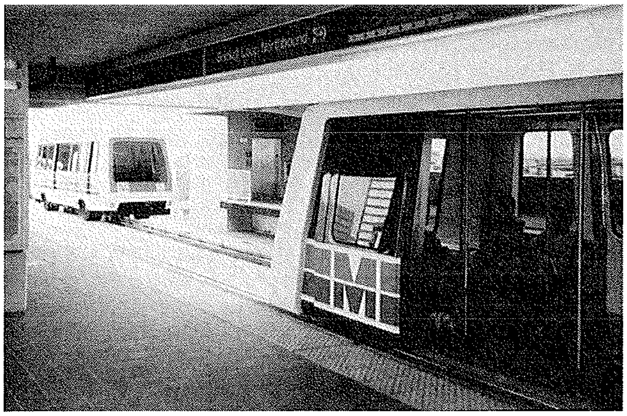

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Figure 4.13 Quadruple-stream doorway, Miami Metromover

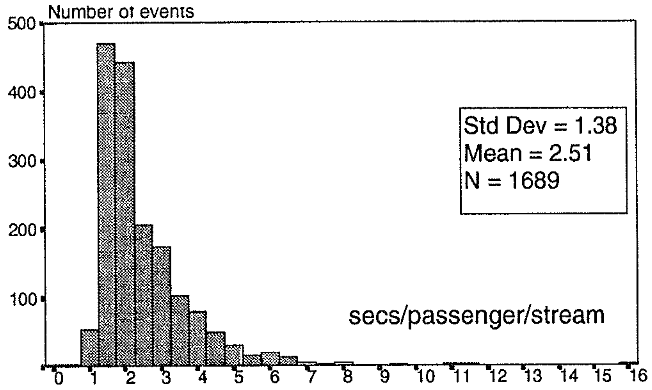


Figure 4.14 Histogram of flow time

relatively simply linear regression formulae with slight improvements in fit using quadratic terms and the number of passengers remaining on-board—a relatively crude surrogate for the level of doorway congestion. Most work in this area has been restricted to limited amounts of data from a single system.

Linear regression would also be possible for the more extensive data collected during this project. However an examination of these data indicated that separate regression equations would be required for each system—and even for different stations and different modes, alighting, boarding and mixed, on a single system. This is undesirable and unsuitable for determining the capacity of new rail transit systems where regional transportation models provide an estimate of hourly passenger flow by station, from which dwell times must be estimated.

tThe project's statistical advisory team pursued the goal of a single regression formula for all systems with level loading, accepting the need for variations between mainly alighting, mainly boarding and mixed passenger flows. The result, in the following sections of this chapter, involves relatively erudite statistical analysis. The only satisfactory results required logarithmic transforms. Readers may elect to skip the remainder of this chapter. Section 7.5.3 in Chapter Seven offers simpler methods to estimate station dwell times and presents the results of the following work in a simplified manner. The computer spreadsheet allows the calculations to be carried out without any knowledge of the underlying methodologies.

4.5.1 DATA TRANSFORMATION

To assess the distribution of the flow time (seconds/passenger/single stream), the explicit outliers (5 zero times and one time of 36.0) were removed. The histogram in Figure 4.14 shows a clear skewing. In the next step logarithmic transformations were made of the flow times to obtain a normally distributed set of data.

This is achieved by a power transformation technique due to Box and Cox, which raises the flow time to a power determined by an algorithmic procedure. The procedure chooses the power to get a best fit (i.e., minimize the residual sum of squares due

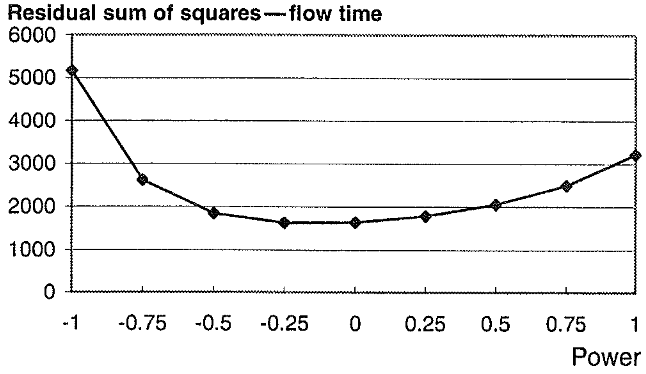


Figure 4.15 Residual sum of squares

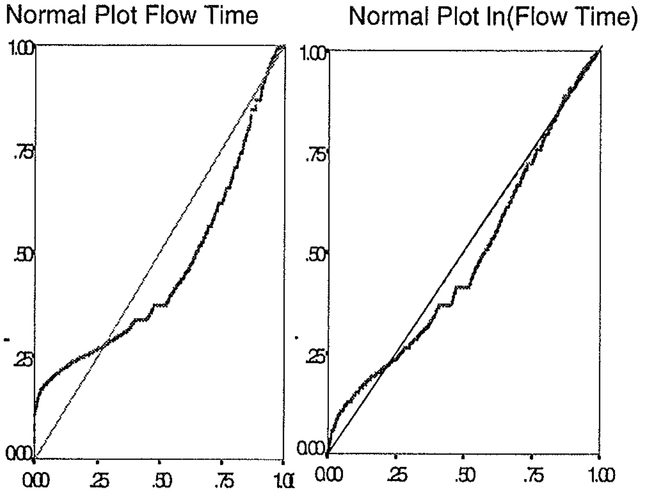


Figure 4.16 Expected flow time cumulative probabilities versus observed cumulative probabilities (abscissa)

to error) in a typical regression. The results of these calculations are shown in Figure 4.15.

This graph indicates that a power of -0.25 or 0 is appropriate. For ease of interpretation a power of zero, which corresponds to a natural logarithm (ln) transform, is preferable. Further calculation shows that this transformation is statistically warranted. Confirmation of this decision can be seen by comparing the normal probability plots obtained from regressions of flow time and ln(flow time) against time of day, shown in Figure 4.16.

4.5.2 COMPARISONS

Box plots are the easiest way to visually compare the natural log transformed flow time data between cities, time of day, loading levels and event types. These plots enable the researcher to quickly compare the central values (the mid box horizontal line is the median) and gauge the spread of the data (the box represents the interquartile range; i.e., the top is the 75th percentile and the bottom is the 25th percentile).

Analysis of variance is used to examine differences in the mean value of ln(flow time) between different levels of a variable (e.g., by system).

Table 4.4 Overall data set summary (seconds)

Variable	Mean	SD	Min	Max	No.
Flow Time	2.51	1.38	.08	16.00	1689
ln(Flow Time)	.81	.44	-2.48	2.77	1689

Table 4.5 System comparison summary ln(flow time (secs))

	Mean	Standard Deviation	Cases
BART	.6939	.4415	297
NYCT	.8893	.3640	254
PATH	.7277	.4345	128
Portland	1.2990	.2788	34
San Diego	1.1208	.2771	105
SF Muni	1.0042	.5346	393
Vancouver	.7437	.3333	155
TTC	.5449	.2178	323

There are highly significant differences between the cities (p<0.0001) which are enumerated in the following table. An 'x' indicates a difference significant at the 5 percent level between the cities.

Table 4.6 Significant differences between systems

#	System	Mean	1	2	3	4	5	6	7	8
1	TTC	0.54								
2	BART	0.69	x							
3	PATH	0.73	x							
4	Vancouver	0.74	x							
5	NYCT	0.89	x	x	x	x				
6	SF Muni	1.00	x	x	x	x	x			
7	San Diego	1.12	x	x	x	x	x	x		
8	Portland	1.30	x	x	x	x	x	x	x	

RESULTS

Overall Descriptive statistics for the overall data set are as follows: where SD or Std Dev = standard deviation, No. = Number of observations or Cases, ln = natural logarithm.

City/system comparison In this comparison all data are used and the descriptive statistics for the eight systems are as follows (Table 4.5): There are highly significant differences between the cities (p<0.0001), which are enumerated in the Table 4.6. An 'x' indicates a difference significant at the 5 percent level between the cities.

Alighting/boarding comparison All trains with greater than or equal to 70% boarding passengers were declared to be boarding

Table 4.7 Alighting/boarding comparison

	Mean	Standard Deviation	No.
Board	0.9021	0.4994	605
Alight	0.6806	0.3787	442

The mean natural log of the flow time was significantly (p<0.0001) less for alighting.

Table 4.8 Time of day comparison ln(flow time (secs))

	Mean		Cases
am	.8389	.4443	804
pm	.7891	.4431	885

The morning mean natural log of the flow time was mildly significantly (p=0.02) higher than that in the afternoon.

Table 4.9 Loading level comparison ln(flow time (secs))

	Mean	Standard Deviation	Cases
High	.6939	.4254	222
Low (1 door)	1.5944	.3516	29
Low (>1 door)	1.3688	.3596	142

There were significant differences in the mean natural log of the flow times between each pair of loading levels (p<0.05).

Table 4.10 Event time comparison ln(flow time (secs))

	Mean	Standard Deviation	Cases
Normal	.8823	.3275	91
Special	.5466	.2260	64

The special event log flow time was significantly (p<0.0001) lower than that during normal peak time

and similarly those with greater than or equal to 70% alighting passengers were declared to be alighting. This reduced the data set to 1047 cases with descriptive statistics as follows (Table 4.7): The mean natural log of the flow time was significantly (p<0.0001) less for alighting.

Time of day comparison All data were used in comparing am and pm natural log flow times. The descriptive statistics are as follows (Table 4.8): The morning mean natural log of the flow time was mildly significantly (p=0.02) higher than that in the afternoon.

Loading level comparison In order to have a homogeneous dataset for comparing the effect of boarding levels, attention was restricted to the SF Muni datasets. The following descriptive statistics were calculated (Table 4.9). There were significant differences in the mean natural log of the flow times between each pair of loading levels (p<0.05).

Event Time Comparison In order to have a homogeneous dataset for the comparison of the normal and special event times, attention was restricted to the Vancouver Sky Train (Table 4.10). The special event log flow time was significantly (p<0.0001) lower than that during normal peak times. Figures 4.17 through 4.21 show the comparison box plots with the following key.

4.5.3 PREDICTION OF DOOR MOVEMENT TIME USING BOARDING AND ALIGHTING

Preliminary regressions indicate that it is preferable to use the natural logarithm of the door movement (DM) time. This is illustrated in Figure 4.22, where the normal plot for the transformed DM time is much closer to the line of identity, that indicates normality. So, as with the flow time, the natural logarithm of the door movement time is modeled, and the resulting prediction is transformed back to the raw scale by exponentiation. There is evidence (p=0.02) that separate fits are warranted for mainly boarding (i.e. > 70% boarding), mainly alighting (i.e. > 70% alighting) and mixed.

A number of parameterizations and combinations of the two independent variables, number boarding (B) and number alighting (A) are possible. The coefficients of determination for the various models are shown in the following table. The coefficient represents the proportion of variation in the data that is explained by the model. In addition to these parameterizations, the natural logarithm of the numbers boarding and alighting were considered, and dummy variables were used to model the levels resulting from a discretization of the variables. However, these latter approaches did not provide better fits than those above and so were not considered further.

The models were applied to the overall dataset and the three mutually exclusive subsets of mainly boarding (i.e. > 70% boarding), mainly alighting (i.e. > 70% alighting) and mixed; results are shown in Table 4.11. From the table, it can be seen that there are gains of up to 16% in the proportion of variation explained by considering separate models for the subsets of mainly boarding, mainly alighting and mixed. The gains in considering more complex models than the simple additive linear model (Model 1) are less clear.

There is little gain from introducing a term for the interaction between the number boarding and the number alighting as in model 2. However, there is an approximate gain of 10 percent, resulting from the introduction of quadratic terms in model 3, but no further gain from adding an interaction to this as in model 4. Similarly, there is no gain from higher order terms and interactions, which also tend to make the prediction more unstable. Hence the quadratic model (Model 3) is chosen as the best fit, explaining 50% to 80% of the variation in the data.

Residual plots from the regression with this quadratic model show an inverse fanning indicating that the residuals are inversely proportional to the logarithms of the flow times. While this could be transformed toward an identical error structure, in the interests of parsimony, no reparameterization of the logarithm of the flow time is attempted. The Durbin-Watson statistic ranges between 1.3 and 1.6 indicating significant first-order positive auto correlation among the residuals and so standard errors for parameters and associated tests must be viewed with some caution.

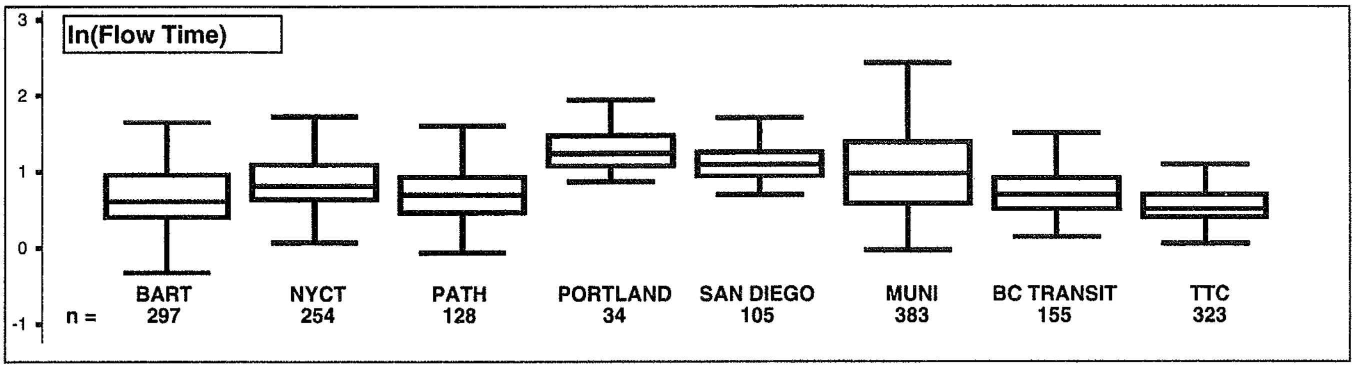
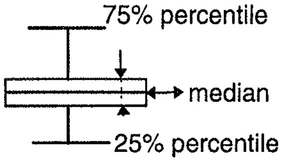


Figure 4.17 City/company comparison



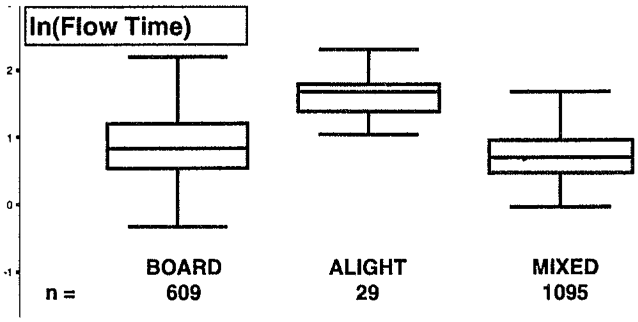


Figure 4.18 Alighting/boarding comparison

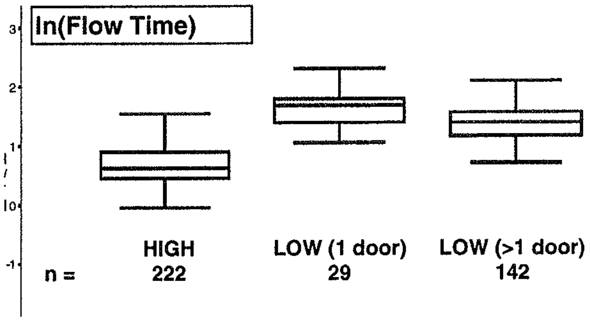


Figure 4.20 Loading level comparison

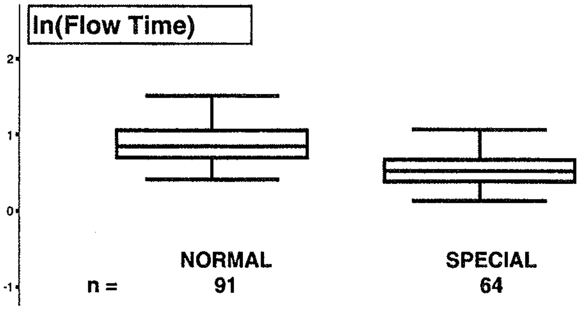


Figure 4.21 Event time comparison

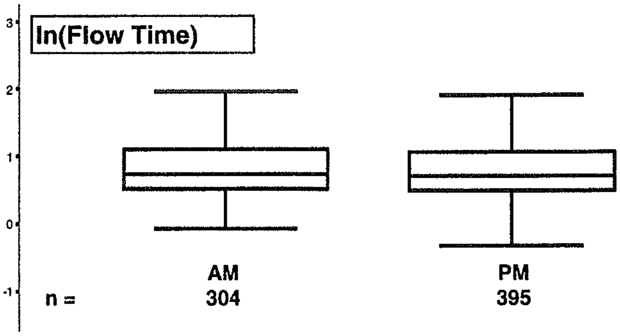


Figure 4.19 Time of day comparison

KEY

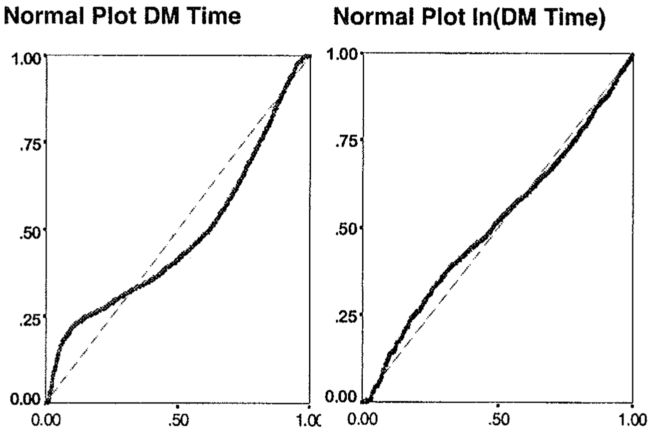
FT = Flow Time = the time in seconds for a single passenger to move through a single-stream doorway

DM Time = Doorway Movement Time, the time in seconds a single doorway is used for all continuous passenger movements during a single dwell

A= number of passengers alighting and;

B= number of passengers boarding through a single stream level loading rail transit car doorway

SN = number of standing passengers on-board the surveyed car at the end of the dwell


Normal Plot DM Time

Normal Plot ln(DM Time)

Figure 4.22 Expected cumulative probabilities versus observed cumulative probabilities of door movement time and ln(door movement time)

Table 4.11 R^2 data for tested models 1-4

Model number and terms	Overall	Mainly Boards	Mainly Alights	Mixed
	n=1749	n=667	n=425	n=657
1—B, A	.59	.43	.63	.71
2—B, A, B*A	.60	.43	.63	.75
3—B,A,B^2,A^2	.66	.55	.71	.78
4–B,A,B^2,A^2,B*A	.69	.56	.71	.79

Table 4.12 Flow time regression results for model 3

Model terms	Overall	Mainly Boards	Mainly Alights	Mixed
	n=1749	n=667	n=425	n=657
Constant	1.514	1.380	1.440	1.368
B	0.0987	0.124	0.0979	0.112
A	0.0776	0.0722	0.0922	0.0948
B^2	-0.00159	-0.00214	-0.00103	-0.00225
A^2	-0.000985	-0.000857	-0.00116	-0.00184

The final regression models are presented in Table 4.12. All coefficients are highly significant ($p<0.001$), except for A^2 in the mainly boarding dataset ($p=0.2$), and B^2 ($p=0.6$) in the mainly alighting dataset. Expressed as equations these are

$$\mathit{ln(flow\ time\ overall)} = 1.514 + 0.0987B + 0.0776A - 0.00159B^2 - 0.000985A^2$$

$$\mathit{ln(flow\ time\ mainly\ boarding)} = 1.380 + 0.124B + 0.0722A - 0.00214B^2 - 0.000857A^2$$

$$\mathit{ln(flow\ time\ mainly\ alighting)} = 1.440 + 0.0979B + 0.0922A - 0.00103B^2 - 0.00116A^2$$

$$\mathit{ln(flow\ time\ mixed)} = 1.368 + 0.112B + 0.0948A - 0.00225B^2 - 0.00184A^2$$

Table 4.13 R^2 data for tested models 5-7

Model number and terms	Overall	Mainly Boards	Mainly Alights	Mixed
n=	963	249	178	531
5—B, A, B^2, A^2, SN	.78	.76	.64	.81
6 — B, A, B^2, A^2, SN, SN^2	.79	.76	.64	.81
7 — B, A, B^2, A^2, SN, SN^2, A*SN, B*SN	.80	.77	.64	.81

Table 4.14 Doorway movement regression results, model 5

Model terms	Overall	Mainly Boards	Mainly Alights	Mixed
	n=963	n=249	n=178	n=536
Constant	1.412	1.0724	1.302	1.363
B	0.0845	0.124	0.147	0.106
A	0.0890	0.104	0.105	0.0864
B^2	-0.00131	-0.00194	-0.00511	-0.00235
A^2	-0.00149	-0.00153	-0.00165	-0.00159
SN	0.0460	0.0782	0.653	0.0563

4.5.4 PREDICTION OF DOORWAY MOVEMENT TIME USING NUMBER BOARDING AND ALIGHTING PLUS THE NUMBER STANDING

The above quadratic model for the logarithm of the DM time was augmented with the number standing standardized for the floor area of the car (SN) to give model 5. Models 6 and 7 introduce quadratic terms in SN and its interactions with B & A.

Data from BART, MUNI and PATH were not used, thus reducing the car numbers to half of those in the previous section. Table 4.13 presents the coefficients of determination for these models. In comparing these models to model 3 of the previous section, there appear to be gains for the mainly boarding and mixed models. However, there is no point in considering more complex models than model 5 which is linear in SN. The residual analyses show similar characteristics to the model without the standardized number standing, so once again all standard errors must be viewed with some caution. The final regression models are presented in Table 4.14. All regression coefficients are highly significant ($p<0.001$) except for B ($p=0.006$), B^2 ($p=0.6$) and SN ($p=0.009$) in mainly alighting dataset. Expressed in equation form the models are

$$\mathit{ln(flow\ time\ overall)} = 1.412 + 0.0845B + 0.0890A - 0.00131B^2 + 0.00149A^2 + 0.0460SN$$

$$\mathit{ln(flow\ time\ mainly\ boarding)} = 1.0724 + 0.124B + 0.104A - 0.00194B^2 - 0.00153A^2 + 0.0782SN$$

$$\ln(\text{flow time mainly alighting}) = 1.302 + 0.147B + 0.105A - 0.00511B^2 - 0.00165A^2 + 0.653SN$$

$$\ln(\text{flow time mixed}) = 1.363 + 0.106B + 0.0864A - 0.00235B^2 - 0.00159B^2 + 0.0563SN$$

where B and A are the numbers boarding and alighting and SN is the number standing normalized for floor area.

This model, with examples, is demonstrated in the computer spreadsheet. The model has limitations and becomes inaccurate with values of A or B > 25.

4.5.5 PREDICTION OF DWELL TIME FROM DOORWAY MOVEMENT TIME

As shown in Figure 4.23 it is desirable to transform the dwell time using natural logarithms, since the normal plot is considerably straighter, indicating a progression toward normality. The dwell time is modeled using its natural logarithm and exponentiated back to the raw scale. Examination of interaction terms shows no evidence (p=0.5) of a need to consider separate predictions for the automatic systems (BART and Vancouver's SkyTrain). The coefficient of determination has a value of 0.34 with a linear model and there is no gain evident from considering quadratic terms.

Residual analysis indicates an inverse fanning that will not be corrected for so as to keep the model simple. However, the Durbin-Watson statistic is 1.2 indicating strong positive serial auto correlation, so that all standard errors and associated tests must be viewed with some caution. The final regression model for the natural logarithm of the dwell time is shown in Table 4.15. It is noted that this relationship is not as strong as those in the previous section. The association is displayed in the scatterplot of Figure 4.24. The mean dwell and DM times, together with their standard deviations, are displayed in Table 4.16.

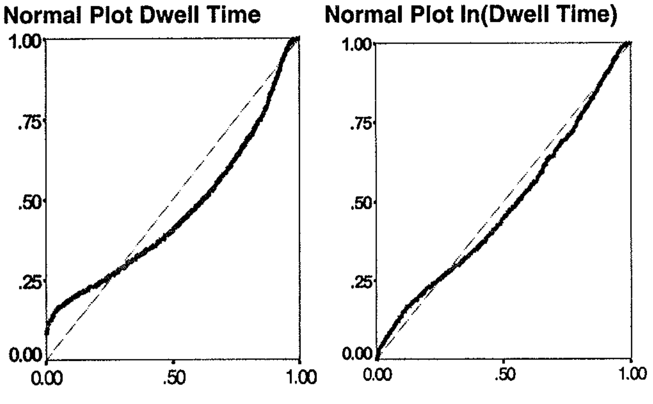


Figure 4.23 Expected cumulative probabilities (ordinates) versus observed cumulative probabilities (abscissa)

Table 4.15 Modeling dwell time on doorway movement time

Model terms	Overall
	n=1661
Constant	3.168
Flow time	0.0254

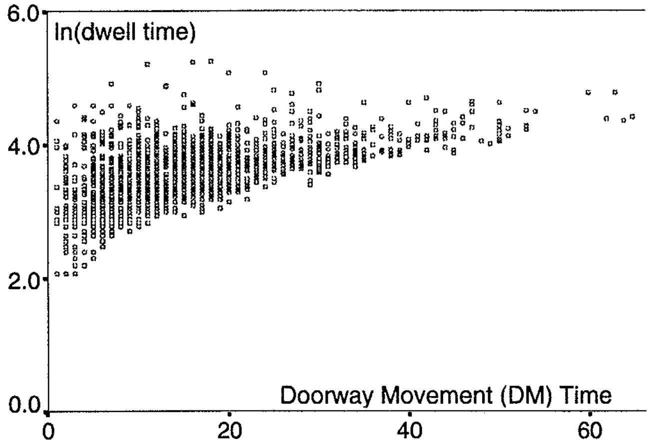


Figure 4.24 Scatterplot of ln(dwell time) versus DM time

Table 4.16 Mean doorway movement and dwell times (with standard deviations) for all data sets of selected systems (s)

	DM Time (secs)		Dwell Time (s)	
	mean	SD	mean	SD
BART	20.1	8.7	46.3	12.0
CTS	9.9	5.0	35.7	15.6
Edmonton	7.7	3.4	24.7	8.8
NYCT	14.5	8.8	30.7	20.9
PATH	20.2	13.5	51.3	22.9
Portland	8.8	4.9	32.0	19.4
San Diego	17.4	5.5	51.1	17.9
SF Muni	11.1	5.8	50.4	21.8
TTC	17.0	11.8	36.6	23.2
Vancouver	14.1	6.6	30.7	7.2

4.5.6 ESTIMATING THE CONTROLLING DWELL

It is usually the longest dwell time that limits the capacity of a rail transit system. This *controlling dwell* is determined at the most heavily used doorway on the peak-15-min train with the highest loading and is typically at the busiest station on the line being examined. Occasionally the controlling dwell may be at other than the busiest station on a line. This can be due to speed restrictions that increase the other headway components at this station or to congestion that increases the passenger doorway movement time—for example platform congestion due to inadequate platform exits, platform obstructions or, at stations with multiple routes, due to passengers waiting for other trains.

There are a number of possible methods for estimating the controlling dwell. In essence, all these methods seek to determine an upper bound for the dwell time below which the bulk of the population falls.

Examples of these methods, comparison with actual field data and suggestions of the most appropriate method to use in different circumstances are discussed in the application chapter: Chapter Seven, *Grade Separated Rail Capacity Determination,* Section 7.5.3 *Determining the Dwell Time.*

ALLE'S METHOD(R02)

This approach focuses on providing a prediction interval for the mean. In other words, in the long run all sample means should fall within these limits 95% of the time. However, it is really a prediction for a typical dwell time that is desired as this will provide the reference limit or bound that is required. As such, Alle's formula seems inappropriate. Moreover it is a nonstandard approach which consists of adding the 95% confidence widths for the distribution of the sample mean and the sample standard deviation. The rationale for adding the confidence width of the sample standard deviation is not clear.

The prediction interval for the sample mean is a random variable itself, and as such, it is possible to construct a confidence interval around it, which may have been the intent. If one were considering the limits for the dwell time of a typical new train, then the variance of the upper prediction limit is approximately $3s^2/n$ where s is the sample standard deviation and n is the sample size. As Alle's method considers a limit for the mean and not a typical unit, it is not considered further.

MEAN PLUS STANDARD DEVIATIONS

This is the traditional approach derived from control theory. It provides a prediction interval for a new train as opposed to one for the mean of all trains. Since it is maximum capacity that is the ultimate objective, only the upper limit is of interest.

A dwell based on the **statistical mean plus one standard deviation** ensures that 83% of the observed data would be equal to or less than this value. A dwell based on the **statistical mean plus two standard deviation** ensures that 97.5% of the observed data would be equal to or less than this value.

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

DWELL TIME PLUS AN OPERATIONAL ALLOWANCE OR MARGIN

Table 4.17 Controlling dwell data limits (seconds)

System	mean	SD	n	m+SD		Operational	
			no. of	upper limit		Mar gin	
	secs	secs	samples	ONE SD	TWO SD	+15 sec	+25 sec
BART	46.3	12.0	290	58.3	70.2	61.3	71.3
CTS	35.7	15.7	91	51.5	67.0	50.7	60.7
ETS	24.7	8.8	18	33.6	42.3	39.7	49.7
NYCT	30.7	20.9	380	51.6	72.6	45.7	55.7
PATH	51.3	23.0	252	64.3	97.3	66.3	76.3
Portland	32.0	19.4	118	51.4	70.8	47.0	57.0
S. Diego	51.1	17.9	34	69.1	86.8	66.1	76.1
MUNI	50.4	21.8	75	72.2	93.9	65.4	75.4
TTC	36.6	23.2	322	59.8	83.0	51.6	61.6
Vanc'ver	30.7	7.2	82	37.9	45.1	45.7	55.7

In many situations, particularly new systems, sufficient data is not available to estimate the dwell standard deviation over a one hour or even a 15 min peak period. In these cases or as an alternate approach an operational allowance or margin can be added to the estimated dwell time due to a specific volume of passenger movements. The figures for the controlling dwell are listed in Table 4.17 using both the mean plus one or two standard deviations and the mean plus operational allowances of 15 and 25 sec.

Chapter Six, *Operating Issues,* discusses the need for, and approaches to, estimating a reasonable operating margin. Application Chapter Seven, *Grade Separated Rail Capacity Determination,* Section 7.5.4, discusses how to select an operating margin in specific cases.

4.6 SUMMARY

The analysis in this chapter has produced methodologies whereby the passenger doorway flow time can be determined from four logarithmic models — overall, mainly boarding, mainly alighting and mixed flow — using as input the number of passenger movements, without reference to a specific mode, system or city.

A fifth model, also logarithmic, but considerably simpler, determines dwell time from passenger doorway flow time. Three alternative methods are then examined to convert the resultant dwell time to the controlling dwell time. The first two methods, traditional dwell plus two standard deviations, which most closely matched the field data, and Alle's method both require information on dwells over the peak hour. This information is not readily available when trying to estimate the capacity of new or modified rail transit systems, leaving the third method, adding an estimated operating margin to the calculated maximum dwell.

These methodologies are deployed in Chapter Seven, *Grade Separated Rail Capacity Determination* and in the spreadsheet as one of several complete methods to calculate system capacity.

5. Passenger Loading Levels

5.1 INTRODUCTION

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

It is important to remember the feedback processes; that train length significantly changes the signaling separation time and that loading levels affect dwell times.

The existing loading levels on North American rail transit vary from the relaxed seating of premium service (club cars) operated on specific trains of a few commuter rail lines to the densest loading of an urban subway car in Mexico City — a range of 1.5 to 0.17 m^2 per passenger (16 to 1.8 sq ft).

This wide range is more than eight to one. A more normal loading level range, discounting Mexico City and commuter rail, is two or three to one. This range makes the precise determination of loading level difficult. The main factor is a policy issue, the question of relative comfort — heavily restrained by economic issues.

Notwithstanding Toronto's subway and PATCO's Lindenwold line, the first new rail transit network in North America in the last half century was BART. In the early 1960s, planning for this network — more a suburban railway than an inner-city subway — was based on the provision of a seat for every passenger. Subsequently economic reality has forced acceptance of standing passengers, particularly for shorter trips in San Francisco and through the Transbay tube. Nevertheless, BART remains an example of a system that was designed to, and succeeded in, attracting passengers from alternate modes.

More so now, entering the twenty-first century, than 30 years ago, rail transit is being planned as an alternative to the automobile. While additions to existing systems can be expected to follow existing standards, new systems have to determine their service standards. The principal standards include speed, frequency of service at peak and off-peak times — often termed *policy headways* — and loading levels. Schedule speed is fixed when the alignment, station spacing and equipment specifications are set; headways are usually closely tied to demand, although unmanned trains, as used on Vancouver's SkyTrain and Miami's Metromover, make short, frequent trains over much of the day more affordable. Loading level is the remaining variable. Loading levels and headways interact as more comfortable standards require either longer or more frequent trains.

Demery(R22) states:

> *Long before crowding levels. . . . . .reached New York levels, prospective passengers would choose to travel by a different route, by a different mode, at a different time, or not at all.*

and

> *Outside the largest, most congested urban areas, the level of crowding that transit passengers appear willing to tolerate falls well short of theoretical "design" or "maximum" vehicle capacity.*

These are important issues to consider in establishing loading standards.

In the next section, existing loading standards are reviewed. The remainder of the chapter determines a range of loading standards that can be applied in specific circumstances for each mode.

It is possible to determine the interior dimensions of a rail transit vehicle; subtract the space taken up by cabs, equipment and, for low-loading light rail, stairwells; then assign the residual floor space to seated and standing passengers on the basis of selected densities. This approach is one of several followed in this chapter. However, the recommended method is simply to apply a passenger loading per unit of train length.

5.2 STANDARDS

A 1992 New York City Transit policy paper, *Rapid Transit Loading Guidelines,*(R48) gives the loading and service standards that have been applied, with minor modifications, to the New York subway system since 1987. The guidelines provide for slightly more space per passenger than those in effect until 1986. Modifications have allowed for a relaxation in the nonrush hour passenger loading guideline to allow for the operation of short trains.

The loading guidelines were established from test loadings of different car types, loading surveys of revenue service at the peak load point and comparisons with the policies of other rail transit operators. Additional concerns such as passenger comfort, dwell time effects, uneven loading within trains, and an allowance for *slack* capacity in the event of service irregularities and fluctuations in passenger demand were also considered. A rush hour standard of 3 sq ft per standing passenger (3.6 passengers per m^2) was generated from this work. The policy recognizes that this condition is only to be met at the maximum load point on a route and so is effective for only a short time and small portion of the overall route. For comparison, the agency's calculations of the maximum capacity of each car type are based on 6.6 - 6.8 passengers per m^2.

Figure 5.1 compares the loading standards of the older North American subway systems. NYCT standards for loading in the nonrush hours are more generous, with a seated load at the maximum load point being the general standard. If this would require headways of 4 min or less, or preclude operation of short trains, a standard of 125% of seated capacity applies. This

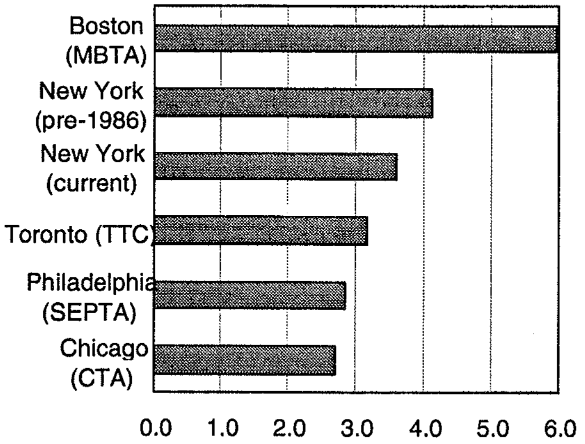


Figure 5.1 Scheduled loading guidelines (passengers/m^2)

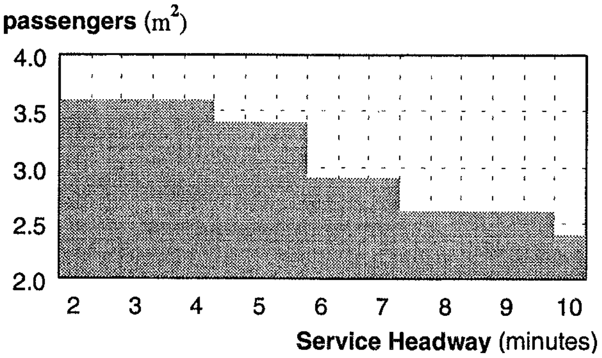


Figure 5.2 New York loading guidelines (passengers/m^2)

Table 5.1 New York policy service levels

Schedule	Time Period	Minimum Headway
Weekday	Rush hours	10 minutes
Weekday	Midday	10 minutes
Weekday	Evening	12 minutes
Saturday	Midday	10 minutes
Saturday	Evening	12 minutes
Sunday	All Day	12 minutes
All days	Midnight	20 minutes

Table 5.2 Passenger space on selected US systems(R22)

City	Passengers/m^2 of Gross Floor Space
New York	2.6 into CBD
Chicago	1.5 into CBD
Philadelphia	1.3 into CBD
Boston	2.0 into CBD
San Francisco	1.2 - 1.9
Washington	0.9 - 2.0
Atlanta	1.4 - 1.6
Toronto	1.8 - 2.4
Montreal	2.6 - 3.2

Table 5.3 Changes in NYCT peak-hour car loading(R22)

NEW YORK LOCATION	Average Passengers per car in peak hour		Change 1976-1991
	1976	1991	15 years
IRT Lexington	155	138	-10.97%
IRT Lexington Loc	147	112	-23.81%
IRT Broad Exp.	152	125	-17.76%
IRT Broad Local	104	95	-8.65%
IRT Flushing	116	115	-0.86%
IND Queens	200	195	-2.50%
IND 8th Exp.	146	128	-12.33%
IND 8th Local	91	74	-18.68%
IND 6th Ave	91	99	8.79%
BMT Astoria	129	108	-16.28%
BMT Canarsie	138	113	-18.12%
BMT Jamaica	103	139	34.95%
BMT Man. Bridge	136	119	-12.50%
BMT Montague	106	101	-4.72%
PATH WTC	79	112	41.77%
PATH 33rd	91	91	0.00%
Average[2]	124.4	120.2	-3.30%
Median	129	115	-10.85%

[2] Average and Median include additional data sets.

consideration of passenger comfort also extends to rush hour service on lines where the headway is longer than 4 min. In these cases a sliding scale is used to ensure lower standing densities on routes with longer headways, as shown in Figure 5.2. Minimum headways for each day and service period are shown in Table 5.1. The NYCT standard of 3.6 passengers per m^2 can be compared with the average occupancy into the CBD over the peak period as shown in Table 5.2. Table 5.3 tabulates and compares daily and peak-hour ridership and passengers per vehicle for 19 New York CBD trunks for 1976 and 1991. This decrease in NYCT car loadings partly reflected the improvement in service standards of 1987, among other factors. Several trunks continue to operate at or near capacity.[1]

Care should be taken in comparing and applying the service standards with hourly average loadings. Service standards are usually based on the peak within the peak—15 min or less.

A loading diversity factor equating 15-min and peak-hour flows was introduced in Chapter One, *Rail Transit In North America.* Section 5.6 of this chapter discusses the issues of loading diversity, provides data on existing factors by system and mode, and recommends factors for use in capacity calculations. The loading diversity factor for New York trunk routes, shown

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[1] Similar comparisons can be made for other cities and earlier years using data from this report and from the TRB's Highway Capacity Manual, Chapter 12 and appendices. Ridership and loading level information in the HCM are based on data to 1976 plus some historic data.(R67)

in Figure 5.3, ranges from 0.675 to 0.925 with an average of 0.817. This diversity must be taken into account to determine peak-hour capacity from a given service standard. NYCT's standard of 3.6 passengers per m^2 over the peak-within-the-peak becomes 3.6 x 0.82 or 2.95 (3.65 sq ft per passenger) on average, over the peak hour.

Outside New York the peak-within-the peak tends to be more pronounced and the peak-hour diversity factor is lower.[3] In part this is due to the long established Manhattan program to stagger work hours and the natural tendency of passengers to avoid the most crowded period—particularly on lines that are close to capacity.

Space occupancy during the peak period on other North American rail transit systems varies widely from below 0.3 passengers per m^2 (3.2 sq ft) to over 1.0 m^2 (11 sq ft) on some commuter rail lines, as shown in Figure 5.4. Note that the highest capacity entry (labeled NYCT) represents two tracks that combine local and express service.

In analyzing this data Pushkarev et al. (R51) suggest a standard of 0.5 m^2 (5.4 sq ft) per passenger. This will be discussed in the next section. In addition to standards or policies for the maximum loading on peak-within-the-peak trains and for minimum headways (*policy headways*) at off-peak times, some operators specify a maximum standing time. This is more often a goal rather than a specific standard—20 min is typical.

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

5.3 SPACE REQUIREMENTS

The surveyed literature contains many references to passenger space requirements. The Batelle Institute(R12) recommends comfort levels for public transport vehicles. The passenger standing density recommendations are

- COMFORTABLE 2-3 passengers per m^2
- UNCOMFORTABLE 5 passengers per m^2
- UNACCEPTABLE >8 passengers per m^2

In contrast, Pushkarev et al.(R51), suggesting *gross vehicle floor area* as a readily available measure of car occupancy, recommends the following standards:

- ADEQUATE 0.5 m^2—provides comfortable capacity per passenger space
- TOLERABLE WITH DIFFICULTY 0.35 m^2—lower limit in North America with "some touching"
- TOTALLY INTOLERABLE 0.2 m^2—least amount of space that is occasionally accepted

Batelle(R12) also provides details of the projected body space of passengers in various situations. The most useful of these for

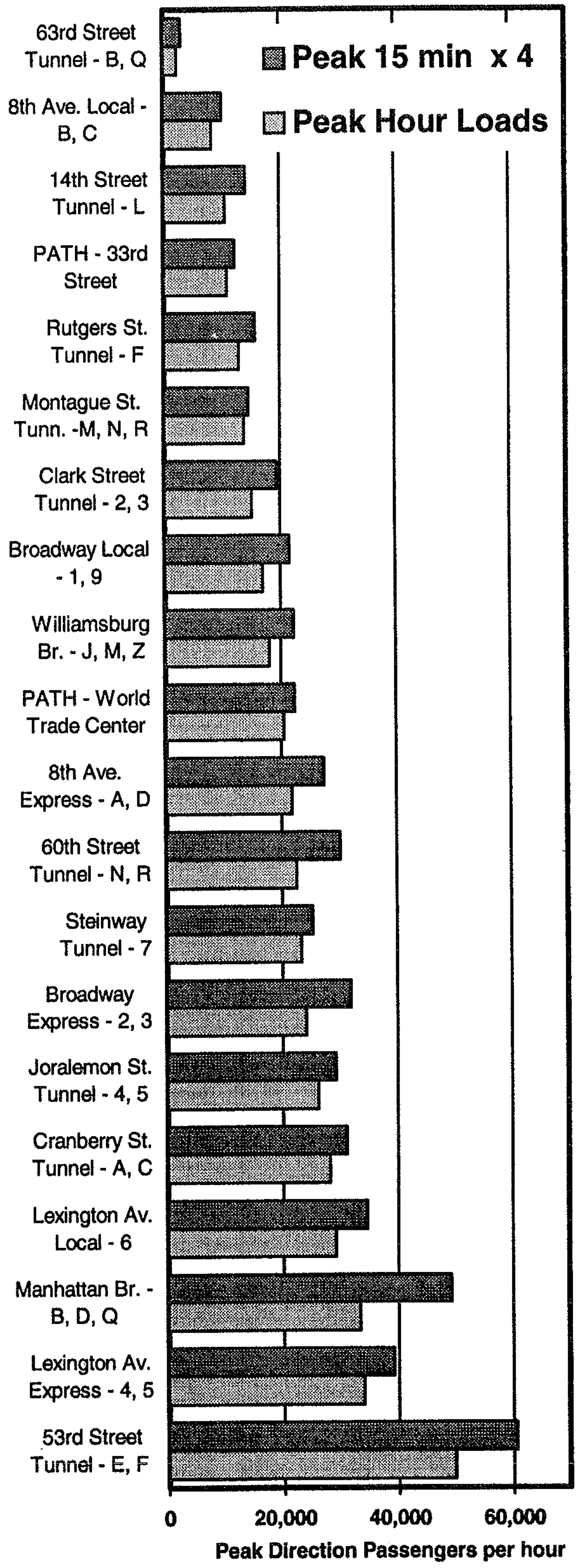

Figure 5.3 15-min peak-within-the-peak compared to full peak-hour ridership on New York subway trunks

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[3] Shown in Chapter One, Figures 1.4 and 1.6.

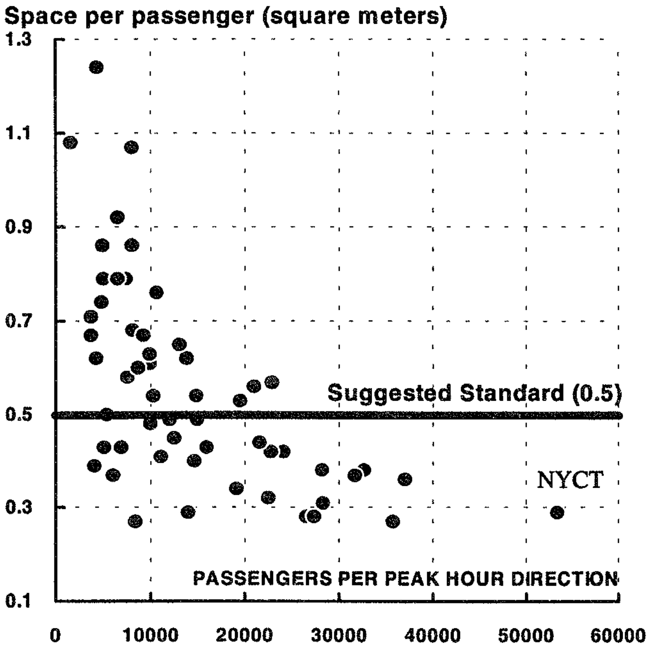

Figure 5.4 Peak-hour space occupancy—all U.S. systems(R51)

Table 5.4 Passenger space requirements (R12)

Situation	Projected Area m^2
Standing	0.13 to 0.16
Standing with briefcase	0.25 to 0.30
Holding on to stanchion	0.26
Minimum seated space	0.24 to 0.30
Tight double seat	0.36 per person
Comfortable seating	0.54 per person

Table 5.5 Passenger space requirements (R30)

CRITERIA	Passenger/ area	Mean space per passenger m^2
Max. practical (NY)	6.0 /m^2	0.17 (1.8 sq ft)
Typical rapid transit	2.2 - 3.6 /m^2	0.34 (3.7 sq ft)
Crush rapid transit	2.6 - 5.4 /m^2	0.26 (2.8 sq ft)
Design rapid transit	1.4 - 4.0 /m^2	0.38 (4.1 sq ft)
Design light rail	2.3 - 4.0 /m^2	0.30 (3.3 sq ft)
Actual light rail	2.9 - 5.7 /m^2	0.25 (2.7 sq ft)
To avoid contact	3.8 - 4.5 /m^2	0.24 (2.6 sq ft)
Unconstrained	1.2 - 2.7 /m^2	0.50 (5.4 sq ft)

Table 5.6 International transit space use (R30)

GROUP	pass/m^2
Some European and most North American	2.0 - 3.0
Some European systems and New York	3.1 - 5.0
Most European large cities	5.1 - 6.0
Large Soviet and Japanese systems	7.1 - 8.0

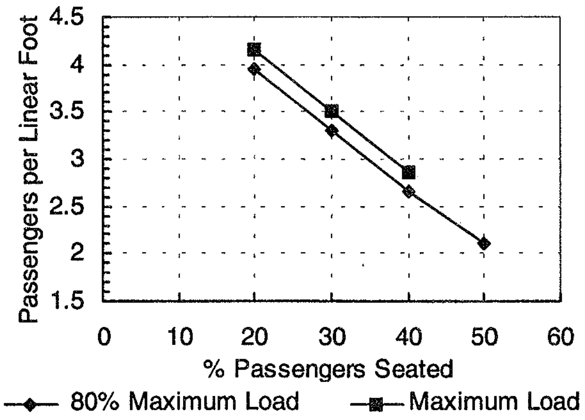

Figure 5.5 Passengers per length of car versus % seated

rail transit capacity are shown in Table 5.4. The tight double seat corresponds closely to the North America transit seating minimum of 34- to 35-in.-wide double seats on a 27- to 33-in. pitch (0.88 m by 0.76 m)— 3.6 sq ft or 0.33 m^2 per seat.

Jacobs et al. (R30) contains a comprehensive section on vehicle space per passenger, stating that while 53% of U.S. rapid transit lines enjoyed rush hour loadings of 0.5 m^2 per passenger or better, the space requirements shown in Table 5.5 are recommended and actual values for the stated conditions. The report is one of the few to discuss the diversity of standing densities within a car—higher in doorways/ vestibules, lower in aisles and at car ends (unless the car has end doors). Table 5.5 is particularly interesting in that the design space allocation for light rail is slightly lower than for heavy rail.

Klopotov(R32) cites typical average peak-hour space requirements from an international survey (Table 5). Lang and Soberman(R39) discuss seating provisions relative to compromises between capacity and comfort. They suggest that all rapid transit cars are substantially similar in width. The report compares passengers per square foot with the percentage seated. This ranges from 0.3 passengers per square foot with 50% seated to 0.6 passengers per square foot with 15% seated. This is then translated into passengers per *linear foot of train*, as shown below in Figure 5.5. The maximum vehicle capacity is 4 passengers per linear foot—approximately 2.5 square feet per passenger. Lang and Soberman also discuss the importance of ease of ingress and egress, recommending minimum distances between seats and doorways and discouraging three abreast seating. Comfort levels are discussed relative to smoothness of operation and the issue of supply and demand. Where systems are oversubscribed and few attractive alternate forms of transportation are available, high levels of crowding will be tolerated. Where systems wish to attract passengers, higher comfort levels, i.e., less crowding, are desirable.

Levinson et al.(R43) and also the Transportation Research Board's Highway Capacity Manual(R67) introduce the concept of loading standards A through F (crush) similar to the alphabetized *level of service* for road traffic. The suggested *schedule design capacity* is 2.8 to 3.3 passengers per m^2, 25% below the "crush" capacity. The peak-hour factor is discussed for 15-min peak-within-the-peak. A range of 0.70 to 0.95 is suggested, approaching 1.0 in large metropolitan areas.

Vuchic$^{(R71)}$ suggests passenger space requirements of 0.30 to 0.55 m^2 per seat and 0.15 to 0.25 m^2 per standee. Vehicle capacity in passenger spaces per vehicle is shown as:

$$C_v = m + \frac{\xi A_g - A_l - m\rho}{\sigma} \qquad \text{Equation 5-1}$$

Where: ξ = vehicle floor area loss factor for walls
A_g = gross vehicle floor area
A_l = vehicle floor area used for cabs, stairwells and equipment
m = number of seats
ρ = floor area per seat
σ = floor area per standing passenger

Young$^{(R76)}$ discusses a wide range of topics dealing with passenger comfort. He cites the "typical" transit vehicle as allowing 0.40 m^2 (4.3 sq ft) per seated passenger and 0.22 m^2 (2.4 sq ft) per standing passenger. The seating ratio is tabulated for a range of North American and European heavy rail and light rail systems. Heavy rail ranges from 25% to 100% seated and light rail from 40 to 50% in North America to 20 to 44% in Europe. Minimum seating pitch is recommended as 0.69 m (27 in.), 0.81 m (32 in.) to a bulkhead.

Several reports suggest vehicle passenger capacity can be stated as a multiple or percentage of the number of seats. Chapter 12 of the Highway Capacity Manual $^{(R67)}$ develops a measure of seated and total passengers per linear foot of car length, introduced in section 5.5 of this chapter.

Recommendations for a range of loading standards are developed in later sections of this chapter and applied in Chapter Seven, "Grade Separated Rail Capacity Determination," and the report's spreadsheet.

Wheelchairs There was no reference to wheelchair space requirements in the literature—much of which predates the 1991 Americans with Disabilities Act. Although wheelchairs come in several sizes, a common space allowance is 0.55 m^2 (6 sq ft), more for electric chairs and those whose occupants have a greater leg inclination, less for compact and sports chairs.

However, it is not the size of the chair that is a concern as much as the maneuvering and stowage space. Typically a chair occupies the space of a double seat whose seat squab folds up. Restraints and seat belts may be provided but the smoothness of the ride allows most rail transit systems to omit these. In certain vehicle layouts additional seats have to be removed to allow access to the designated wheelchair location.

In optimum designs wheelchair space occupancy should be assigned as the space of a double seat—0.8 m^2 (8.6 sq ft) with a 50% increase considered as an upper limit—1.2 m^2 (13 sq ft) No further allowance is necessary for maneuvering space as this will be occupied by standing passengers when circumstances dictate.

In several rail transit vehicle designs, capacity has actually increased with the removal of seats to provide a designated space for wheelchairs, or, selectively, bicycles. Where the designated space does not involve a fold-up seat the empty space is frequently used by standing passengers or to store baggage, baby strollers etc. Providing locations to store such potential obstacles away from doorways and circulation areas can assist in reducing dwell times.

Wheelchair effects on dwell times are discussed in Chapter Four, *Station Dwells*, and Chapter Eight, *Light Rail Capacity Determination.*

5.4 VEHICLE CAPACITY

In estimating the capacity of a rail transit vehicle one of the following approaches should be selected.

5.4.1 COMMUTER RAIL

Commuter rail capacity is based on the number of seats. Table A 3.5 in Appendix Three lists the dimensions and seating of all rail transit vehicles in North America. A summary extracted from this table is shown in Table 5.7. Commuter rail seating per car ranges from a maximum of 185 to below 60 on certain club cars and combination cars.[5] Seats will be reduced where staff, toilet, wheelchair, baggage or bicycle space is provided. The highest seating densities use 3+2 seating. Although suitable for shorter runs, 3+2 seating is not popular with passengers. The middle of the three-seats is often under utilized and capacity should be factored down accordingly by a suggested further 5%.

Table 5.7 Commuter rail vehicle summary data

System — Car Type[4] Date Built	Length (m)	Width (m)	Seats
ConnDOT Comet II 1991	25.91	3.2	118
GO Transit Bi-Level 77-91	25.91	3.0	162
LACMTA Bi-Level V 92-3	25.91	3.0	148
LIRR M-1 1968-71	25.91	3.28	122
LIRR P-72 1955-56	25.2	3.18	123
MARC Coach 1985-87	25.91	3.2	114
MBTA BTC 1991	25.91	3.05	185
MBTA BTC-1 1979	25.91	3.2	099
Metra CA2E 1978	25.91	3.38	147
Metra Gallery 1995	25.91	3.33	148
Metro-North M-1A B 71	25.91	3.2	122
Metro-North M-6 B 1993	25.91	3.2	106
NICTD EMU-1 1982	25.91	3.2	093
NJT Arrow III 1977-78	25.91	3.2	119
NJT Comet I 1971	25.91	3.2	131
SEPTA SL IV 1973-77	25.91	3.2	127
CalTrain California 1993	25.91	3.05	135
STCUM Gall. Trailer 1970	25.91	3.03	168
Tri-Rail Bi-Level 1988-91	25.91	3.0	162
VRE Trailer 1992	26.01	3.05	120

[4] Bi-level cars are sometimes designated as tri-levelas there is an intermediate level at each end over the trucks.

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[5] Not tabulated. Cars with baggage space, crew space or head-end (hotel) power.

Table 5.8 Light Rail Equipment Summary

System Car Designation Date Built	No.	Length (m)	Width (m)	Seats	Total Pass[5]	Door No. Width (m)
Bi-State U2A 1992-93	31	27.28	2.67	72		4—
Calgary U2, U2AC 1980-84, 86	85	24.28	2.66	64	158	4—1.3 m
Edmonton U2 1978-83	37	24.28	2.66	64	140	4—1.3 m
GCRTA Cleveland 800 1981	48	24.38	2.82	84	126	3—
LACMTA LRV 1989-94	69	27.13	2.67	76	137	4—
MBTA LRV Green 1986-88	100	21.95	2.69	50	112	3—
Metrorrey LRV 1990	25	29.56	2.65	58		
Sacramento MTA LRV 1991-93	35	28.96	2.9	85	201	4—
MUNI LRV 1995	40	22.86	2.74	60		
MUNI SLRV 1978	100	21.64	2.69	68		3—
NFTA Buffalo LRV 1983-84	27	20.37	2.62	51	180	2—
NJT PCC 1946-49	24	14.15	2.74	55	125	2—
PAT Pittsburgh U3 1986	55	25.73	2.54	63	125	4—
SCCTA SCLRV 1987	50	26.82	2.74	76	167	4—
San Diego U2 1980-89	71	24.26	2.64	64	96	4—1.3 m
San Diego U2A 1993	52	24.49	2.64	64	96	4—
SDTEO Guadalajara LRV 1989	16	29.56	2.65	52		
SEPTA LRV (S-S) 1980-82	112	15.24	2.59	51		2—
SEPTA N-5 1993	26	19.99	3	60	90	
SRTD U2A 1986-91	36	24.38	2.64	60	144	4—
STE Mexico LRV 1990-91	12	29.56	2.65	46		
Tri-Met LRV 1983-86	26	26.49	2.64	76	166	4—
TTC A-15 (PCC) 1951	22	14.15	2.54	45	103	2—
TTC L-1/2 (CLRV) 1977-81	196	15.44	2.59	46	102	2—
TTC L-3 (ALRV) 1987-89	52	23.16	2.59	61	155	3—

Table 5.9 Heavy rail equipment summary

System, Car Designation Date Built	# of Units	Length (m)	Width (m)	Seats	Total Pass[6]	Door #	Door Width
CTA 2600 B 1981-87	299	14.63	2.84	49	150	2	1.27 m
CTA 3200 (A&B) 1992	256	14.63	2.84	39	150	2	1.27 m
GCRTA Cleveland RT 84-85	60	23.01	3.15	80	128	3	1.27 m
LACMTA HRV 1991-93	30	22.86	3.2	59			
MARTA CQ 310 1979	100	22.86	3.2	68	136	3	1.27 m
MBTA 00600 Blue 1979	70	14.78	2.82	42	94		
MBTA 01200 Orange 1980	120	19.81	2.82	58	132		
MBTA 01400 Red 1962	86	21.18	3.18	54	160		
Metro-Dade Heavy Rail 1984	136	22.76	3.11	76	166	3	1.2 m
MTA Married Pair 1984-86	100	22.76	3.11	76	166	3	1.27 m
NYCT R46 1975-77	752	22.77	3.05	74		4	1.27 m
NYCT R62 1984-85	325	15.56	2.68	44		3	1.27 m
PATCO, PATCO II 1980-81	46	20.68	3.09	80	96	2	1.27 m
PATH PA-4 1986-88	95	15.54	2.81	31	130	3	1.37 m
SEPTA Single End: B-IV 1982	76	20.57	3.09	65	180	3	1.32 m
STCUM MR-73 1976	423	16.96	2.51	40			
TTC H6 1986-89	126	22.86	3.15	76	226	3	1.14 m
WMATA B3000 Chopper 1984	290	23.09	3.09	68	170	3	1.25 m

[6] Total passengers based on the agency's or manufacturer's nominal crush load.

Commuter capacity should be calculated as 90 to 95% of the total seats on a train, after allowing for cars with fewer seats due to other facilities. Where there are high incremental passenger loads for relatively short distances — for example the last few kilometers into the CBD — a standing allowance of 20% of the seats may be considered. However, this is unusual and standing passengers should not normally be taken into account on commuter rail.

5.4.2 EXISTING SYSTEMS

The vehicle capacity on existing systems should be based on actual loading levels of a comparable service. Actual levels on cific system or line should be adjusted for any difference r size and interior layout—particularly the number of —as outlined in section . If the average occupancy over peak hour is used then the loading diversity factor should mitted. If the higher peak-within-the-peak loading is used, n the loading diversity factor should be applied to reach an urly achievable capacity.

Particular care should be taken in applying any passenger loading level based on car specifications. The often cited *total, maximum, full* or *crush load* does not necessarily represent a realistic average peak hour or peak-within-the-peak occupancy level. Rather it reflects the specifier or manufacturer applying a set criteria—such as 5 or occasionally 6 passengers per square meter—to the floor space remaining after seating is deducted. Alternately it can represent the theoretical, and often unattainable, loading used to calculate vehicle structural strength or the minimum traction equipment performance.

Tables 5.8 and 5.9 provide dimensions and capacity information of selected, newer, heavy rail and light rail equipment in North America.

Table A 3.5 in Appendix Three lists the dimensions and seating of all rail transit vehicles in North America.

5.4.3 VEHICLE SPECIFIC CALCULATIONS

Detailed calculations of vehicle passenger capacity are possible, however, given the wide range of peak hour occupancy that is dependent on policy decisions, elaborate determination of interior space usage is generally overkill. Reasonably accurate estimation of vehicle capacity is all that is needed. The following procedures offer a straight forward method.

Converting Exterior to Interior Dimensions

Rail transit vehicle exterior dimensions are the most commonly cited. Where interior dimensions are not available, or cannot be scaled from a floor plan, approximate interior dimensions can be estimated.

Typically the interior width is the exterior width less the thickness of two walls—0.2 m (8 in.). Heavy rail configurations are most commonly married pairs with one driving cab per car. The typical exterior length is quoted over the car anticlimbers. Although cab sizes vary considerably, the interior length can be taken to be 2.0 m (6.7 ft) less than the exterior length. This reduction should be adjusted up to 2.5 m if the exterior dimension are over the couplers and down to 1.5 m if only half width cabs are used, or 0.5 m if there is no cab.

Beware of rare pointed or sloping car ends which require this deduction to be increased. Curved side cars are measured from the widest point—waist level—allowing seats to fit into the curve and so increasing the aisle width. This maximum "waist" width should be used, not the width at floor level.

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

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

- 0.69 m (27 in.)[8] for transverse seating
- 10.43 m (17 in.) for longitudinal seating

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

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

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

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

Standing passengers can be assigned as follows:

- 5 per square meter (0.2 m^2, 2.15 sq ft per passenger)—an uncomfortable near crush load for North Americans[10] with frequent body contact and inconvenience with packages and brief cases; moving to and from doorways extremely difficult.
- 3.3 per square meter (0.3 m^2, 3.2 sq ft per passenger)—a reasonable service load with occasional body contact; moving to and from doorways requires some effort

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

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

[9] For more accurate results the sidewall should be divided into the lengths between each set of doors (and, when appropriate, between the door and any articulation) and checked, or adjusted, to ensure that an integer of the seat pitch is used. The computer spreadsheet carried this out by dividing the interior free wall length by the number of doorways plus one. The number of integer seat pitches in each space is then determined and used to calculate the total vehicle seating. The appropriate seat pitch is used automatically, 0.43 m for N=2, 0.69 m for N>2.

However, this approach can result in the seating changing radically with a small change in vehicle length, articulation length or door width, any of which are sufficient to add or remove a row of seats between each set of doors. On a four door car with 2+2 seating this results in the seating adjusting up or down by 20 seats at a time—five rows of four seats. Neither Equation 1.3 nor the computer spreadsheet can substitute for a professional interior design, which can optimize seating with a combination of transverse and longitudinal seats. Other design criteria can also be accommodated, including the provision of wheelchair spaces and maximizing circulation space around doorways.

[10] Loading levels of over 6 passengers per square meter are reported on Mexico City's metro, lines 1 and 3. These are a unique exception in North America.

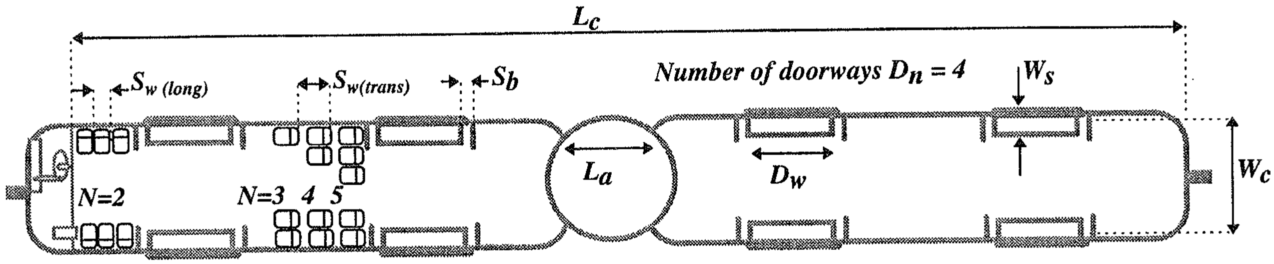

Figure 5.6 Schematic of rail car showing the dimensions of Equation 5.2

- 2.5 per square meter (0.4 m^2, 4.3 sq. ft. per passenger)[11]—a comfortable level without body contact; reasonably easy circulation, similar space allocation as seated passengers.

The middle level above is slightly relaxed from the often stated standard of four standing passengers per square meter. So-called crush loads are frequently based on 5 or 6 passengers per square meter, the latter being more common in Europe. Asian standards for both maximum and crush loads reach 7 or 8 standing passengers per square meter.

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

The above process can be expressed mathematically as

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

Equation 5-12[12]

where V_c = vehicle capacity—peak-within-the-peak
L_c = vehicle interior length
L_a = articulation length for light rail
W_s = stepwell width (certain light rail only)
W_c = vehicle interior width
S_{sp} = space per standing passenger
  0.2 m^2 (2.15 sq ft) maximum
  0.3 m^2 (3.2 sq ft) reasonable
  0.4 m^2 (4.3 sq ft) comfortable
N = seating arrangement
  2 for longitudinal seating
  3 for 2+1 transverse seating
  4 for 2+2 transverse seating
  5 for 2+3 transverse seating [13]
S_a = area of single seat
  0.5 m^2 (5.4 sq ft) for transverse
  0.4 m^2 (4.3 sq ft) for longitudinal
D_n = number of doorways
D_w = doorway width
S_b = single set-back allowance
  0.2 m (0.67 ft)—or less
S_w = seat pitch
  0.69 m (2.25 ft) for transverse
  0.43 m (1.42 ft) for longitudinal

Figure 5.6 shows these car dimensions.

The equation can be worked in either meters or feet. An expanded version of this equation is included on the computer spreadsheet. The spreadsheet calculation automatically applies the S_w seat pitch dimension through an IF statement acting on *N*, the seating arrangement factor, using the longitudinal dimension *if* N=2.

Offset Doors A small number of rail vehicle designs utilize offset doors. These do not merit the complexity of a separate equation. Provided that each side of the car has the same number of doors Equation 5.2 will provide an approximate guide to vehicle capacity with a variety of seating arrangements and standing densities.

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

5.4.4 RESULTS OF THE CALCULATION

Light Rail Applying the calculations of section produces passenger loading levels for typical light rail vehicles as shown in

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[11] This upper level is a peak-within-the-peak occupancy level for standing passengers. Over the peak hour, it corresponds closely to Pushkarev(R50) and Jacobs(R30) estimates of a United States rush-hour loading average of 0.5 m^2 per passenger—both seated and standing. It also corresponds to Pushkarev and Batelle's(R12) recommendation for an *adequate* or *comfortable* loading level.

[12] $\lfloor\ \rfloor$ = expression rounded down to nearest integer (whole number).

[13] 2+3 seating is only possible on cars with width greater than 3 meters, not applicable to light rail or automated guideway transit.

Table 5.10 Calculated light rail vehicle capacity

RAIL MODE	EXTERIOR WIDTH	EXTERIOR LENGTH	STANDING SPACE	DOOR NUMBER	SEATING FACTOR	TOTAL SEATS	STAND PAX	TOTAL PAX
	Wc (m)	Lc (m)	Ssp (m^2)	Dn	N	Sc	Ps	Vc
Siemens	2.65	25	0.2	4	4	52	151	203
Siemens	2.65	25	0.3	4	4	52	101	153
Siemens	2.65	25	0.4	4	4	52	75	127
Baltimore	2.9	29	0.2	4	4	76	189	265
Baltimore	2.9	29	0.3	4	4	76	126	202
Baltimore	2.9	29	0.4	4	4	76	94	170

Table 5.11 Calculated heavy rail vehicle capacity

RAIL MODE	EXTERIOR WIDTH	EXTERIOR LENGTH	STANDING SPACE	DOOR NUMBER	SEATING FACTOR	TOTAL SEATS	STAND PASS	TOTAL PASS
	Wc (m)	Lc (m)	Ssp (m^2)	Dn	N	Sc	Ps	Vc
Generic	3.1	23	0.2	4	4	60	192	252
Generic	3.1	23	0.4	4	4	60	96	156
Generic	3.1	23	0.2	3	4	80	157	237
Generic	3.1	23	0.3	3	4	80	104	184
Generic	3.1	23	0.4	3	4	80	78	158
Generic	3.1	23	0.2	4	2	60	207	267
Generic	3.1	23	0.3	4	2	60	138	198
Generic	3.1	23	0.4	4	2	60	103	163
Vancouver	2.6	13	0.2	2	4	36	75	111
Vancouver	2.6	13	0.3	2	4	36	50	86
Vancouver	2.6	13	0.4	2	4	36	37	73
Chicago	2.84	14.7	0.2	2	3	36	98	134
Chicago	2.84	14.7	0.3	2	3	36	65	101
Chicago	2.84	14.7	0.4	2	3	36	49	85

Table 5.10. Two articulated light rail vehicles are shown, the common Siemens-Düwag car used in nine systems (with some dimensional changes) and the largest North American light rail vehicle used by the MTA in Baltimore. The resulting capacities are for a generic version of these cars. Reference to Table 5.9, *Light Rail Equipment Summary*, shows that the actual number of seats in the Siemens-Düwag car varies from 52 to 72 while rated total capacity varies from 96 to 201. This stresses the wide, policy related, car capacity issue.

The calculation cannot encompass all options. However, the calculation provides a policy surrogate in the form of the allocated standing space,—0.2, 0.3 or 0.4 m^2 per passenger. Seating should be adjusted accordingly. A need for high standing levels would suggest longitudinal seats, low standing levels, the 2+2 transverse seats.

Heavy Rail Applying the calculations of section produces passenger loading levels for typical heavy rail vehicles as shown in Table 5.11. Data is shown for a generic 23 meter heavy rail car with variations of seating arrangements and standing space allocations. Two data sets follow for the smaller cars used in Vancouver and Chicago.

5.5 LENGTH

In this section the above calculations are converted to the passengers per unit length method suggested by Lang and Soberman(R39) and others, stratified into classes, then compared with actual peak-within-the-peak loading levels of North American rail transit. Given the variation in loading levels that depend on policy — the standing density used and seat spacing — this simplified method is appropriate in most circumstances. It is the recommended method of estimating peak-within-the-peak car capacity except for circumstances and rolling stock that are out of the ordinary.

Light Rail Applying the calculations of section produces passenger loading levels for typical light rail vehicles as shown in

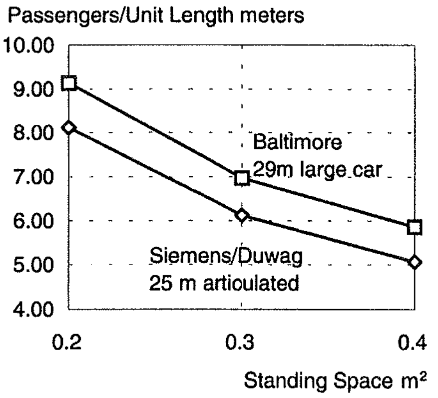

Figure 5.7 Linear passenger loading of articulated LRVs

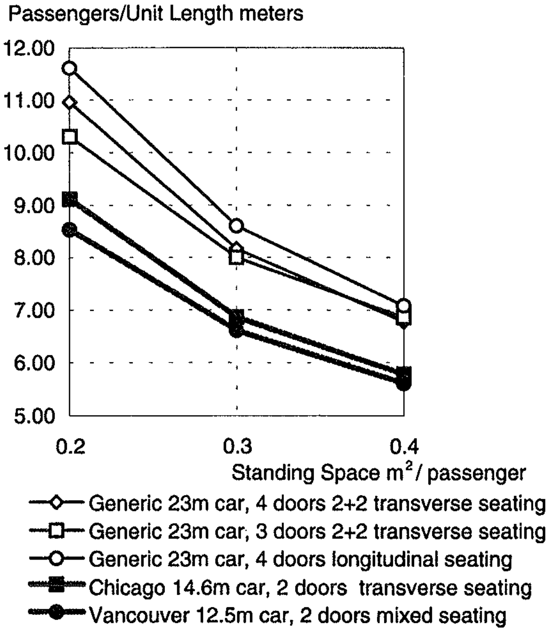

Figure 5.8 Linear passenger loading of heavy rail cars

Table 5.10 and as passengers per unit length in Figure 5.7. As would be expected, the wider and longer Baltimore car has proportionately higher loadings per meter of length. The typical Siemens-Düwag car used on nine systems (with some dimensional changes) has a range of 5.0 to 8.0 passengers per meter of car length. The lower level of five passengers per meter length—with a standing space per passenger of 0.4 m^2—corresponds closely with the recommended *quality* loading of a an average of 0.5 m^2 per passenger.

Heavy Rail Applying the calculations of section 5.4.3 produces passenger loading levels for typical heavy rail vehicles as shown in Table 5.11 and, as passengers per unit length, in Figure 5.8. As would be expected, the smaller and narrower cars in Vancouver and Chicago have lower loadings per meter length.

The more generic 23-m-long cars used in over 12 North American cities have a remarkably close data set for each of the three variations, 4 and 3 door versions, and transverse or longitudinal seating—with a range of 7.0 to 11.5 passengers per meter of car length. The lower end of the range of seven to eight passengers per meter length—with a standing space per passenger of 0.4 to 0.3 m^2—is an appropriate range for higher use systems. A lower figure of six corresponds closely with the recommended *quality* loading of an average of 0.5 square meters per passenger and is appropriate for a higher level of service on new systems. In both cases a reduction by one should be used for smaller, narrower cars.

These calculated linear loading levels can be compared with actual levels on major North American rail transit lines shown in Table 5.12 and summarized in Table 5.13.

Heavy Rail outside New York shows a level comparable with the recommended *comfortable* level of 6 passengers per meter of train length. New York is higher by some 25%, averaged over 11 trunk routes. Commuter rail, with most passengers seated, has an average only 13% lower than the average of heavy rail outside New York. Only two light rail lines are running close to capacity and peak-within-the-peak ridership is not available for these.

5.6 LOADING DIVERSITY

Passengers do not load evenly into cars and trains over the peak hour. This unevenness is the diversity of passenger loading. There are three different types of loading diversity: unevenness of passenger loading within a car; unevenness of passenger loading within cars of a train; unevenness of passenger loading within peak-hour trains. The loading diversity factor developed in this section essentially encompasses all three.

In individual cars, the highest standing densities occur around doorways, the lowest at the ends of the cars. Several European urban rail systems add doors, sometimes only single stream, at the car ends to reduce this unevenness. London Transport's underground system is the most notable with this feature on most rolling stock,[14] except at car ends with a driving cab. The end door on the low-profile cars are 0.75 m (2.5 ft) wide compared to the main doors of 1.56 m (5.1 ft). These exceptionally wide doors, with their 0.17 m (6.8 in) set-backs often accommodate three streams of passengers.

No data exist to determine such loading diversity within a car and the variations are accommodated in the average loadings of the previous sections. It is important in cars designed for high occupancies to minimize this effect by using wide aisles, uncluttered vestibules and suitable hand holds that encourage passengers to move into the extremities of a car. Very little information was found on car interior design efficiency in the literature search with the exception of Young[(R76)] *Passenger Comfort in Urban Transit Vehicles*.

A second level of diversity occurs in uneven loading among cars of a train. This second level is also included in the average loading data of the previous sections and in the application chapters. Cars that are closer to station exits and entrances will be more heavily loaded than more remote cars. This inefficiency can be minimized by staggering platform entrances and exits

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[14] London's Docklands Light Railway does not have end doors.

Table 5.12 Passengers per unit train length, major North American trunks

System	Trunk Name	Length	Width	Seats	15 min. peak	Average passengers per car	Passengers per meter of car length
CalTrain	CalTrain	25.91	3.23	146	932	117	4.5
GO Transit	Lakeshore East	25.91	3	162	4094	152	5.9
LIRR	Jamaica - Penn Stn.	25.91	3.28	120	12380	117	4.5
Metra	Metra Electric	25.91	3.2	156	4765	113	4.4
CTS	Northeast Line	24.28	2.66	64	1495	125	5.1
CTS	South Line	24.28	2.66	64	1840	153	6.3
BCT	SkyTrain	12.4	2.49	36	2056	73	5.9
CTA	Dearborn Subway	14.63	2.84	46	2616	82	5.6
CTA	State Subway	14.63	2.84	46	3601	75	5.1
MARTA	East/West	22.86	3.2	68	926	77	3.4
MARTA	North/South	22.86	3.2	68	1796	82	3.6
NYCT	53rd Street Tunnel	18.35	3.05	50	15154	210	11.4
NYCT	60th Street Tunnel	22.77	3.05	74	7534	126	5.5
NYCT	Broadway Express	15.56	2.68	44	7962	119	7.6
NYCT	Broadway Local	15.56	2.68	44	5398	135	8.7
NYCT	Clark Street	15.56	2.68	44	4873	102	6.6
NYCT	Joralemon St. Tunnel	15.56	2.68	44	7305	122	7.8
NYCT	Lexington Ave. Express	15.56	2.68	44	9800	123	7.9
NYCT	Lexington Ave. Local	15.56	2.68	44	8648	144	9.3
NYCT	Manhattan Bridge	22.77	3.05	74	12306	162	7.1
NYCT	Rutgers St. Tunnel	22.77	3.05	74	3937	123	5.4
NYCT	Steinway Tunnel	15.56	2.68	44	6318	144	9.3
PATH	33rd St.	15.54	2.81	31	3080	88	5.7
PATH	World Trade Center	15.54	2.81	31	5595	92	5.9
TTC	Yonge Subway	22.7	3.15	80	8285	197	8.7

Table 5.13 Summary of linear passenger loading (per meter) Additional passenger loading per unit length data are compiled in Tables 7.4, 7.5 and 7.6 of Chapter Seven.

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

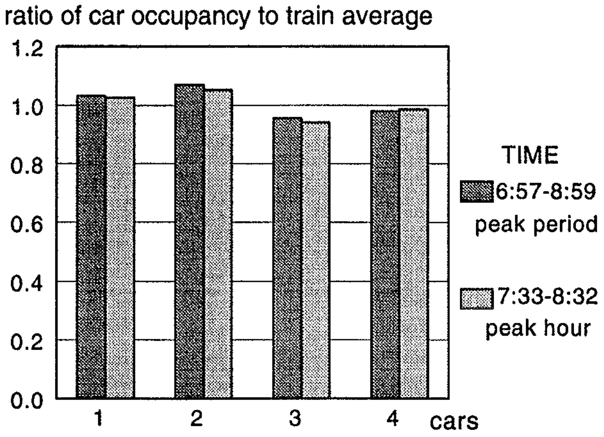

Figure 5.9 Vancouver, Broadway Station inbound peak-hour passenger distribution between cars of train. October 27 1994, 50 trains, 12,173 passengers

between ends, centers and third points of the platforms. This is not always possible or practiced. The busiest, most densely occupied rail lines in North America, lines 1, 2 and 3 of Mexico City's metro all have stations with center entrances/exits. Even so, relatively even loading occurs both here, and on rail transit lines at or near capacity elsewhere, due to the duress factor that encourages passengers to spread themselves along the platform during heavily traveled times—or risk being unable to get on the next arriving train.

Few systems count passengers by individual cars when these are *crush* loaded. This is difficult to do with any accuracy and the results differ little from assigning a set *full* load to each car of a fully loaded train. Data are available from two Canadian properties.

BC Transit operates four car trains on headways down to 90 sec. Pass-ups are routine at the busiest suburban station, Broadway with an end and two third-point entrances/exits. The relative loading of the four cars is shown in Figure 5.9. The main entrance/exit is provided with escalators and lies between the

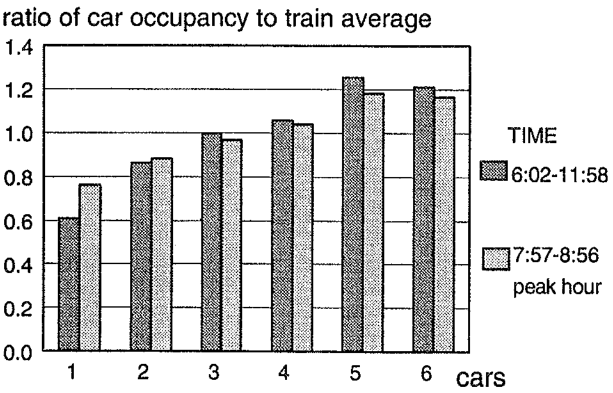

Figure 5.10 TTC Yonge Subway, Wellesley Station southbound, a.m. peak-period average passenger distribution between cars of train. Jan 11, 1995, 99 trains with 66,263 passengers

second and third cars of the train. While the second car is the most heavily loaded, the third is the lightest loaded indicating the influence of entrance/exit locations at other major stations.

There is no significant variation in the average loading diversity between the peak hour and the peak-period both of which remain within the range of +5% to -6%. The unbalance for cars on individual trains ranges from +61% to -33%. The uniformity of loading can be attributed to four factors — the short trains, wide platforms, close headways and dispersed entrance/exit locations between the stations of this automated, driverless system. The Toronto Transit Commission's Yonge Street subway shows a more uneven loading between cars in Figure 5.10. In the morning peak period the rear of the train is consistently more heavily loaded reflecting the dominance of the major transfer station at Bloor with the interchange at the northern end of the Yonge platform. As would be expected, there is little variation in the average car loading diversity between the peak hour and the peak period due to the pressures on passengers to spread along the platforms at busy times. The average diversity of individual car loading over the peak period has a range of +26%to -39%. The unbalance for cars on individual trains ranges from +156% to -89%.[15] In the afternoon peak period shown in Figure 5.11, the reverse occurs with the front of the train most heavily loaded — despite the principal entrances at the two major downtown station being toward the rear of the train. There is less variation in the average car loading diversity between the peak hour and the peak period than in the morning. The average diversity of individual car loading over the peak period has a range of +13% to -28%. The unbalance for cars on individual trains ranges from +113% to -72%. These ranges are lower than in the morning reflecting the less intense peak-within-the-peak in the pm rush hour.

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

$$D_{ph} = \frac{R_{hour}}{4R_{15\mathrm{min}}} \qquad \text{Equation 5-1}$$

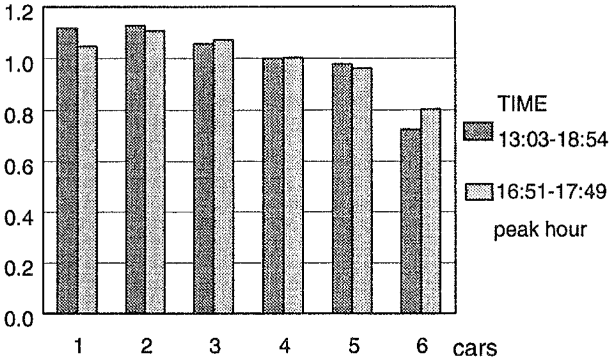

Figure 5.11 TTC Yonge Subway, Wellesley Station northbound, p.m. peak-period average passenger distribution between cars ot train. Jan 11, 1995, total 69,696 passengers on 108 trains

where D_{ph} = Diversity factor — peak hour
R_{hour} = Ridership in peak hour
R_{15min} = Ridership in peak 15 min

Passengers do not arrive evenly and uniformly on any rail transit system as shown dramatically over the extended peak period in

Table 5.14 Diversity of peak hour and peak 15 min[16]

Type	System	Routes	Diversity factor
CR	CalTrain	1	0.64
CR	GO Transit	7	0.49
CR	LIRR	13	0.56
CR	MARC	3	0.60
CR	MBTA	9	0.53
CR	Metra	11	0.63
CR	Metro-North	4	0.75
CR	NICTD	1	0.46
CR	NJT	9	0.57
CR	SCRRA	5	0.44
CR	SEPTA	7	0.57
CR	STCUM	2	0.71
CR	Tri-Rail	1	0.25[17]
CR	VRE	2	0.35
CR	**Sum/Average**	**74**	**0.56**
LRT	CTS	2	0.62
LRT	Denv. RTD	1	0.75
LRT	SEPTA	8	0.75
LRT	Tri-Met	1	0.80
LRT	**Sum/Average**	**12**	**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
RT	PATH	4	0.79
RT	STCUM	4	0.71
RT	TTC	3	0.79
RT	**Sum/Average**	**46**	**0.79**
All	**Sum/Average**	**133**	**0.67**

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[15] One car of one train was completely empty (-100%), possibly due to an incident or defective doors. This outlier was excluded from the data set.

[16] This peak-hour diversity factor is the same as the peak-hour factor (phf) in the Highway Capacity Manual(R47).

[17] Service is only one train per hour and is not included in the average.

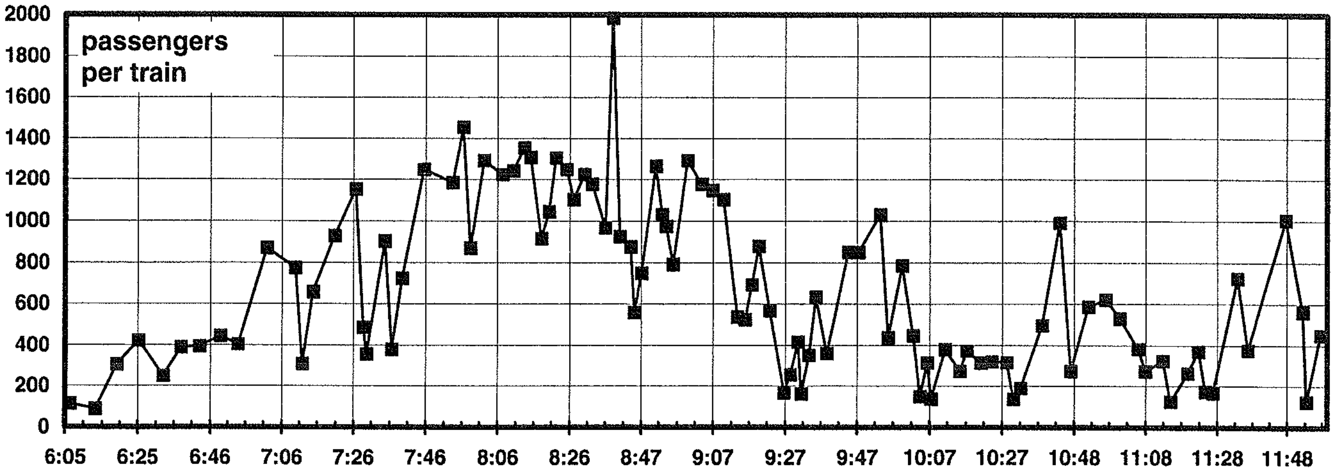

Figure 5.12 Individual train loads, TTC Yonge Subway, Wellesley Station southbound Jan. 11, 1995 (5-min tick marks)

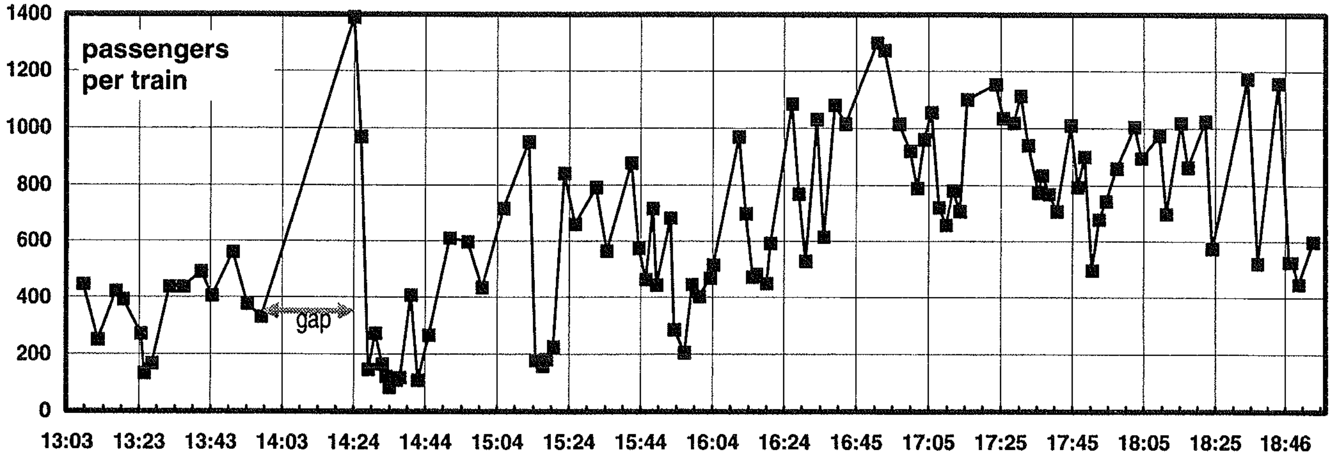

Figure 5.13 Individual train loads TTC Yonge Subway, Wellesley Station northbound Jan. 11, 1995 (5-min tick marks) Note cluster of low occupancy trains at 14:24 to 14:44h following a crush load train after a 29-min gap in service.

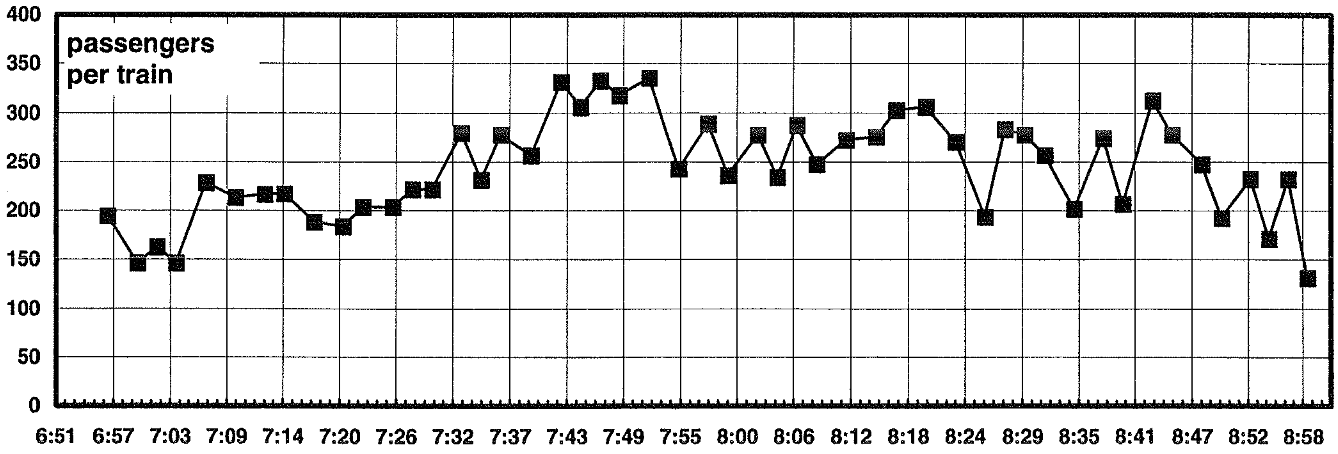

Figure 5.14 Individual train loads Vancouver, Broadway Station inbound October 27, 1994 a.m. peak (1-min tick marks)[18]

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[18] The courtesy of the Toronto Transit Commission and British Columbia Rapid Transit Company in providing car by car and train by train checker data is acknowledged. The willingness of the Toronto Transit Commission to allow use of data with unusual erratic headway operation is particularly appreciated.

Figures 5.12 and 5.13 for the Toronto Transit Commission's Yonge subway.

These figures do not show the smooth peaks-within-the-peak often displayed in texts but rather the realities of day-to-day rail transit operation. The morning peak-within-the-peak has a pronounced abnormality at 8:35h following a short gap in service.

The afternoon peak actually occurs at 14:24h following a 26-min delay due to a suicide. Next are two abnormally low troughs as the delayed trains move through—and the commission's control center strives to normalize service prior to the start of the real peak hour.

In both charts the different loading, train by train, is striking and it is difficult to visually pick out the peak hour or the 15 min peak-within-the peak. This entire data set of car by car loadings and headways, representing 1,242 individual car counts of 135,000 passengers, is contained on the computer disk.

Figure 5.14 shows an a.m. peak-period for BC Transit that, although without major delays, shows the irregular loading from train to train due to the interlacing of short-turn trains with regular service from 07:30h onwards. The loading diversity factor was obtained for most systems. The principal data deficiency was for light rail where few systems count passengers by train.

The diversity of train loading over the peak hour is shown in Table 5.14. Note that the values can be strongly affected by the level of service provided. This is particularly true of infrequent commuter rail lines. (Infrequent service on two of GO Transit's lines contributes to GO's relatively low average.) Rail rapid transit (RT) is generally the most frequent mode and so has relatively low values for the diversity factor. Values for light rail transit are intermediate.

Diversity of loading within a car and among cars of a train are included in the recommended peak-within-the-peak loading levels. The peak-within-the-peak *loading diversity factor* is not so included and must be used to adjust passenger volumes from the estimated *design capacity* to a more practical *achievable capacity*. This important loading diversity factor is discussed further in Chapter Seven, *Grade Separated Rail Capacity Determination*, and subsequent mode specific chapters. Here suitable values are recommended for use in calculating the maximum achievable capacity.

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-to-day 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, under-performing 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 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 trainlined — 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 in-service failures. It is not uncommon for many classes of modern rail equipment to achieve 100,000 km (60,000 mi) between in-service 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 bi-directional 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(R01), 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 cross-overs 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 bi-directional 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 one-way 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 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 peak-hour 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

HEADWAY and DWELL TIMES seconds

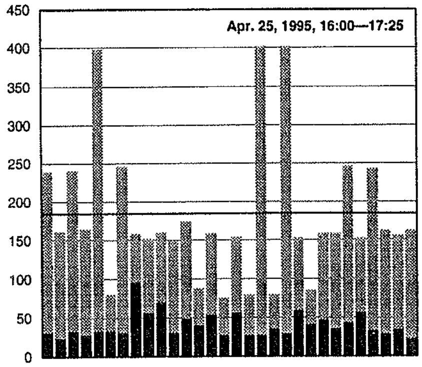

Figure 6.1 CTS 3rd St. SW E/B

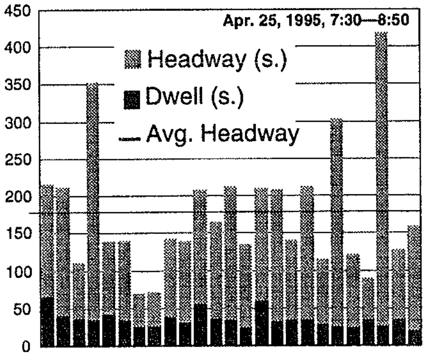

Figure 6.2 CTS 1st St. SW W/B

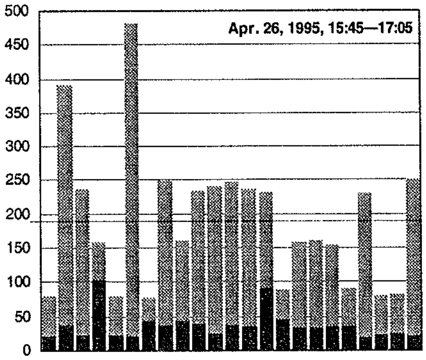

Figure 6.3 CTS City Hall E/B

▩ **Dwell Time** seconds ▨ **Headway** seconds — **Average Headway** seconds

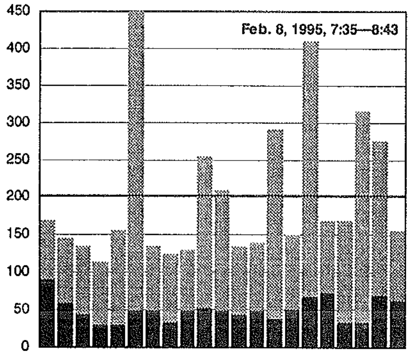

Figure 6.4 BART Embarcadero W/B

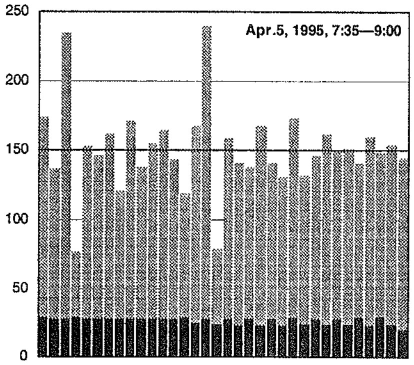

Figure 6.5 BC Transit Burrard W/B

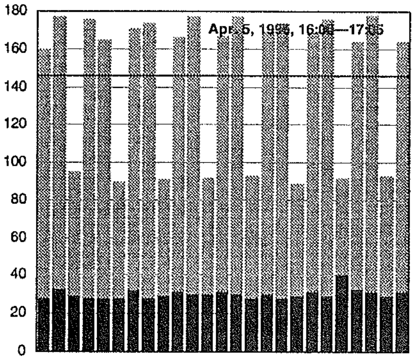

Figure 6.6 BC Transit Broadway E/B

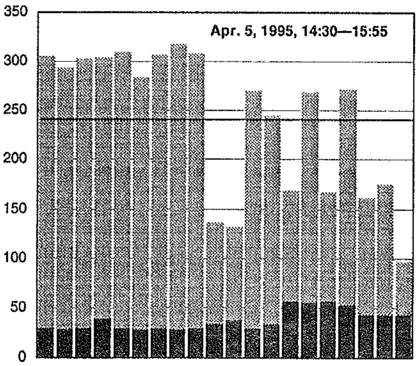

Figure 6.7 BC Transit Metrotown E/B

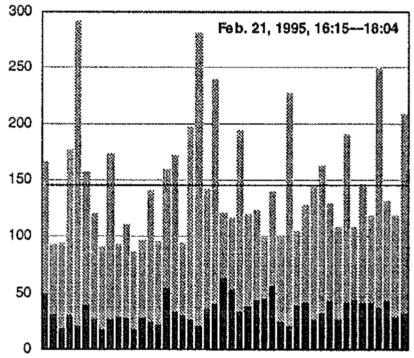

Figure 6.8 Muni Montgomery W/B

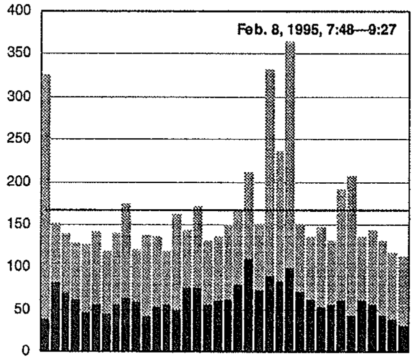

Figure 6.9 NYCT Grand Cen. S/B Exp.

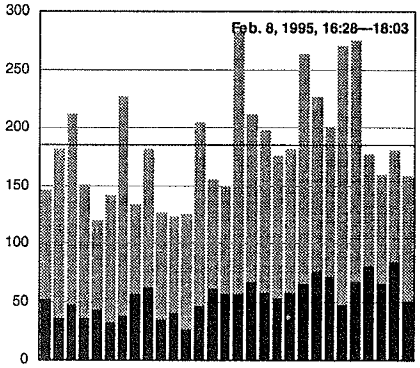

Figure 6.10 NYCT Grand Cen. N/B Exp.

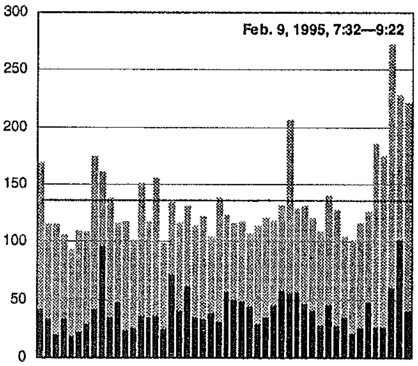

Figure 6.11 NYCT Queens Plaza W/B

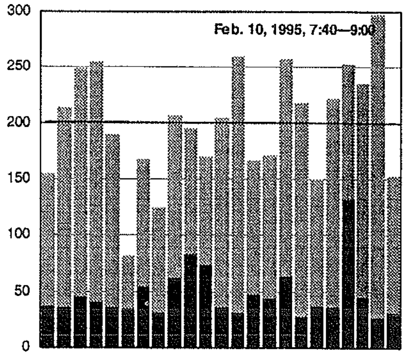

Figure 6.12 PATH Journal Square W/B

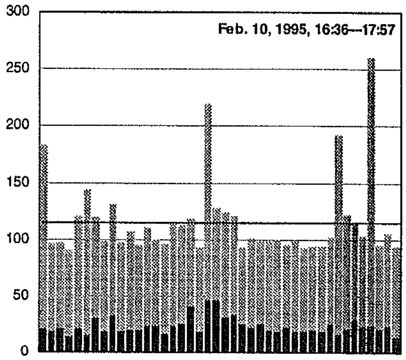

Figure 6.13 PATH Exchange Place E/B

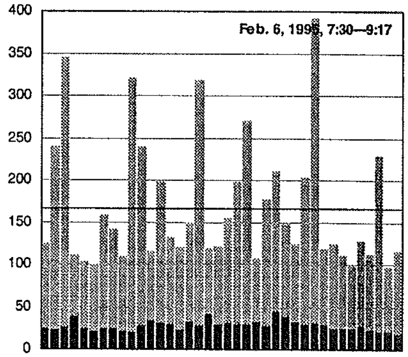

Figure 6.14 TTC King S/B

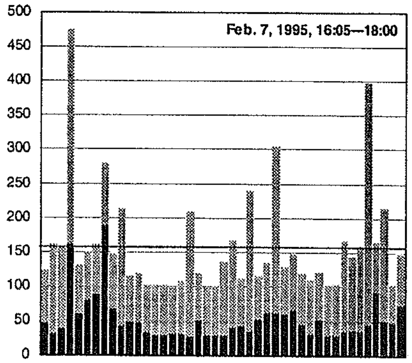

Figure 6.15 TTC Bloor N/B

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

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	[1]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
[2]BCT3	Metrotown E/B Off-peak	37.8	10.4	241.3	74.0	15.7	0.307	40.0	58.5	142.8

[1] Adjusted to remove long delay at beginning of peak-period.
[2] 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 power-supply 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.

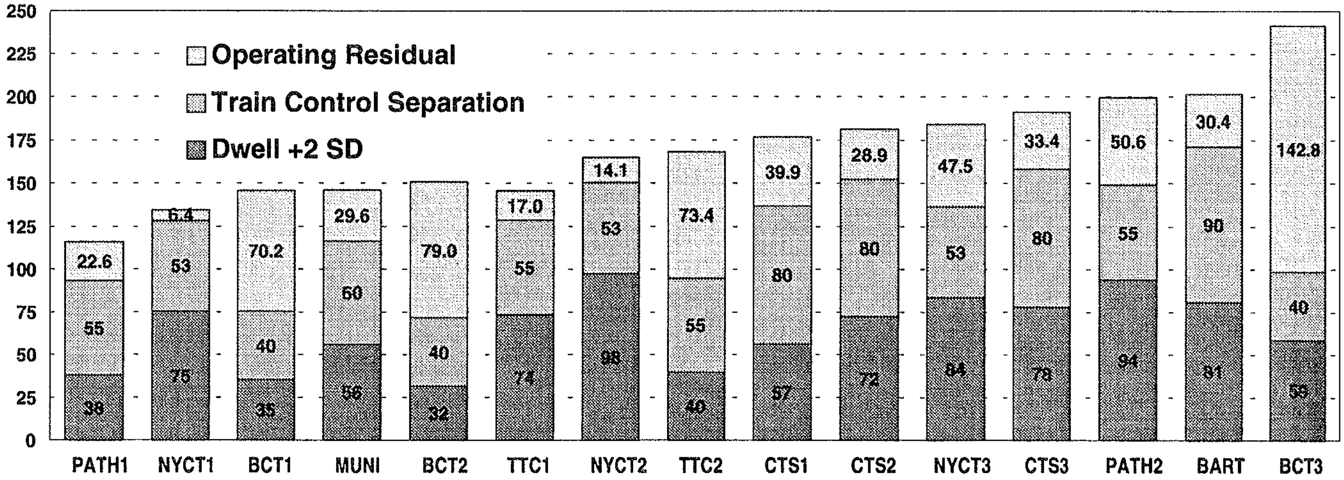

Figure 6.16 Headway components of surveyed North American rail rapid transit lines at or close to capacity (seconds)

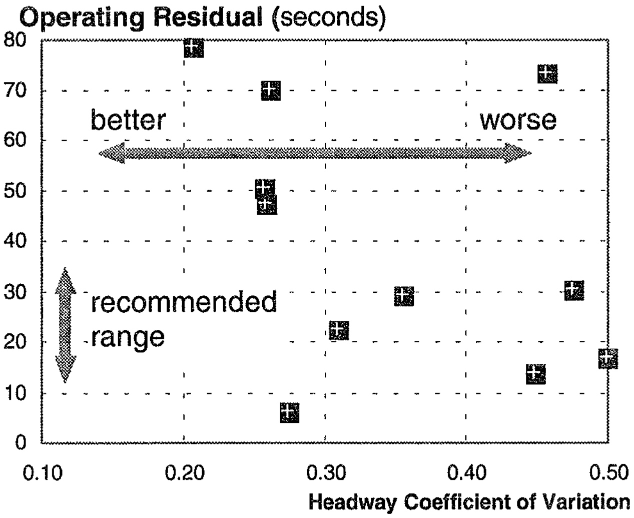

Figure 6.17 Relationship between operating residual and the headway coefficient of variation

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.[3]

All systems have been visited by the Principal Investigator. The Russian[4] systems appear to have a high level of staff

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[3] 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.

[4] Similar operating arrangements occur on the Russian-designed metros in Warsaw and Prague.

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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[5] 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.[6] 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.[7]

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 peak-hour 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 door-traction/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*

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[5] 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.

[6] 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.

[7] 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 on-demand operating policy is adopted. This requires on-board passenger stop signals that can range from the traditional pull-cords 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 low-volume 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 distance-related fares, by tickets with inadequate stored value. Typically 10% of fare gates should be assumed to be out-of-service at any time. About one in 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

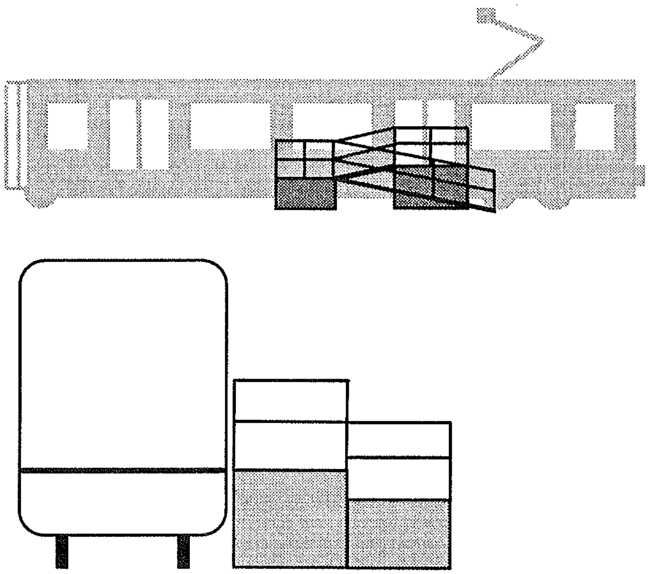

Figure 6.19 **Wheelchair loading platform and ramp**

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.[8] An example of this mini-high or high-block loading arrangement is shown in Figure 6.19.

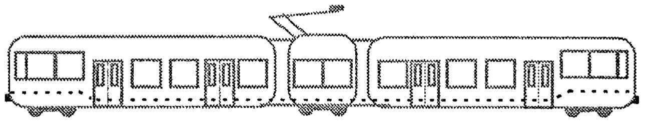

Figure 6.20 Tri-Met's Siemens-Düwag partial low-floor car

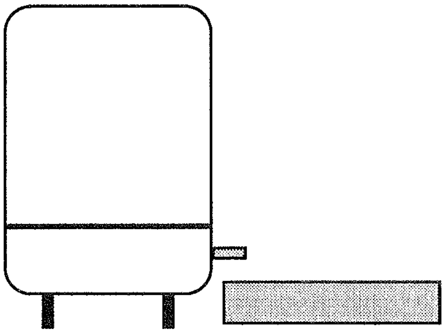

Figure 6.21 Profiled light rail platform showing slide out or fold down step that avoids any internal steps

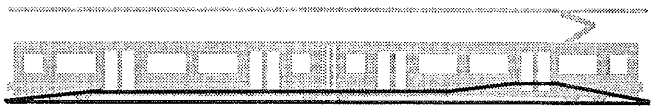

Figure 6.22 Profiled light rail platform Provides two steps into all doors, except the front door which is wheelchair accessible. All slopes are a maximum of 8.5° to meet ADA requirements. Most of the platform is only slightly higher than a sidewalk. *Additional details on light rail wheelchair facilities 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

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

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Figure 6.23 Wheelchair user in designated space — BC 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 non-interference 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 close-in 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 achievable peak hour passenger capacities for grade separated lines at their maximum capacity.

The necessary choices are only two, the type of train control system and the train length. The range is provided by assigning 1) a range centered around a typical dwell time plus operating margin, and 2) a small loading range centered around the recommended peak-hour average space per passenger of 0.5 m^2 (5.4 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 specifications. The procedure, as does the study as a whole, assumes an adequate supply of rolling stock. If any of these assumptions are not met then the simple procedure may be used only as a guideline and the complete procedure 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.

Table 7.1 Simple method performance assumptions

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

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

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[1] 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.

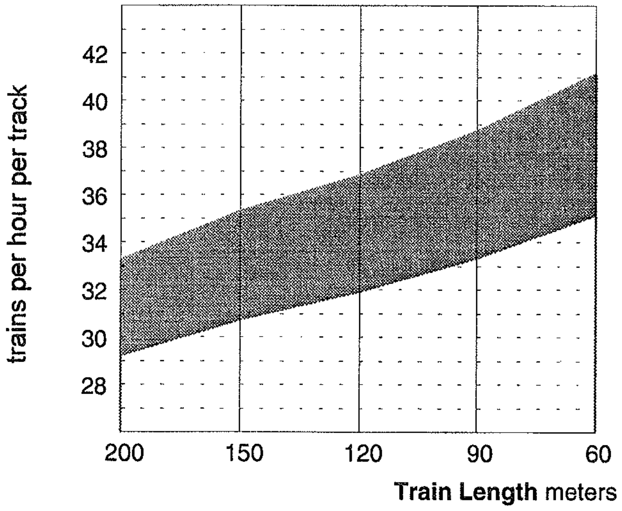

Figure 7.1 Cab control throughput in trains per hour with a range of dwell times plus an operating margin from 45 sec (lower bound) to 70 sec (upper bound)

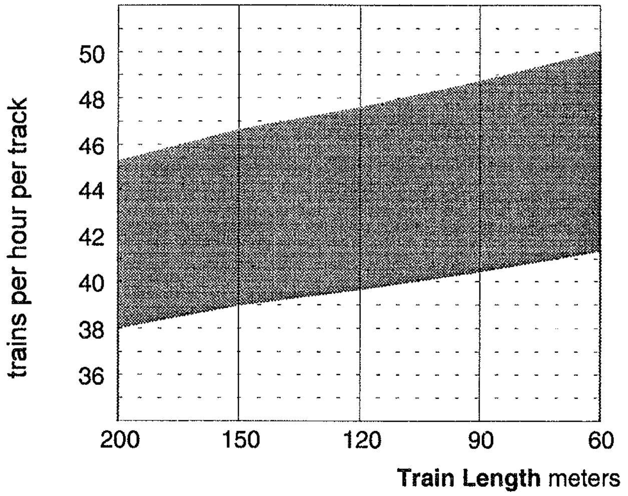

Figure 7.2 Moving-block throughput in trains per hour with a range of dwell times plus an operating margin of 45 sec (lower bound) to 70 sec (upper bound)

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.

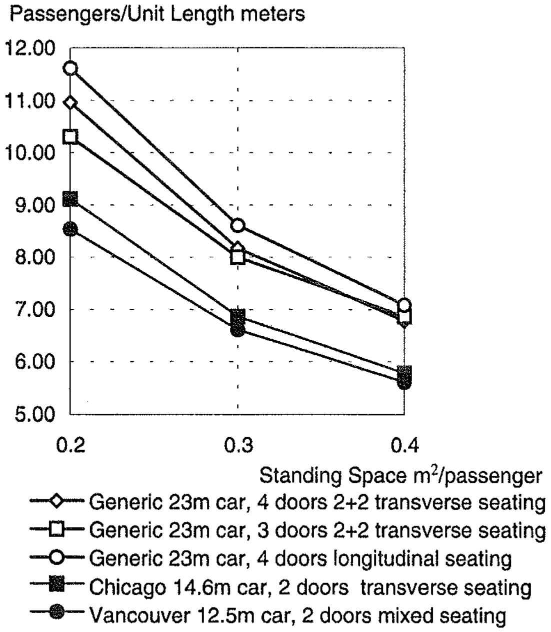

Figure 7.3 Linear passenger loading of heavy rail cars

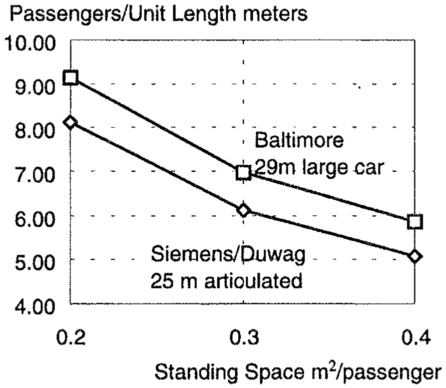

Figure 7.4 Linear passenger loading of articulated light rail cars

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 turn-back 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

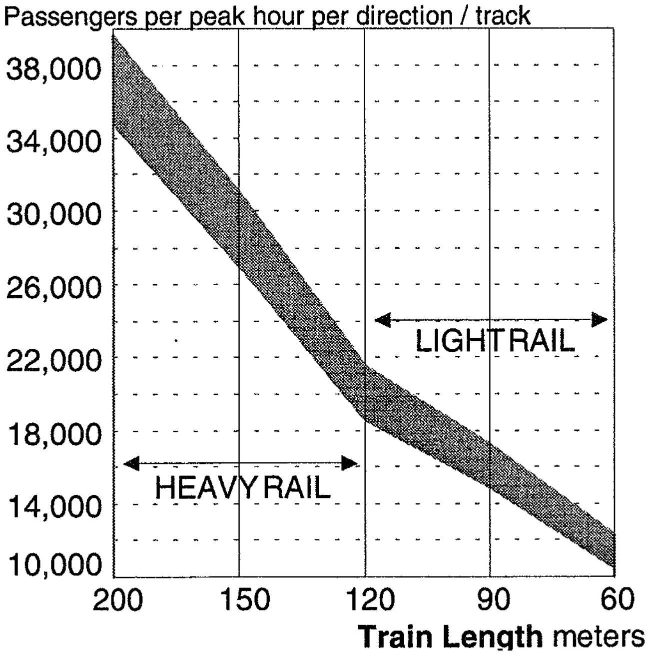

Figure 7.5 Achievable capacity with multiple command cab-control signaling system and peak-hour average loading of two passengers per square meter for one track of a grade separated rail transit line

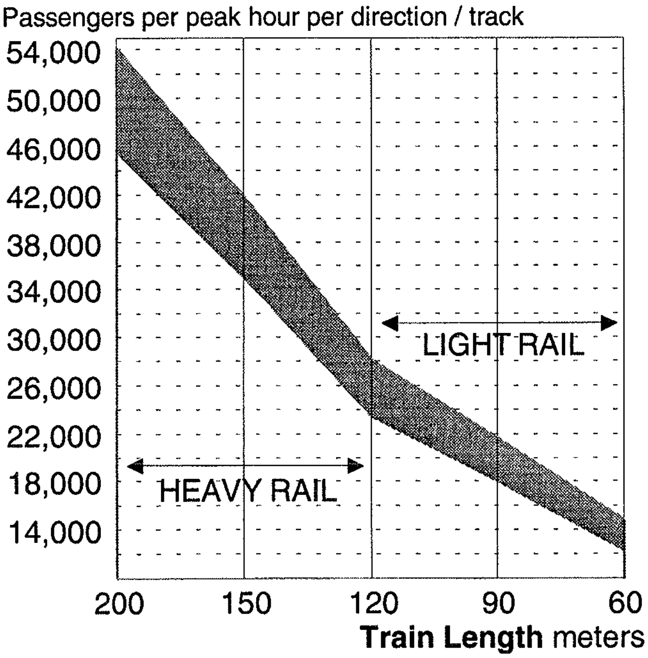

Figure 7.6 Achievable capacity with moving-block signaling system and peak-hour average loading of two passengers per square meter for one track of a grade separated rail transit line Note: The number of trains per hour vary with train length, refer to Figures 7.1 and 7.2. With the exception of San Francisco's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

DEFAULT VALUE	TERM	DESCRIPTION
calculated	$T(s)$	train control separation in seconds
200 meters	L	length of the longest train
10 meters	D	distance from front of stopped train to start of station exit block in meters
calculated	v_a	station approach speed in m/s
29.2 m/s	v_{max}	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 1.2 – cab cont 1 — mov block	B	separation safety factor — equivalent to number of braking distances (surrogate for blocks) that separate trains
3.0 seconds	t_{os}	time for overspeed governor to operate on automatic systems — to be replaced with driver sighting and reaction times on manual systems
0.5 seconds	t_{jl}	time lost to braking jerk limitation
1.5 seconds	t_{br}	brake system reaction time
1.3 m/s^2	a_s	initial service acceleration rate
1.3 m/s^2	d_s	service deceleration rate
0%	G_i	grade into station, downgrade = negative
0%	G_o	grade out of station, downgrade = negative
90%	l_v	line voltage as percentage of specification
6.25 meters	P_e	positioning error — moving block only
50 meters	S_{mb}	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 three-aspect 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

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

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

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

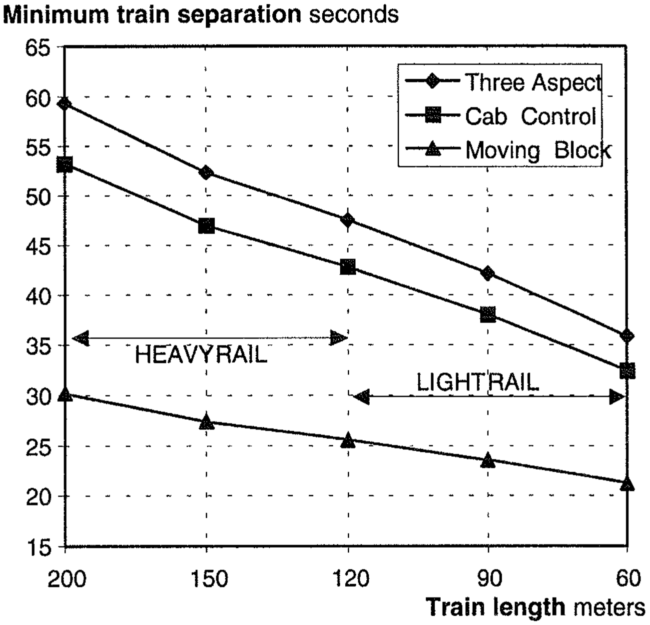

Figure 7.7 Minimum train separation versus length

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 sub-optimal 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[2] 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

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[2] Distance from the front of the approaching train to the stopping point.

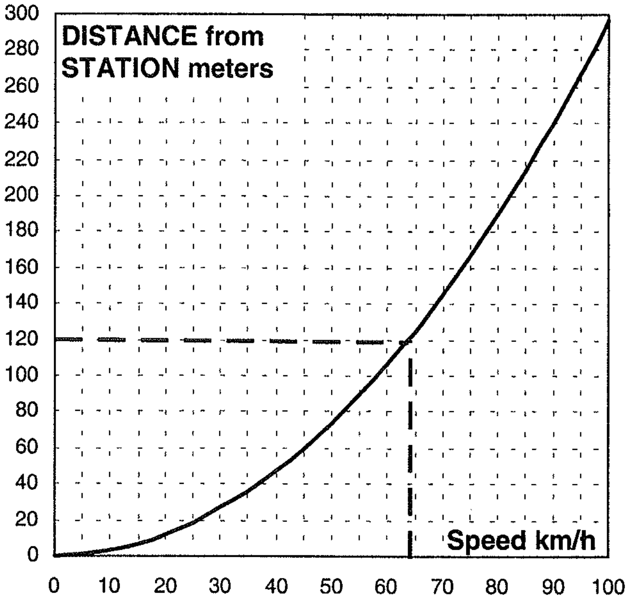

Figure 7.8 Distance — Speed braking into a station

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.[3]

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[4] the busiest systems

Table 7.3 Peak-period dwells for heavily used systems

System	Location	Total Pass	Time/Date 1995	Mean Dwell	Mean 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
TTC	King	1602	am Feb. 6	27.5	129.5
TTC	Bloor	4907	pm Feb. 7	44.0	135.0

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[3] 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.

[4] 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[5] *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 headway—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 peak-within-the-peak, the next step is to adjust the flow to the peak-within-the-peak 15 min rate using a loading diversity factor.

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

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

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

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

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

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, $F_{\max}$ is

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

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-the-peak, a ratio of 1.2 is recommended for heavy rail and 1.5 for light rail.

The regression equations of Chapter Four, *Station Dwells,*

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[5] 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]

$$\ln(FT_{\max}^{alight}) = 1.440 + 0.0922F_{\max}^{alight} - 0.00116(F_{\max}^{alight})^2$$

Equation 7-8

$$\ln(FT_{\max}^{board}) = 1.380 + 0.124F_{\max}^{board} - 0.00214(F_{\max}^{board})^2$$

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:

$$\ln(t_d) = 3.168 + 0.0254FT_{\max}^{(\text{mode})}$$

Equation 7-11

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

$$\ln(t_d) = 3.168 + 0.0254e^{1.440+0.0922\left(\frac{RP_{hour}(T(s)+t_d+t_{om})}{3{,}600D_nN_cD_{ph}}\right)-0.00116\left(\frac{RP_{hour}(T(s)+t_d+t_{om})}{3{,}600D_nN_cD_{ph}}\right)^2}$$

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 ± 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 step-by-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 capacity 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

Table 7.4 Values used to compute Figure 7.9

Unit	Value	Description
D_{ph}	0.8	Diversity factor— peak hour
T(s)	55	Train Control Separation in seconds
t_{om}	20	Operating margin in seconds
D_n	4	Number of double stream doors per car
N_c	8	Number of cars per train
R	1.2	Ratio busiest/average door usage
L	184	Train Length, meters
P_m	7.5	Loading Level, passengers per meter

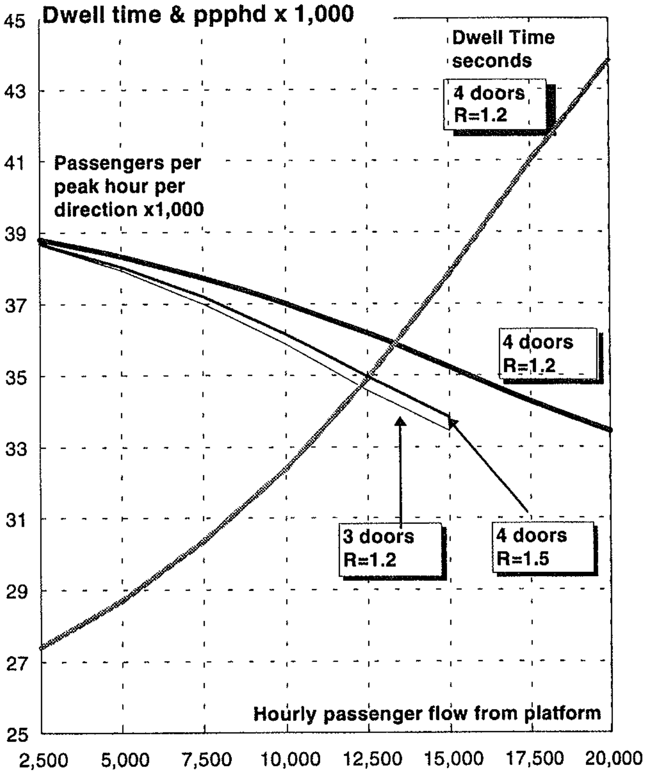

Figure 7.9 Dwell time and achievable capacity at a maximum load point station versus hourly alighting passengers at a single platform — unit values from Table 7.4.

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[6] 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 ± 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 incidentsdelaying 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.[7] 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 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

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[7] 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 Date Built		Seats	Total Pax[8]	Passengers per meter
CTA 2600 B 1981-87	HR	49	150	10.3
CTA 3200 (A&B) 1992	HR	39	150	10.3
TTC H6 1986-89	HR	76	226	9.9
NFTA Buffalo LRV 1983-84	LR	51	180	8.8
NJT PCC 1946-49	LR	55	125	8.8
SEPTA Single End: B-IV 1982	HR	65	180	8.8
PATH PA-4 1986-88	HR	31	130	8.4
NYCT R32 1964-65	HR	50	145	7.9
NYCT R68 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

[8] 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.

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 [9]	50/70	197/227	10.4[9]
NYCT	Lexington Ave. Local HR	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

[9] 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 the busiest NYCT lines using each car type included)

System	Location	Pass./m	
		Nominal	Actual
NYCT	53rd St. Tunnel HR	7.8[10]	10.4
NYCT	Lexington Ave. Loc. HR	7.1	9.3
TTC	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

[10] This is the weighted average for scheduled loadings of both car types used on this trunk. See also note 9.

7.5.6 DETERMINING AN APPROPRIATE LOADING DIVERSITY FACTOR

The next step is to adjust the hourly capacity from the peak-within-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 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.**

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

Type	System	Routes	Diversity factor
CR	LIRR	13	0.56
CR	Metra[11]	11	0.63
CR	Metro-North	4	0.75
CR	NJT[11]	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[12]
RT	PATH	4	0.79
RT	STCUM	4	0.71
RT	TTC	3	0.79
RT	**Average**		**0.79**

[11] Mainly diesel hauled—not EMU.
[12] 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.

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

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

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

The maximum capacity $C_{\max}$ 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.

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

where $H_{\min}$ = minimum headway in seconds
$T(s)$ = minimum train separation in seconds
t_d = dwell time in seconds
t_{om} = operating margin in seconds
T_{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 multiple-unit (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.

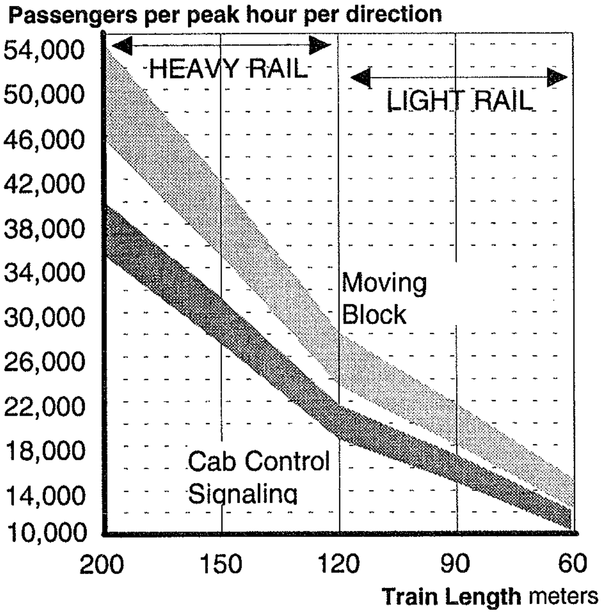

Figure 7.10 Typical maximum passenger capacities of grade separated rail transit—excluding all-seated commuter rail.

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 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.

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

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 right-of-way would permit double track. In other areas single track has been built because widening the right-of-way and structures is impossible. Single-track sections can be very short in order to by-pass a particular obstacle; for example, the San Diego Trolley had a short single-track segment[1] 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

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[1] 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 single-track 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 double-tracked.

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.[2] 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[3]—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

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

where t_{bs} = time to brake to stop *(s)*
v_{max} = maximum speed reached *(m/s)*
d_s = deceleration & acceleration rate *(m/s²)*
t_{jl} = jerk limiting time *(s)*
t_{br} = operator and braking system reaction time

The distance covered in this time is

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

where s_{bs} = braking distance to stop

The distance and time covered to reach the maximum single-track 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

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

where t_{ss} = time from start to stop

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

where s_{ss} = distance covered start to stop

The time to cover a single-track section becomes

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

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

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

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[4] *rate (m/s²)*
t_{jl} = jerk limiting time *(s)*
t_{br} = operator and braking system reaction time
SM = speed margin[5] *(constant)*
t_{om} = operating margin *(s)*

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[2] See Allen, Duncan W., *Practical Limits of Single-Track Light Rail Transit Operation* in Appendix One.

[3] 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.

[4] Also used as a surrogate for twice the average acceleration from 0 to $v_{\max}$.

[5] 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 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.

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[4]	1.3 m/s^2
speed margin	1.1 to 1.2
operating margin time	10-30 seconds

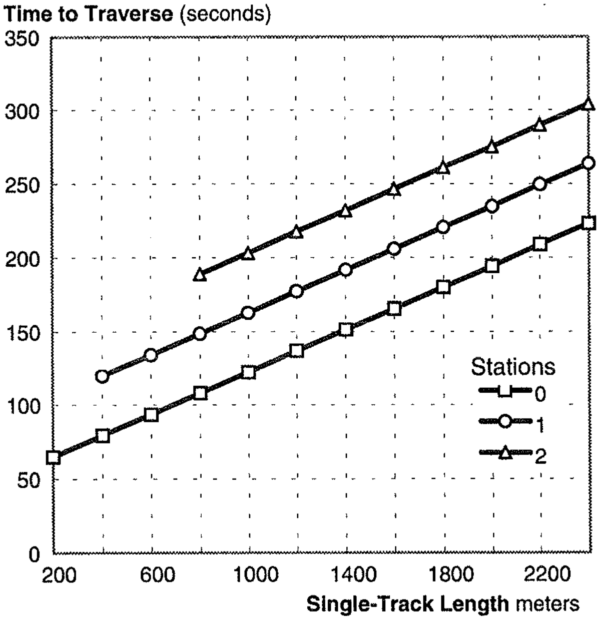

Figure 8.1 Light Rail travel time over single-track section with speed limit of 55 km/h and various numbers of stations train length 56 m, dwell time 20 sec, operating margin 20 sec, other data as per Table 8.2. *The closest headway with a single-track section is TWICE the above traverse plus operating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

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

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

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	160	180	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 [(R67)] and the ITE Transportation Planning Handbook[(R42)(R43)].

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.

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[6] 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 7th 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 transit crossings (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)

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

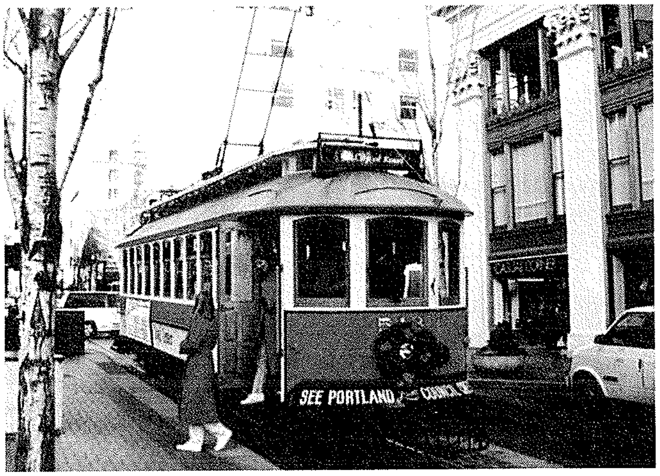

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Figure 8.2 Heritage streetcar service in Portland. These cars are accurate reconstruction’s of the historic *Council Crest* series cars. They are built on relatively modern (PCC) trucks and provide the acceleration, braking and safety features — but 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 far-side platforms is advantageous for the operational reasons given above, reduced right-of-way requirements, and, for median operation, allowing left turn bays to be readily incorporated into the street.

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

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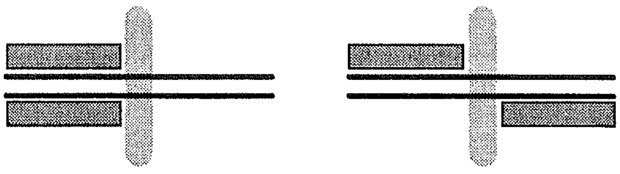
Figure 8.3 Tri-Met light rail train approaching an angled gated crossing *(Note the gate is across the highway).* The potential delay to cross traffic at these crossings is almost three times longer than with the 100% pre-empted signalized intersections closer to downtown. At higher train frequencies 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.



a) facing platforms b) far-side platforms

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

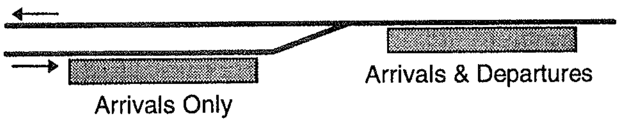


Figure 8.5 Single-track terminus with separate unloading platform (Baltimore)

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.[8]

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 1½ 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.

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[8] 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, high-floor light rail cars is the use of *mini-high* or *high-range* platforms that provide level loading to the wheelchair accessible door of the train. This method is mechanically simple and 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 mini-high platforms at key locations on its surface lines (the downtown subway is high platform). The cars must make a special stop to board and alight passengers using the mini-high platforms as the moveable steps on the car must be raised and the center door aligned with the platform in order for level loading to take place. The steps are usually raised before the car has come to a stop. An elastic gap filler is used between the platform edge and car doorway. No bridge plate is needed and the train operator does not have to leave the cab. This arrangement, aside from the need for a second stop, is very efficient with the time required for a passenger movement being 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[9] 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[10]. Low-floor cars provide much of the benefit of level loading without the need for high platforms. Typical floor height is 350 mm[11] (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, low-floor 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 street-running with long traffic signal phases, a section of single track, or the length of signal blocks where block signaling is used.

The key factors to be considered are 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.

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[9] 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.

[10] Some low-floor car/station platform arrangements require a manually positioned bridging plate that can extend dwell times.

[11] Certain low-floor designs ramp down the doorways to achieve a 280-300-mm 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 x 80 sec including an operating margin—a total of 160 sec. The system operates four-car 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 mid-point loading of 5 passengers per meter produces an hourly capacity, inclusive of a loading diversity factor, of 4 × 25 × 5 × 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 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.

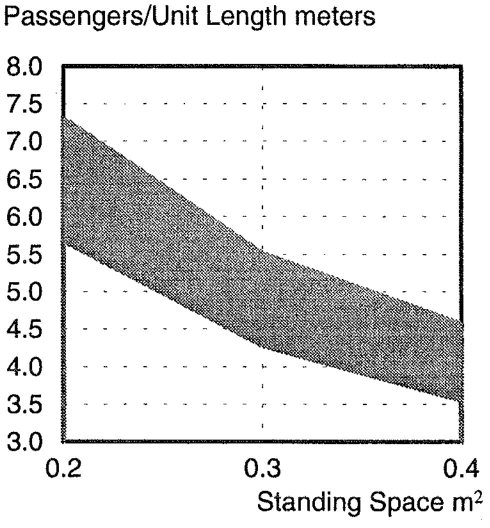

Figure 8.6 Recommended loading level range for light rail vehicles in simple capacity calculation, loading diversity factor 0.70 to 0.90

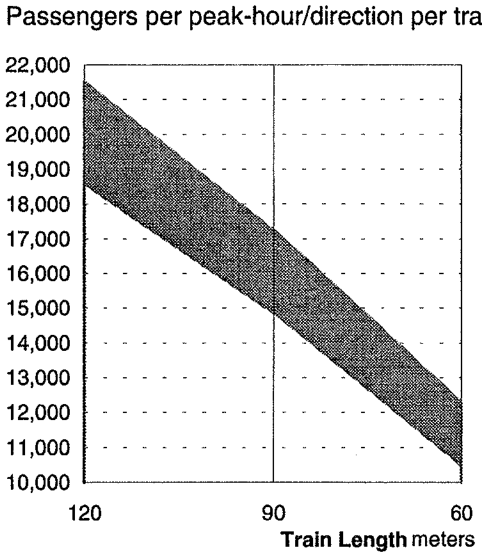

Figure 8.7 Light rail capacity on segregated right-of-way with maximum cab-control signaling system throughput based on range of dwell time plus operating margin of 45 to 70 sec. (headway varies with train length, refer to Fig. 7.1)

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

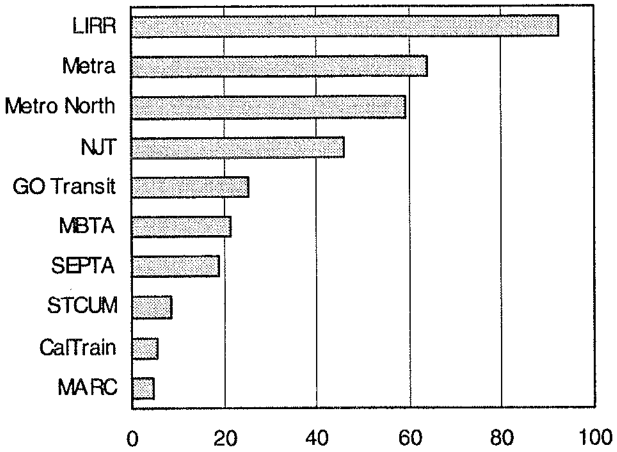

Figure 9.1 Commuter rail ridership (millions per year)

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.[1] 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 3½ 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 uni-directional and so are not slowed by passengers attempting to board while others alight and vice-versa. Exceptions are locations where major transferring activity takes place between trains but these are limited. Jamaica station on the LIRR is 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.[3]

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.

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[1] Other typical commuter rail headways can be found in the ITE Transportation Planning Handbook (R42 and R43).

[2] 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.

[3] 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:

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

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 built-up features. Passengers must take care to be in the correct car(s) if alighting at a station with short platforms.[4] 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[5] 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

System	Designation	Builder	Date Built	Seats	Seats/m
LIRR	C-1	Tokyu Car	1990	190	7.3
MBTA	BTC	Kawasaki	1991	185	7.1
LIRR	C-1	Tokyu Car	1990	181	7.0
MBTA	CTC	Kawasaki	1991	180	6.9
Metra	TA3A, TB3A	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	5.6
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
STCUM	Sing. Lev.700	Bombardier	1989	130	5.0
MBTA	BTC-1A	Bombardier	1987	127	4.9
SEPTA	SL II	Budd	1964	127	4.9
SEPTA	SL IV	General Electric	1973-77	127	4.9
LIRR	P-72	Pullman Standard	1955-56	123	4.9
LIRR	PT-72	Pullman Standard	1955-56	123	4.9
Metro-North	M-4 D	Tokyu Car	1988	126	4.9
Metro-North	M-6 D	Morrison Knudsen	1993	126	4.9
NJT	Comet IIB	Bombardier	1987-88	126	4.9
NJT	Comet I	Pullman Standard	1971	125	4.8
SEPTA	SL II	Budd	1963	125	4.8
NJT	Comet IA	GE	1977, 82	123	4.7
LIRR	M-1	Budd	1968-71	122	4.7

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[4] Another common station limitation, lack of park and ride capacity, is considered in Chapter Six, *Operating Issues.*

[5] 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
LIRR	M-1	GE	1972	122	4.7
MBTA	BTC-1B	Bombardier	1989-90	122	4.7
MBTA	CTC-1A	Bombardier	1989-90	122	4.7
Metro-North	M-1A B	Budd	1971	122	4.7
LIRR	P-72	Pullman Standard	1955-56	118	4.7
LIRR	PT-72	Pullman Standard	1955-56	118	4.7
NJT	Comet IB	Pullman Standard	1968	121	4.7
LIRR	M-3	Budd	1985	120	4.6
MARC	Coach	Sumitomo	1992-3	120	4.6
Metro-North	M-3A A	Budd	1984	120	4.6
VRE	Trailer	Mafersa	1992	120	4.6
NJT	Arrow II	GE	1974-75	119	4.6
NJT	Arrow III	GE	1977-78	119	4.6
Conn DoT	Comet II Mod	Bombardier	1991	118	4.6
LIRR	M-1	GE	1972	118	4.6
LIRR	M-1	Budd	1968-71	118	4.6
MARC	E/H Toilet	Nippon Sharyo	1991	118	4.6
Metro-North	M-1A A	Budd	1971	118	4.6
Metro-North	M-2 A	GE	1973	118	4.6
Metro-North	M-4 A	Tokyu Car	1988	118	4.6
Metro-North	M-6 A	Morrison Knudsen	1993	118	4.6
Metro-North	Shoreliner	Bombardier	1986-91	118	4.6
NJT	Comet III	Bombardier	1990-91	118	4.6
SEPTA	JW2-C	Bombardier	1987	118	4.6
NJT	Comet IIB	Bombardier	1987-88	117	4.5
NJT	Arrow II	GE	1974-75	115	4.4
NJT	Arrow III	GE	1977-78	115	4.4
NJT	Comet I	Pullman Standard	1971	115	4.4
NJT	Comet IB	Pullman Standard	1968	115	4.4
LIRR	M-3	Budd	1985	114	4.4
MARC	Coach	Nippon Sharyo	1985-87	114	4.4
MARC	E/H Cab	Nippon Sharyo	1991	114	4.4
MARC	E/H Coach	Nippon Sharyo	1991	114	4.4
Metro-North	M-2 B	GE	1973	114	4.4
Metro-North	M-3A B	Budd	1984	114	4.4
Metro-North	M-4 B	Tokyu Car	1988	114	4.4
NJT	Arrow III	GE	1977-78	113	4.4
NJT	Comet II/IIA	Bombardier	1982-83	113	4.4
VRE	Cab	Mafersa	1992	112	4.3
SEPTA	SL III	St. Louis	1967	111	4.3
STCUM	Class B	CC&F	1953-54	109	4.3
NICTD	EMU-2	Sumitomo	1992	110	4.2
Metro-North	SPV 2000	Budd	1981	109	4.2
NJT	Comet III	Bombardier	1990-91	108	4.2
Metro-North	M-6 B	Morrison Knudsen	1993	106	4.1
MARC	E/H Cab	Nippon Sharyo	1985-87	104	4.0
NJT	Comet III	Bombardier	1990-91	103	4.0
Conn DoT	C&O 1600	Pullman Standard	1950	102	3.9
STCUM	MU (emu)	CC&F	1952	84	3.9
STCUM	MU (trailer)	CC&F	1952	84	3.9
MBTA	BTC-1	Pullman Standard	1979	99	3.8
VRE	BTC-2	Budd	1955	99	3.8
MARC	Coach	Budd	1949	96	3.7
MBTA	BTC-3	MBB	1987-88	96	3.7
MARC	Coach	Budd	1949	95	3.7
MBTA	CTC-1	Pullman Standard	1979	95	3.7
STCUM	MR90 (emu)	Bombardier	1994	95	3.7
STCUM	MR90 (trailer)	Bombardier	1994	95	3.7
MBTA	CTC-3	MBB	1987-88	94	3.6
NICTD	EMU-1	Sumitomo	1982	93	3.6
NICTD	EMU-1A	Sumitomo	1983	93	3.6
VRE	CTC-2	Budd	1955	92	3.6
MARC	Toilet Coach	Budd	1949	88	3.4
MARC	Toilet Coach	Budd	1949	88	3.4
NJT	Comet IIB	Bombardier	1987-88	88	3.4
STCUM	Coach	CC&F	1942	83	3.3
Conn DOT	SPV 2000	Budd	1979	84	3.2
MARC	Coach	Budd	1949	80	3.1
MARC	Toilet Coach	Budd	1949	80	3.1
Conn DOT	C&O 1600	Pullman Standard	1950	66	2.5
LIRR	PP-72	Pullman Standard	1955-56	44	1.7

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.

10. Automated Guideway Transit Capacity Determination

10.1 INTRODUCTION

Automated guideway transit (AGT) generally fits into the category of *Grade Separated Rail* whose capacity determination is specified in Chapter Seven. However, there are some nuances specific to AGT that must be considered. AGT is an almost negligible part of urban, public, fixed guideway transit—less than 1/10th of one percent. Technology ranges widely from the standard gauge advanced light rapid transit downtown people mover in Detroit to small scale monorails in amusement parks.

Setting aside the possible interpretation of the Tandy shuttle in Fort Worth as AGT—operated by heavily rebuilt, manned PCC streetcars—all AGT systems are proprietary designs. As such their performance, acceleration, braking rate, balancing speed and vehicle size and capacity vary greatly.[1]

10.2 TRAIN CONTROL SEPARATION

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

These variants are not fully accommodated in the methodology of Chapters Three and Seven. If the basic AGT performance indices are known then the procedures of Chapter Seven will provide an approximation of the minimum train separation time for a range of AGT train controls—from a moving-block signaling system to a simple fixed-block system. A surrogate of this can be roughly simulated by setting the train detection uncertainty factor (B) at four times the minimum braking distance.

The results are shown in Table 10.1 and Figure 10.1 for trains of typical AGT lengths—12.5 m (40 ft), 25m (80 ft) and 50m (160 ft)—based on the specific AGT values in Table 10.2, with terms adjusted from typical rail transit values shaded Refer to Chapter Three, *Train Control and Signaling,* Equation 3-15. The results show that separation times with a simulated single-aspect block system are two to three times longer than with the more complex — and expensive — moving-block signaling system. The moving-block results agree with those of Auer(R09), the only

Table 10.1 AGT minimum train separation times

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

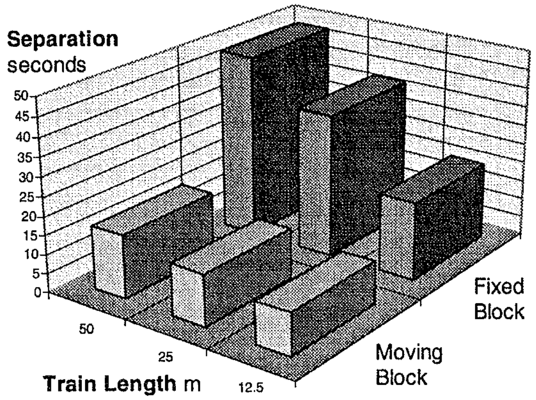

Figure 10.1 AGT train separation versus length

Table 10.2 Suggested AGT separation calculation values

TERM	UNIT	DESCRIPTION	Normal[2]	AGT
P_e	m	positioning error	6.25	6.25
L	m	length of the longest train	200	50
D	m	distance from front of train to exit block	10	0
K	%	% service braking rate	75	75
B		train detection uncertainty constant—fixed block	2.4	4
B		train detection uncertainty constant—moving block	1	1
t_{os}	secs	time for overspeed governor to operate	3	1
t_{jl}	secs	time lost to braking jerk limitation	0.5	0.5
a_s	m/s²	service acceleration rate	1.3	0.6
d_s	m/s²	service deceleration rate	1.3	1
t_{br}	secs	brake system reaction time	1.5	0.5
V_{max}	km/h	maximum line velocity	100	80
mb_{sd}	m	moving block safety distance	50	25

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[1] Details of AGT system characteristics and technology are outside the scope of this report. Details of selected systems can be found in Table 5.15 of the ITE Transportation Planning Handbook (R42).

[2] Default values for heavy rail. Refer to Chapter Three, *Train Control and Signaling.*

reviewed paper specializing in AGT train control. Here, typical short train AGT separation with moving-block control was cited at 15 sec. The separation range is wide and highly dependent on the train control system of the proprietary AGT system. The best method of determining the minimum train separation is from the system manufacturer or designer. Using the methodology of Chapter Three should be a last resort when specific separation information is not available.

10.3 PASSENGER FLOW TIMES AND DWELLS

AGT systems that are part of a normal transit system can assume flow rates and dwells as determined in Chapter Four, *Station Dwells.* However, most AGT systems are classed as institutional and the majority of passengers are unlikely to be regular, experienced transit users. Doorways are rarely of typical transit width or configuration. The most common arrangement is the quadruple-flow door with associated platform doors—shown in Figure 10.2. Doorway flow times and the associated dwells were monitored on the three C-100 systems at SeaTac airport in May 1995. The range of users varied greatly and included many people with bags and a few with baggage carts. After the arrival of a full flight with a preponderance of business passengers, flow rates reached and exceeded transit levels. At other times, doorway flow rates were below the transit rates documented in Chapter Four.

Under these circumstances, calculating flow times—and from them dwell times—is unwise. The results are unlikely to be accurate or may reflect only a very specific subset of users.

The recommended solution for AGT systems outside the transit sphere is simple. Accept a headway, inclusive of train control separation, dwell time and any operating margin, that conforms with existing operations or is suggested by the system manufacturer. The typical headway of airport systems is 120 sec with a few operating down to 90 sec. Claims have been made for closer headways with some proprietary systems. Headways shorter than 90 sec are possible but may limit dwell times and constrain the operating margin. They should be considered with caution unless off-line stations are adopted—see section 10.5. Off-line stations make closer headways possible and practical—at a price.


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Figure 10.2 Orlando Airport people-mover doorways Adtranz (previously Westinghouse) C-100 system.

10.4 LOADING LEVELS

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

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

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

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

10.5 OFF-LINE STATIONS

Off-line stations maximize system capacity. They are used on several rail transit lines in Japan to achieve some of the highest throughput for two-track rapid transit lines in the world. In North America they are the exclusive preserve of one AGT—Morgantown.[3]

Off-line stations permit a train throughput that is partly independent of station dwell time. Throughput is that of the train control system plus an allowance for switch operation, lock and clearance and a reduced operating margin.[4] Morgantown and certain other AGT systems use on-vehicle switching techniques where even this allowance—typically 6 sec—can be dispensed with. In theory, trains or single vehicles can operate at or close to the minimum train control separation—which can be as low as every 15 sec—refer to Figure 10.1.

Major stations with high passenger volumes may require multiple-platform berths, otherwise partial dwell times must be added to the train separation times to obtain the minimum headway. The achievable capacity of such specialized systems should

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

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

be determined through consultation with the system manufacturer or design consultant.

To avoid decreasing main line capacity, the diverging moves for off-line stations should be made at line-operating speeds with adequate off-line station trackage for the deceleration and acceleration distances.

Where full provision is made for these distances system throughput becomes independent of stations and dwells Equation 3-12 or 3-13 in Chapter Three, *Train Control and Signaling,* can be used to calculate the line headway with data values, principally length, adjusted for the specific AGT system.

11. Future Research

11.1 INTRODUCTION

Two issues for future research emerged from the work on this report. The first issue was an inability to obtain meaningful information or data on the reliability of service. The second was the wide disparity between total station dwell time and the actual time used for passengers boarding and alighting.

11.2 SERVICE RELIABILITY

One of the goals of this study was to develop a relationship between closer headways and reliability of service, leading to recommendations for how much operating margin should be accommodated in the headway to avoid routine headway interference and service delays. It is intuitive that as trains run closer together the potential for service irregularities and delays increases. A related margin, the schedule recovery provided at each turn-back station, rarely affects achievable capacity and was not analyzed. Schedule recovery time increases the number of staff and cars to carry a given volume of passengers and is an issue of economy — subject to space limitations at each turn-back.

The project's survey and subsequent telephone and field data collection tasks failed to obtain any suitable material. Some operators calculated the percentage of runs that were missed, others had various assessments of on-time arrivals — trains that reached their destination within five to ten minutes of schedule.

As a result, the project had to rely on the observed headway regularity during the field data collection and on limited headway information provided by a few operators. The results are contained in Chapter Six, *Operating Issues,* Table 6.1. Regularity was tabulated as the coefficient of variation — the standard deviation divided by the mean. The results are shown in Figure 11.1, in descending order of reliability.

It would be expected that light rail with on-street sections at, or ahead, of the survey point would have less reliable headway adherence; that automated systems should be better than manually driven systems; and that systems with longer headways would be better than those running trains close together.

The results are both mixed and contrary to these intuitions. Although Calgary's three light rail entries,[1] all with on-street sections, are at the bottom of the chart, they are mixed with BART's automated and longer headway entry and with the TTC's manual subway operation (Bloor Station). BC Transit, with its advanced automatic train supervision, meets expectations at the top of the chart, but PATH's Journal Square and NYCT's Grand Central listings, both manually driven and among the closest headways in the survey, share this honor.

Surveys have frequently shown that reliability is a key concern if the rail transit industry is to meet the higher customer expectations of the future. Reliability — specifically headway adherence — was a secondary issue in this study. The data from 15 peak periods on seven systems is inadequate to draw conclusions.

This topic merits additional research. The first two of the TCRP's four strategic priorities for 1996 and 1997 transit research are

- *Place the customer first and*
- *Improve transit productivity.*

Research into the reliability of service delivery will meet both these goals as even headways move passengers more efficiently with fewer trains and staff.

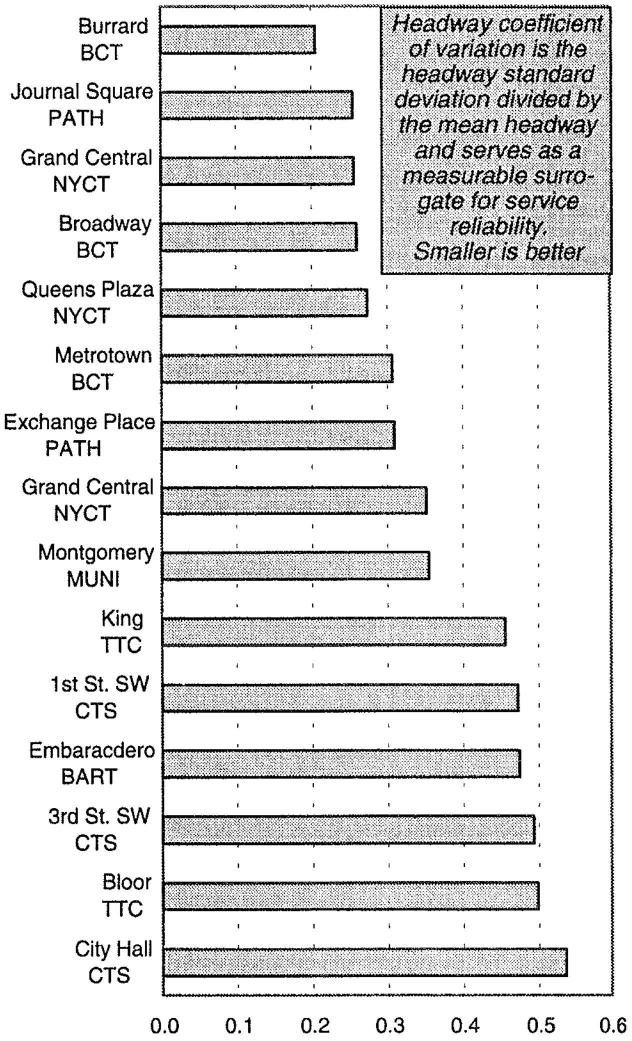

Figure 11.1 Headway coefficient of variation (from Table 6.1)

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[1] Calgary's three lines are not scheduled to interlace evenly on the downtown trunk. This result is therefore a result of scheduling — not poor operation.

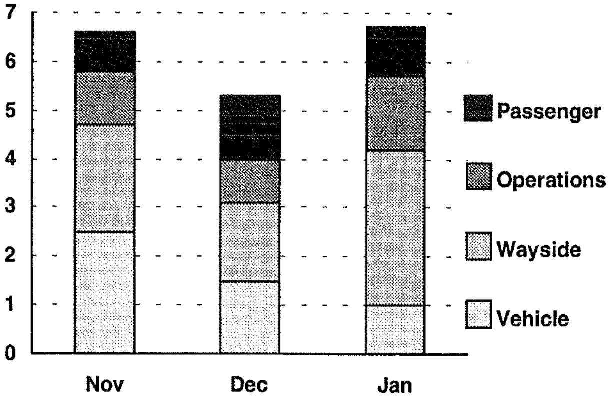

Figure 11.2 Total train operating hours lost per month (equivalent to 0.005% of total hours operated)

Future research should summarize the many surveys of passenger expectations; develop criteria and uniform reporting methods for reliability; establish reliability on existing rail transit systems through telephone and field surveys; relate reliability to efficiency; and produce conclusions and recommendations on the many factors that contribute to, or reduce, system reliability—and so efficiency.

An example of one performance criterion is shown in Figure 11.2., taken from BC Transit's automated SkyTrain operation.

11.3 STATION DWELLS

The station dwell field data collection and analysis showed a wide variation between the length of the dwell and the time productively used for passenger flow. The bulk of the wasted time was between flow stopping and the train starting to leave the station. A few systems also had a significant loss between the train stopping and the doors opening. The percentage of productive time is shown in Figure 11.3. All data are from the maximum load point station of lines at or close-to capacity.

Two thirds of systems with headways under 200 sec have a flow to dwell ratio of less than 40%; five systems are at or below 30%. Some of this unproductive time is essential. Door opening and closing takes 4 to 6 sec. Confirmation that a train is stopped and correctly positioned at a platform takes less than 1 sec on some automated and most manual systems, but several seconds on others. Safety considerations require some leeway from door closing to train leaving. There is dispute about how much delay is required for safety. Two to 5 sec appears to be a reasonable range used on many systems. The remaining unproductive time, averaging 30-40% of all dwell is wasted—whether due to operational slackness or over cautious safety concerns.

TCRP Report 4, *Aids for Car Side-Door Observation,* (R77) and NCTRDP Report 13, *Conversion to One-Person Operation of Rapid-Transit Trains,* (R78) concentrated on methods to permit train operators to observe side doors as a step towards reducing crewing from two to one on older rail rapid transit systems. Safety and efficiency at the door interface were only reviewed peripherally.

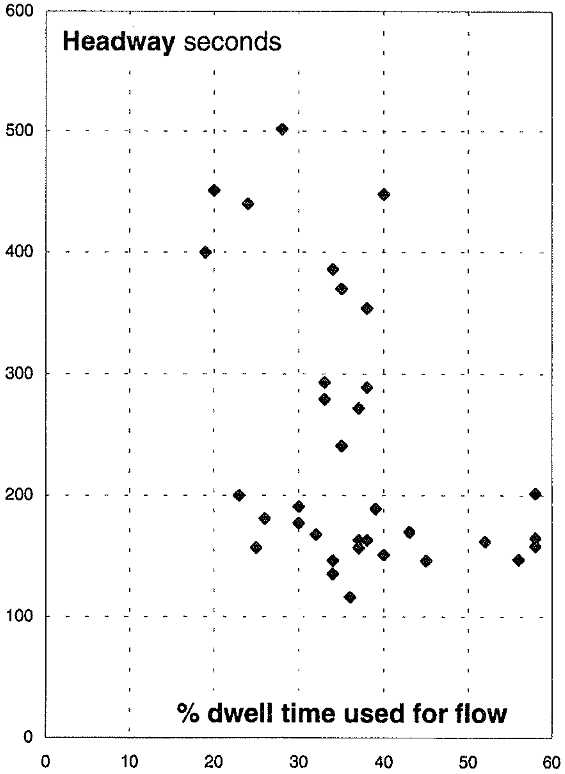

Figure 11.3 Percentage of dwell time at maximum load point stations used for peak-door passenger movements

Two North American systems, Vancouver and Miami's Metromover; a few foreign systems; and elevators worldwide maintain exceptional safety standard using pre-programmed dwells without any door observation. The opportunity to tighten up dwells and gain the associated economies is considerable. Research into the passenger-door interface, the effects of different door closing tones or announcements, marking platform door positions, training passengers to wait to the side of the door position and take more responsibility for their actions, and reviewing interior car designs that improve flow rates is overdue.

The benefits are considerable and consistent with the transit industry goal to *improve transit productivity.* Dwell times make up 20 to 40% of total travel time on urban rail rapid transit systems. A modest goal of an overall 10% dwell time reduction would reduce operating costs and car requirements by 3%. On U.S. rail rapid transit alone that saves $120 million a year and 330 cars—a future capital saving of over $600 million [2] at the estimated replacement cost of $2 million per car.

Even such modest dwell reductions would reduce overall travel times, thus making rail rapid transit more attractive to passengers, increasing ridership and meeting another TCRP goal of *placing the customer first.*

The research brief could be expanded to examine the entire issue of operating efficiency. This project found wide variations across the continent. Many of the slack operating practices were not related to restrictive labor practices but to a lack of concern for the brisk, efficient operation that typified the better systems.

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[2] Based on U.S. rail rapid transit annual operating costs of $3.9 billion and a fleet of 11,000 cars.

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GLOSSARY

Sources: *Most of the definitions in this glossary are taken from the Transportation Research Board's "Urban Public Transportation Glossary" (1989) and from the American Public Transit Association's "A Glossary of Transit Terminology" (1984).*

Caution: *There is inconsistency in terminology used in the North America transit industry. Many systems have there own specific terminology, a motorman and guard on one system can be an operator and conductor on another.*

ABS—see *control system, automatic block signal.*

ABSOLUTE—A block that no train may enter while the block is occupied by another train.

ABSOLUTE PERMISSIVE—A signal system for a single track or guideway that prevents simultaneous opposing train movements between sidings but permits following movements at a safe distance.

ACCESSIBILITY—A measure of the ability or ease of all people to travel among various origins and destinations

AGT—Automated guideway transit; automated guided transit; see *transit system, automated guideway.*

ALIGHT—To get off or out of a transportation vehicle.

AREA OCCUPANCY—In station and other facility design and in pedestrian movement, the area provided per person.

ARTICULATED RAIL VEHICLE (*articulated car*)—1. An extra-long rail vehicle with two or more bodies connected by joint mechanisms that allows bending in curves yet provide a continuous interior. Typically, the vehicle is 56-100 ft (17-33 m) long. It is very common on light rail transit systems but is also found on several rail rapid transit systems. 2. Rapid transit cars with separate bodies that share a common center truck.

ATO—Automatic train operation.

AUTOMATED GUIDEWAY TRANSIT SYSTEM (AGT)—A transportation system in which automated, driverless vehicles operate on fixed guideways with exclusive right-of-way.

AUTOMATIC BLOCK SIGNAL (*ABS*)—a system governing train separation in which the signals are controlled by the trains themselves. The presence or absence of a train in a block is determined by a track circuit. If the circuitry fails, a restrictive signal is displayed.

AUTOMATIC TRAIN CONTROL SYSTEM (*ATC system*)—1. A system for automatically controlling train movement, enforcing train safety, and directing train operations by computers; see also *automatic train operation, automatic train protection, and automatic train supervision.* 2. A trackside system working in conjunction with equipment installed on the train, arranged so that its operation will automatically result in the application of the brakes to stop or control a train's speed at designated restrictions, should the operator not respond. The system usually works in conjunction with cab signals.

AUTOMATIC TRAIN OPERATION (*ATO*)—The subsystem within automatic train control that performs such functions as speed control, programmed stopping, and (sometimes) door operation.

AUTOMATIC TRAIN PROTECTION (*ATP*)—The subsystem within automatic train control that provides fail-safe protection against collisions, excessive speed, and other hazardous conditions.

AUTOMATIC TRAIN STOP SYSTEM (*ATS* SYSTEM)—A trackside system that works in conjunction with equipment installed on the electric rail car or locomotive to apply the brakes at designated restrictions or on a dispatcher's signal, should the operator not respond properly.

AUTOMATIC TRAIN SUPERVISION (*ATS*)—The subsystem within automatic train control that monitors trains, adjusts the performance of individual trains to maintain schedules, and provides data for adjusting service to minimize the inconveniences otherwise caused by irregularities. May also be used for systems that merely display train status and rely on staff intervention for any corrective action.

BARRIER-FREE—Containing no obstacles that would prevent use by a mobile physically handicapped person or any other person.

BASIC OPERATING UNIT—In rail rapid transit, the smallest number of rapid transit vehicles that can operate independently in revenue service, usually one to three (exceptionally more) cars.

BI-LEVEL—a rail car that has two levels for passenger accommodation. The upper level may extend through the entire length of the car or only over a part of it; this level is sometimes restricted to seated passengers only. Bi-level cars are used principally on commuter rail lines. Double deck cars and gallery cars are types of bi-level cars.

BLOCK—1. A section of track or guideway of defined limits on which the movement of trains is governed by block signals, cab signals, or both; also known as a ***signal block.*** 2. A section of track of defined length, the occupancy of which is regulated by fixed signal(s), telephone or radio orders, or timetables; also known as a ***block section***.

BLOCK SIGNAL—a standard railroad signal system that uses a fixed signal at the entrance of a block to govern the separation of trains entering the block.

BOARDING—Getting on a transit vehicle.

BUNCHING—With transit units, a situation that occurs when passenger demand is high and dwell times at stops are longer than scheduled. Headways become shorter than scheduled, and platoons of transit units (vehicles or trains) develop, with longer intervals between platoons. The same effect (one transit unit caught by the following) can also be caused by lack of protection from general road traffic congestion or by traffic signal timing. Bunching can become cumulative and can result in delay to passengers and unused capacity.

CAB—1. A rail car with a driving cab. 2. A passenger carrying car used in push-pull service and fitted with a cab at one end, to be used to operate the train when the locomotive is pushing; see also *commuter rail.*

CAB SIGNAL—in rail systems, a signal located in the cab, indicating a condition affecting the movement of a train and used in conjunction with interlocking signals and in conjunction with or in lieu of block signals.

CAPACITY. . .achievable—A term used in this report to avoid the confusion whereby design capacity can mean either a theoretical or practical maximum number of passengers that can be transported over a given section of a transit line in one direction during a given time period. Achievable capacity is the design capacity factored down to reflect the uneven passenger demand during the peak hour and the uneven loading of cars within a train.

CAPACITY. . .crush (*crush load)*—the maximum feasible passenger capacity of a vehicle, that is, the capacity at which one more passenger cannot enter without causing serious discomfort to the others. Note that the crush load specification for some rail transit vehicles does not relate to an achievable passenger loading level but is an artificial figure representing the additional weight for which the car structure is designed or for which the propulsion and braking system will meet minimum criteria.

CAPACITY. . .design—1. For transit, the maximum number of passengers that can be transported over a given section of a transit line in one direction during a given time period (usually 1 hour) under prevailing traffic conditions and design comfort standards. 2. For vehicles, the total number of spaces or people a vehicle can accommodate.

CAPACITY. . .fleet *(rolling stock capacity)*—the total number of passenger spaces in all vehicles of a transit fleet.

CAPACITY. . .line—the maximum number of spaces that transit units (vehicles or trains) on a line can transport past a fixed point in one direction per unit of time (usually 1 hour) under actual operating conditions; see also *capacity, theoretical line.*

CAPACITY. . .normal vehicle—see *capacity, vehicle.*

CAPACITY. . .rolling stock—see *capacity, fleet.*

CAPACITY. . .practical—The maximum number of passengers that can be transported over a given section of a transit line in one direction during a given time period (usually 1 hour) under prevailing traffic conditions and design comfort standards.—after allowing for the uneven passenger demand during the peak hour and the uneven loading of cars within a train. In this report Achievable Capacity is used instead of Practical Capacity to avoid confusion with variable definitions of this term used in other capacity work.

CAPACITY. . .seating *(seated capacity)*—the number of passenger seats in a vehicle.

CAPACITY. . .standing—the number of standing passengers that can be accommodated in a vehicle under specified comfort standards, expressed in area per standee.

CAPACITY. . .theoretical line—the maximum number of transit units (vehicles or trains) or spaces that can be carried over a line segment during a given time period with every transit unit operating at the minimum headway that the control system permits. Real operating conditions may reduce this capacity. See also *capacity, line.*

CAPACITY. . .vehicle *(normal vehicle capacity, total vehicle capacity)*—the maximum number of passengers that the vehicle is designed to accommodate comfortably, seated and standing; may sometimes refer to number of seats only.

CBD—central business district.

CENTRAL BUSINESS DISTRICT (CBD)—The downtown retail trade and commercial area of a city or an area of very high land valuation, traffic flow, and concentration of retail business offices, theaters, hotels and services.

CENTRAL CITY—as defined by the Bureau of the Census, the largest city, or one of the largest cities, in a metropolitan statistical area or urbanized area. The criteria for designating a central city vary with the type of area and the particular census.

CENTRALIZED TRAFFIC CONTROL *(CTC)*—in rail systems, a traffic control system in which signals and switches are controlled from a remotely located (centralized traffic control) panel.

CHECK—in transit operations, a record of the passenger volume on all transit units that pass a specific location or time point (also known as a *passenger riding count or check),* the actual time the unit passes it (also known as a *schedule check),* the number of passengers who board and alight at each stop on a route or line (also known as an *on-and-off count or check)*, or any combination of these items. The checker may ride the transit unit (an *on-board check)*, follow it in another vehicle, or check the transit units from a particular location (a *point* or *corner check).*

CHECKER—in transit operations, a person who observes and records passenger counts, timing, speeds, vehicle counts, schedule adherence, or other data useful in transit planning and scheduling. The position may be further specified as *schedule checker, traffic checker,* and so on.

CLOSE-UP—in rail transit operations the process where a train approaching a station will close-up to the train berthed in the station to the minimum distance permitted by the signaling or train control system. This is usually the critical line condition that, combined with the dwell at the maximum load point station, establishes the minimum headway.

COMMUTER RAIL CAR—a passenger rail car designed for commuter rail services. It usually has many more seats than a conventional long-distance rail passenger car. The car may be hauled by a locomotive, have a self-contained internal combustion engine, or be electrically propelled by power from a third rail or overhead wire. See also *cab*.

COMMUTER RAIL—The portion of passenger railroad operations that carries passengers within urban areas, or between urban areas and their suburbs, but differs from rail rapid transit in that the passenger cars generally are heavier, the average trip lengths are usually longer, and the operations are carried out over tracks that are part of the railroad system in the area.

CONDUCTOR—1. In rail transit operations, the operating employee who may control the doors on rail transit vehicles, or who may have fare-collecting duties, or both—also called guard on some systems. 2. In railroad operations, the operating employee in charge of the train and trail crew.

COUPLER—a device for connecting one rail vehicle to another. The mechanism is usually placed in a standard location at both ends of all rail cars and locomotives.

COUPLER. . .automatic—1. a coupler that operates automatically. It may also be capable of uncoupling automatically. 2. An automatic connector that joins electric or pneumatic train lines together between rail cars.

CRITICAL LINE CONDITION—in rail transit operations the factor that constrains headway. This is usually the close-in at the maximum load point station or the terminal turnback process, occasionally at junctions.

CRUSH LOAD—The maximum passenger capacity of a vehicle, in which there is little or no space between passengers (i.e., the passengers are touching on another) and one more passenger cannot enter without causing serious discomfort to the others.

CTC—see *centralized traffic control*

DEADHEAD—The movement of a transit vehicle without passengers aboard - often to and from a garage, or from one route to another.

DISPATCHER—The individual who is responsible for keeping trains or other vehicles on schedule.

DOOR MOVEMENT TIME—The time during a rail transit station dwell that passengers are moving through train doorway

DIVERSITY loading—The ratio between achievable (practical capacity) and design capacity (maximum capacity) over the peak hour, reflecting that passengers do not evenly load a car, cars of a train or trains over the peak hour (the 3 levels).

FARE COLLECTION SYSTEM—the procedures and devices used to collect fares and to accumulate and account for fares paid.

FARE COLLECTION SYSTEM. . .automatic (*AFC)*—the controls and equipment that automatically admit passengers on insertion of the correct fare in an acceptable form, which may be coins, tokens, tickets, or farecards (stored-value farecards must be inserted again on exit, at which point an additional fare may be required). The system may include special equipment for transporting and counting revenues.

FARE COLLECTION SYSTEM. . .fare-registering turnstile *(faregate)*—a turnstile that unlocks to allow a passenger to enter the paid area after a pass or farecard or the correct amount of money or token is inserted in it. It records the fares paid.

FARE COLLECTION SYSTEM. . .self-service, proof of payment, barrier-free, honor system—a fare collection system that has no fare-registering turnstiles. This system requires that the passenger be able to display proof of payment (e.g., validated ticket, prepaid pass, valid transfer) while on board the transit vehicle or in a station. Compliance is monitored through random checking by designated transit employees.

FAREBOX—a device that accepts coins, bills, tickets, tokens, or other fare media given by passengers as payment for rides.

FIXED-GUIDEWAY SYSTEM—A system of vehicles that can operate only on its own guideway constructed for that purpose (e.g., rapid trail, light rail). Federal usage in funding legislation also includes exclusive right-of-way bus operations, trolley coaches, and ferryboats as "fixed-guideway" transit.

FLOW RATE *(rate of flow)*—in transportation, the number of units (passengers or vehicles) passing a point on a transportation facility during some period of time, usually counted or computed in units per hour. For example, if 8 buses pass a point in the first half hour and 15 in the second, the volume for the hour is 23. However, the flow rate for the first half hour is 16 buses/hour, and for the second half hour the flow rate is 30 buses/hour.

GALLERY CAR—A bilevel rail car that has seating and access aisles on a second level along each side of an open well. Tickets of passengers on the second level can be inspected or collected from the lower level.

HANDICAPPED PERSONS—people who have physical or mental impairments that substantially limit one or more major life activities. In the context of transportation, the term usually refers to people for whom the use of conventional transit facilities would be impossible or would create a hardship. These people are also known as *transportation handicapped* or as people who have a *public transportation disability.*

HANDICAPPED ACCESSIBILITY (*full accessibility*)— The extent to which facilities are free of barriers and usable by mobile handicapped people, including wheelchair users.

HEADWAY—the time interval between the passing of the front ends or successive transit units (vehicles or trains) moving along the same lane or track (or other guideway) in the same direction, usually expressed in minutes; see also *service frequency.*

HEADWAY MANAGEMENT—a technique for managing the operation of transit units (vehicles or trains) that focuses on maintaining a certain spacing between units on the same line, instead of on adhering to a timetable. For example, if units become bunched, corrective measures might include delaying the units at the rear of the bunch to provide regular headways and hence load distribution, even at the expense of reducing timetable adherence.

HEADWAY. . .base—the scheduled headway between transit unit (vehicle or train) trips during an off-peak (usually midday) period.

HEADWAY. . .interference—headway that is so close that one vehicle or train interferes—delays—the next.

HEADWAY. . .non-interference—headway (usually including an operating margin) such that in normal operations one train does not delay another.

HEADWAY. . .policy—1. headway prescribed by reasons other than matching capacity to demand. 2. the maximum permissible headway as established by the transit agency or (often) the policy board, usually for off-peak, low demand periods.

HEAVY RAIL—A type of electric rail transit system characterized by exclusive rights-of-way, multi-car trains, sophisticated signaling and high-platform loading; with the capacity to carry a "heavy volume" of traffic. Also called subways or metropolitan railways (metros). see also *transit system, rail rapid.*

JUNCTION POINT—1. A location at which a rail branch line track connects with a main-line track. 2. A location at which two or more railroads interchange cars over connecting tracks. 3. A location at which several transit lines converge.

LAYOVER-TIME—Time built into a schedule between arrivals and departures, used for the recovery of delays and preparation for the return trip.

LEVEL OF SERVICE *(LOS)*—1. A set of characteristics that indicate the quality and quantity of transportation service provided, including characteristics that are quantifiable *(system performance*, e.g., frequency, travel time, travel cost, number of transfers, safety) and those that are difficult to quantify *(service quality*, e.g., availability, comfort, convenience, modal image). 2. For pedestrians, sets of area occupancy classifications to connect the design of pedestrian facilities with levels of service (A for best through F for worst). 3. For transit rights-of way, see *right-of-way.*

LIGHT RAIL CAR *(LRV, LIGHT RAIL VEHICLE)*—a rail vehicle similar to a streetcar. It may be larger, however, and is often articulated. A light rail car is capable of boarding and discharging passengers at either track or car-floor level.

LIGHT RAIL TRANSIT SYSTEM (LRT)—see *transit system, light rail*

LINE—1. A transportation company (e.g. a bus line). 2. A transit service operating over a specified route or combination of routes. 3. An active (in-use) railroad track or AGT guideway. 4. In network coding, a route and its service level, including mode designation (type of service), line number, headway, and sequence of transfer points (nodes). These factors describe the line's route as an ordered set.

LINE-CLEAR—in rail transit, operation such that trains do not have to stop or slow down due to the train ahead but receive a succession of green signals. See also Headway—non-interference.

LINE. . .double-track main—a rail main line that has two tracks, usually one for each direction.

LINE. . .single-track main—a rail main line that has one track. It requires passing sidings for bi-directional operation.

LOAD FACTOR—1. The ratio of used capacity to offered capacity of equipment or a facility during a specified time period. It is usually expressed as a percentage of seats occupied at a given point or (in continuous form) passenger miles (kilometers) divided by seat miles (kilometers). For rail services, the load factor is sometimes expressed as passenger miles (kilometers) per train mile (kilometer) to account for the ability to couple rail cars together to achieve efficiency. 2. The ratio of passenger capacity of a vehicle; also known as a *utilization coefficient.*

LOAD FACTOR—The ratio of passengers actually carried versus the total passenger capacity of a vehicle.

LOADING ISLAND—1. A pedestrian refuge within the right-of-way and traffic lanes of a highway or street. It is provided at designated transit stops for the protection of passengers from traffic while they wait for and board or alight from transit vehicles; also known as a *pedestrian island.* 2. A protected spot for the loading and unloading of passengers. It may be located within a rail transit or bus station.

MANUAL BLOCK—a system of manually governing train movement in a block or a series of consecutive blocks by means of signals, train orders, telephone, or radio.

MANUAL TRAIN OPERATION—a system in which train movement is controlled by the operator (motorman) or engineer.

MAXIMUM LOAD POINT *(MLP)*—the point on a transit line or route at which the passenger volume is the greatest. There is one maximum load point in each direction.

MAXIMUM LOAD SECTION *(MLS)*—the section of a transit line or route that carries the highest total number of passengers for that line or route and direction.

MARRIED PAIR *(MP)*—two semi permanently coupled rail cars (A car and B car) that share some mechanical and electrical equipment and must be operated together as a unit.

MODE—a particular form of travel, for example, walking, traveling by automobile, traveling by bus, traveling by train.

MODE. . .transit—a category of transit systems characterized by common characteristics of technology, right-of-way, and type of operation. Examples of different transit modes are regular bus service, express bus service, light rail transit, rail rapid transit and commuter rail.

MOTORMAN—Traditional term for train operator or engineer on rapid transit systems. No longer politically correct but still in common use.

MOVING BLOCK (*dynamic block control)*—an automatic train control system that spaces trains according to their location and (sometimes) their relative velocity, stopping performance, and a prescribed safety factor. Moving-block signaling systems are also called transmission or communication based systems. The latter is becoming the preferred term.

MULTIPLE-UNIT *(MU)*—a powered rail car arranged either for independent operation or for simultaneous operation with other similar cars, when connected to form a train of such cars. It may be designated as *DMU (diesel multiple-unit)* or *EMU (electric multiple-unit)*, depending on the source of power.

OFF-LINE—not in the main flow of traffic or not on the main line of traffic, for example, off-line station.

ON-TIME PERFORMANCE—the proportion of the time that a transit system adheres to its published schedule times within stated tolerances; for example, a transit unit (vehicle or train) arriving, passing, or leaving a predetermined point (time point) along its route or line within a time period that is no more than "x" minutes earlier and no more than "y" minutes later than a published schedule time. (Values of 0 minutes for "x" and 5 minutes for "y" are the most common).

OPERATOR—An employee of a transit system who spends his or her workday in the operation of a vehicle, e.g., bus driver, streetcar motorman, trolley coach operator, cable car gripman, rapid transit train motorman, conductor, etc. see also *property, operator*

OPERATING MARGIN—An employee of a transit system who spends his or her workday in the operation of a vehicle, e.g., bus driver, streetcar motorman, trolley coach operator, cable car gripman, rapid transit train motorman, conductor, etc. see also *property, operator*

PASSENGER—a person who rides a transportation vehicle, excluding the operator or other crew members of that transportation vehicle; see also *trip, passenger; trip, linked;* and *trip, unlinked.*

PASSENGER COUNT—a count of the passengers on a vehicle or who use a particular facility.

PASSENGER FLOW (*passenger traffic)*—the number of passengers who pass a given location in a specified direction during a given period.

PASSENGER FLOW TIME. . .doorway— the time, in seconds, for a single passenger to cross the threshold of a rail transit car doorway, entering or exiting, per single stream of doorway width.

PASSENGER LOAD—the number of passengers on a transit unit (vehicle or train) at a specified point.

PASSENGER MILES *(passenger kilometers)*—the total number of passengers carried by a transit system for a unit of time multiplied by the number of miles (kilometers) they travel. A comparison of passenger miles (kilometers) and seat miles (kilometers) provides a measure of transit system efficiency.

PASSENGER VOLUME *(line volume)*—the total number of passengers carried on a transit line during a given period.

PASSENGER. . .revenue—a passenger who pays (or has prepaid) a fare.

PASSENGER. . .transfer—a passenger who changes from one route or line to another route or line.

PCC CAR *(PCC, Presidents' Conference Committee car)*—a streetcar first produced in 1935. Its performance and efficiency were significantly improved over those of any streetcar previously built. The PCC car, characterized by (relatively) lightweight construction, smooth and rapid acceleration and deceleration, and soft ride, became the standard for U.S. streetcars for many years.

PEAK ***(peak period, rush hours)***—1. The period during which the maximum amount of travel occurs. It may be specified as the morning (a.m.) or afternoon or evening (p.m.) peak. 2. The period when demand for transportation service is heaviest.

PEAK-HOUR FACTOR ***(peak-hour conversion factor)***—the ratio of the volume during the peak hour to the maximum rate of flow during a selected period within the peak hour.

PEAK/BASE RATIO ***(peak/off-peak ratio)***—1. The ratio between the number of vehicles operating in passenger service during the peak hours and that during the base period. 2. The ratio between the number of passengers carried during the peak hours and that during the base period.

PEOPLE MOVER—an automated transportation system (e.g., continuous belt system or automated guideway transit) that provides short-haul collection and distribution service, usually in a major activity center. Once almost synonymous with automated guideway transit. Now primarily used for smaller systems such as those internal to airports.

PLATFORM ***(passenger platform)***—that portion of a transit facility directly adjacent to the tracks or roadway at which transit units (vehicles or trains) stop to load and unload passengers. Within stations, it is often called a *station platform.*

PLATFORM. . . .center—a passenger platform located between two tracks or guideways so that it can serve them both.

PLATFORM. . . .high—a platform at or near the floor elevation of the transit unit (vehicle or train), eliminating the need for steps on the transit unit.

PLATFORM. . . .low—a platform at or near the top of the running surface of the transit unit (vehicle or train), requiring the passenger to use steps to board and alight.

PLATFORM. . . .side—a passenger platform located to the outside of the tracks or guideways, as distinguished from a center platform located between the tracks or guideways.

PLATFORM TIME—The time a vehicle is in revenue service.

PROPERTY ***(operation, operator, system)***—in the transit industry, a public transit agency or a private transit company with responsibility for transportation services such as bus, ferry, rail; see also *transit district.*

RAIL DIESEL CAR ***(RDC, diesel rail car)***—a self-powered rail car that usually has two diesel engines and can usually operate in multiple units (diesel multiple-unit car).

RAIL RAPID TRANSIT—see *transit system, rail rapid*

RAIL RAPID TRANSIT CAR ***(rapid transit car, subway car)***—a rail car for rapid transit systems. It is bi-directional, usually powered, and equipped with a control cab at one or both ends. It may be designed to operate in single or multiple units. It has two to five double doors per side, designed for fast boarding and alighting from high-level platforms.

RAPID RAIL—A system which operates high speed, high capacity passenger trains using exclusive fixed guideways, grade separated and with high level station platforms for boarding passengers.

RAPID TRANSIT—Transit service which is operated completely separate from all other modes of transportation. The term "rail rapid transit" frequently refers both to operation of light rail transit vehicles over exclusive right-of-way and heavy trail transit vehicles; the term "bus rapid transit" refers to operation of motor buses over exclusive bus roads or busways.

REGIONAL RAIL SERVICE—see *service, regional rail*

REVENUE MILES ***(revenue kilometers)***—miles (kilometers) operated by vehicles available for passenger service.

RIGHT-OF-WAY ***(ROW)***— A general term denoting land, property, or interest therein, usually in a strip, acquired for or devoted to transportation purposes. For transit, rights-of-way may be categorized by degree of their separation: A-fully controlled without grade crossings, also known as *grade separated, exclusive,* or *private*; B-longitudinally physically separated from other traffic (by curbs, barriers, grade separation, etc.) but with grade crossings; C-surface streets with mixed traffic, although transit may have preferential treatment.

RIGHT-OF-WAY. . . .exclusive transit—a right-of-way that is fully grade separated or access controlled and is used exclusively by transit; transit ROW category A.

ROLLING STOCK—The vehicles used in a transit system, including buses and rail cars.

ROUTE MILES ***(route kilometers)***—various definitions exist for this statistic: 1. One-way duplicating is total mileage (kilometers) of routes, where the roadway or guideway segments of each individual route are summed up in one direction. For example, a 1 mile (kilometer) segment over which buses operate in both directions would be reported as 2 miles (kilometers); also known as *directional route miles* (kilometers) or *miles (kilometers) of roadway or route.* 2. One-way non-duplicating is total mileage (kilometers) of routes, where a particular roadway or guideway segment is only counted once regardless of number of routes or direction of travel on that segment; also known as *line miles (kilometers)* or *miles (kilometers) of directional roadway.* 3. Two-way mileage (kilometers) is total mileage (kilometers) of each route covered from start to finish. No attention is given to direction of routes or number of routes using any particular segment of roadway or guideway.

RUNNING GEAR—The wheels, axles, springs, axle boxes, frames, and other carrying parts of a bus, truck, rail car, or locomotive.

SECTION 15—The section of the Urban Mass Transportation Act of 1964, as amended, that authorizes the Department of Transportation to gather statistical information about the financing and operations of public transportation systems, based upon a uniform system of accounts and records.

SERVICE—a system or method of providing people with the use of something, for example, transportation.

SERVICE. . .base period—the level of transit operations during the base period.

SERVICE. . .commuter—transportation provided on a regularly scheduled basis during peak travel periods for users commuting to work, school and similar destinations.

SERVICE. . .express—service that has fewer stops and a higher operating speed than regular service.

SERVICE. . .limited—1. A transit service that operates only during a certain period of the day, or that serves only specific stops (also known as *limited stop service)* or in a specified area, or that serves only certain segments of the population. 2. Line service with some restrictions on boarding and alighting.

SERVICE. . .local—1. Transit service that involves frequent stops and consequent low average speeds, the purpose of which is to deliver and pick up transit passengers close to their destinations or origins. 2. Transit operation in which all transit units (vehicles or trains) stop at all stations. 3. Transit service in a city or its immediate vicinity, as distinguished from regional transit service or interurban lines.

SERVICE. . .regional rail *(RGR)*—regional rail passenger service, usually provided by railroad agencies, that consists of electric or diesel-powered trains on grade-separated railroad lines (sometimes with protected grade crossings); see also *transit system, commuter rail.*

SERVICE. . .revenue—1. Transit service excluding deadheading or layovers. 2. Any service scheduled for passenger trips.

SERVICE. . .service frequency—the number of transit units (vehicles or trains) on a given route or line, moving in the same direction, that pass a given point within a specified interval of time, usually 1 hour; see also *headway.*

SERVICE. . .skip-stop—service in which alternate transit units (vehicles or trains) stop at alternate sets of stations on the same route. Each set consists of some joint and some alternate stations.

SHORT TURN—see *turn back*

SIGNAL ASPECT—1. The appearance of a fixed signal conveying an indication, as viewed from the direction of an approaching rail unit. 2. The appearance of a cab signal conveying an indication, as viewed by an observer in the cab of a rail unit.

SIGNAL PRE-EMPTION—in highway operations, an automatic or manual device for altering the normal signal phasing for the sequence of a traffic signal to provide preferential treatment for specific types of vehicles, such as buses or trains.

SIGNAL. . .automatic block—a system in which signals are actuated automatically by the presence of a train on the track section. Some block signal systems can use an electric circuit to detect the presence of any vehicle, switch positions, broken rail, and so on.

SIGNAL. . .block—a fixed signal installed at the entrance of a block to govern trains entering and using that section of track.

SIGNAL. . .wayside—in rail operations, a fixed signal that is located along the track right-of-way.

SINGLE UNIT *(SU)*—a powered rail car, equipped with a control cab at one or both ends, that operates alone.

SPACING—the distance between consecutive vehicles, measured front to front.

SPEED see *velocity*

SPEED. . .overall trip *(effective operating speed, cycle speed)*—in transit operations, the average speed achieved per round trip, including layover time but excluding deadheading time. It is calculated by individual trips, by running time periods, or for the entire schedule.

SPILL-BACK—in on-street light rail transit operations where trains or motor vehicles fail to clear a signalized intersection and so prevent the following train from entering that block. Particularly acute in downtown streets where the light rail train can be the full length of the block.

STATION—1. An off-street facility where passengers wait for, board, alight, or transfer between transit units (vehicles or trains). A station usually provides information and a waiting area and may have boarding and alighting platforms, ticket or farecard sales, fare collection, and other related facilities. It is also know as a *passenger station.* 2. In railroad operations, a place designated in the timetable by name, at which a train may stop for traffic or to enter or leave the main track, or from which fixed signals are operated.

STATION ACCESSIBILITY—A measure of the ability of all people within a defined area to get to a specific transit station.

STATION. . .all-stop—in transit systems with skip-stop schedule or express service, a station that is served by all scheduled transit units (vehicles or trains).

STATION. . .maximum load point—The busiest station on a line where the longer dwell establishes the minimum headway.

STATION. . .off-line—a station at which a transit unit (vehicle or train) stops outside of the main track or travel lane so that other units can pass while passengers board and alight.

STATION. . .on-line—a station in which transit units (vehicles or trains) stop on the main track or travel lane. This is the common design, and the term is used only to distinguish this station from off-line stations.

STREETCAR—an electrically powered rail car that is operated singly or in short trains in mixed traffic on track in city streets. In some areas it is also know as a *trolley car* and, primarily in Europe, as a *tram.*

SUBWAY—1. That portion of a transportation system that is constructed beneath the ground surface, regardless of its method of construction. 2. An underground rail rapid transit system or the tunnel through which it runs. 3. In local usage, sometimes used for the entire rail rapid transit system, even it is not all beneath the ground surface. 4. A pedestrian underpass.

TERMINAL—1. The end station or stop on a transit line or route, regardless of whether special facilities exist for reversing the vehicle or handling passengers; also known as a *terminus.* 2. An assemblage of facilities provided by a railroad or intercity bus service at a terminus or at an intermediate location for the handling of passengers and the receiving, classifying, assembling, and dispatching of trains or dispatching of buses; also known as a *depot.*

TERMINAL. . .stub—a dead-end terminal in which the entering rail (or other guided) transit unit must depart by the same guideway on which it entered. Because no loop is provided, a bi-directional transit unit (vehicle or train) is necessary.

THROUGH ROUTING—the practice of joining the ends of radial transit routes to travel through downtown instead of having each route turn back in the downtown and return to its origin.

THROUGHPUT—The volume of vehicles passing or people transported past a point or series of points during a given period of time.

TIME. . .delay—the amount of time by which a transit unit (vehicle or train) in service is delayed from its scheduled time.

TIME. . .dwell—the time a transit unit (vehicle or train) spends at a station or stop, measured as the interval between its stopping and starting.

TIME. . .running—the actual time required for a transit unit (vehicle or train) to move from one point to another, excluding time for stops.

TIME. . .terminal—1. For passengers, the time required at the ends of trips to unpark and park their private vehicles, including any necessary walking time. 2. For rail vehicles, the time allowed at a terminal between arrival and departure for turning vehicles, recovering delays, and preparing for the return trip. 3. The time required for a passenger to pass through a terminal when there is a change of mode.

TRACK MILES *(track kilometers)*—the sum of the one-way linear miles (kilometers) of all trackage in a system, including all main track and trackage in yards, car barns, switches, and turnouts.

TRACK MILES. . .revenue *(revenue track kilometers)*—the number of miles (kilometers) of track used in passenger-carrying service.

TRACK MILES. . .service *(service track kilometers)*—the number of miles (kilometers) of track used exclusively in non revenue service.

TRACTION SAFETY INTERLOCK—in rail transit a series circuit of electrical switches that prohibits a train from starting unless all passenger doors are closed and locked.

TRAFFIC—in traffic engineering and transportation planning, the vehicles, people or both that pass a specified point during a given period.

TRAFFIC. . .annual average weekday *(AAWDT)*—daily traffic that is averaged over a calendar or fiscal year and that includes only weekdays (Mondays through Fridays). It may also exclude holidays.

TRAFFIC CONTROL DEVICE—a sign, signal, marking, or other device placed on or adjacent to a street or highway, by authority of a public body or official that has jurisdiction, to regulate, warn, or guide traffic.

TRAFFIC COUNT—a record of the number of vehicles, people aboard vehicles, or both, that pass a given checkpoint during a given time period. It may be classified by type of vehicle. See also *count.*

TRAILER—1. An unpowered rail car operated in trains with powered cars (rapid transit) or towed by locomotives (regional rail). 2. In some rail rapid transit systems, a trailer may be powered; however, it does not have operator's controls and thus can only be operated in consists with cars that do.

TRAIN—1. Two or more transit vehicles physically connected and operated as a unit; see also *transit unit.* 2. One or more locomotives or self-propelled rail cars, with or without other cars but with marker lights. 3. On a headway sheet, a single transit unit (vehicle or train) and all the scheduled work that it performs during the operating day.

TRAIN BERTH—in rail operations, the space designated for a train of given length to occupy when it is stopped at a station platform, in a terminal, on a transfer track, or at some other designated place.

TRAIN OPERATION—the way in which a train is operated, for example, automatic with automatic overspeed control, or manual with either automatic or manual speed control, or skip-stop.

TRAIN. . .push-pull — a locomotive and a set of cars equipped with one or more cab cars from which the locomotive can be controlled. The train is either pulled and controlled from the locomotive in the conventional manner or pushed by the locomotive and controlled from the leading car.

TRANSFER—1. A passenger's change from one transit unit (vehicle or train) or mode to another transit unit or mode. 2. A slip of paper, card, or other instrument issued to passengers (either free or with a transfer fee) that gives the right to change from one transit unit or mode to another according to certain rules that may limit the direction of travel or the time in which the change may be made.

TRANSFER PASSENGER—A passenger who transfers to a line after paying a fare on another line.

TRANSIT SYSTEM—the facilities, equipment, personnel, and procedures needed to provide and maintain public transit service.

TRANSIT SYSTEM. . .automated guideway *(automated guided transit, AGT)*—any guided transit mode with fully automated operation (i.e., no crew on the transit units). The term usually refers, however, only to guided modes with small and medium-sized vehicles that operate on guideways with exclusive right-of-way. The term includes the personal rapid transit concept and group rapid transit or people mover systems.

TRANSIT SYSTEM. . .commuter rail—a passenger railroad service that operates within metropolitan areas on trackage that usually is part of the general railroad system. The operations, primarily for commuters, are generally run as part of a regional system that is publicly owned or by a railroad company as part of its overall service. In some areas it is called *regional rail.*

TRANSIT SYSTEM. . .light rail *(LRT)*—as defined by the TRB Subcommittee on Light Rail Transit, a metropolitan electric railway system characterized by its ability to operate single cars or short trains along exclusive rights-of-way at ground level, on aerial structures, in subways, or occasionally, in streets, and to board and discharge passengers at track or car floor level.

TRANSIT SYSTEM. . .light rail rapid *(LRRT)*—light rail transit with exclusive, grade-separated right-of-way for the entire system. It may have low or high-level platforms and visual or signal control.

TRANSIT SYSTEM. . .major activity center *(MAC system)*—a transit system that provides service for short trips within small, densely populated major activity centers, such as shopping centers and downtown areas.

TRANSIT SYSTEM. . .rail— —any of the family of transit modes with rail technology. The major ones, generally in ascending order of performance, are streetcars, light rail transit, rail rapid transit, and commuter or regional rail.

TRANSIT SYSTEM. . .rail rapid *(heavy rail transit, rapid rail transit)*—a transit system that generally serves one urban area, using high-speed, electrically powered passenger rail cars operating in trains in exclusive rights-of-way, without grade crossings (Chicago is an exception) and with high platforms. The tracks may be in underground tunnels, on elevated structures, in open cuts, at surface level, or any combination thereof. Some local terms used for rail rapid transit are *the elevated, the metro, the metropolitan railway, the rapid, the subway, the underground.*

TRANSIT SYSTEM. . .streetcar *(street railway, tramway, trolley system)*—a street transit system consisting of electrically powered rail vehicles operating in one to three-car transit units, mostly on surface streets with mixed traffic.

TRANSIT UNIT—one or more transit vehicles coupled and operated together. The term includes single vehicles (bus, rail, or other guideway) and multiple car trains (rail or other guideway).

TRIP—1. A one-way movement of a person or vehicle between two points for a specific purpose; sometimes called a *one-way trip* to distinguish it from a round trip. 2. In rail operations, a mechanical lever or block signal that, when in the upright position, activates a train's emergency braking system. 3. The movement of a transit unit (vehicle or train) in one direction from the beginning of a route to the end of it; also known as a *run.*

TRIP. . .inbound—a trip toward the central urban area, into the central business district, or to a timed transfer point or major activity center.

TRIP. . .linked *(linked journey, linked passenger trip)*—a trip from the point of origin to the final destination, regardless of the number of modes or vehicles used.

TRIP. . .outbound—a trip away from the central urban area, out of the central business district, or away from a timed transfer point or major activity center.

TRIP. . .passenger—one passenger making a one-way trip from origin to destination.

TRIP. . .unlinked—1. A trip made in a single vehicle. 2. The boarding of one transit vehicle in revenue service; also known as an *unlinked passenger trip.* 3. Any segment of a linked trip.

TRIPPER—1. A train inserted in the schedule to make one peak period trip. 2. An assignment of work to an operator that is not long enough to qualify as a full day's work.

TURN-BACK—1. In transit operations, to cut short a transit trip (to turn back before reaching the end of the route or line), usually to get back on schedule or to meet peak passenger demands; also known as a *short turn.* 2. In rail operations, a point along a track at which a train may reverse direction.

TURNOUT—1. In rail transportation, the assembly of a switch and a frog with closure rails by which rolling stock or trains can travel from a track onto either one of two diverging tracks; also known as a *track switch.* 2. A short side track or passage that enables trains, automobiles, and similar vehicles to pass one another.

UNIDIRECTIONAL CAR—a rail car (usually light rail or streetcar) that has doors on one side and an operating cab at only one end so that it mush be turned around by separate means at terminals.

URBAN RAIL CAR—a light rail, rail rapid transit, or commuter rail car.

VEHICLE HOUR—the operation of a vehicle for a period of 1 hour.

VEHICLE MILE *(vehicle kilometer)*—the movement of one vehicle over a distance of 1 mile (kilometer).

VELOCITY *(speed)*—the distance passed per unit of time, or the rate of change in location relative to time. For transportation vehicles it is usually measured in miles (kilometers) per hour.

WHEELCHAIR LIFT—a device used to raise and lower a platform that facilitates transit vehicle accessibility for wheelchair users and other handicapped individuals. Wheelchair lifts may be attached to or built into a transit vehicle or may be located on the station platform *(wayside lifts).*

YARD—1. In rail systems, a facility within defined limits that has a system of tracks used for making up trains, storing rail cars, and other purposes. 2. In transit systems, an open storage lot for light rail vehicles, streetcars, electric trolley buses, and motor buses.

A1. APPENDIX ONE
Review of North American Rail Transit Capacity Analysis Methodologies

This appendix is the result of Task 1 of the project.

> *Conduct a review of North American rail transit capacity experience and capacity analysis methodologies.*

Figures, tables and equations abstracted from the literature are not titled, numbered or indexed, but are inserted in the text, as reviewed. Those figures, tables and equations from this review that are used in the report are titled, numbered and indexed therein.

There is considerable inconsistency in use of terminology in the transit industry. In this appendix the author's terminology is used. Where this could be confusing an explanatory footnote is inserted. Similarly the author's mensuration is used with conversion to the metric units used in the report where applicable.

Inevitably in so wide a literature survey there are contradictions between reports. No attempt is made to reconcile these except where specific material is used in the main body of the report.

A1.1 INTRODUCTION

Literature searches were carried out through BC Transit's and Transport Consulting Limited's libraries and files, and through electronic searches of the Library of Congress; University of British Columbia and University of Minnesota libraries; the transportation libraries of Northwestern University and University of California, Berkeley; and the National Technical Information Service and the Transportation Research Board's Transportation Research Information System—with listings from British and European sources, including the International Public Transport Union (UITP).

The electronic searches used multiple combinations and permutations of two or three key words:

- rail
- capacity,
- light rail
- commuter
- signaling
- public transport
- transit
- rapid transit
- LRT
- AGT
- train control
- metro
- local transport—Library of Congress terminology

The electronic search was disappointing; even with broad generic key words, such as *rail transit* alone, it failed to turn up several relevant documents known to the Principal Investigator or suggested by the Panel. In part this reveals an inadequacy in the abstracts or summaries used. In particular, multiple-paper documents and reports could not realistically cover a dozen or more papers in a 200-word (or less) abstract. One important source of rail transit information, the American Public Transit Association's Annual Rail Transit Conference, is referenced only by paper title—and then only for the past few years. Similarly, many electronic databases are recent and do not include older sources.

Mitigating these deficiencies were valuable references obtained from the initial search reports, plus reports known to the Principal Investigator or suggested by the Panel, which were read and synthesized. This process doubled the number of documents and provided some of the richest and most useful material.

A total of 381 potential documents were identified in the electronic searches. Abstracts were obtained on the 65 of these that appeared useful, resulting in 33 books and reports being obtained or ordered in hard copy. The above mentioned iterative process increased the final total to the 67 reports listed below.

The literature search and synthesis produced considerably more relevant material than had been envisaged. It served as a comprehensive source to guide and steer the project's development and evolution, and equally important, indicated deficiencies, problems and pitfalls that the project should correct or avoid.

A1.2 LITERATURE SUMMARIES

More than 70 papers, books and reports were read and synthesized with respect to Rail Transit Capacities and Capacity Analysis Methodologies. Each item is summarized below in alphabetic order by author.

Only material relevant to TCRP A-8 study is included. *The synthesis is not intended to be a complete précis of any item.* Following most summaries is a brief commentary indicating the Principal Investigator's opinion of the material's strengths and weaknesses, and expectation of the usefulness of the material to this project.

A brief overall Summary of the literature follows as section 3 of this appendix.

1 ABRAMOVICI, MARC, Optimization of Emergency Crossovers and Signals for Emergency Operations in Rail Rapid Transit Systems, *APTA Rapid Transit Conference, June 1982*

Summary: The paper presents a methodology for determining signaling requirements and cross-over locations that will minimize disruption from single-track working—whether due to maintenance or an emergency.

An example is given for typically spaced rapid transit cross-overs, with an intermediate running time of 4 min, (approximately 3 km or 2 mi). Uni-directional signaling would reduce throughput to 33% of normal. Bi-directional signaling would permit platooning with capacity reduced to 60% of normal.

The paper provides means to calculate the restriction of single-track working with and without intermediate stations. It shows that closer cross-over spacing can provide emergency capacity that is 80-90% of normal.

Comment: The straightforward methodology also permits calculations of headway for light rail with single-track sections. The report raises the issue of how much allowance capacity calculations should contain for irregular operations.

2 ALLE, P., Improving Rail Transit Line Capacity Using Computer Graphics, Logistics and Transportation Review, Volume 17, Number 4, University of British Columbia, Faculty of Commerce, Dec. 1981

Summary: The study asks the following questions: "How many trains can realistically pass a point in one hour?" "What is the impact of station dwell times on this throughput?"

The study analyses the E and F trains on the NYCTA at Queens Plaza Station, using actual dwell time data and statistical probability theory to show that, by trapping 85% of the area under the normal distribution curve, the actual dwell time will be below 75.23 sec, 85% of the time. Using this figure it concludes that a single track can support trains every 130 sec—almost identical to NYCT's throughput of 29 trains per hour (124 sec), which the agency says is saturation level.

The study's dwell time methodology is:

A 95% confidence interval for the true mean is given by:

$$\mu_{95} = \left[\bar{X} + t_{n-1};\ 0.025S / \sqrt{n}\right]$$

where: X = sample mean of dwell time data
S = sample standard deviation
n = number of observations

The interval estimator for the true standard deviation makes use of the chi-square (X^2) distribution. A 95% confidence interval for δ is given by:

$$\delta_{95} = \frac{\sqrt{n-1}}{\chi_{n-1}} \frac{(s)}{;\ (.025)},\ \frac{\sqrt{n-1}}{\chi_{n-1}} \frac{(s)}{;\ (.975)}$$

To trap 85% of the area under the normal distribution curve, the upper control limit becomes the mean plus one standard deviation. Conservatively assuming the above defined μ and δ to be the upper limits of their respective 95% confidence interval, the upper control limit for the peak-hour station dwell becomes ($\mu + \delta$).

The study observed dwell times over the morning peak hour at Queens Plaza Station from 07:30 to 08:30.

Dwell Times Used in Analysis (seconds)

45	30	25	30	35	125
50	35	45	30	40	60
40	45	45	40	30	35
30	35	35	30	50	40
40	75	35	40	35	

These dwell times produce a sample mean of 42.7 sec and a sample standard deviation of 18.74. (Using exact rather than the rounded data above.) The median is 37.5 and the maximum 125 sec.

The resultant upper control limit ($\mu + \delta$) calculates to 75.23 sec from this data. The throughput in trains per hour (T_h) becomes:

$$T_h = 3600/[M + (\mu + \delta)]$$

Where M is the minimum time separation in sec provided by the three-aspect signal system on the immediate approach to the station. This is determined as $M = 55$ sec through a graphical computing process that inserts train performance and the physical location of signal block boundaries. The three restrictive signal blocks approaching the station are each 200 ft long and there are blocks at 200, 400 and 700-ft-along the platform, the latter being the departure signal for the 700-ft-long platform. This maximizes throughput by allowing a train (with yellow aspects) to enter the platform before the preceding train has completely vacated it.

The computed figure cannot be determined for other locations without access to the study program and considerable physical data on the signal system. However Barwell(R11) and Auer(R09) provide simpler means to calculate this minimum signal system time separation figure for conventional signal systems and the 55 sec can be taken as a typical figure for the common three-aspect rapid transit signal systems in North America.

Comment: This is a valuable paper with data and methods usable in the study to show line capacity with three-aspect signal system and variable dwell times.

The merit of this paper is that, using real life data at one of New York's heavy use stations, it produces train throughput results that are very close to actual experience without applying any of the judgment factors used in many other calculation methods to calibrate theory with practice. The disadvantage is that only one station, typical as it may be, is examined.

The main lesson is that although the average peak-hour dwell time is 43 sec, the median is 37.5 and the maximum or worst case dwell is 125 sec, the upper control limit dwell time used to calculate maximum train throughput—on a sustainable and reliable basis—is calculated to be 75 sec. This is some 74% higher than the mean, 100% higher than the median, 150% higher than the often quoted "typical" dwell of 30 sec and 40% lower than the maximum—all figures used in methods suggested elsewhere in this review.

3 ALLEN, DUNCAN W., Practical Limits of Single-Track Light Rail Transit Operation, *Transportation Research Record 1361, 1992: pp. 305-311*

Summary: The author discusses a number of assumptions applicable to light rail transit. These assumptions equate the travel time in both directions, establish the fixed headway, and optimize the signaling for the performance of the light rail vehicles to be operated. In addition, the author assumes that the single-track occupancy direction alternates with train meets occurring every half headway. The paper then goes into considerable detail to include tolerable delay factors in the optimum design calculations.

The paper also offers some observations and opinions that a practical application of single track to light rail operations may take into account. The author notes that "several iterations or adjustments may be required to reach a satisfactory solution".

The specific assumptions and methodology are:

- vehicle performance is uniform in both directions.
- headways are fixed.
- all light rail vehicles have equal priority.
- signaling is optimized for vehicles used.
- occupation of single-track alternates by travel direction.
- meets occur every half-headway (H/2).
- length of single-track is determined by design allowances for early and late vehicles.

The amount of tolerable delay, as given in the following table, is a key factor.

Condition	Definition
B	Little or no delay in either direction
C	Some delays, few complete stops
E	All or most vehicles are delayed but traffic is still moved.

Condition E produces a maximum occupancy time for single-track segments. This is given by:

$$T_1^E = H/2 - T_{Clear} - T_{Pass}$$

For conditions C and B, the corresponding equations are:

$$T_1^C = H/2 - T_{Crit} - T_{Pass} - T_{Clear}$$

$$T_1^B = H/2 - T_{Crit} - T_{Pass} - T_{Clear} - T_{Stop}$$

where: T_1^E = occupancy time of section
H = headway
T_{Clear} = signal clearance time (typical light rail value 8 sec)
T_{Pass} = time for an entire vehicle to pass a control point (typical value for light rail: 3 sec)
T_{Crit} = sum of expected early and late train times at meet point

A "Condition D" has been empirically derived and may give a safer, more realistic, estimate of maximum occupancy time than does Condition E. It is given by:

$$T_1^D = 0.66(T_1^C) + 0.39(T_1^E)$$

Required trackage can be determined from:

$$TK = 2.0(RK)(1.0 - T_1/H)$$

where: TK = track kilometers
RK = route kilometers

Comment: This is an interesting paper that presents an organized but theoretical approach to determining operational throughput of single-track sections of light rail transit operations. While the author's observations may be incomplete or not apparently relevant to this project's purpose, this study may find the conditions of "tolerable delay" useful.

A potential deficiency is the paper's suggestion that single-track sections less than 500-m long are unlikely to be economic—because of the costs of special work. This is incomplete and possibly misleading. It is precisely short-single track sections that can save capital costs by squeezing light rail through an underpass or over a bridge. The high special-work (switch) costs can be avoided by use of gauntlet track. Short single-track sections can have little impact on capacity and service reliability and can often be scheduled on a random arrival, first-come first-served, basis.

4 AMERICAN PUBLIC TRANSIT ASSOCIATION, 1992 Transit Operating and Financial Statistics

Summary: Used for basic information in the study database.

5 AMERICAN PUBLIC TRANSIT ASSOCIATION, 1994 Membership Directory

Summary: Used for basic information in the study database.

6 AMERICAN PUBLIC TRANSIT ASSOCIATION, Equipment Roster 1993

Summary: Used for equipment data not in the more current and detailed rapid transit roster (R03) above. Much missing door information has been obtained in the data collection task.

7 AMERICAN PUBLIC TRANSIT ASSOCIATION, Roster of North American Rapid Transit Cars, 1993 Edition.

Summary: Used to enter rapid transit equipment dimensions, door widths and other data in the study database.

8 ANDERSON, J. EDWARD, Transit Systems Theory, *Lexington, 1978*

Summary: Anderson provides a comprehensive and analytic review of transit system theory for automated guideway transit (AGT), including spiral transition curve and super-elevation calculations, modal split modeling and analytic methods of project economic evaluation.

Two sections pertain to rail transit capacity. Chapter Two introduces the basic equations of motion and shows how to calculate performance. Jerk tolerance for standing and seated passengers is introduced showing how in initiating and ending both acceleration and braking the rate must be tapered to control jerk. This results in actual performance being lower than the simplistic performance calculation common elsewhere.

The book shows how these "transitions" together with accelerating performance limitations (whereby the initial starting rate of acceleration diminishes rapidly as the train gains speed and "follows the motor curve") result in a rate of acceleration from start to balancing (cruise) speed that will be less than half the initial acceleration—significantly so if the train is heavily loaded and/or on a grade.

A critical issue in the accurate calculation of close headways is the acceleration leaving a station and Anderson's formulas suggest that the average rate of acceleration during this period may be 20 to 30% lower than the rate often used—depending on grade, load and the power-to-weight ratio of the equipment.

In Chapter Four, Anderson shows formulas to calculate the minimum separation of trains. The most restrictive headway occurs in the approach, stop and acceleration away from the station.

$$X_{\min} = kV_{\min}^2/2a_e$$

where:
$X_{\min}$ = the minimum separation distance
k = a safety constant
$V_{\min}$ = the speed of the trailing vehicle
a_e = the braking rate of the trailing vehicle adjusted for jerk transitions

This separation distance enables the minimum headway H_{min} to be calculated

$$H_{\min} = T_c + 2T_r + T_d + 2X_{\min}/V_{\min}$$

where:
T_c = time for exiting train to clear platform (or blocks), calculated in the same manner as $X_{\min}$
T_r = control and/or train operator delay and/or reaction time
T_d = station dwell time

Comment: Transit System Theory is a misleading title because the book deals only with AGT systems. The minimum headway calculations use a safety multiplier in calculating braking and clearance distances. This approach is less clear than adding a safety distance which can be calculated from set criteria. In the TCRP A-8 study this latter method, as outlined in Auer $^{(R09)}$ and Motz $^{(R47)}$ following, is preferred and has been used.

Anderson's Commentary on jerk limitation, transitions to braking and acceleration rates, and the rapid fall-off of the acceleration rate as a train gains speed is invaluable.

9 AUER, J.H., Rail-Transit People-Mover Headway Comparison, *IEEE Transactions on Vehicular Technology, Institute of Electrical and Electronics Engineers, 1974*

Summary: Discusses the application of conventional block signaling to rapid transit and AGT with details of maximum train throughput under various conditions for both modes. Shows how the WMATA signaling system is designed for 75-sec minimum headways with trains of maximum length. This can be reduced to 18 sec on AGT systems—with the same *brick-wall* safety standards.

The author describes time delays that limit signaling throughput:

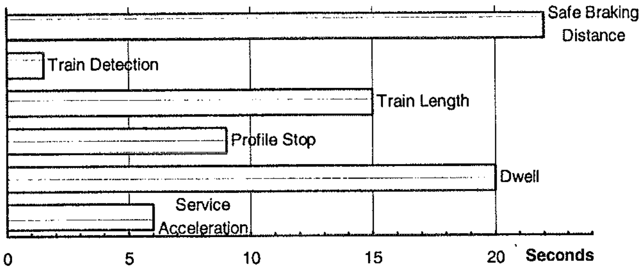
- train operator reaction time varies, 0 with ATO
- cab signal communication delay, 2.0 sec
- overspeed detection delay, 0.75 sec
- switch lock-to-lock time, 3.0 sec

$$\text{MLH} = 0.682\text{K}(\text{TL} + \text{SBD} + \text{TDUD} + \text{SCBD})/\text{CS}$$

where:
MLH = Minimum Line Headway (sec)
K = Safety Factor, must be ≥ 1 for brick-wall standard
TL = Train Length
SBD = Safe Braking Distance based on runaway propulsion failure plus reduced braking factor
TDUD = Train Detection Uncertainty Distance
SCBD = Service Control Buffer Distance (AGT only)
CS = Command Speed

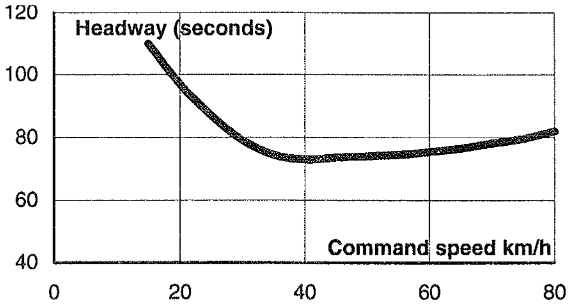
Other equations are developed to calculate the headway on a conventional three-aspect block signaling system under a variety of conditions and assumptions, including the impact of Automatic Train Operation (ATO) and cab signals over manual operation. Cab signals can improve minimum headway by a calculated 1.7 sec at an approach speed of 50 km/h while ATO can effect a further reduction of some four sec at the same speed.

Auer shows the components in the minimum headway, at a command speed of 50 km/h, for a conventional three-aspect signaling system. The total headway of 73 sec includes a 20-sec dwell. The minimum line headways can be expressed as 53 sec plus the controlling dwell. This corresponds closely to Alle's work (R02) which suggests a three-aspect signal system with ATO can sustain a headway of 55 sec plus the upper control limit dwell time.



The variation of this minimum headway (73 sec) with train length is shown in the following figure.

The variation of headway with train command speed is shown below. The minimum headway is 71.2 sec at 44 km/h— including a nominal 20-sec station dwell.



Note that the command speed is the speed restriction imposed by the signal system approaching and leaving a station—not the cruise or maximum speed between stations. Typical command speeds will be in the 30 to 40 km/h range allowing a 75-sec headway—close to the optimal minimum of 71.2 sec. However where there are restrictions, approaching or leaving a station, due to special work or curves, the minimum headway can increase significantly. At a more restrictive command speed of 20 km/h, the headway increases to 100 sec. Discounting the 20-sec station dwell, this is an increase from 55 to 80 sec—45%.

Comment: Auer's paper provides one of the best, concise summaries of a conventional three-aspect signaling system throughput for both rapid transit and AGT. The results correspond closely to actual field data. When combined with the upper control limit dwell time calculations of Alle(R02) it suggests both simple and complete methods for the study to determine line throughput. It has been used in the study as the best representation of three-aspect signaling systems.

10 **BARDAJI, JORDI F.**, Regulating Headway in Barcelona, *The Urban Transport Industries Report, Campden Publishing Limited, 1993, pp. 175-176*

Bardaji describes how automatic regulation increased the practical capacity of the Barcelona subway by 5%.

11 **BARWELL, F. T.,** Automation and Control in Transport. 2nd Revised Edition *Pergamon Press Limited, 1983*

In this standard text, the late Professor Barwell covers many aspects of rapid transit operation and control. Among his many Comments are that "transport problems generally reduce to the consideration of headway at a bottleneck" and admonitions that some of the mathematical theory presented does not correspond to actual field experience without practical adjustments.

In discussing multiple-aspect signaling systems he points out that the "law of diminishing returns operates very powerfully". It is rarely economic to move beyond the typical three-aspect signaling system although four aspects have been used to increase capacity on some European high-speed inter-city railroads. In noting that track circuits were first used in 1872 and coded circuits in 1933, he suggests that moving-block systems may take over many high speed inter-city applications where the signal system must accommodate trains of differing lengths, performance and speeds.

Barwell discusses rail junction optimization techniques and the simulation of train following behavior—particularly relevant when train spacing is perturbed. He develops the minimum train separation S_e as:

$$S_e = TL + BL + 0.75V^2/aK$$

where: TL = train length
BL = block length plus safety distance *or* block overlap plus sighting distance
V = train speed
a = braking rate
K = a safety constant

Minimum headway ($H_{\min}$) is shown as:

$$H_{\min} = S_e/V + \begin{matrix}\text{maximum}\\ \text{station dwell}\end{matrix} + \begin{matrix}\text{recovery}\\ \text{time}\end{matrix} + \begin{matrix}\text{reaction}\\ \text{times}\end{matrix}$$

Comment: Barwell provides a useful way to calculate the minimum train spacing for a moving block system—where theory corresponds closely with practice. However both here and in the train separation equation above, the introduction of safety factors makes the calculation subjective. Barwell's work provides methods to calculate junction constraints on capacity.

12 **BATELLE INSTITUTE**, Recommendations en vue de l'amènagement d'une installation de transport compte tenu de donnèes anthropomètriques et des limites physiologiques de l'homme, *Geneva, 1973*

Summary: The relevant parts of this report deal with recommended comfort levels for many aspects of public transport vehicles, including temperature, ventilation, noise, floor slope, acceleration, rate of change of acceleration (jerk) and passenger standing density. Information is provided for three conditions, *comfortable, uncomfortable and unacceptable.*

The passenger standing density recommendations are

• comfortable	2-3 passengers per m^2
• uncomfortable	5 passengers per m^2
• unacceptable	>8 passengers per m^2

Details are provided on the projected body space of passengers in various situations. The most useful of these for rail transit capacity are tabulated for males.

Situation	Projected Area m^2
Standing	0.13 to 0.16
Standing with briefcase	0.25 to 0.30
Holding on to stanchion	0.26
Minimum seated space	0.24 to 0.30
Tight double seat	0.36 per person
Comfortable seating	0.54 per person

13 **BERGMANN, DIETRICH R.**, Generalized Expressions for the Minimum Time Interval between Consecutive Arrivals at an Idealized Railway Station, *Transportation Research, 1972 Vol. 6, pp. 327-341*

Summary: Bergmann's mathematical treatise explores the principal determinant in rail transit throughput—the minimum time between successive arrivals at a station.

He expands on the basic equations of motion, examining in particular limitations and effects of train approach speed, train length, and the emergency braking rate. Four expressions are developed for differing limits of these three variables.

The basic expression for minimum headway $T_{A;i/i+1}$ without limits is:

$$T_{A;i/i=1} = t_d + t_r + \frac{L_i}{V_m} + \frac{V_m}{2(D_e + D_o + A)}$$

where t_d = station dwell time
t_r = emergency braking response time of following train
L_i = length of leading train
V_m = constant speed station approach
D_e = emergency deceleration rate
D_o = operational deceleration rate
A = acceleration rate

Three other expressions are derived for variations or limits to approach speed, train length, and the emergency braking rate. These are plotted against approach speed to show a minimum headway of 31 sec plus station dwell at an approach speed of approximately 35 km/h (22 mph). Higher approach speeds show a linear relationship to headway when operational and emergency deceleration are equal. When emergency deceleration is higher than operational deceleration the minimum headway remains constant with approach speed.

Bergmann then compares his results with other authors before concluding that increasing the emergency deceleration rate will decrease minimum headways—with the caution that the approach is theoretical and does not take into account the effect of finite signal blocks on train separation.

Comment: The paper's extensive analysis is interesting in introducing the difference in minimum headways due to operational and emergency deceleration rates and showing the optimum approach speeds under various conditions. The analysis does not take into account practical limits on acceleration and deceleration with respect to passenger comfort, not does it allow for performance variations, grades or operational allowances. His calculated minimum headway of 31 sec plus dwell is applicable only to moving-block signaling systems but provides an interesting lower limit for such systems.

14 **BERRY, RICHARD A., CERVENKA, KENNETH J. AND SU, CHANG-AN,** Traffic and Light Rail Transit: Methods of Analysis for DART's North Central Corridor, *Transportation Research Record 1361, 1992: pp. 224-234*

Summary: This paper presents a detailed summary of the application of computer modeling of delays to automobile traffic caused by DART's (Dallas, Texas) North Central light rail line. Grade crossing methods, at-grade or grade separated, are proposed based on the effect of light rail on traffic.

Comment: Berry *et al.* are concerned exclusively with the effect of the light rail on general traffic flow and do not address the capacity of the light rail line itself. As such, this work is of little use to the project except to confirm other similar work that grade crossings have little, if any, impact on light rail capacity compared with the constraint of signaled sections.

15 **BOORSE, JACK W.**, Blending LRT into Difficult Traffic Situations on Baltimore's Central Light Rail Line, *Transportation Research Record 1361, 1992: pp. 197-206*

Summary: Discusses light rail and traffic signal control for intersections with long (110-sec) cycle time. Travel time improvements are possible with sequencing. Confirms other work that suggests on-street segments with traffic control are generally less restrictive of capacity than the signal system used on segregated track sections. For example, two trains platooned through each traffic light cycle provide a throughput of 65 trains an hour—versus the 30 trains per hour of the signaling system and 8 trains an hour limit of the single-track sections.

16 **BURGIN, EDWARD A.**, Light Rail Transit Signaling, *Transportation Research Board Special Report 182, 1978, pp. 119-123*

Summary: Overview of light rail signaling, cab controls and interlockings with breakdown of safety critical areas and non-vital areas. Details Muni's original Market Street light rail subway cab control signaling with the three codes for 16, 43 and 80 km/h and automatic overspeed braking that occurs at 3.2 km/h over the set limit. (This signaling is now being replaced by a moving-block system to increase capacity.)

17 **BUSHELL, CHRIS.**, Jane's Urban Transport Systems, *Jane's Information Group Ltd., UK, 1989*

Summary: A comprehensive reference to rail transit systems.

18 **CALLAN, DENNIS R.,** Toronto Transit Commission's 90 Second Headway Study: Getting More Out of Existing Infrastructure, *APTA Rapid Transit Conference, Vancouver 1990*

Summary: See reviews $^{(R61)}$ and $^{(R68)}$ on which this paper is based.

19 **CANADIAN URBAN TRANSIT ASSOCIATION**, Canadian Transit Handbook, 2nd Edition, Chap. 8—Capacity, *Canadian Urban Transit Association. and the Roads and Transportation Association of Canada, Toronto, 1985*

Summary: This work gives a broad-ranging introduction to the subject of transit capacity. Capacity is cited as being an "*elusive figure*." Both rail and bus modes are covered in easily comprehensible language.

The chapter deals with the following determinants of capacity: loading standards, headways and signaling, dwell times and vehicle performance. The paper closes with a table of design flows for selected transit modes.

Full utilization of capacity is limited to short periods of time. Capacity is an elusive figure which is determined partly by the level of service (speed, degree of crowding) desired. The handbook defines three terms relating to capacity:

- volume = actual flow
- demand = potential flow
- capacity = possible flow

A basic equation for determining capacity is given. Units are passengers per hour.

$$Capacity = Q = fnp = \frac{60np}{h} \tag{1}$$

$$Capacity = Q' = \frac{p\bar{V}n'}{2L} \tag{2}$$

where: h = headway (minutes)
f = frequency (units per hour)
n = number of vehicles per transit unit
p = passengers per vehicle

The author states that capacity is determined by a number of factors which can be readily grouped into categories as follows:

1. **Vehicle Characteristics**
   - fleet size
   - maximum number of vehicles per transit unit
   - vehicle dimensions
   - seating configuration
   - number and location of doors
   - maximum speed
   - acceleration and deceleration rates
2. **Right of Way Characteristics**
   - cross-section design
   - degree of separation from other traffic
   - intersection design (at-grade or separated)
   - horizontal and vertical alignment
3. **Stop Characteristics**
   - stop spacing
   - on-line or off-line (latter allows passing stopped vehicles)
   - fare collection method
   - high- or low-platform loading
   - length of platforms
   - turnaround facilities at terminals
4. **Traffic Characteristics**
   - volume and nature of other traffic (for shared right-of-way)
   - cross-traffic at intersections (at-grade)
5. **Method of Headway Control**
   - type of control separation standards for safety.

The report states that the permissible level of passenger crowding on transit vehicles is an important determinant of capacity. Standing densities of 0.1 m^2 per passenger have been observed in some cities but a value of between 0.2 and 0.7 m^2 per passenger is more typical in North America.

Passenger behavior is also important in determining loading standards as loading in cars and trains tends to be uneven. Allowing passengers to travel between cars through end doors can help even loading on a train. Irregular densities in cars can be caused by passengers congregating around doors, stanchions and the like.

Minimum headway is determined by the degree of separation from other traffic, the method of headway control, and by dwell time effects. Most rail transit modes other than streetcars have "controlled" headways. For streetcars, the maximum frequency is around 120 units per hour in mixed traffic. However, at this frequency the service quality is reduced due to poor service reliability. At such frequencies the traffic lane used by transit essentially becomes a transit-only lane by default. A more realistic maximum frequency would be 60 units per hour in mixed traffic or 75 units per hour on an exclusive right-of-way.

Headways are governed by the type of signaling system. With automatic train operation (ATO), door control and initiation of acceleration remain under manual control. Automatic train control (ATC) fully automates all aspects of train operation and allows full driverless operation with possible throughput increases.

The minimum headway for a block-signaled line can be determined from:

$$h' = T = \frac{L}{V} + \frac{KV}{2d} + \frac{V}{2a} + t$$

where: h' = minimum headway(s)
T = station dwell time (s)
L = train length (m)
V = operating speed (m/s)
d = deceleration (m/s^2)
a = acceleration (m/s^2)
t = reaction time (s)
K = safety factor

A common value of h' for lines signaled for minimum headway is 90 sec. Sustained headways of 120 to 130 sec are more common and allow for peak station delays. Headways of diesel-electric commuter rail service tend to be on the order of 10 to 12 min to allow for grade crossings, longer braking distances and mixed use of the rail line.

Average speed depends upon vehicle characteristics, traffic, stop separation and dwell times. It is given by the following equations:

$$\bar{V} = \frac{S}{T + \frac{S}{V} + \frac{V}{2a} + \frac{V}{2d}}$$

where: S = stop spacing in meters

If S is not constant then:

$$\bar{V} = \frac{L}{\frac{L}{V} + k\left(\frac{V}{2a} + \frac{V}{2d}\right) + \sum_{i=1}^{k} T_i + r}$$

where: k = number of stops
r = terminal time to turnaround (sec)
L = route length (m)

The main vehicle independent factors governing average speed are dwell times and stop separation. For wide stop separation, maximum speed is the most important vehicle characteristic, while acceleration and deceleration rates are more important with narrow stop separation. Acceleration and deceleration values also partly regulate safe following distances. A value of 1.25 m/s^2 is reasonable for these characteristics.

Dwell times are controlled by the following factors:

- number of passengers boarding and alighting
- method of fare collection
- number of loading positions
- high/low level car entry and exit
- door arrangement and number
- seating arrangement

Typical ranges for on-board fare collection, low loading equipment are 2–3 sec per boarding passenger and 1.5–2.5 sec for each alighting passenger.

The chapter closes with a discussion of comparative design flows and a table of capacities for various transit modes. Two key points are that service quality and reliability are compromised at the upper limits of design capacity, and that design flows are generally only reached for short periods. Some sample hourly capacities for the various modes are:

Streetcars, mixed traffic	6,060 ppphd
Streetcars (2 cars) exclusive lanes	15,150 ppphd
Commuter rail, bi-level	13,750 ppphd
LRT, articulated cars	24,300 ppphd
Rail Rapid Transit	43,000 ppphd

Comment: The chapter gives a broad ranging introduction to the subject of transit capacity. It discusses full capacity as limited to short periods of time because of practical peak service considerations. These are covered in considerable detail with regard to vehicle characteristics, right-of-way characteristics, and methods of operational control. In addition, the chapter covers the effect on capacity of passenger loading standards, and on the physical and control limitations on headway for various transit modes. The chapter closes with a comprehensive view of expected capacities for urban transit.

20 **CELNIKER, STEPHEN, and TERRY, E. WAYNE,** Trolley Priority on Signalized Arterials in Downtown San Diego, *Transportation Research Record 1361, 1992: pp. 184-188*

Summary: The trolley priority signaling system in downtown San Diego was altered in 1990 as a result of the original system's inadequacy following increases in San Diego Trolley services. The original pre-emption mechanism gave light rail vehicles full priority at all intersections. With more frequent light rail service, this resulted in excessive delays to pedestrian and vehicular traffic crossing streets used by the light rail. A lack of an allowance for light rail trains traveling in the opposite direction and a tendency to fail further high-lighted the need for improved signaling.

The replacement system integrates light rail operations into the downtown traffic signal progression system. This allows the light rail trains to travel unimpeded from one station to the next in a "green window". In theory, all waiting for signals is done as dwell time at stations. In the morning peak, some trains must leave stations after the "green window" has passed but while the nearest signal is still permissive. This allows the following train to enter the station but results in the first train waiting between stations.

Comment: The installation of an improved trolley priority signaling system has improved light rail travel times in Centre City San Diego. A capacity limitation created by the uni-directional nature of the earlier signal system has been removed.

21 **DELAWARE RIVER PORT AUTHORITY,** 90 Sec Headway Feasibility Study, Lindenwold Line, *Delaware River Port Authority, January 1973*

Summary: To accommodate proposed new branches, methods were examined to decrease headways on the inner (Camden - Philadelphia) portion of the PATCO line to 90 sec. The analysis shows that this headway can be achieved by a combination of adjusting block boundaries and both increasing and reducing speeds — increasing speeds where speed limits (curves) increase the critical station close-in time, reducing those speeds that produce *limiting* safe braking distances.

To mitigate the cost and inconvenience of increased travel time, options were presented to increase the assured braking rate and reduce the braking system reaction time within the capabilities of adhesion and the existing slip-slide detection and control — specifically the overspeed control reaction time — which applies the brakes if the non-vital speed governor fails.

The report states "Braking distance is one of the most important factors in the calculation of minimum headways because it determines minimum safe train separation." A train must always be separated from the train ahead, or end-of-line bumping block, by at least the worst case stopping distance plus safety margins—termed the *safe braking distance*—a function of speeds, curves, grades, braking rate, available adhesion and the reaction times of on-board and wayside train control equipment.

PATCO uses automatic train operation with full automatic driving. On this equipment the worst case reaction time occurs when the speed governor fails just before receiving a lower speed code with the train already close to the overspeed limit. This worst case failure assumes the train is under full power until the vital overspeed protection system intercedes and applies braking. In a worst case, such emergency braking assumes the failure of one set of braking equipment (independent for each truck) on the shortest consist.[1]

A separate analysis examined changes necessary to accommodate 90 sec headways in the downtown turnback. To achieve this involved a combination of reducing the terminal approach speed, relocating the terminal scissors cross-over from behind to in front of the station and extending the tail tracks behind the station.[2] This had the added benefit of decreasing turn-around time, in part compensating for increased running times elsewhere.

The analysis in this report was based, in part, on the separately summarized paper: Weiss, David M., and Fialkoff, David R., *Analytic Approach to Railway Signal Block Design,* Transportation Engineering Journal, February 1974.

Comment: This report provides useful information on providing higher capacity by reducing headways with track circuit-based automatic train operation. The thorough, yet concise, description of *safe braking distance*, and its constituent components, is applicable to many rapid transit systems.

22 DEMERY, LEROY W., Jr., Supply-Side Analysis and Verification of Ridership Forecasts for Mass Transit Capital Projects, *American Planning Association Journal, Summer 1994*

Summary: Demery's paper deals extensively with the difference—and often confusion—between the *demand for* and the *supply of* service on rail transit.

> *. . . peak-period capacity is not an issue in most United States and Canadian cities . . . . . . observed peak-point loads outside New York, Montreal and Toronto are well below the theoretical capacity of the heavy-rail and light-rail modes.*

Four supply-side parameters are defined:

- Peak traffic share (PTS) (passengers per peak-hour direction as a percentage of weekday ridership)
- Vehicles per hour
- Passengers per vehicle
- Average weekday ridership (AWR)

The relationship between these four parameters is expressed as:

$$(AWR) \times (PTS) = (Veh/hr) \times (Pass/veh).$$

Following further discussions of the supply-side, the report details the relationship between average weekday and peak-hour ridership, citing data from many cities to show a North American range of 9 to 24 percent with a mean of 15 percent.

The maximum service that a fixed-guideway transit facility can supply or "field" is stated to be a function of maximum train length and maximum frequency of service, with the former determined by platform length and the latter by the train control system. Other factors are stated to be vehicle performance, maximum speed between stations, average dwell times at stations and other operating considerations.

The report tabulates average peak-hour occupancy derived from data between 1976 and 1990.

City	Passengers/m^2 of Gross Floor Space
New York	2.6 into CBD
Chicago	1.5 into CBD
Philadelphia	1.3 into CBD
Boston	2.0 into CBD
San Francisco	1.2 - 1.9
Washington	0.9 - 2.0
Atlanta	1.4 - 1.6
Toronto	1.8 - 2.4
Montreal	2.6 - 3.2

The report discusses capacity limitations on recent light rail lines as they relate to the signaling system, single track sections and maximum train length.

City	Max. train length	Closest headway
Buffalo	4	5.0 minutes
Pittsburgh	2	3.0 minutes
Portland	2	5.0 minutes
Sacramento	4	15.0 minutes
San Diego[3]	4	7.5 minutes

[3] Demery states the maximum train length in San Diego's Centre City is 3 cars and that the four-car trains have a car added or removed at the 12th and Imperial station. Other sources state that four-car trains are broken into 2 two-car trains to move through city streets.

Demery discusses three reasons why vehicle loadings fall "far short" of the theoretical levels.

- Maximum peak-period demand occurs over intervals of 15 to 20 min (quoted as the "sub-peak" rather than peak-within-the-peak).
- As the number of standing passengers increases, loading and unloading times also increase, extending dwells and reducing schedule adherence.

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[1] Reviewer's Note: The worst case safe braking distance (sometimes called the safety distance) is calculated from the worst case reaction time assuming the heaviest passenger load, plus any possible snow and ice load, tail wind (if any), steepest applicable down grade, adhesion limits, and partial brake system failure. Note that the terminology *worst case* is misleading. The truly worst case would be a total braking failure. In these analyses *worst case* means *reasonable failure situations.* Total brake failure is not regarded as a realistic scenario on modern rail transit.

[2] Reviewer's Note: The report recommended extending the underground tail tracks by 125 ft. The possible alternate of energy absorbing train arrestors was not discussed.

- Outside the largest, most congested urban areas, the level of crowding that transit passengers appear willing to tolerate falls well short of theoretical "design" or "maximum" vehicle capacity.

After brief reference to different vehicle lengths and widths, Demery suggests that, for the purpose of capacity calculations, an upper plausible limit for vehicle occupancy is 150 passengers per car with occupancy higher than 100 unlikely to occur outside, New York, Boston, Montreal and Toronto. "*Long before crowding levels . . . reached New York levels, prospective passengers would choose to travel by a different route, by a different mode, at a different time, or not at all.*"

The report tabulates and compares daily and peak-hour ridership and passengers per vehicle for 19 New York CBD trunks for 1976 and 1991, as abbreviated below:

New York Location	Average passengers per car in peak hour		Change 1976-1991 15 years
	1976	1991	
IRT Lexington Exp.	155	138	-10.97%
IRT Lexington Local	147	112	-23.81%
IRT Lexington JT	132	149	12.88%
IRT Broadway Exp.	152	125	-17.76%
IRT BroadwayLocal	104	95	-8.65%
IRT Broadway CT	98	137	39.80%
IRT Flushing	116	115	-0.86%
IND Queens	200	195	-2.50%
IND 8th Exp.	146	128	-12.33%
IND 8th Local	91	74	-18.68%
IND 8th CT	148	134	-9.46%
IND 6th RT	91	99	8.79%
BMT Astoria	129	108	-16.28%
BMT Canarsie	138	113	-18.12%
BMT Jamaica	103	139	34.95%
BMT Man. Bridge	136	119	-12.50%
BMT Montague	106	101	-4.72%
PATH WTC	79	112	41.77%
PATH 33rd	91	91	0.00%
Average	124.4	120.2	-3.30%
Median	129	115	-10.85%

The report then makes a case that ridership forecasts are prepared with little or no reference to supply-side parameters and that ridership will be below forecast when the delivered service frequency is below initial plans — often because too few cars were purchased or there are inadequate operating funds — or the line was not designed or signaled to accommodate the frequencies used in initial forecasts.

Ridership figures can be misleading in cities with free downtown zones. In Pittsburgh 20% of use is short trips in the free zone.[4]

Ridership can increase without additional peak-hour supply due to spreading periods of peak demand, a rise in off-peak and reverse-peak use, and/or a willingness of passengers (and prospective passengers) to tolerate higher levels of crowding.

The report states that effective capacity — or likely maximum ridership — falls well below the routinely quoted capacity figures such as 30,000 to 50,000 passengers per peak hour direction for heavy rail and 10,000 to 30,000 for light rail. It also says rail transit ridership stabilizes when peak-period vehicle occupancy reaches the point where prospective riders are no longer willing to board — often at a point well below that implied by the phrase "full standing load".

Comment: The gist of Leroy Demery's recent report deals with the relationship between the *demand for* and the *supply of* service on rail transit and is not relevant to this study. However there are numerous useful insights on the issue of capacity. One is the caution with respect to ridership data from the four light rail systems that have CBD free zones. Another is the relatively low average loading density in the peak hour on all US and Canadian systems in the range of 0.9 to 3.7 passengers per m^2 with the highest outside New York, Boston, Toronto and Montreal being 2.3 passengers/m^2.

The tabulation of average peak hour loadings per vehicle in New York in 1976 and 1991 shows an 11 per cent decline in the median over 15 years. Despite a few lines showing increases, many others — deemed, now and then, to be saturated or at capacity — have lower loading densities. This would suggest an expectation of better standards and Demery comments clearly that new rail transit systems in cities with palatable transport alternatives will not achieve these densities — and if they reduce service levels to increase vehicle loadings, as appears to be the case on several systems, then riders will go elsewhere.

This suggestion has significant implications for a study of future capacity based on existing and past ridership.

23 ENVIRODYNE ENGINEERS, INC., Metro-North Speed and Capacity Improvement Study. Tasks 1 to 5 *US Department of Transportation, Urban Mass Transportation Administration, 1989*

Summary: The volumes in this series summarize the major locations on the Metro-North rail system where capacity is constrained. The key limitations include the following: interlocking locations and layout, lack of grade-separation at junctions, inadequate number of tracks, and short platform lengths. The Port Jervis line faces an additional problem of competition with freight trains for track access.

The capacity at each of the locations studied is given in combinations of the number of express and local trains which could be operated given current and future conditions. Generally, express operations allow a higher throughput of trains since there are no station stops during which time the track is occupied. A particular problem is in finding pathways for local trains which stop in more than one of the express zones as the current track configuration is often not designed for this. The provision of more local trains between zones is necessitated by the growing suburb to suburb travel market.

Comments These reports outline specific instances of many of the general capacity constraints faced by commuter rail operators. An emphasis on conclusions reached, rather than the

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[4] Reviewer's Note: The percentage is lower in Pittsburgh and Portland and higher in Calgary (30%).

simulation methodology used, restricts the usefulness of these studies for general application.

24 EUROPEAN CONFERENCE OF MINISTERS OF TRANSPORT, Report of the 38th Round Table on Transport Economics - Scope for the Use of Certain Old-Established Urban Trans. Techniques, *Transport Capacity, OECD, Paris, 1979, pp. 24-25*

Summary: Provides a European aspect to capacity with the following list for maximum capacity by mode:

Mode	Trains/hour	Passengers/ hour/direction
Metro (heavy rail)	40	40,000
Expres stram (light rail)	46	21,000
Tram (streetcar)	54	12,500

Comment: The passenger capacity figures can be misleading because they do not indicate consistent length or loading density. The maximum number of trains per hour reflects European practice and is higher than similar North American data.

25 FOX, GERALD D., Light Rail/Traffic Interface In Portland: The First Five Years, *Transportation Research Record 1361, 1992: pp. 176-183*

Summary: Fox summarizes the use of railway crossing gates, traffic signals and stop signs to control grade-crossings on Tri-Met's 24.3 km light rail line in Portland. Signaling of the line is also dealt with peripherally. The majority of the line is operated on sight with 11.3 km of private right-of-way being governed by automatic block signals (ABS).

A description of traffic signal pre-emption techniques is given, ranging from wayside push-buttons to the Philips Vetag inductive loop system. Installation of the latter system allowed the addition of two intermediate stations to the line while maintaining the same overall travel time.

The principal traffic control lessons learned from Tri-Met's initial light rail line are:

- Use conventional traffic signal equipment for public familiarity and ease of maintenance.
- Do not give motorists more information than they need because it only causes them confusion.
- Controlling traffic movements is generally more effective than prohibiting them. Motorists tend to ignore prohibitions but are more receptive to controls.
- Light rail construction often involves lengthy street closures which alter traffic flows. Such adjustments in traffic flow can continue after construction is complete, so reducing conflicts between light rail and vehicular traffic.

Comment: This paper updates previous work by the author on this subject with practical experience gained from five years of operation. It addresses a number of ways of reducing light rail travel time through traffic signal pre-emption and shows that with careful traffic engineering neither road not light rail capacity is reduced by the grade crossings—at the headways and specific circumstances of the Portland system.

26 GILL, D.C., and GOODMAN C.J., Computer-based optimisation techniques for mass transit railway signalling design, *IEE Proceedings-B, Vol. 139, No. 3, May 1992*

Summary: This recent British paper compares and presents analytic treatment of the capacity of fixed-block, multi-aspect cab control and transmission based train control systems before suggesting that the many nuances are beyond analytic methods and require computer simulation.

The authors state that, in addition to the major headway components of station close-in time plus station dwell, a margin must be added to allow for small delays and variations in train performance. They suggest an allowance of 15-20 sec and use the term *minimum service headway* when this margin is included, or *signal headway*[5] when it is not.

Increases in line capacity require either increases in train length or increases in positional resolution by creating shorter block sections, possibly with an increase in either the number of visual aspects or the number of automatic train protection codes—or the introduction of a moving-block signaling system.

Theoretical minimum headway (between stations), H, is defined as:

$$H = \frac{v}{2b} + \frac{l}{v}$$

where v = velocity
b = deceleration
l = train length

Maximum train frequency, F, is 3600/H, setting dF/dv to zero produces the speed (v_{op}) for the closest headway)

$$v_{op} = \sqrt{(2bl)}$$

As capacity is proportional to train length and inversely proportional to headway—itself a function of train length, the above equations can be merged to show that *capacity is a function of the square root of train length.*

At the optimal running speeds in the above figure, train frequencies range from 150 to 260 per hour without station stops or with off-line stations. With station stops the typical maximum practical train throughput is a much reduced 20 to 30 trains per hour. As these high throughputs (between stations) are not required, block lengths can be extended away from stations with considerable cost saving and no impact on throughput.

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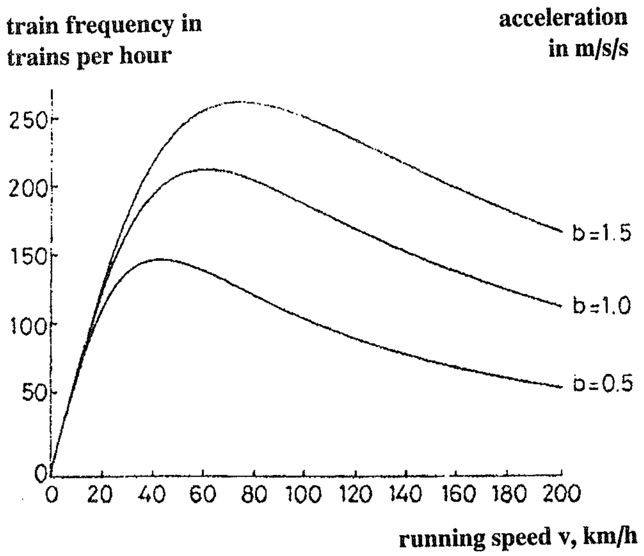
[5] Reviewer's Note: CAUTION. Other authors rarely include station dwell in the definition of signal headway.



On conventional rail transit systems with stations theoretical headway calculations must take into account the time a train takes to decelerate from line speed, stop at the platform and accelerate out. With simplifying assumptions, Bergmann[6] shows that the theoretical minimum headway $H_{\min}$ is given by:

$$H_{\min} = \frac{v_m}{b} + t_r + t_w + \sqrt{\left(\frac{2l}{a}\right)}$$

where v_m = maximum velocity
t_r = ATO equipment response delay
t_w = station dwell time
a = acceleration
b = deceleration
l = train length

Under typical rail transit conditions, with a 140 m (460 ft) train and a 30-sec dwell, this equation gives a minimum headway of 70-sec plus any operational margin.

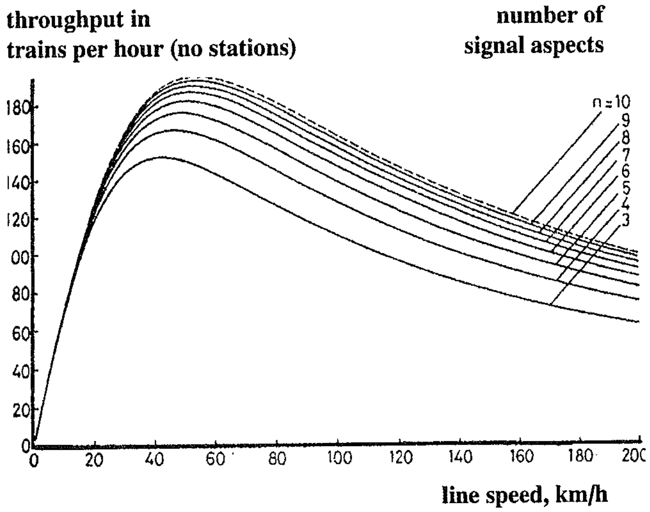
Bergmann also derives the optimal line speed for maximum throughput as:

$$V_{op} = \sqrt{\frac{2ab_s b_e l}{ab_s + ab_e + b_s b_e}}$$

where b_s = minimum service deceleration
b_e = inimum emergency deceleration

Under typical rail transit conditions this equation gives an optimal line speed of 37 km/h. The authors specifically note that this is the station approach speed and does not preclude higher inter-station speeds.

The paper then analyzes the improvements in headways which are possible by increasing the number of visual signalling aspects or the number of automatic train protection codes. The results, shown below, support their conclusion of diminishing returns and indicate the optimum line speed approaching a station of approximately 40 km/h.



The paper then adjusts Bergmann's work to add allowances for jerk limits into and out of acceleration and deceleration, grades and curves—specifically in station approaches and safety distance adjustments. The equations are complex and still require assumptions for train control and vehicle equipment response or reaction time, driver reaction time (if any) station dwell time, an operations allowance or margin, reduction in the nominal acceleration rate as speed increases and fluctuations in traction power voltage (and hence train performance) as trains accelerate in each specific supply section.

Recommendations are made that computer simulation is the preferred approach, combining a train performance program with a signal layout design program. To compensate for such refinements as traction voltage fluctuation and jerk, such programs should be run at increments of 0.1 sec. The paper points out that programs do not necessarily take coasting into account.[7]

The results of such computer simulations are provided for the following typical rail transit conditions:

train length	140 m (460 ft)
maximum speed	80 km/h (50 mph)
aspects	4
reference speeds	80.0, 69.5, 53.3, 0.0 km/h
service braking	1.0 m/s/s (m/s^2)
emergency braking	1.3 m/s/s (m/s^2)
minimum jerk rate	0.75 m/s/s/s (m/s^3)

The resulting minimum headway was 74.8 sec plus dwell time and an operational allowance. A 30-sec dwell and a 15-sec operational allowance would produce a headway of 120 sec. The programs were run for a moving-block signaling system under the same conditions. The close-in headway was reduced to 43.9 sec, producing a minimum headway of 89 sec—leading to the

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[6] BERGMANN, D.R.: *Generalized expressions for the minimum time interval between consecutive arrivals at an idealized railway station. Transportation Research 1972, Vol. 6, pp. 327-341.*

[7] Reviewers Note. Coasting is a period when neither power nor braking is applied. It is required by some operators as an energy conserving measure and is often omitted in peak periods when the maximum system performance is required. While coasting increases running time between stations—and hence decreases system capacity with a given vehicle fleet size—it should not affect the *minimum service headway* (other than by causing minor increases in supply voltage).

conclusion that, under typical conditions, a moving-block signaling system can increase line capacity by 33%.

Comment: Gill and Goodman's lengthy paper provides the most detailed analysis of train control system throughput in the reviewed literature. Despite the analysis accommodating nuances such as jerk and multiple equipment and driver reaction times, ignored in most other work, there are still many variables that are best accommodated by computer simulation.

The initial analyses of throughput without station stops appear somewhat academic but allow the determination of any inter station speed controls or speed limits. Such restrictions may reduce throughput with stations only if they reduce the station approach speed below the optimum 37 km/h (23 mph). Otherwise inter station speed controls or speed limits only reduce running times and impose the economic penalty of requiring additional vehicles to serve a given passenger demand.

The results show *minimum service headways* that are longer than most other work reviewed, even with station dwells only estimated. The comparison of conventional multiple aspect signaling systems and moving-block signaling systems is valuable.

27 **GRAHAM, IAN R.,** Optimizing Headways on an Automated Rapid Transit System: The SkyTrain Experience, *American Public Transit Association, Rapid Transit Conference, Vancouver, B.C., 1990*

Summary: Describes how the use of moving block train control with sophisticated Automatic Train Supervision allows close matching of supply to demand by varying headways second by second through each peak period.

Comment: Provides useful information on the relationship of peak-within-the peak to average peak-hour demand. Data show the loading standard difference between normal operation and after delays where standing passenger density increases from a mean of 2.8 per m^2 to 5 per m^2.

28 **GRAY, GEORGE E.,** and HOEL, LESTER A., Public Transportation Planning, Operations and Management, *Prentice-Hall Inc., 1979*

Summary: Comprehensive transit textbook with chapters by individual authors.

Professor Vukan Vuchic's Chapter 4 defines transit modes and various terms, offering the following capacity ranges.

Mode	passengers per peak hour direction
Light Rail	6,000 - 20,000
Rapid Transit	10,000 - 40,000
Regional Rail	8,000 - 35,000

William Vigrass in Chapter 5 cites planned and actual maximum capacities for selected examples. Muni's light rail metro is designed for 9,000 passengers per peak-hour direction. The NYCTA sets crush loading standards at 255 passenger per 18 m car—a density of 5 per m^2. This makes the maximum capacity of a ten-car train on a single track—with a signaling throughput of 30 trains an hour—some 76,500 passengers per peak hour direction. Such a capacity is not realistic, however, as it is based on the crush capacity of the cars.

John Fruin in Chapter 10 shows that the shoulders of the 95th percentile male occupy 0.14 m^2, and that unavoidable contact between standees occurs at a space occupancy of 0.26 m^2. Space requirements in free standing lines or platform waiting areas are 0.5 to 1.0 m^2 per person.

Comment: Fruin's work is valuable in discussing the preferred and minimum space per standing and per waiting passenger.

29 **HOMBURGER, WOLFGANG S.,** Urban Mass Transit Planning, *The Institute of Transportation and Traffic Engineering, Univ. of California, 1967*

Summary: A comprehensive course text with examples of actual rail system capacities. Useful table, albeit with out-dated data, of peak-within-the-peak relationships (data from various sources).

Location	Trains/ hour	15-20 min rate	Full hour	% short term over full hour
IND Queens	32	71,790	61,400	+17%
IND 8th Av. Ex.	30	69,570	62,030	+12%
IRT Lexington. Av.	31	50,700	44,570	+14%
IRT Express.	—	38,520	36,770	+5%
TTC Yonge	28	39,850	35,166	+13%
Chicago	—	14,542	10,376	+40%

Comment: The ratio of peak hour to peak-within-the-peak capacity is an important part of TCRP A-8's approach to Rail Transit Capacity. The above table has been extended, recompiled with current data, and disaggregated by mode in the study—which designates this ratio as the *first level of diversity.*

30 **JACOBS, MICHAEL., SKINNER, ROBERT E.,** and **LERNER, ANDREW C.,** Transit Project Planning Guidance—Estimate of Transit Supply Parameters, *Transportation Systems Center, US Department of Transportation, Oct. 1984*

Summary: Chapter 4 deals with the estimation of capacities, with many data from sources referenced elsewhere in this study. The chapter cites level-loading doorway flow at 1.5 to 2.0 sec per person per door lane with low-loading light rail increasing to 1.5 to 2.5 sec per person per door lane unloading and 2.0 to 8.0 sec per person per door lane boarding—the higher figures relating to train operator fare collection.

The following factors in train headway are listed:

- braking rate (with adjustment for any grade)
- maximum speed
- train length
- block length
- train control delays
- type of signaling
- dwell times

North American platform lengths ranged from 70 to 213 m. The closest European light rail headways at low speeds is quoted in the range of 37 to 58 sec, North American range is quoted at 90 to 120 sec with the possibility of down to 40 sec.

A comprehensive section on vehicle space per passenger suggests that gross vehicle area is the most practical data to use. While 53% of U.S. rapid transit lines enjoyed rush hour loadings of 0.5 m^2 per passenger or better, the following data were offered. (compiled from two separate tables from different sources, average of 58 routes):

Criteria	Passenger/area	Mean
Max. practical (NY)	6.0 /m^2	6.0
Typical rapid transit	2.2 - 3.6 /m^2	2.9
Crush rapid transit	2.6 - 5.4 /m^2	3.8
Design rapid transit	1.4 - 4.0 /m^2	2.6
Design light rail	2.3 - 4.0 /m^2	3.3
Actual light rail	2.9 - 5.7 /m^2	4.0
To avoid contact	3.8 - 4.5 /m^2	4.1
Unconstrained	1.2 - 2.7 /m^2	2.0

The report is one of the few to discuss the diversity of standing densities within a car—higher in doorways/vestibules, lower in aisles and at car ends (unless the car has end doors). The report includes extensive references, tables of data and a glossary.

Comment: As one of the most comprehensive compilations of loading standards, this has been useful to the project.

31 **JANELLE, A., POLIS, M.P.,** Interactive Hybrid Computer Design of a Signaling System for a Metro Network: *IEEE Transactions on Systems, Man and Cybernetics, 1980*

This comprehensive computer modeling approach looks at how to obtain the maximum train throughput in designing a three-aspect signaling system for rapid transit. Although specific to Montreal's rubber tired Metro, the approach is adaptable to any three-aspect signaling system.

The model makes use of the repetitive nature of rapid transit operations and assumes Automatic Train Operation that regulates speed and controls station stopping. Block ends are assumed fixed at station platform ends and interlockings, and a train separation of two blocks is maintained at all times. The model adjusts other block lengths to maximize throughput using the following relationship among travel time, block length and capacity.

The basic modeling equation is:

$$T_j = T(x_{j+3} - TL_{\max}) - T(x_j)$$

with the constraint

$$T_j \leq T_D \text{ for all } j$$

where: j = block number
T_i = block cycle time
x_i = block length of controlling joint
x_{i+3} = block length of controlled joint (3 blocks downstream from the controlling joint)
$T_{\max}$ = maximum train length
T_D = desired headway (less dwell)

The model showed that the block lengths could be defined for nine car trains (162 m) to permit a headway of 83 sec, plus station dwell of 37 sec, for the design total of 120 sec, this is down from the initial Montreal design standard of 150 sec.

Comment: An interesting and comprehensive approach to optimizing the throughput of a conventional three-aspect signaling system without overlays.

32 **KLOPOTOV, K.,** Improving the Capacity of Metropolitan Railways *UITP, 40th International Congress, The Hague, 1973*

Summary: Klopotov's report is derived from questionnaires sent to 38 international rapid transit systems, three-quarters of which stated they were working to increase capacity.

The percentage of peak-hour passengers that are seated ranges from 12.5% in Tokyo to 70% in Liverpool (PATH 30%, SEPTA 55%). (Systems with a 100% seated policy are excluded.) Average peak-hour loading density varies widely:

Group	pass/m^2
Some European and most North American	2.0 - 3.0
Some European systems and New York	3.1 - 5.0
Most European large cities	5.1 - 6.0
Large Soviet and Japanese systems	7.1 - 8.0

Controlling station dwell to increase capacity shows that 54% of the systems surveyed have four double doors per car side, each in the range of 1.2 to 1.4-m wide with the great majority close to 1.4 m. Door opening and closing times range from 1.0 to 4.5 sec with most in the 2- to 3-sec range. Brief mention is made of the Paris Metro's dwell control method of closing off platform entry as a train approaches and Copenhagen's method which is to start opening the doors before a train has come to a full stop.

A common dwell reduction feature is doorway setbacks so that standing passengers do not block the flow. 71% of surveyed systems had setbacks of 200 mm or more.

Most systems had sustained peak-hour headways at or greater than 120 sec with the exception of Tokyo (110 sec), Leningrad and Philadelphia Market-Frankford (105 sec), Paris (95 sec), PATH (90 sec) and Moscow (80 sec) The latter required an expensive move from a two- or three- aspect to four-aspect signaling system.

Methods employed or planned to increase capacity ranged from decreasing seating space to removing cabs from all but the end cars, with the most common approach being new or improved signaling to reduce headways.

Signaling changes including adding automatic train operation and automatic train supervision, using more realistic safety distances, adjusting block lengths or adding blocks. Where station capacity was a limitation, improvements were suggested to increase passenger flow to and from platforms. These included separating entry and exit flows and operating escalators at higher speeds. While most escalators in the United States run at 0.46 m/s, 0.6 to 0.75 m/s is used occasionally in Canada and frequently in Europe with certain former Soviet bloc cities doubling flows with speeds of 0.75 to 0.9 m/s.

Comment: Although outdated, this report presents comprehensive information on rail transit capacity, unfortunately diminished by the poor translation and editing from Russian. Russian and Japanese rapid transit systems achieve the highest capacity in the world by a combination of very close headways and high densities of standing passengers.

Several countries show that close headways can be operated reliably and (when adjusted for North American loading levels) provide an upper limit to rapid transit capacity.

33 **KOFFMAN, D., RHYNER, G.** and **TREXLER, R.,** Self-service Fare Collection on the San Diego Trolley, *US Department of Transportation, 1984*

Summary: Chapter 3—*Transit Operations* provides a comparison of dwell times between light rail in San Diego and Boston. In both cities observers with stop watches rode the light rail lines counting and timing passengers entering and leaving each car, along with the number of passengers remaining on-board. Data was collected at all stations in San Diego and in three sets for Boston: fare free (station collection) zones (two routes) and inbound cars with train operator fare collection.

The model used multiple regression analysis with loading time (dwell time) as the dependent variable and total on, total off, total on-board as the independent variables. (The San Diego model included zero-one variables to represent whether there was any boarding or alighting activity at a stop.) The coefficients of these variables include the extra time needed in San Diego for the first boarding or alighting passenger who operate the doors themselves. (Similar variables were tested in Boston but, as could be expected, performed poorly).

After testing a variety of variables, including various powers, exponentials, logarithms and interaction terms, a linear model produced the best results. The only non-linear terms which improved any models were the squares of ons and offs in San Diego. These made "only a minor improvement and were not used as they have no physical interpretation, may be due to errors in the data collection process and make the comparison between the two cities difficult."

The result was a two part loading model with one linear relationship for passengers movements from zero to one and another linear relationship for all passengers movements above one.

Only the San Diego model results are shown below.

San Diego	Intercept	Any Ons	Any Offs	Tot.Ons
Coefficient	8.14	1.91	1.12	0.67
Std. Error	(.54)	(,43)	(.45)	(.04)
Student's t	(15.0)	(4.4)	(2.5)	(17.4)
Prob (coeff=0)	<.0001			

	Total Offs	On-Board	R^2	Std. Err.
Coefficient	0.59	0.034	.43	5.4
Std. Error	(.04)	(.007)		
Student's t	(14.9)	(4.8)		
Prob. (coeff=0)	<.0001			

Note that data is excluded from terminal stations and train operator relief points, dwell times are from first door open to last door shut and excludes time when the door is open without any passenger activity.

Finally, a composite model was developed using the constant and zero-one coefficients from the San Diego model and the remaining coefficients from the Boston inbound model.

Loading Time = 7.76 + (1.91) (Any Ons):
+ (1.12) (Any Offs):
+ (3.12) (Cash Ons):
+ (1.94) (Non-cash Ons):
+ (1.61) (Offs):
+ (0.87) (Passengers on-board):

The 95% confidence interval is ± 2 sec, computed from the estimated variances and co-variance's in each component model. The report shows that without self-service fare collection the San Diego running times would increase from the then 42 min, to 47 to 48 min.

Comment: Chapter 3 provides a comparison of loading times between San Diego MTDB's self-service fare collection system and that part of the MBTA's Green Line where on-board train operator collection is used. The methodology and data provide useful information for use in estimating light rail station dwells with low loading.

34 **KORVE, HANS W.** and **WRIGHT, PATRICK M.,** New Standards for Control of At-Grade Light Rail Transit Crossings, *Transportation Research Record 1361, 1992: pp. 217-223*

Summary: There is very little consistency of traffic control devices used on American light rail lines. Variation can be found not only between, but also within systems. Korve and Wright outline the need for an American standard system of traffic control devices and the efforts of an Institute of Transportation Engineers committee to create such a standard.

35 KORVE, HANS W. Traffic Engineering for Light Rail Transit, *Transportation Research Board Special Report 182, 1978, pp. 107-114*

Summary: Korve provides an alternative definition of light rail and shows that light rail road crossings can be separated in space or time, detailing control options for the latter.

Stop signs are acceptable for grade crossings with traffic < 5,000 vehicles/day and light rail > every 5 min. Total preemption is feasible down to 2-min light rail headways with multiphase traffic signals and cross-traffic as high as 25,000 vehicles/day. On inter-connected traffic signals, progression can be adjusted to favor light rail. Where possible, light rail stop placement can be arranged to enhance progression speed.

The report contains acceleration and braking curves for modern light rail vehicles and shows various methods to accommodate traffic turning left across median light rail tracks.

Comment: The report shows that light rail grade crossings should rarely impact line capacity as good engineering can ensure that a train can move through a grade crossing on each light cycle—and, in certain circumstances (limited train length), a platoon of two trains per cycle. This condition permits a throughput of 60 to 120 trains per hour, well beyond the capacity of any signaling system on other sections of a typical light rail line.

However, such throughput will impose delays which can be minimized (or eliminated) with properly timed progression and coordinated station placement—but only in one direction. Progression timing can be adjusted to favor the peak direction.

36 KRAFT, W. H., and BERGEN, T. F., Evaluation of Passenger Service Times for Street Transit Systems. *Transportation Research Record 505, Transportation Research Board, Washington DC 1974*

Summary: Kraft analyzed 1500 entry and exit observations to derive an expression for passenger loading times, using the method of least squares. All were on surface vehicles, disaggregated by type of fare payment, time of day and by the following types of flow.

- all passengers boarding
- all passengers alighting
- mixed flows

The results show linear relationships with distinct differences for elderly, handicapped and commuter passengers. Off-peak passenger times were more leisurely. The applicable results for low-loading streetcar (light rail) with exact fare, and double-doors were:

Boarding Only Time = 3.4 + 0.9(ons)
Data sets = 7
Coefficient of Determination = 0.64
Standard error of estimate = 0.90

Boarding and Alighting Time = -4.0 + 2.0(ons)
$1 \leq \text{(offs)} \leq 8$ and $6 \leq \text{(ons)} \leq 13$
Data sets = 5
Coefficient of Determination = 0.94
Standard error of estimate = 1.50

Comment: The wide variation in results from city to city, vehicle to vehicle and mode to mode suggest caution in developing a general equation for dwell times. Kraft comments that platform congestion could increase alighting times but provides no data to substantiate this.

There are several deficiencies in this report which has been quoted in several other papers. As such, the report is of little value to the study other than to suggest caution in system to system comparisons.

37 KUAH, GEOK K. and ALLEN, JEFFREY B., Designing At-Grade LRT Progression: Proposed Baltimore Central Light Rail, *Transportation Research Record 1361, 1992: pp. 207-216*

Summary: Kuah and Allen analyze the effect of modifying the traffic signal progression in downtown Baltimore to allow the light rail service on Howard Street to benefit from progressive signaling. Computer modeling of the proposed changes shows a 10% increase in downtown traffic flows.

Comment: The paper does not directly address capacity but does provide information on the related issue of light rail signaling on city streets. It is interesting that the current signaling is not mentioned as a capacity limitation.

38 KYOSAN ELECTRIC MFG. CO., LTD. Total Traffic Control System—TTC, *Yokohama, Japan, 1986*

Summary: Many Japanese electric railways, typically a cross between rapid transit and commuter rail, operate intensive service. This report describes the track layout, signaling system and operations of one of the busy two-track lines in the suburbs of Tokyo.

The Keio Teoto Electric Railway has a two-track main line between Keio-Hachioji and Shunjuku. Four branches merge into this line and many trains continue through into central Tokyo via joint running with the subway system. There are 49 stations and a total of 63 route kilometers.

The Keio Teoto Electric Railway operates 30 trains in the peak hour over a single track, combining four levels of express, semi-express and local service. This frequency is made possible by four platform and off-line platform stations, where faster trains pass local trains, and an Automatic Train Supervision system. The signaling system is a relatively conventional three-aspect block system.

Comment: This manufacturer's description shows how commuter rail capacity can be increased with multi-track stations, precision operation and the assistance of a computerized automatic train supervision system.

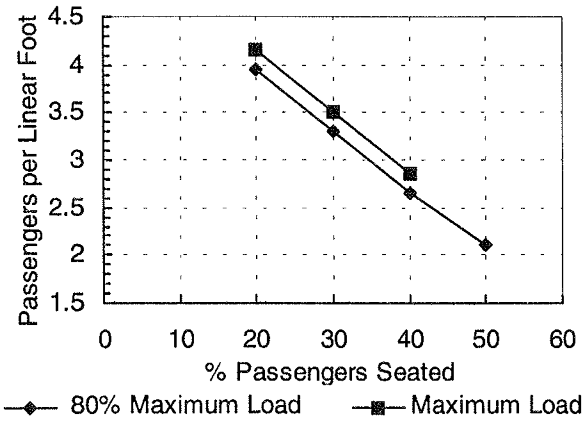
39 LANG, A SCHEFFER, and SOBERMAN, RICHARD M., Urban Rail Transit: Its Economics and Technology, *MIT Press, 1964*

Summary: Lang and Soberman's book on rail transit economics and technology is reportedly the first since Dooliitle's treatise of 1916. Three sections relate to the A-8 rail transit capacity project.

Parts of Chapter Three, Stations, deal with the interaction of train and station design with dwell times. Loading time is dependent on the distribution of passengers along the platform, the ratio of total door width to car length and the number of boarding passengers. Obtaining a uniform distribution of passengers along the platform is desirable but difficult, particularly so when crowded platforms impede flows in the rush hour.

Sufficient entries and exits to adequately sized platforms are necessary and must be evenly spaced for best distribution. Passageway flow rates of up to 100 passengers per minutes per meter of width are quoted (30 per minute per foot). Downward stairs reduce this flow by some 25%, upward stairs by 40%. These flow rates diminish when crowding exceeds 4 persons per square meter (0.4 square feet per person).

In Chapter Four, Rail Transit Vehicles, Section 4.5 Car Capacity and Dimensions discusses seating provision relative to compromises between capacity and comfort. Suggesting that all rapid transit cars are substantially similar in width, the report equates passengers per square foot versus the percentage seated. This ranges from 0.3 passengers per square foot with 50% seated to 0.6 passengers per square foot with 15% seated. This is then translated into passengers per Linear Foot of Train, as shown below. The maximum vehicle capacity is 4 passengers per linear foot—approximately 2.5 square feet per passenger.



The authors also discuss the importance of ease of ingress and egress, recommending minimum distances between seats and doorways and discouraging three abreast seating. Comfort levels are discussed relative to smoothness of operation and the issue of supply and demand. Where systems are oversubscribed and few attractive alternate forms of transportation are available, high levels of crowding will be tolerated. Where systems wish to attract passengers, higher comfort levels, i.e., less crowding, are desirable.

Chapter Five of this text deals entirely with capacity. Capacity is calculated as the number of trains per hour multiplied by train length and the passengers per linear foot from the above graph. Using the mathematics of Appendix A the minimum headway is expressed as:

$$h = T + \frac{L}{V} + \frac{V}{2a} + \frac{5.05V}{2d}$$

where h = headway (s)
L = total train length (ft)
T = station stop time (s)
V = maximum train speed[8] (ft/s)
a = rate of acceleration (ft/s^2)
d = rate of deceleration (ft/s^2)

Applying this equation at a maximum approach (close-in) speed of 32 km/h (20 mph) and a dwell of 40 sec produces the following optimum headways for different train lengths, and capacity in passengers per peak-hour direction. These use a vehicle loading of 3.1 passengers per linear foot with average acceleration (a) of 3.0 mph/s (1.33 m/s^2) or 2.0 mph/s (0.89 m/s^2)

Train Length (m/ft)	120/400	150/500	180/600
Minimum Headway	75 secs	79 secs	83 secs
Capacity (a=3.0)	60,600	72,400	83,200
Capacity (a=2.0)	44,600	55,100	65,000

Appendix A, Some Considerations of Minimum Headway, develops the above minimum headways with equations for wayside signals and theoretical minimum headways and minimum headways with automation.

The theoretical minimum headway is expressed as

$$h = T + 2\sqrt{\frac{L}{a}}$$

The minimum headway with cab signals, assuming the following train stops behind the preceding train before entering the station is

$$h = T + 2\sqrt{\frac{L + s}{a}} + r$$

For a completely automated system

$$h = T + 2\sqrt{\frac{L}{a}} + c$$

where h = headway (s)
L = total train length (ft)
T = station stop time (s)
a = rate of acceleration (ft/s^2)
s = safety distance (ft)
r = operator reaction time (s)
c = communication time (s)

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[8] Reviewer's Note: The maximum train speed, in feet per second, is the maximum speed in the final approach to the station—not the maximum speed between stations.

Comment: In one of the earliest modern texts on rail transit Lang and Soberman have provided a succinct yet thorough outline of capacity issues. Their calculations, regarded by the authors as conservative, tend to show passenger volumes higher than would be regarded as practical—due to their use of dwell times of 30 to 40 sec—which do not take into account an allowance for irregular running.

40 **LEVINSON, HERBERT S.,** and **HOEY, WILLIAM E.** Some Reflections on Transit Capacity *Proceedings of the International Symposium on Highway Capacity, Karlsruhe, July 1991*

Summary: The authors comment that "transit capacity is far more complex than highway capacity." They show that train headway is the sum of dwell time plus the reaction time, braking time, acceleration time and time to clear the station.

They caution that *"because actual capacities may vary in a way that cannot actually be described in a formula . . . capacities obtained by analytical methods must be cross-checked against operating experience. . ."*

The study cites the historic high train throughput on the Chicago Loop with visual rules (70 trains per hour) versus the maximum NYCTA throughput on a three-aspect signaling system of 35 trains per hour, achieved by use of "key-by" procedures. Similar historic experience has shown streetcar throughput on a single track of up to 145 cars per hour.

The same general (transit, all modes) capacity formula is shown as in the ITE *Transportation Planning Handbook* below.

Comment: A useful general paper which repeats the cautions necessary in an analytic approach.

41 **LEVINSON, HERBERT S.,** Capacity Concepts for Street-Running Light Rail Transit, *Australian Road Capacity Conference 1994*

Summary: The report compares historic streetcar service capacities of up to 150 cars per track per hour with current services that reach 96 cars per track per hour (Hong Kong) and a passenger volume up to 8,500 passengers per peak hour direction (Calgary).

On-street light rail capacity is related to the loading and unloading times at the busiest stop, train length and traffic signal cycles. Train length is limited to the shortest city block. Dwell time is related to the loading level (platform height) and fare collection system.

Basic capacity is defined with a simplified version of the formula in the same author's *Chapter 12 Capacity in Transportation Planning,* of the *Transportation Planning Handbook.*

The formula for trains per hour per direction with signalized intersections is given as:

$$C_p = \frac{(g/C)\cdot 3{,}600R}{(g/C)D + t_c}$$

where: C_p = trains per hour per track

tc = clearance 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 length 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 variables 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, sec, reflecting the reductive effects of on-street parking and pedestrian movements as well as any impacts of pre-emption

c = cycle length, sec

Passenger spaces per car, needed in this equation to determine capacity, are suggested at an occupancy level of two passengers per m^2, compared with a crush load of 4 per m^2.

The results quote a maximum capacity of 40 to 45 trains per track per hour at level of service "E,"[9] reducing to 36 to 40 trains when variations in arrival and dwell times are considered—equivalent to 10,000 to 13,500 passengers per peak-hour direction with trains 46 to 69 m long.

System planning based on level of service "D" is recommended. The following table extract shows light rail capacities in trains per track per hour at level of service "D", with 23-m long cars, a typical 50% green cycle ratio, an R of 0.80, a station clearance time of 5 sec per 25 m of train, and a further reduction to 80% of maximum capacity.

Dwell Time	1 car	2 car	3 car	4 car
20 secs	48	41	36	32
30 secs	41	36	32	29
40 secs	36	32	29	26
50 secs	32	29	26	24
60 secs	29	26	24	22

Mention is made of the possibility that two single-car trains may be able to berth in a station simultaneously—doubling the capacity. Train spill back[10] is discussed and two recommendations made:

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[9] Levinson, Herbert S, Chapter 12 Urban Mass Transit Systems, Transportation Planning Handbook,

[10] Failure of a train to clear an intersection within the green cycle.

- The length of trains should not exceed the street block length.
- There should be no more that one train every other block to reflect variations in arrival and dwell times, suggesting that there should not be more than one train every other signal cycle where blocks are less than 122 m.

These recommendations result in a design capacity of 30 trains per hour for 60-sec cycles, reducing to 20 for 90-sec cycles and 15 for 120-sec cycles. The equivalent capacity, based on a 30-sec dwell time, ranges from 4,500 to 10,000 passengers per peak-hour direction for two-car trains to 6,000 to 13,500 for three-car trains.

The report concludes with a list of useful planning guidelines.

- dwell times should be minimized by using cars with high platforms or low floors, multiple doors and fare pre-payment.
- Green time for trains should be maximized.
- Exclusive lanes should be provided
- Routing patterns should minimize the number of on-street turns
- Central area junctions should be kept to a minimum.

Comment: This recent paper adds to the substantial transit capacity work by author Levinson with information on light rail on-street operation. It contributes useful information to the study.

The "one train every two light cycles" provides a basis for the "simple" capacity calculations and conveniently coincides with the typical maximum frequency on signaled segregated track of 30 trains per hour—although several new U.S. light rail lines are only signaled for 17 trains per hour. (3.5-min headways). The spill back situation has been investigated in the study and the more detailed calculations can be used to help determine dwell times and to analyze junction clearance and turnback times.

42 LEVINSON, HERBERT S., Chapter 5 Urban Mass Transit Systems, *Transportation Planning Handbook, Institute of Transportation Engineers, Prentice Hall, 1992*

Summary: The author provides a comprehensive outline of transit services with definitions and extensive data tables. Characteristics and capacities are shown for numerous transit vehicles, including some performance curves and formulas to calculate performance.

Figures 5.10 and 5.11 show the relationship between maximum speed, station spacing and average speed is documented and a tabulation[11] shows one second per passenger per lane for level boarding and alighting and 1.7 sec for low-level (light rail) alighting.

A table of *Factors Influencing Transit Capacity,* derived from the *Highway Capacity Manual* and *Canadian Transit Handbook* is the most comprehensive in the literature.

FACTORS INFLUENCING TRANSIT CAPACITY

(* non-rail factors removed or adjusted)

1. **Vehicle Characteristics**
    - a. Number of cars in train
    - b. Car dimensions
    - c. Number and configuration of seats
    - d. Number, location, width and actuation of doors
2. **Rights of Way Characteristics**
    - a. Number of tracks
    - b. Degree of separation from other traffic
    - c. Intersection design
    - d. Horizontal and vertical alignment
    - e. Route branching and junctions
    - f. Turnaround conditions at terminals
3. **Stop Characteristics**
    - a. Spacing
    - b. Dwell Time
    - c. Design (on-line or off-line)
    - d. Platform height (high or low level boarding)
    - e. Number and length of loading positions
    - f. Method of fare collection
    - g. If on-board fares, type of fare
    - h. Common or separate areas for boarding or alighting passengers.
    - i. Passenger accessibility to stop
4. **Operating Characteristics**
    - a. Service types* (express, local)
    - b. Layover and schedule adjustment practices
    - c. Time losses to obtain "clock headways" or crew reliefs
    - d. Regularity of arrivals at a given stop
5. **Passenger Traffic Characteristics**
    - a. Passenger distribution among major stops
    - b. Passenger concentration and interchange at major stops
    - c. Peaking of traffic (peak-hour factors)
6. **Street Traffic Characteristics**
    - a. Volume and nature of traffic (on shared right-of-way)
    - b. Cross traffic at intersections (where at grade)
    - c. Curb parking practices
7. **Method of Headway Control**
    - a. Automatic or by train operator
    - b. Policy spacing between trains (* or safety distance)

Comment: A wealth of information. The above table and certain performance information has been used in developing the Analytic Framework.

43 LEVINSON, HERBERT S.; ROBINSON, CARLTON, C. and GOODMAN, LEON, Chapter 12 Capacity in Transportation Planning, *Transportation Planning Handbook, Institute of Transportation Engineers, Prentice Hall, 1992*

Summary: Chapter 12 follows the more general information of Chapter 5 to present a wide range of capacity information with material synthesized from many sources.

The general equation for capacity of a transit line is given as:

$$C_p = \frac{3{,}600nSR}{(D+t_c)}$$

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[11] Table 5.16 Average Boarding and Alighting Intervals for Transit Vehicles

and for light rail with controlled intersections:

$$C_p = \frac{(g/C) \cdot 3{,}600nSR}{(g/C)D + t_c}$$

where: C_p = passengers per hour per track
t_c = clearance between successive cars or trains, in sec
D = dwell time at the major stop on the line under consideration, in sec
n = number of cars in train
R = reductive factor to compensate for dwell time and arrival time variations (0.833 suggested in text for maximum theoretical capacity for buses, 0.89 in later rail-specific references)
g = traffic light green time, in sec
c = traffic light cycle length, in sec

Various passenger load factors are shown based on a percentage of seats. Loading standards A through F (crush) are tabulated. The suggested "schedule design capacity" is 2.8 to 3.3 passengers per m^2, 25% below the "crush" capacity. The peak-hour factor is discussed for 15-min peak-within-the-peak. A range of 0.70 to 0.95 is suggested, approaching 1.0 in large metropolitan areas. Diversity of loading between cars of a train is mentioned but only limited data is provided.

Specific capacity for rapid transit is shown as:

$$\frac{Passengers}{Hour} = \frac{Trains}{Hour} \times \frac{Cars}{Train} \times \frac{Seats}{Car} \times \frac{Passengers}{Seat}$$

or

$$\frac{Passengers}{Hour} = \frac{Trains}{Hour} \times \frac{Cars}{Train} \times \frac{Floor\ Area\ per\ Car}{Area\ per\ Passenger}$$

Numerous examples are given of actual capacity with rapid transit maximums ranging from Hong Kong's 81,000 passengers per peak hour direction to NYCT's 53rd Street tunnel at 54,500 in 1982, down from 61,400 in 1960. The calculated maximum "attainable" for 10 car trains every 120 sec is shown as 57,300 passengers per peak hour direction after a 15% reduction for unequal passenger distribution.

Historic streetcar or light rail volumes are shown reaching 10,000 passengers per peak hour direction in North America. Three articulated light rail vehicles are calculated to handle up to 17,000 passengers per peak hour direction, with 35 trains per hour and a density of 3.25 passengers per m^2.

Commuter rail in North America is shown as achieving 15,500 passengers per peak hour direction with 15 trains per hour per track (LIRR). Comparable European capacities can reach 28,520 passengers per peak hour direction with 30 trains per hour. As a result, several European cities signal and operate commuter rail in a manner equivalent to rapid transit. (The lower volume is due to the common commuter rail policy of a seat per passenger.)

Comment: An outstanding and comprehensive report.

44 **LIN, TYH-MING** and **WILSON, NIGEL H.M.,** Dwell Time Relationships for Light Rail Systems, *Transportation Research Record 1361, 1992: pp. 287-295*

Summary: Lin and Wilson make a detailed analysis of dwell time determinants at two stations on the subway portion of the Massachusetts Bay Transportation Authority's Green Line light rail. Both linear and non-linear models are used to explain the dwell time data with the latter being only slightly more effective. Data for one- and two-car trains were analyzed separately so exposing a considerable difference in contributing factors according to train length.

The linear equations giving the best fit to the data as a whole are reproduced below.

For one-car trains:

$$DT = 9.24 + 0.71 * \mathrm{TONS} + 0.52 * \mathrm{TOFFS} + 0.16 * \mathrm{LS}$$

This gives an R^2 value of 0.62.

For two-car trains:

$$DT = 13.93 + 0.27 * \mathrm{TONS} + 0.36 * \mathrm{TOFFS} + 0.0008 * \mathrm{SUMASLS}$$

This gives an R^2 value of 0.70.

where: DT = Dwell time(s)
$TONS$ = Total boarding passengers
$TOFFS$ = Total alighting passengers
LS = Number of departing standees
$SUMASLS$ = Sum of ($TOFFS$)*(arriving standees) +($TONS$)*(departing standees)

The constant term for two-car trains in the equations is larger but the lower multipliers give a lower marginal dwell time for boarding compared with one-car trains. Note that the effect of crowding on the cars (the last term in the equations) is much lower for two-car trains. There is also evidence that the effect of crowding may cause a non-linear increase in dwell time during congested periods.

The paper closes with a brief discussion of the service implications of variable dwell times. Uneven dwell times cause uneven loading in a self-perpetuating cycle. Mixing different train lengths on the same service is likely to cause uneven loading.

Comment: While the information given by Lin and Wilson is specific to Boston's Green Line, the basic form of their equations and conclusions is likely applicable elsewhere. As such, this paper is a valuable reference in discussions of dwell times and their effects on capacity.

45 **MEDVECZKY, GEORGE.** Hub-Bound Travel 1991, *New York Metropolitan Transportation Council 1992*

Summary: Comprehensive statistics on transit and vehicular movements in Manhattan. Cordon counts provide peak-point passengers on trunk lines. Additional New York cordon counts for the study were acquired directly from MTA - New York City Transit.

46 **MILLER, E. J.** and **BUNT, P. D.,** Simulation Model Of Shared Right-of-Way Streetcar Operations, *Transportation Research Record 1152 1987: pp. 31-41*

Miller and Bunt introduce the reader to a computer program designed to simulate streetcar operation on the *501 Queen* line in Toronto, Ontario. The number of inputs to the model is exhaustive and includes a directly proportional relationship between standee numbers and boarding passenger service times.

Comment: Much of the effort expended in the program is in creating a routine for explaining the short-turning of cars to assist in determining the best way to increase service regularity and capacity on the Queen line. As traditional streetcar service is only a small part of the capacity study, this report is of limited value.

47 **MOTZ, D.,** Attainable Headways using SELTRAC, *Alcatel Canada, Toronto, September 1991 (Proprietary Report—only non-confidential data used for the A-8 study)*

Summary: Seltrac was one of the first transmission-based moving-block signaling systems. It is now in its fifth generation and is used in five North American locations. It is currently being installed on the Muni Metro light rail subway to increase throughput.

The system is based on the "brick-wall stop safety criteria" and allows trains to operate at the closest possible spacing with separation defined as the normal braking distance plus a safety distance. Braking distance is a readily determined or calculated figure for any system. The safety distance is less tangible, being comprised of a calculated component adjusted by agency policy. In certain systems this safety distance is a fixed quantity; however, the maximum throughput is obtained by varying the safety distance with speed and location.—and where different types of equipment are operated, by equipment type.

In theory, the safety distance is the maximum distance a train can travel after it has failed to act on a brake command before automatic override (or overspeed) systems implement emergency braking. Factors in this calculation include:

- system reaction time
- brake actuation time
- speed
- train load (mass)
- grade
- emergency braking rate
- normal braking rate
- train to track adhesion
- an allowance for partial failure of the braking system

The paper shows safety distances in "worst case failure situation" for the London Underground's new Jubilee Line that could be as long as 190 m for a fully loaded train at maximum speed (90 km/h) on a maximum down grade (5%).

In contrast, the constant safety distance used on the Seltrac equipped rapid transit system in Vancouver is 50 m, in part due to the better assured emergency braking provided by magnetic track brakes.

The paper describes the simulation of other capacity constraints at junctions, turnback and terminal stations, including situations with late trains, to show that a throughput of 36 trains per hour can be sustained with a train irregularity (behind schedule) of up to 60 sec.

Comment: It is not usually appropriate to reference a proprietary paper that is not available in the public domain. However, this is the only known source that explains and derives the safety distance for a moving-block-signaling system with conventional rapid transit equipment.

As such it sets the upper limit of throughput that could be achieved on any existing or new rapid transit whether that system uses Seltrac or one of the other moving-block signaling systems that have recently entered the market, including French and British systems and the recently announced BART/Hughes Aircraft development.

In principle, a moving-block signaling systems allows headways to decrease from the optimum with a three- aspect signaling system of 55 sec plus dwell to 25 to 35 sec plus dwell. However, at such closer headways, constraints at junctions and terminals and the issue of irregular operation become increasingly critical. (Note that the "worst case" braking rate used in the report is relative and does not assume total braking failure but rather no electric braking and partial air brake failure—retaining 75% of normal braking ability.)

The paper does not comment on the safety distance selected by the London Transport management or the regulatory authority (the United Kingdom Railway Inspectorate) as a result of this study, but it is possible that it is less than the 190 m calculated.

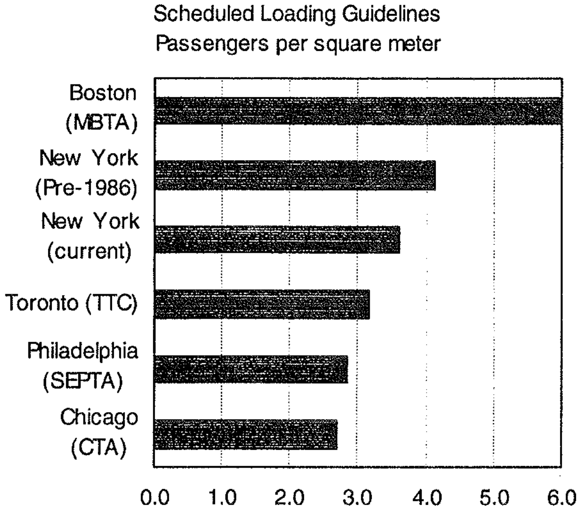
Moving-block signaling systems, constraints and recovery issues are fully discussed in the study. The data in the paper have been used to set a range of safety distances that, in conjunction with the maximum dwell time, establishes the minimum headway on both moving-block signaling systems and conventional multiple-aspect signaling systems.

48 **NEW YORK CITY TRANSIT AUTHORITY,** Rapid Transit Loading Guidelines, *April 1992*

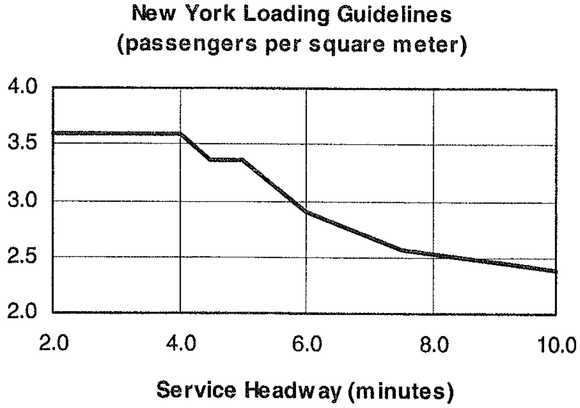
Summary: This policy paper gives the loading and service standards which have been applied, with minor modifications, to the New York subway system since 1987. The guidelines provide for slightly more space per passenger than those in effect until 1986. Modifications have allowed for a relaxation in the non-rush hour passenger loading guideline to allow for the operation of short trains.

The loading guidelines were established from test loadings of different car types, loading surveys of revenue service at the peak load point and comparisons with the policies of other rail transit operators. Additional concerns such as passenger comfort, dwell time effects, uneven loading within trains, and an allowance for "slack" capacity in the event of service irregularities and fluctuations in passenger demand were also considered. A rush hour standard of 3 sq ft per standing passenger (3.6 passengers per m^2) was generated from this work. The policy recognizes that this condition is only to be met at the maximum load point on a route and so is effective for only a short time and small portion of the overall route. For comparison, the agency's calculations of the maximum capacity of each car type are based on 6.6 - 6.8 passengers per m^2.

The graph below compares the loading standards of a number of systems.



Standards for loading in the non-rush hours are substantially more generous with a seated load at the maximum load point being the general standard. If this would require headways of four minutes or less, or preclude operation of short trains, a standard of 125% of seated capacity applies. This consideration of passenger comfort also extends to rush hour service on lines where the headway is longer than 4 min. In these cases a sliding scale is used to ensure lower standing densities on routes with longer headways, as shown in the following graph.



Minimum headways for each day and service period were also developed with the results shown in the following table:

Schedule	Time Period	Minimum Headway
Weekday	Rush hours	10 minutes
Weekday	Midday	10 minutes
Weekday	Evening	12 minutes
Saturday	Midday	10 minutes
Saturday	Evening	12 minutes
Sunday	All Day	12 minutes
All days	Midnight	20 minutes

The application of these guidelines resulted in a 6.4% increase in weekday train miles, a minor increase (0.3%) on Saturdays and a 1.0% decrease on Sundays.

Comment: This useful paper gives a look at how loading standards are developed and their effects. It confirms the importance of considering the effects on dwell times when creating loading standards. The need to give passengers with access to alternative transportation a comfortable ride is also given importance with the variable loading standards applied to less frequent rush hour and non-rush hour services.

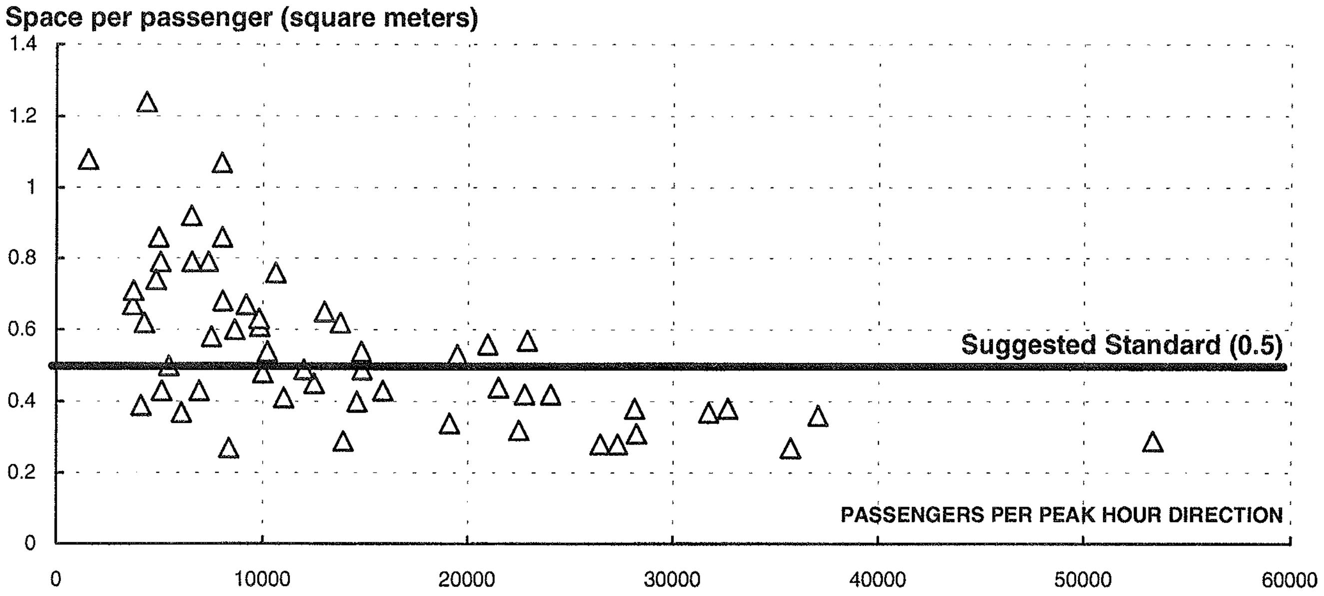
49 **O'BRIEN, W., SCHNABLEGGER, J.** and **TEPLY, S.,** Control of Light Rail Transit Operations in Edmonton, *Transportation Research Board Special Report 182, 1978, pp. 115-118*

Summary: This paper gives a pre-opening report on the control of light rail and traffic on the Edmonton, Alberta Northeast light rail line. The signal blocks on the light rail are stated to be 1-km long which places a severe constraint on capacity. The authors place emphasis on the need to maintain consistent service on the outlying portion of the light rail line in order to ensure proper utilization of the downtown tunnel. This is achieved with light rail pre-emption of the nine grade crossings on the line. Grade crossing signals and gates are integrated into the signal controllers of adjacent intersections to ensure smooth traffic flow and prevent queuing on the rail tracks.

Comment: This report supports other literature information that signaling systems, not grade crossings, are generally the capacity constraints on light rail systems.

50 **PARKINSON, TOM E.,** Passenger Transport in Canadian Urban Areas, *Canadian Transport Commission, Ottawa 1971*

Summary: The Principal Investigator's 1971 report quotes maximum rapid transit volumes from sources referenced elsewhere in this review. The ratio for the peak-within-the-peak is discussed for both a 5-min and 20-min flow level. The report looks briefly at the difference between theoretical and practical maximum capacities for rail transit and the headway reductions possible with automatic train operation.



Comment: This study is one of a small number that suggest higher throughput with automatic train operation compared to manually driven systems.

51 PUSHKAREV, BORIS S., ZUPAN, JEFFREY M., and CUMELLA, ROBERT S., Urban Rail In America: An Exploration of Criteria for Fixed-Guideway Transit, *Indiana University Press, 1982*

Summary: Pushkarev et al. use a unique approach to rail transit, discussing the number of rail transit tracks (65) that enter CBD's in the USA and Canada; of which 38 operate in the peak hour with the luxury of more than 0.5 m^2 of space per passenger. Only 6 "tracks" operate at system capacity, 5 in New York and one in Montreal. The authors point out that in the United States outside New York, no rail system operates at more than 33% of nominal system capacity.

Data compilations and presentations are numerous and have been cited and reproduced elsewhere. The relationship between peak hour volumes, space per passenger and theoretical capacity of lines in the United States is shown. The first two data sets are illustrated below:
The report suggests using "gross vehicle floor area" as a readily available measure of car occupancy and applies the following quality of service standards:

- ADEQUATE—0.5 m^2 provides comfortable capacity per passenger space
- TOLERABLE WITH DIFFICULTY—0.35 m^2 lower limit in North America with "some touching"
- TOTALLY INTOLERABLE—0.2 m^2 least amount of space that is occasionally accepted

The report discusses two of the three types of occupancy diversity—*peak-within-the-peak* and *uneven loading between cars of a train.*

The book states that the physical capacity of a rapid transit line is "frequently misunderstood" but is basically controlled by:

1. Policy determination
2. Car Width
3. Platform Length
4. Minimum operational headway

Car width can be assigned to two groups: narrow-2.5 to 2.8 m (generally old systems — IRT, PATH, SEPTA Market-Frankford, Montreal, Chicago and Boston) and wide-3.05 to 3.20 m (IND, SIRT, SEPTA Broad Street, Cleveland, Toronto—and all newer systems). Platform length ranges from 70 m (Boston, currently being extended) to 213 m (BART). The authors comment that minimum operational headway must be sustainable reliably and has three major components:

- type of signaling
- complexity of route
- dwell times

They cite the common limit of 30 trains per hour with the typical three-aspect signaling system and state that in practice this is lower if there are merges but can be increased with careful and precise operation, as for example, with the NYCT's 33 trains an hour on the Flushing Line or the 38 on PATH's World Trade Center line—made possible only by the multiple track terminal. The highest routine frequencies in the world (on a two-track system with on-line stations and no junctions) are the 40 trains an hour of the Moscow Metro. However, AGT can operate at closer headways using off-line station as shown in the 15-sec and 18-sec headways in Morgantown and Dallas-Fort Worth.

The report has only minor content on light rail quoting Pittsburgh PCC car headways of 23.5 sec with on-sight operation and SEPTA's 29 sec with block signals on the Market street subway at a reasonable schedule speed of 20 km/h. This is achieved by allowing train operators to pass red signals, operating on-sight, and with multiple station berths (4).

The authors discuss performance in terms of installed power per tonne, suggest 80 km/h as a suitable maximum speed which should be achieved in 25 sec—but takes 60 sec in a few cases where old, under-powered equipment is still in service. They address some confusion in defining average speeds and use the terms:

Schedule Speed is the net average operating speed without terminal layover time. *Gross Average Operating Speed* adds terminal layover time.

Comment: Pushkarev, Zupan and Cumella's book is one of the most comprehensive, readable and complete treatises on North American rail transit. It uses principally new data, specifically acquired for the book, presented with outstanding clarity and exceptional graphics.

The section on headways is perceptive, introducing one of the factors not mentioned elsewhere in the literature—that capacity is heavily dependent on policy—ranging from New York with 290 passengers per car (crush load) through Washington with service specified for an average of 170 passengers per car to BART with a policy of 90 in a larger car—but not currently achieved. The authors clearly indicate that passenger loading densities of the older subway systems will not be accepted on new North American systems.

52 **RADWAN, A. E.,** and **HWANG, K. P.,** Preferential Control Warrants of Light Rail Transit Movements, *Transportation Research Board State-of-the-Art Report 2, Light Rail Transit: System Design for Cost-Effectiveness, 1985: pp. 234-240*

Summary: Radwan and Hwang attempt to quantify the delay caused to light rail and general traffic by the use of light rail traffic signal pre-emption. The following version of Webster's delay model was used in their research:

$$d = 9/10 \left\{ \left[\frac{c(1-\lambda)^2}{2(1-\lambda x)} \right] + \left[\frac{x^2}{2q(1-x)} \right] \right\}$$

where: d = average delay per vehicle on the particular intersection approach
c = cycle time
λ = proportion of the cycle that is effectively green for the phase under consideration (g/c)
q = flow
s = saturation flow
x = degree of saturation

The authors have endeavored to create a model that does not discriminate against the transit mode; as most comparisons based on intersection level of service do. As a result, their model assesses both the delay and savings experienced by road vehicles and the light rail trains.

Their findings showed that, for a two-phase intersection with no left turns, the overall intersection gain due to signal pre-emption is linearly proportional to light rail volume. For a three-phase intersection with an exclusive light rail phase almost no intersection gain was observed. In the case of a three-phase intersection with an exclusive left-turn phase "it was found that there is an optimum main-arterial volume at which the overall intersection gain is maximum for a given constant left-turn volume."

Comment: While providing some interesting results, the model used in the study has some faults which may have biased the results. The most important of these are assuming an overly optimistic car occupancy of 1.4 and light rail volumes of 40-50 trains per hour. This level of light rail service is far beyond that operated on North American lines running at-grade with signal pre-emption.

The study does not mention that at-grade light rail capacity is limited by grade-crossings.

53 **RAINVILLE, WALTER S.,** and **HOMBURGER, WOLFGANG S.,** Capacity of Urban Transportation Modes, *Journal of the Highway Division, American Society of Civil Engineers, 1963*

Summary: The late Walter Rainville was Chief of Research for the then American Transit Association (now APTA) and was noted for his no-nonsense approach. In the transit section of this paper he defines:

Effective transit capacity =
Vehicles per hour x Passengers per vehicle

The paper then lists typical fully loaded capacities of rapid transit cars 35 years ago, the number of trains per hour (20 to 32) and a range of actual capacities. The paper points out that in theory a two-track rapid transit system could be built to handle 90,000 passengers per peak-hour direction whereas in practice the maximum in the country, then, was the NYCTA IND 6th and 8th Avenue expresses at 71,790.

Rainville discusses peak-hour loading diversity and shows an average for heavy volume lines in New York and Toronto of 87.6 (peak hour/peak-within-the-peak rate), an exceptional 95.6 for the NYCTA 7th Avenue line and the lower figure of 72.9 for less heavily loaded lines in other cities.

Comment: The now historic data in this, and other references, provides an insight into the maximum capacity of rail transit in an era when ridership and loading levels were higher.

54 **RICE, P.,** Practical Urban Railway Capacity—A World Review, *Proceedings of the 7th International Symposium on Transportation and Traffic Theory. Kyoto*

Summary: Rice's long paper combines two diverse areas. The first is a survey of the headways, capacities and commercial speeds of 53 urban railway systems throughout the world based on available published data. The second is an analysis of minimum headways that expands on the work of Lang and Soberman [(R39)] and Bergmann [(R13)] to compensate for reduced acceleration as a train increases speed

- coasting between stations
- closely spaced stations that result in a station approach below the optimal speed for minimum headways[12]
- the distance a train must move out of a station before the following train receives signal clearance to enter

The survey shows three[13] systems that operate 40 trains per hour, thirteen systems that operate 30 to 36 trains per hour and twelve that operate 24 to 27 trains per hour on a single track. The highest quoted capacity is 72,000 passengers per peak-hour direction per track, three systems quote capacity between 60,000 and 70,000. All other systems (49) show capacities below 50,000 passengers per peak-hour direction per track. The data shows that the 53 rail transit systems have a mean route length of 14.6 km and a mean overall station spacing of 1.1 km.

Rice analyzes a typical station to station run of 1.6 km (1 mi) with modern rail transit equipment. Constant acceleration to the point where station braking must commence produces a theoretical run time of 89 sec. However as the speed of a train increases acceleration tapers off—ultimately to zero—as the train *moves along the motor performance curve.* Using a typical performance curve results in a practical station to station time to 111 sec—25% higher.

Adding the maximum realistic level of coasting increases travel time by a further 9 sec to 120 sec—an 8% increase with an estimated energy saving of 23%.[14]

Rice also tabulates performance and capacity data for the 53 systems. The overall mean normal service braking rate is 1.14 m/s^2, the mean emergency braking rate is 1.51 m/s^2 and the mean initial acceleration rate is 1.12 m/s^2. The overall mean design maximum speed is 79.4 km/h (50 mph). The overall mean packing density is 3.61 passengers per square meter.

The headway equations that are developed contain constraints for conditions where the optimal approach speed cannot be obtained due to coasting practices (or to speed control), due to tapering of the initial acceleration, and due to any run out distance from a station—a distance that a train must cover before the following train receives.

Rice acknowledges the importance of dwell time in determining the minimum practical headway—and the difficulty in estimating the dwell time. He quotes a dwell time in sec for a *heavy departure load* at

Dwell = 17.5 + 0.55(number of passengers per double door)

and for a *medium departure load* at

Dwell = 13 + 0.49(number of passengers per double door)

Only limited results of applying the numerous equations derived in the report are shown. The most significant are (for a 1.6 km station to station run):

- the optimum approach speed for typical rolling stock is 32 km/h (19 mph) which produces a headway of 80.4 sec with a nominal 30-sec dwell
- headways increase at approach speeds above and below this optimum. For example at 50 km/h (31 mph) the headway increases to 86 sec, a 7.5% decrease in capacity; at 20 km/h (12.5 mph) the headway increases an identical amount to 86 sec
- removing the adjustments due to the tapering of the acceleration curve results in a linear acceleration decreasing the headway to 80.1 sec, a 0.4% improvement. (0.6% improvement without considering the dwell)

Comment: Rice, in attempting to accommodate performance and station spacing nuances in train performance has added considerable complexity to the calculations and imposed several conditions. The results do not seem to justify the complexity. There are few conditions of station spacing, (or speed control) and train performance where an optimal approach speed of 32 km/h (19 mph) cannot be achieved. Using actual motor characteristics rather than assuming linear acceleration only changes the calculated headway by 0.4%. The calculation of the actual impact of this improvement is valuable.

Despite the added complexity several assumptions have still to be made, for example driver and equipment reaction time, and the use of the very variable emergency braking rate, rather than the service braking rate, to determine minimum separation times is unusual. This higher braking rate and a lower estimate of reaction time than other workers (2 sec) may explain why Rice's calculated minimum headway of 50 sec plus dwell—for a three-aspect fixed-block system with typical train lengths and performance—is lower than the 55 sec typical of other work.

The largest deficiency, considering the elaborate analysis, is that no allowance is made for schedule recovery to avoid any headway interference.

55 **SCHUMANN, JOHN W.,** Status of North American LRT Systems: 1992 Update, *Transportation Research Record 1361, 1992: pp. 3-13*

Summary: This paper provides a concise overview of recent North American light rail developments. Future plans of systems are also outlined. Seven tables are used to gather together many of the basic statistics for U.S. and Canadian light rail systems operating in 1992. A brief section also discusses the interest in low-floor light rail cars shown by many transit agencies.

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[12] This constraint would be the same is speed controls were used that limit the optimal approach speed.

[13] The three closest headway systems (40 trains per hour) are quoted as Moscow, PATH and NYCT. As NYCT operates no more than 30-32 trains per hour on its heaviest trunk routes the data are suspect. It may be that the information relates to the theoretical throughput of the signaling system rather than actual trains operated.

[14] The calculation of energy consumption is not specified and probably does not take into account power other than traction use. i.e. hotel load power, the bulk of which is for heating or air conditioning. On systems with weather extremes—most East coast systems—the hotel load can be as high as the traction load cutting the coasting savings in half.

Comment: Schumann provides a useful but brief summary of some of the aspects of light rail which are relevant to this project. The information in the tables may be directly useful or form a base to seek more current data. The introduction of low-floor cars will have effects on capacity as a result of reduced dwell times through faster passenger movements and better accessibility to the mobility impaired.

56 SONE, SATORU, Squeezing Capacity out of Commuter Lines, *Developing Metros, Railway Gazette International 1990.*

Summary: Professor Satoru of the University of Tokyo gives a broad outline of many of the factors limiting rail transit capacity. Station dwells are introduced as the key factor in determining capacity. The minimum practical headway on an uncomplicated line is around 40 sec plus dwell time at the busiest station plus the time needed for a train to move its own length from a standing start. Even with an infinitesimally short dwell time, the minimum headway is thus at least 50 to 60 sec.

One method of reducing overall line headway is to have some trains by-pass lightly used stations or to use an A/B stopping pattern where lighter stations are served by either the A or B services with heavier locations and transfer points being served by both.[15] Dwell times at AB stations are still a major limitation on headway. Commuter rail services with complex stopping patterns are often able to be more flexible than rail rapid transit and so trains can be scheduled to pass through relatively busy outlying stations when other services are provided.

An even passenger distribution on board the trains is important to ensure that maximum use is made of the rolling stock. Station design can be used to create an even distribution of passengers throughout the train. This can be achieved by designing cross-platform transfers, and distributing platform entrances and exits along the length of the platform and varying their locations at different stations. Stub-ended termini are a particular problem which can, at least, be partially improved by adding platform access at the outlying ends of the platforms.

Additional platforms can be used to reduce dwell times by allowing boarding on one side of a train and alighting on the other. Throughput can also be increased with additional track by converting side platforms to island platforms and running alternate trains on either side of the platform. This is a much more economical solution than adding a parallel main line.

Junctions can be improved with grade separation or by shifting the interchange function to a major station nearby with excess platform capacity.

The city terminus is a common limiting station on rail transit lines. Creating run-through stations by linking terminus stations is an excellent, albeit expensive, solution. Building a loop giving direct access to all platform tracks is another successful way of increasing station throughput. Allowing higher speed approaches to stub-end stations by extending the station tracks a short safety distance beyond the platforms is also possible in some cases. Double-decking is another effective but expensive station improvement. Train schedules can also be adjusted to increase throughput. Three main categories can be defined:

- All trains stop at each station.
- Fast trains over-take slower ones at four-track stations.
- Each train serves all stations in a zone then runs express to the city terminus.

The first pattern works best with less than 10 stations of similar traffic generation. The second is effective with a large homogeneous system but does not give the higher number of fast trains near the central hub which is desirable on a radial system.

The last pattern (3) is ideal for branching, radial commuter lines since it gives high capacity and fast journeys. Passengers traveling between intermediate stations may be inconvenienced by the need to change trains but their numbers are small.

A number of Japanese examples of capacity increases are given. Several of these are of running trains of similar service characteristics in succession in a practice commonly known as "platooning". In one case the first train leaves 130 sec before the second, stops at one additional station and arrives at the terminus 90 sec before its slightly faster counter-part. The double-track Seibu Railway, which operates such patterns, runs 30 trains into its Tokyo terminus in the morning peak hour and has plans to add three additional trains. This is despite the terminus being stub-ended with only three full length tracks.

Care must be taken when increasing capacity to ensure that additional ridership does not simply create another choke-point at stairs or passageways.

Future capacity increases will likely require the use of off-line stations, on-board switching, and train-to-train safety control or collision avoidance technologies.[16] Off-line stations can only be practical where the platform loop track is long enough to allow acceleration and deceleration to take place off the main line. Headway improvements may, however, be marginal since a train approaching a facing points switch must be able to stop short if the switch has failed in mid-position. On-train switching equipment could remove this restriction with more development.

Comment: This paper presents a comprehensive overview of the factors restricting the upper limits of rail transit capacity. It gives useful examples of capacity increases obtained on several Japanese rail transit services—several of which have both the highest train, and highest passenger, densities in the world

57 STRAUS, PETER., Light-Rail Transit: Less Can Mean More, TRB Special Report No. 182, Light-Rail Tran: Planning and Technology. 1978: pp. 44-49

Summary: Mr. Straus makes a strong argument for keeping the "light" in light rail transit and resisting the temptation to build light rail lines to rapid transit standards. A particularly interesting

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[15] The AB skip stop system was used extensively on the Chicago Transit Authority's rail lines until 1995.

[16] Reviewer's Note: Essentially a moving-block signaling system.

table showing capacities of various light rail alignment options is reproduced here.

Right of way option	Passengers per hour
Exclusive subway	20,000 to 30,000
Exclusive aerial	20,000 to 30,000
Exclusive grade-separated surface	20,000 to 30,000
Semi-exclusive: median or side of road	10,000 to 20,000
Separated but in-street surface	10,000 to 20,000
Mixed-traffic surface operation	5,000 to 10,000

Another relevant point made in the article is that higher speeds can lead to reduced capacity because of the need for longer following distances. Mention is also made of the faster boarding possible with high-level platforms, as found in the Muni Metro subway[17]. The use of low level platforms (with moveable steps on the cars) on the surface maintains the flexibility and simplicity of light rail operation elsewhere on the system.

58 **SULLIVAN T. J.**, New York City Transit New Technology Signals Program Status Report, *MTA New York City Transit Division of Electrical Systems, APTA Rapid Transit Conference, Sacramento, June 1994*

Summary: NYC Transit's existing train control system is an automatic fixed block wayside signal system. Virtually all track circuits are single rail. Much equipment dates to the original installation and has a high failure rate and maintenance costs. Following the 1992 14th Street derailment, a $14 million speed protection system is being installed at 31 priority locations.

A 5-year, $1 million study of train control systems has concluded with broad support for Communications-based signaling — also referred to as transmission-based or moving-block signaling. The principal attribute is continuous two-way communication and control, increased safety, increased functionality, and lower life cycle costs.

A survey of signaling technology around the world showed numerous advantages for moving-block signaling systems, including increases in capacity. Other advantages include improved schedule adherence, reduced power consumption and the inherent ability to operate in both direction on any track with full automatic control.

The report discusses the issue of adapting the traditional fail-safe signaling concept to the equivalent, but different, safety standards of computer based controls. Despite concerns, and resistance to the introduction of new technology in train control, many rail transit operators have selected moving-block signaling systems, including London Transport and Stockholm Transit. An overlay track-circuit system, SACEM, with some moving-block attributes, has increased train throughput on the Paris RER line A. The report describes the selection and successful operation of moving-block signaling systems by eight other rail transit operators in North America and Europe.

The report expresses concern with acquisition of a single proprietary system. The market for moving-block signaling systems has been dominated by one company for two decades. However all the signaling suppliers contacted had or were developing moving-block systems. NYC Transit intends to work with the international signal industry, to seek an engineering partner and to use a development-driven approach to test and select moving-block signaling systems. Sullivan expresses hope that this process will develop a standard for such systems and that NYC Transit will have more than two suppliers to ensure competition and the lower costs that moving-block signaling systems have the potential to deliver.

Comment: The strong endorsement of moving-block signaling systems by two of the world's largest rail transit operators, MTA New York City Transit and London Transport indicates that this technology and its multiple advantages has become acceptable.

59 **TABER, JOHN** and **LUTIN, JEROME**, Investigating the Potential for Street Operation of Light Rail Transit, Transportation *Research Board Special Report 182, 1978: pp. 161-166*

Summary: While using data collected in 1973, this paper has some interesting figures of delay for streetcars in Toronto. Traffic signals were found to cause 50% of the delays to streetcars while passenger service (boarding) times accounted for 40%.[18] Delays caused by traffic congestion were only 3.3% of the total. On the St. Clair line boarding delays accounted for only 27% of total delay. This is believed to be a benefit of the extensive use of island stops on this route.

60 **TAYLOR, P. C., LEE, L. K.** and **TIGHE, W. A.**, Operational Enhancements: Making the Most of Light Rail, *Transportation Research Board Special Report 221, 1989: pp. 578-592*

Summary: This mis-titled work summarizes the efforts to minimize the effects of the Los Angeles Blue Line light rail on roadway capacity. This is achieved by varying the priority given to the light rail trains according to road traffic volumes. During peak traffic periods, the light rail is accorded a lower signaling priority to prevent disruption of motor traffic. At off-peak hours, the light rail can be allowed greater priority with minimal impact on motor traffic.

Comment: At the 6-min headways under consideration, the light rail is seen as limiting road capacity and not the reverse. Reducing priority for light rail at peak hours — when it is most needed — is negative. It reflects badly on the traffic engineering process whereby the number of vehicles, rather than the number of people, moved is prioritized.

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[17] Reviewer's Note. In the subway the double front door is not used due to the large gap created by the tapered car end.

[18] Reviewer's Note. The latter figure has no doubt dropped since the adoption of an exact fare policy.

61 **TIGHE, W. A.** and **PATTERSON, L. A.,** Integrating LRT into Flexible Traffic Control Systems, Transportation Research Board State-of-the-Art Report 2, Light Rail Transit: System Design for Cost-Effectiveness, 1985: pp. 213-220

Summary: Tighe and Patterson offer a general discussion of integrating light rail into vehicular traffic signaling. Their ideas are then applied to the Woodward corridor in Detroit, and the Guadalupe corridor in Santa Clara County, Different solutions are offered in each case to reflect the specific alignment characteristics.

For the Woodward Corridor, the light rail is proposed to run in the exceptionally wide median of Woodward Avenue. This allows the use of two-phase traffic signals (i.e. no left turns permitted) at all intersections since the median can be used to create U-turn bays between intersections. Cars wishing to turn left are able to use a combination of right-turns and U-turns to achieve the same result. Intersection spacing is such that the light rail can easily run with the progressive signaling at cross-streets while pre-empting the U-turns when required.

In the Guadalupe corridor example, the medians of North First Street and Tasman Drive are of a more conventional width making the U-turn arrangement impractical. Instead, multiple phase traffic signal controllers with a total of up to 16 phases (some of which can run concurrently) will be used to accommodate heavy volumes of turning traffic. The degree of light rail pre-emption will be variable so as not to unduly hinder automobile flows at peak times. During off-peak periods a greater degree of pre-emption will be permitted.

Comment: The omission of any mention of a reduction of light rail capacity due to less than full signal pre-emption in this paper indicates that, at the headways under consideration (4 - 6 minutes), pre-emption is not necessary for providing sufficient light rail capacity.

62 **TOPP, R. M.,** Improving Light Rail Transit Performance in Street Operations: Toronto Case Study, *Transportation Research Board State-of-the-Art Report 2, Light Rail Transit: System Design for Cost-Effectiveness, 1985*

Summary: The Queen streetcar line in Toronto, ON experiences service irregularities due to extremely heavy use (75,000 passengers per day) and a lack of transit priority. This paper summarizes some of the operational problems of the route and details the results of two studies aiming to solve them. Key to improving the service on the route is a reduction in the number of unscheduled short-turns required to maintain headways and capacity on the central portion of the line.

One approach was solely to look at operational adjustments which would improve service reliability. Passenger service time was found to take 12 - 18 percent of total travel time. Signal and queue delays accounted for 13 - 15 percent of total travel time. Suggestions included extending running times, increasing the service gap required to initiate a short-turn, adding scheduled short-turns, and using larger, articulated vehicles.

The second approach was to study ways of improving service through the use of transit priority measures such as pre-emptive signaling. In some cases this could simply mean re-timing the traffic signals to improve general traffic flow.

Comment: This is one of few papers to address the operational problems of a traditional streetcar service in mixed traffic with no priority measures.[19] The speed of the service and number of cars required is heavily affected by the current conditions.

63 **TORONTO TRANSIT COMMISSION,** Yonge-University-Spadina Improved Headway Study, Final Report *Toronto Transit Commission, December 1988*

Summary: This staff report, based on studies by consultants Trans mode and Gibbs and Hill, examines a range of options to increase capacity on the TTC's Yonge-University-Spadina (YUS) subway.

In 1988 the Yonge subway south of Bloor was close to its rated capacity of 34,000 passengers per peak hour direction.[20] This capacity is based on maximum length six-car trains, 140-m (450-ft) long, operating at headways of 130 sec (28 trains per hour).

The Yonge subway, opened in 1953, was the first new post-war subway in North America. It uses a conventional three aspect color light signaling system based on track circuits designed for 120-sec headways (30 trains per hour), on the basis of station dwells of no more than 30 sec. Actual dwells at the major Bloor-Yonge interchange station of 45 sec prevent undisturbed operation of more than the 28 trains per hour.

Analysis of downtown developments had indicated a future demand, on this critical section of the subway, increasing by 33% to 45,000 passengers per peak hour by the year 2011.

A detailed analysis of the signaling system confirmed that the Bloor station dwell was the only bottleneck preventing 120-sec headways. However if the signaling system was upgraded for closer headways other bottlenecks would appear, particularly the Finch turnback used by all trains. (At the other end of the line a short-turn divided the turnbacks between two stations, so avoiding any restrictions.)

The study examined three signaling improvements that would progressively reduce headway. The first option made minor signal adjustments in the vicinity of Bloor station to permit 122-sec headways. The second set of improvements to signaling reduced the headway to 112 sec but required a major reconstruction of the Bloor station to ensure dwell times within 30 sec, and changes to the terminal at Finch.[21]

The third improvement was to replace the signaling system

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[19] The Toronto Transit Commission has recently managed to obtain priority for streetcars on sections of its network.

[20] Ridership has decreased in the last few years.

[21] A fourth option that would permit a 105-sec headway required extensive modifications to the existing signaling system and was discarded as impractical.

with automatic train operation that would permit 90-sec headways — again with a major reconstruction of the Bloor station and both terminals.

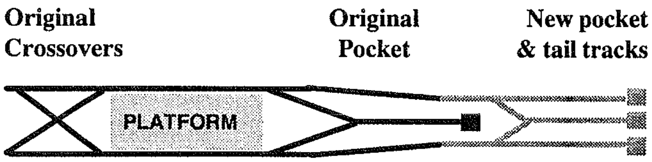
	Option 1	Option 2	Option 3
Minimum Headway	122 secs	112 secs	90 secs
Capacity in ppphd	36,400	38,800	48,400
Capacity Increase	10.7%	14.1%	42.3%
Bloor Dwell	45 secs	30 secs	30 secs
Implementation	1 year	4 years	8 years
Signaling Cost	$1M	$8M	$134M
Bloor Station Cost	--	$120M	$120M
Turnback Costs	--	$35M	$99M
Vehicle, Power & Yard Costs	$36M	$78M	$515M
TOTAL	$37M	$241M	$868M
Cost /10% capacity increase	$35M	$171M	$204M

Each option required additional vehicles and the yard expansions to accommodate them. The results are summarized above with cost estimates in millions of 1988 Canadian dollars.

The study showed that the most cost effective way of reducing dwells at Bloor station was to widen the station and add a Centre platform so that trains could simultaneously open doors on both sides.

Terminal changes involved extending the tail tracks and adding a second pocket track so that peak period trains could reverse behind rather than in front of the station. The improved headways could not be accommodated by using the scissors crossover ahead of the station due to the wide track separation dictated by the center platform and the resulting high traverse time.

PROPOSED TERMINAL CHANGES (Not to Scale)



The study did not evaluate the considerable operating cost repercussions. All options required additional crews to permit a set-back operation at the terminals while the first two options imposed speed controls that reduced the average system speed, increasing vehicle and crew requirements. Option Three's automatic train operation offered the significant potential saving of reducing train crews from two to one.

Implementation of Options Two and Three was lengthy and difficult as changes had to be made while the subway was operating, work being restricted to limited hours, even with proposed early closing each night.

The study also reviewed alternate methods of increasing capacity. Widening vehicle doors was suggested as a way to reduce dwells. An increase of 22 cm (9 in.) to a total width of 1.37 m (4.5 ft) was proposed. This was not practical on existing cars but may be implemented on future car orders.

Adding a short (50 ft) car to each train would be possible within the existing platform length of 152 m (500 ft). This would increase capacity by 11% while concurrently reducing dwell time by an estimated 12%. The costs was estimated at $47 million.

Comment: The TTC's capacity problem stems from a failure to operate the Bloor-Danforth subway as originally planned. A wye junction at Bay/St. George was designed so that each alternate Bloor-Danforth train ran downtown via the University subway — avoiding the need for passengers to physically transfer to downtown trains. This operation was abandoned after a six month trial in 1966 as uneven train arrivals made the merge difficult. The uneven arrivals were primarily due to the lack of any intermediate timing points on the long cross-town Bloor-Danforth subway.

Twenty years after the subway opened, intermediate timing points (dispatch signals) were added. By this time the University subway had been extended along Spadina and the wye operation was no longer feasible. 30% of Yonge subway's peak-point passengers and 48% of the University subway's peak-point passengers transfer from the Bloor-Danforth subway.

The study offers valuable information on capacity limitation and upgrade alternatives. The possibility of operating 7 car trains of existing cars does not seem to have been considered. Such a consist would extend beyond the station platform but all doors would be (just) within the platform — automatic train operation would be desirable or necessary to achieve the required berthing accuracy.[22] There is no supporting evidence that widening doors would reduce dwells. Information elsewhere suggests that the 1.15 m (3.75 feet) wide door, while narrower than normal for heavy rail vehicles, supports two streams of passengers and that little gain would be achieved until the doorway is sufficiently wide for three streams.

The addition of automatic train operation and rebuilding Bloor station appear to be the only way to meet future passenger demand. This would be easier, cheaper and faster using a transmission based signaling system (moving-block), avoiding the difficult, potentially service disruptive, changes to the existing signaling equipment. Transmission based signaling systems have been selected by MTA-NYCT and London Transport as the most practical way to upgrade or replace existing conventional signaling systems. This omission from the study is all the more surprising considering that the TTC already operates a transmission based signaling system on the Scarborough line,—an extension to the Bloor-Danforth subway.

64 TORONTO TRANSIT COMMISSION,
Yonge-University-Spadina Improved Headway Study, Signaling Report *Toronto Transit Commission, December 1988*

Summary: This staff report, based on studies by consultants Trans mode and Gibbs and Hill, expands on the signaling system options required to increase the capacity of the TTC's Yonge-University-Spadina subway described in *Yonge-University-Spadina Improved Headway Study, Final Report* (above).

65 TRANSPORTATION RESEARCH BOARD,
Collection and Application of Ridership Data on Rapid Transit Systems, Synthesis of Transit Practice, *Washington DC, 1991*

Summary: A comprehensive account of rapid transit data collection practices. The report comments on the generally low

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[22] The transmission based automatic train control on the TTC's Scarborough line achieves stopping accuracy ± 8 cm (3 inches).

technology approach that is mainly devoid of any field survey design or sampling techniques. Toronto is an exception using optical readers to enter field data into the computer. Several systems are starting to use electronic registers in the field.

Indications of accuracy are not quantified but the report infers that most operators achieve the FTA Section 15 requirements in passenger counts of accuracy within 10% at the 95% confidence level. Toronto and Atlanta claim accuracy to within 5%. NYCT states its checkers cannot monitor heavily loaded trains and at a certain (unspecified) level of crowding just mark such cars as crush loaded. NYCT also estimates that its exit counts are light by 15%.

On-board counts vary widely with the NYCT's Rapid Ridecheck being among the most comprehensive, measuring: actual arrival time; alighting passengers; boarding passengers; passenger load leaving; actual departure time and scheduled departure time.

Comment: Provides a useful indication of the data collection process and probably accuracy level. NYCT offers possibility for a detailed dwell time analysis from the large quantity of Rapid Ridecheck data but actual NYCT peak counts and any loading diversity within a train is tainted by the lack of actual checker counts on crush loaded cars.

66 TRANSPORTATION RESEARCH BOARD, Gray, Benita, editor. Urban Public Transportation Glossary, *1989*

Summary: A comprehensive glossary used with the APTA glossary and definitions from several summarized reports, to compile the rail transit capacity specific glossary in this report.

67 TRANSPORTATION RESEARCH BOARD, Highway Capacity Manual, *Special Report 209, 1989*

Summary: This much referenced report devotes a modest space to rail transit capacity. It tabulates observed peak hour capacities in the United States and Canada, suggesting that peak 15- to 20-min volumes are about 15% higher. Typical maximum train throughput is suggested at 30 with reference to higher levels—PATH's 38 trains per track per hour and the CTA's 78 (prior to the use of a cab control signaling system on the elevated loop.)

The formula for rapid transit capacity is the same as shown above in Levinson. Suggested loading levels for capacity calculations are, level "D", an average of 5 sq ft per passenger ($0.46m^2$).[23] The resulting suggested maximum capacity for two-track rapid transit lines is 18,000 to 30,000 passengers per peak-hour direction.

The formula for light rail capacity is also shown above in Levinson[(R42)]. The resulting suggested maximum capacity for two-track light rail lines with three-car articulated light rail vehicles is 11,000 to 13,000 passengers per peak hour direction. (30 to 35 trains per hour) at level of service "D". This range increases to 17,500 to 20,000 passengers per peak hour direction at passenger service level "E" with 0.3 m^2/passenger.

Comment: The simple set of capacity information and calculations derived in this study are expected to be a suitable replacement for the Highway Capacity Manual's rail transit capacity section.

68 US DEPARTMENT OF TRANSPORTATION FEDERAL TRANSIT ADMINISTRATION Characteristics of Urban Transportation Systems, Revised Edition, *1992*

Summary: Contains many tabulations of rail transit information including a compiled range of rapid transit passenger space occupancies.

• seated passengers	0.28 - 0.46 m^2
• standing passengers	0.22 - 0.26 m^2
• crush loading	0.17 m^2

A list of AGT car capacities has been used in the AGT data table. Examples of dwell times are higher than used by many other examples in this literature survey.

Location	Mean dwell times-secs	Standard deviation
NYCTA Lexington Avenue	53	17
CTA Evanston	42	14
MBTA Green Line	58	24
Milw. Road commuter rail	19	6

Comment: The values for seated floor occupancy and for commuter rail dwell appear low.

69 US DEPARTMENT OF TRANSPORTATION, National Transportation Statistics, *Annual Report, Sept., 1993*

Summary: A comprehensive tabulation of transportation statistics with limited general information on urban transit.

70 VANTUONO WILLIAM C. Signaling and Train Control, High-Tech for High Capacity. *Transit Connections, September 1994*

Summary: This magazine article discusses advanced train control systems relative to a need to increase capacity. Communication based[24] signaling systems in use and under development are summarized.

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[23] Reviewer's Note. Much the same as the 0.5 m^2 of Pushkarev (reviewed above)—particularly when Pushkarev's use of gross vehicle floor area is taken into account.

[24] AUTHOR'S TERMINOLOGY. Communication based signaling systems are also called transmission based or moving-block systems. As not all communication or transmission based signaling systems are moving block the A-8 report will use moving-block signaling system to avoid confusion.

Pointing out that moving-block signaling systems have been in use in Europe and Vancouver, Canada for several years the author discusses the selection of the Seltrac system for San Francisco's MUNI resignaling and an unspecified similar system for the modernization on New York's subway lines. It comments that other US rail systems are expected to follow New York's lead, quoting NYCT "after an intensive study and international peer review, communications based technology is the best, most cost-effective system for our purposes".

The article describes moving-block signaling systems from nine suppliers[25]:

- General Railway Signal—ATLAS ®™
- Union Switch & Signal—MicroBlok ®™
- AEG Transportation Systems—Flexiblok ®™
- Alcatel Canada—SELTRAC ®™
- Harmon Industries—UltraBlock ®™
- Siemens Transportation Systems
- Matra Transport—METEOR ®™, SACEM ®™, MAGGALY ®™
- CMW (Odebretch Group Brazil)
- Morrison Knudsen (with Hughes and BART)

Comment: One of the most comprehensive and current descriptions of moving-block signaling system. The only known system omitted is that of Westinghouse Brake and Signal (UK) currently being installed on a portion of London Transport's Underground.

The article is somewhat optimistic, claiming possible headway reductions to 60 sec. It also steers around the considerable industry controversy related to moving-block systems in which the hardware based fail safe features of conventional signaling are replaced by a software equivalency. Until NYCT announced the selection of a transmission based system, several of the above manufacturers were vociferously opposed to the software based train control systems (despite some of them offering software controlled interlockings).

71 **VUCHIC, VUKAN R.,** Urban Public Transportation Systems and Technology, *Prentice-Hall Inc., 1981*

Summary: Professor Vuchic's comprehensive text devotes 70 pages to capacity, introducing some unique definitions and taking an approach that defines two capacities: C_w—way capacity and C_s—station capacity. Maximum offered line capacity C is defined as the minimum of way or station capacity.

$$C_s = \frac{3600(n)(C_v)}{h_{s\ min}} \cdot \left| \frac{C_s}{sps\ /\ h} \right| \frac{n}{veh\ /\ TU} \left| \frac{C_v}{sps\ /\ veh} \right| \frac{h}{\text{sec}\ /\ TU} \right|$$

where: n = numbers of vehicle per Train Unit
C_v = Passenger spaces per vehicle
$h_{s\ min}$ = minimum headway (station)

The vehicle capacity (passenger spaces per vehicle) is shown as:

$$C_v = m + \frac{\xi A_g - A_l - m\rho}{\sigma} \cdot \left| \frac{m}{seats\ /\ veh} \right| \frac{A}{m^2} \left| \frac{\rho,\sigma}{m^2\ /\ space} \right| \frac{\xi}{1} \right|$$

where: ξ = vehicle floor area loss factor for walls
A_g = gross vehicle floor area
A_l = vehicle floor area used for cabs, stairwells and equipment
m = number of seats
ρ = floor area per seat
σ = floor area per standing passenger

Suggested values for space per seat are 0.30 to 0.55 m^2, for space per standee 0.15 to 0.25 m^2. Operating capacity, C_o, is defined as:

$$C_o = C_{\text{one hour}} < C$$

The scheduled line capacity utilization factor, δ, is defined as:

$$\delta = \frac{C_o}{C}$$

The capacity utilization coefficient[26] α is defined as:

$$\alpha = \frac{P}{C_o}$$

where: P = number of passengers transported past a point in one hour

Professor Vuchic develops the concept of *Linear Vehicle Capacity* Π

$$\Pi = C_v/l'$$

where: l = length of vehicle

Suggested values of Π are 7.0—8.5 for light rail vehicles and 8.0—10.0 for heavy rail cars. The maximum way capacity C_w is developed as:

$$C_w = \frac{3600nC_v}{(nl' + s_o)\ /\ v + t_r = Kv\ /\ 2b}$$

where: s_o = safety separation
t_r = reaction time[27]
K = safety factor
v = train speed
b = braking rate

Ten different safety regimes from Friedrich Lehner (1950) are introduced.[28] Using the above equation for way capacity and the brick-wall scenario, Vuchic calculates the way capacity for BART at 185 trains per hour and 350 trains per hour for 2 car articulated light rail vehicles.

The book then develops a station capacity equation incorporating dwell times. Station capacity is shown to be 1/4 to 1/7th of

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[25] Reviewer's Note. Several of these moving-block signaling systems are under development and it will be some years before they are proven in service.

[26] Reviewer's Note The capacity utilization coefficient is more commonly called the *load factor.*)

[27] Reviewer's Note: Operator and equipment reaction time for manual trains, equipment (brake) time only for automatic train operation.

[28] Reviewer's Note: Only one is accepted in North American rapid transit, namely the brick wall scenario with a service braking rate

way capacity. The theoretical throughput and optimum speed is shown as:

Train	Speed km/h	Passengers per peak hour direction
10 car rapid transit	44.7	90,000
6 car rapid transit	32.0	56,000
2 car articulated LRT	22.5	30,000

Suggested practical capacities are 15,000 to 20,000 passengers per peak-hour direction for light rail and 55,000 to 65,000 passengers per peak hour direction for rapid transit.

The Yamanote Line in Tokyo is referenced as possible the highest capacity line with 165,000 passengers per peak-hour direction on four tracks. Actual examples of minimum headways and capacities are tabulated. Streetcars are shown to have operated historically at headways down to 23 sec on street and 30 sec on segregated tracks. Signaled light rail has demonstrated headways down to 27 sec.[29]

Rail rapid transit headways as low as 70 sec are shown in the Soviet Union with 90 sec the closest operated elsewhere. Vuchic's mathematical analysis of capacity concludes with extensive comments on the relation ship between theoretical and practical capacities of transit modes:

- Capacity is not a single fixed number but is closely related to system performance and level of service.
- Operation at capacity tends to "strain" the system to its maximum abilities and does not represent a desirable condition.
- There is a significant difference between design capacity and the number of persons transported during one hour.
- Theoretical capacities are often quite different from practical capacities.
- Way capacity is a different concept from station capacity, station capacity always governs line capacity.
- There can be friction between boarding and alighting passengers that impacts dwell time calculations.

Comment: Professor Vuchic develops by far the most comprehensive mathematical treatise of rail transit operation and capacity. As with other mathematical treatments, the difference between theory and practice is difficult to reconcile or quantify.

The concept of passenger capacity per linear unit of a train has merit and is developed in the study.

Except possibly for automated guideway transit with off-line stations, the use of "way capacity" has little relevance and produces dubious results. It is difficult to see the value of a line without stations and questionable whether such a line could throughput the calculated 185 BART trains per hour or 350 light rail trains per hour.

The book acknowledges this and states that station stops are the capacity constraint on rail transit systems. In calculating the clearance times for these station stops dwell times are poorly dealt with and several factors are omitted—particularly issues of a train's initial acceleration diminishing rapidly, speed limits and/or grades entering and leaving stations, braking transition times (jerk limitation) and worst case braking conditions due to either equipment failures or adhesion limitations.

Other sources (Alle (R02) on dwell times, Auer (R09) on minimum headways and Motz (R47) on safety distances) provide methods to calculate minimum headways that include better treatments of dwell time and incorporate factors not considered in this book.

72 **WALSHAW, J. R.,** LRT On-Street Operations: The Calgary Experience, Transportation Research Board State-of-the-Art Report 2, *Light Rail Transit: System Design for Cost-Effectiveness, 1985. pp. 221-226*

Summary: This paper describes the operation of the 7th Avenue transit mall in Calgary, AB. In the peak hour, 176 trains and buses use the mall. Light rail headways were expected to be reduced from 5 min to 2.5 min with the opening of the Northeast Line in 1985. Light rail operation benefits from a progressive signaling system that keeps signal delays down to 7-8 % of mall travel time.

Comment: The paper provides useful information with respect to buses and light rail sharing a right-of-way.

73 **WEISS, DAVID M.,** and **FIALKOFF, DAVID R.,** Analytic Approach to Railway Signal Block Design, *Transportation Engineering Journal, February 1974*

Summary: This paper describes computer based methods to design a fixed-block signaling system for high capacity rail lines. Five programs were developed.

1. A passenger station dwell time program using information on passenger traffic, number and size of doors, distribution of passengers on the platform and train and the ratio of boardings to alightings.
2. 1A train performance simulator that produces train speed, time and location based on a line's grades and curves and on the train's traction performance.
3. A braking distance program that utilizes braking rates, jerk limitation and reaction times. This program calculates the worst case stopping distance plus safety margins—termed the *safe braking distance*—a function of speeds, curves, grades, braking rate, jerk rates, available adhesion and the reaction times of car-borne and wayside train control equipment. The exactness of the *safe braking distance* calculation contributes to higher capacity and eliminates the need for additional margins to be added—termed *ignorance factors.*
4. A minimum headway program utilizing the outputs from the above three programs.
5. 1A graphical plotting program.

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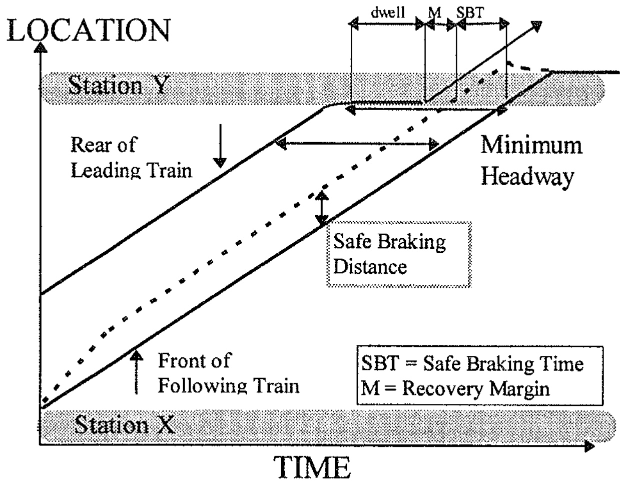
[29] Reviewer's Note: With multiple berth stations and without automatic train stops to allow operators to proceed through red signals on a *line of sight* basis.

A composite schematic of the final output is shown below:



NOTE *Recovery margin is operationally desirable but not essential.*

The paper describes the selection of cab signal speed commands, locating signal block boundaries and the development of the optimum train design profile.

An appendix calculates the value of train speed which minimizes headway as:

$$MT = \frac{V}{2B} + N + \frac{L}{V}$$

where MT = minimum headway in sec
V = constant train velocity
B = constant braking rate
N = brake application reaction time
L = train length

Differentiating this equation relative to V shows that for minimum headway:

$$V = \sqrt{2BL}$$

Substituting this optimum value of velocity back into the minimum headway equation results, relative to two trains traveling at a constant speed, in an expression for minimum headway that is independent of velocity:

$$MH = \sqrt{\frac{2L}{B}} + N$$

The authors warn that trains do not usually maintain constant velocity and that the factors influencing braking distance are continually changing, making the calculation of minimum headways more complex. In most situations it is the station stop times that determine the minimum headway—not the speed between stations.

Comment: This paper provides a useful and concise outline of signaling system optimization. In most cases the minimum headway is the station stop time, comprising the sum of the close-in time, dwell time and recovery margin. The paper shows that the braking distances that establish the close-in time can be approximated by quadratic functions of train velocity.

Braking distances cause large headways at high speeds—where between station maximum speeds may become the limiting factor in minimum headway. However the time to travel a train length—critical to the close-in time—will blow up hyperbolically at low speeds. "*In between lies a speed or profile that will optimize headway.*"

The paper tantalizingly offers a method to equate passenger volume with dwell times but offers no details.

74 WILKINS, JOHN D., and BOSCIA, J. F., Considerations For Effective Light Rail Street Operation,*Transportation Research Board State-of-the-Art Report 2, Light Rail Transit: System Design for Cost-Effectiveness, 1985: pp. 195-202*

Summary: Wilkins and Boscia outline their views on designing light rail for on-street operation. Some portions are relevant to capacity issues.

- Throughput is lower but this can be partially offset by train operation.
- Dwell times are longer with low platforms unless self-service fare collection and safety islands are used.
- Average speed is reduced because of pedestrian and vehicle interference.

Comment: The paper provides indications of capacity limitations with on-street light rail operation.

75 WILSON, NIGEL H. M., MACCHI, RICHARD A., FELLOWS, ROBERT E. and DECKOFF, ANTHONY A., Improving Service on the MBTA Green Line Through Better Operations Control, *Transportation Research Record 1361, 1992: pp. 296-304*

Summary: Wilson *et al.* examine the operational control system of the MBTA Green Line light-rail system in Boston in this paper. Particular attention is paid to methods of maintaining even headways, such as short-turning, express running and deadheading, in order to maintain as even a service as possible.

The existing operating practice relies on the intuition of inspectors stationed in the subway stations to decide the action to be taken to maintain service. Interestingly, all the correctional methods described are applied in the downtown portion of the line, not the outlying branches. The actions of the inspectors were examined by the authors and found to be generally beneficial to reducing passenger travel time. The researchers also created a correctional decision making routine for each line which is based on the preceding and following headways for each train. A different routine is required for each line given the discrete riding patterns on the individual branches. This framework would take much of the guess work out of dispatching and further reduce the number of deleterious dispatching decisions.

Determining the following headway is not possible with the current manual train supervision methods but this problem will be more readily corrected with utilization of the recently installed Automatic Vehicle Identification (AVI) system for field dispatching. While the AVI system does not automatically calculate preceding and following headways, the authors argue that modification of to the AVI system could enable automatic headway calculation and so make correctional actions still more effective.

Comment: This paper examines the operational control of the busiest light rail system in the United States. The discussions of maintaining even headways are highly relevant to the provision of capacity on any rail transit line. As the authors point out, their work is especially applicable to the light rail systems in Philadelphia and San Francisco which, like Boston, have multiple surface lines funneling into a downtown tunnel trunk line.

76 **YOUNG J.A.,** Passenger Comfort in Urban Transit Vehicles, *Ontario Ministry of Transportation and Communications, 1976*

Summary: Contains useful tables:

- transit seat dimensions for several rail systems
- detailed car dimensions
- chart of ratio of door openings to car length
- transit vehicle entry step heights
- transit vehicle door flow rates

Useful recommendations on optimal door widths, aisle widths and interior designs. Data on car lighting, noise and vibration levels are not relevant to the TCRP A-8 study.

Comment: The seat data should allow the development of a North American rapid transit average which could avoid the complexity of determining floor space used by seats on a system by system basis. Equating the total door width along the side of a car as a percentage of the car's length and relating this percentage to boarding and alighting flows has merit.

A1.3 REVIEW SUMMARY

The literature review of North American Rail Transit Capacities and Capacity Analysis Methodologies has produced a wealth of information, data and methodologies.

A1.3.1 BASICS AND CAUTIONS

Several authors caution that there is no absolute determination of rail transit capacity, that capacity is subject to many variants which can change from mode to mode and system to system. There are several cautions concerning the accuracy of ridership information, particularly with respect to individual car counts under crowded conditions.

There is general agreement that the definition of rail transit capacity is the number of passengers that can be carried past a single point, in a single direction, in a single hour. Many authors discuss the relationship between peak hour and peak-within-the-peak capacity, others concentrate on the latter short term capacity. This results in an overstatement of a full hour's capacity.

One author argues that a case can be made that the peak-within-the-peak is the actual maximum capacity of the system and, if there were an adequate supply of passengers, that rate could be sustained for a full hour.[30] Several authors discuss this issue of supply versus demand, both with respect to capacity and in two cases with respect to the quality of service. Here the argument is that if service is provided that exceeds demand, the level of crowding will decrease and more passengers may be attracted.

A valuable input on this topic is the suggestion that new rail transit systems must move away from providing service based on the loading levels of older systems. If their goal is to attract riders then the quality of service must be improved. Three papers peripherally mention that this was the original goal of BART—that all passengers have a seat—subsequently lost to the realities of operating economics.

A1.3.2. INFLUENCING FACTORS

The literature clearly indicates the two major factors that, multiplied together, determine rail transit capacity. The first is line capacity, the throughput of trains per hour, the second is train capacity.

Line capacity is a function of two major factors, each of approximately equal weight. One is the time between a train starting from a station and the next train berthing at that station. This is a function of the train control system, both the type of system and the design of that type. For example the conventional three aspect signaling system can be designed for a minimum station separation of 55 sec, but is often, particularly for light rail, designed for longer separation times which require fewer blocks and lower capital and maintenance costs.

The literature introduces several minor factors that influence line capacity. These include speed limits at station approaches and exits and the rapid fall off of the acceleration rate as a train gains speed. Three authors state that automatic train operation can increase throughput within a range of 5 to 15%. None provide data to support this proposition. Many of the discussions on line capacity fail to consider constraints due to junctions or turnbacks. Where such limitations are discussed it is invariably without the detailed analysis that has been applied to the headway limitation at stations. Several papers indicated that the maximum or average speed of trains between stations is a factor in capacity. This is only true when a finite quantity of rolling stock is taken into account.

The second major factor pertaining to line capacity is the station dwell time. This is extensively dealt with in 26 papers, listed in the framework chapter, section 3.6.5. Suggestions range

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[30] Reviewer's Note: This argument glosses over the practice of several operators who insert one or more trains to handle the peak-within-the-peak demand, then remove them at the end of their run as the system cannot reliably sustain that number of trains over a longer period.

from using average or typical dwells in the 20- to 30-sec range, to a detailed methodology to calculate an upper control limit based on measured dwells over a peak hour at the busiest station.

The relationship between passenger movements and dwell times is a component of most dwell discussions. Those that included analysis concluded, without exception, that linear regression provided the most suitable fit for both rapid transit and light rail with high and with low loading. Three references improved the data fit by including the number of passengers onboard a car as a variable. One study used multiple regression and showed a small improvement in data fit with the variable of on-board passengers to the power of 2.0 or 2.5. One paper evaluated a variable to account for passenger actuated doors on the San Diego Trolley.

The literature contained many references to train or car capacity, methods of calculation based on net floor area, gross floor area and length of train, and examples of loading levels throughout North America. One paper contains useful information on capacity variations with different door and interior arrangements.

Although the literature had an abundance of information on these three major factors, train control throughput, dwell times and train or car capacity with one exception it was mainly silent on the fourth major capacity issue—policy. While this is a difficult area to analyze it can have a massive impact on capacity. Suggestions that new rail lines should be based on all passengers with a seat can reduce capacity, as normally defined, by a factor of three or four. In effect such policy issues are the most important of the four main rail transit capacity factors.

A1.3.3 GROUPING

The literature generally dealt clearly and specifically with the different modes, rapid transit, light rail, commuter rail and automated guideway transit. It became clear that for the purpose of capacity calculations the modes were better grouped by the types of operation. These groups are defined and presented in the framework chapter, section 3.3.

A1.3.4 LIGHT RAIL SPECIFICS

No fewer than 37 of the reviewed papers dealt specifically with light rail. In particular the issue of traffic engineering for shared right-of-way and grade crossings was extensively covered. Capacity issues on lines without full grade separation broke the literature into two groups. One group indicated that capacity was rarely an issue as the demand for service under such situations was far below the train headways that could be provided.

Other work suggested that capacity on lines with grade crossings was effectively limited to one train per traffic signal cycle.[31] Another suggested that where train length approached the street block length, one train every second traffic signal cycle was more realistic.

A1.3.5 STATION CONSTRAINTS

Beyond two unsuccessful attempts to equate dwell times with the level of crowding on station platforms there was little discussion in the literature on the impact of station constraints on capacity. This is not unreasonable as most of the station constraints impact the number of people using that station, that is the demand, not the capacity of the rail transit line.

A1.3.6 CONCLUSIONS

The literature has produced a wealth of information, methodologies and data so aiding this project to maximize its use of existing information and data.

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[31] Reviewer's Note: Papers that dealt with traditional streetcar operation suggested much higher throughputs—reaching as high as two or occasionally three single cars per cycleor over 100 cars per hour.

A2. APPENDIX TWO
Rail Transit Survey

This appendix is the result of Task 3 of the study.

> *Survey rail transit services in North America to determine system characteristics and factors that influence and constrain capacity.*

The survey was carried out in June and July 1994. Data have been updated using 1993 FTA Section 15 reporting contained in the 1993 National Transit Database, published in 1994.

A2.1 INTRODUCTION

A2.1.1 PURPOSE OF SURVEY

A telephone survey of North American rail transit systems was conducted to determine the availability of existing ridership data, capacity and capacity constraints from each system. The opportunity was also taken to ask other relevant questions regarding line and station constraints, dwell times, signaling systems, and other issues of relevance to the A-8 study. Table A 2.1 through Table A 2.4 show the systems surveyed by mode. The Vancouver SkyTrain and Toronto Scarborough RT lines are included in the rail rapid transit category as they are not typical of automated guideway transit in ridership and route characteristics.

A2.1.2 SURVEY METHODOLOGY

Letters were sent to the CEO or General Manager of each agency in mid April, 1994 requesting the designation of a contact person. 22 responses were received from 43 letters. Contact persons from non-responding agencies have been obtained by telephone query. Multiple mode systems often required separate contacts for each mode or division.

As a result of the principal investigator's work on a light rail system in Mexico City, English speaking contacts were obtained for four of the five Mexican rail systems and complete data acquired for two systems. Limited data was obtained for a third system. The remaining two systems were dropped after three telephone calls failed to get responses. Basic information and annual ridership was obtained from other sources to enable complete survey listings.

A questionnaire was developed from a relational database derived from APTA data and the initial analytic framework, showing each system and mode. System and vehicle data, including car dimensions has been incorporated in this database. The questionnaire was tested with a series of initial telephone interviews. It was not satisfactory and numerous changes resulted. A sample of the final questionnaire, completed for the Washington Metropolitan Area Transit Authority, is attached.

The survey itself was conducted in June and July 1994 with each system answering the same 24 questions. The same one page survey was used for all modes to ensure consistency in the study. For multi-modal systems, a separate questionnaire was completed for each mode. A few mode-specific questions were included to deal with unique aspects of particular modes, such as passenger actuation of light rail transit doors. Emphasis was also placed on determining the accessibility of each system to the mobility impaired and the resulting effects on service quality and capacity. When possible, ridership reports, car details and timetables were obtained. Information gathered from this survey was used to update and expand the database in preparation for the remainder of the study.

A variable in the survey was the level of interest and knowledge shown by the contacts. Many were enthusiastic to talk about their system and volunteered additional useful information. Other staff members were more restrained and only dealt with questions asked directly. In numerous cases the contact requested that the questionnaire be faxed to allow additional staff people to assist in answering the questions. Others wished to answer the questionnaire in written form to ensure accuracy. Project staff met these requests with some reservations as voice communication can convey nuances and useful asides which are not readily given in short written answers.

Sample Telephone Survey

TCRP A-8 DATA QUESTIONNAIRE

RT System ID: **54**
Washington Metropolitan Area TA

600 Fifth Street NW
Washington DC 20001

Telephone:202-962-1251 Date June 9th
Fax: 202-962-1133 Time

Contact: Mr. Larry Levin
Position: Rail Analyst
Department: Rail Services

Directional Route Miles	156.2
Number of Through Routes	5
Number of Stations	67
Total Vehicles	664
Peak Vehicles	442
Unlinked Passenger Trips	188,252,916
Passenger Miles	966,860,097
Revenue Vehicle Miles	36,035,610
Revenue Vehicle Hours	1,498,740
Total Operating Expense	$268,900,000.00
Fare Collection System	Turnstile Mag Tick.
Platform loading height	High
Wheelchair accessibility	Full

DATA FROM APTA AND OTHER SOURCES 1991/1992

1. Do you have individual route peak point ridership data by hour ☑ by trains ☑ by short time periods ☐ how many ___ mins?
   Do you have riding counts (ride-checks) ☑ **2-4/month**
   On systems with 4-car or longer trains. Do you have individual car counts for peak hours at the peak points on one or two representative days?
   ☑ ____
2. Do you issue ridership statistics or a summary? ☑ Can you send us this as a starting point? ☑ *Offer address, fax number.*
3. No of cars in trains? **2-4-6** ____
4. Are there any stations on the system which regularly experience pass-ups? ☐ Which route and station(s) ____
   sometimes at Union after commuter train arrives
   ____
5. Do you serve stadiums? ☑ have any event ridership? ☐ notice higher densities? ☑ ____
6. Do you have any station constraints that reduce ridership?
   Full parking lots ☐ ____Ticketing line ups ☐
   Long walks ☐ ____ Congested platforms ☐
   Other congestion ☐ ___ Safety/security issues ☐
   No transfers ☐____ Poor access ☐
   Transfer cost ☐ ____Other reasons ☐
   Not really, some may apply i.e. walks ____
7. Do you calculate the maximum capacity of the system in passengers per peak hour direction? ☑
   How? **170 x no. of cars**
8. What is the full peak-hour capacity of your cars? seats **68 / 80** standing total **170** *Use end of form if different car types.*
   Is this determined by a formula? ☐ **by experience** ____
   Is this an agency policy? ☐____
   Do you have any folding seats ☐ ____
9. Do you have any published standards or policies you can send us? ☑ **policy headway of 6 mins in peak** ____
10. Do you measure the ratio of ridership to capacity? ☐ ____
11. What type of signaling system is used? ____
    3 aspect cab signals with ATO ____
12. What is the closest headway scheduled? **2 mins**
    ____**00 secs**
13. What is the theoretical closest? ____**1 mins30 secs**
14. What limits the closest headway? Station Dwells ☑
    Turnbacks ☐ ____ Signaling ☑
    Station Approach ☐ ____ Single track ☐
    Junctions ☐ ____ Other ☐
    occasional turnback problems ____
15. Is driving manual ☐ or Automatic Train Operation ☑ If ATO is manual driving allowed or practiced ☑ ? **once a week/driver** ____
16. *If not tabulated above* Type of fare collection system?
    Cubic stored value, being upgraded____
17. *If not tabulated above* Wheelchair accessible ☐ ? Type?____
18. We are trying to relate stations dwells with passenger volume and door width to passenger flow per second. Do you have information on maximum station dwells, number of passengers entering and exiting a train versus stopped time.
    ☐ ____
    Contact rail superintendent Tom Ferer 962-2760 may have some dwell data ____
19. *Only for systems at or close to minimum headway.* We are interested in schedule adherence at close headways. Do you have peak hour, peak point information ☐ ?____
    Not to level you seem to want ____
20. *Only for heavy volume systems if there is no dwell data.* Later this year we may want to time dwells in the peak period at peak-point stations. Would this be possible? How should we set it up?
    Probably ____
21. *Only for LRT* Are car doors passenger actuated ☐ ? ____
    Does this cause any delays ☐ ____
    Do you have any data on such delays ☐ ____
22. *Only if accessible.* How many wheelchairs are carried each day ___, each month ____? Line

by line ______? Is there data on any delays so caused? ☐ **contact Avon Mackel 962-1083 for use data (Task 5)** ______________________

23. *Only where no APTA data (not CR)* Do you have dimensioned floor plans of major car types in order to determine number of seats, area for standing passengers and door widths? ☐ _____

24. **Further Notes and Comments**

Both Rohr (80 seats) and Breda (68 seats) are deemed to have same peak capacity of 170 and counts support this compares with manufacturers rated crush capacity of 220-230 respectively 2 min. headway from 2 6 min. services plus inserted extra train(s) __________

Possible dwell time survey location __________

Follow up wheelchair data in Task 5 __________

Very helpful & informative ________________

____

Use other side of form for more comments or information

Table A 2.1 Light rail systems surveyed

System Name	Abbreviation	Directional Route km	Lines	Stations	Unlinked Passenger Trips (1993)
Bi-State Development Agency (St. Louis)	Bi-State	61.2	1	18	7,920,000
Calgary Transit	CTS	57.6	2	31	32,614,900
Denver Regional Transportation District	Denv. RTD	17.1	1	14	
Edmonton Transit	ETS	22.4	1	10	3,458,000
Greater Cleveland Regional Transit Authority	GCRTA	43.0	2	29	4,113,683
Los Angeles County Metropolitan Transit Authority	LACMTA	69.5	1	21	11,809,196
Mass Transit Administration of Maryland	MTA	76.3	1	23	3,457,361
Massachusetts Bay Transportation Authority	MBTA	89.9	5	10	26,703,669
Metrorrey (Monterrey, Mexico)	Metrorrey	35.0	1	17	19,200,000
New Jersey Transit Corporation	NJT	13.4	1	11	2,986,781
Niagara Frontier Transportation Authority (Buffalo)	NFTA	20.0	1	14	8,209,120
Port Authority of Allegheny County (Pittsburgh)	PAT	77.9	4	4	8,837,078
Regional Transit Authority - New Orleans	RTA - N.O.	25.7	2		6,440,087
Sacramento Regional Transit District	SRTD	58.2	1	29	6,571,393
San Diego Trolley Incorporated	SDT	66.8	2	36	16,504,499
San Francisco Municipal Railway	SF Muni	80.0	5	9	39,331,872
Santa Clara County Transportation Auth. (San Jose)	SCCTA	62.8	2	30	6,245,385
Servicio de Transportes Eléctricos del DF (Mexico)	STE	25.7	2	18	
Sistema de Transporte Colectiva (Mexico)	STC	35.4	1	10	48,746,500
Sistema del Tren Eléctrico Urbano (Guadalajara)	SDTEO	47.9	2	29	64,000,000
Southeastern Pennsylvania Transportation Authority	SEPTA	111.5	7	8	38,065,812
Toronto Transit Commission	TTC	219.5	10	3	98,788,000
Tri-Met of Oregon (Portland)	Tri-Met	48.6	1	30	7,770,651

Table A 2.2 Rail rapid transit systems surveyed

System Name	Abbreviation	Directional Route km	Lines	Stations	Unlinked Passenger Trips (1993)
BC Transit (Vancouver)	BCT	56.0	1	20	33,799,000
Chicago Transit Authority	CTA	354.5	6	143	135,369,734
Greater Cleveland Regional Transit Authority	GCRTA	61.5	1	18	6,563,270
Los Angeles County MTA	LACMTA	9.7	1	5	3,748,200
Mass Transit Administration of Maryland	MTA	42.8	1	12	11,114,213
Massachusetts Bay Transportation Authority	MBTA	122.0	3	53	190,329,524
Metro-Dade Transit Agency (Miami)	MDTA	67.9	1	21	14,817,894
Metropolitan Atlanta Rapid Transit Authority	MARTA	130.0	2	29	65,005,000
MTA - New York City Transit	NYCT	793.1	12	469	1,178,121,493
Port Authority Trans-Hudson Corp. (New York/NJ)	PATH	46.0	4	13	61,814,595
Port Authority Transit Corporation of Pa. and NJ	PATCO	50.7	1	13	11,232,302
San Francisco Bay Area Rapid Transit District	BART	228.5	4	34	78,301,800
Sistema de Transporte Colectiva (Mexico City)	STC	314.6	9	135	1,387,324,600
Southeastern Pennsylvania Transportation Authority	SEPTA	122.4	2	76	94,332,492
MTA - Staten Island Railway (New York)	SIR	46.0	1	22	5,141,005
Soc. de transport de la Comm. urbaine de Montréal	STCUM	122.3	4	70	196,984,213
Toronto Transit Commission	TTC	152.4	2	60	311,080,000
Washington Metropolitan Area Transit Authority	WMATA	260.8	6	83	191,428,020

Table A 2.3 Commuter rail systems surveyed

System Name	Abbreviation	Directional Route km	Lines	Stations	Unlinked Passenger Trips (1993)
Connecticut Department of Transportation	Conn. DOT	105.6	1	7	274,021
GO Transit (Toronto region)	GO Transit	426.1	7	54	25,300,000
Mass Transit Administration of Maryland	MARC	600.8	3	38	4,747,380
Massachusetts Bay Transportation Authority	MBTA	852.4	11	101	21,595,853
Metropolitan Rail - Chicago	Metra	1,390.8	10	224	64,074,627
MTA - Long Island Railroad	LIRR	1,026.9	11	134	92,462,000
MTA - Metro-North Railroad	Metro-North	861.5	8	118	59,119,405
New Jersey Transit Corporation	NJT	1,885.1	12	157	45,806,216
North County Transit District (San Diego)	Coaster	132.3	1	8	
Northern Indiana Commuter Transportation Dist.	NICTD	222.7	1	27	2,531,169
San Mateo County Transit District (San Francisco)	CalTrain	247.1	1	34	5,745,654
Southeastern Pennsylvania Transportation Authority	SEPTA	712.5	7	154	19,018,730
Southern California Regional Rail Auth. (Metrolink)	SCRRA	748.6	5	35	939,456
Soc. de transport de la Comm. urbaine de Montréal	STCUM	180.2	2	31	8,700,000
Tri-County Commuter Rail Authority (Miami)	Tri-Rail	213.7	1	15	2,697,456
Virginia Railway Express	VRE	260.3	2	16	1,394,419

Table A 2.4 AGT systems surveyed

System Name	Abbreviation	Directional Route km	Lines	Stations	Unlinked Passenger Trips (1993)
Detroit Transportation Corp.	DTC	4.6	1	13	2,518,916
Jacksonville Transportation Authority	JTA	1.9	1	3	301,478
Metro-Dade Transit Agency (Miami)	MDTA	6.3	3	21	2,343,571
West Virginia University	Morg. PRT	11.6	1	5	4,800,000

A2.2 RIDERSHIP INFORMATION

A2.2.1 COLLECTION AND AVAILABILITY OF RIDERSHIP INFORMATION

Ridership data collected from agencies is presented in Appendix Three *Data Tabulations*. Not all information categories requested are included in the appendix and reference may be made to the files on the computer disk for categories not appearing in the tables in the appendix.

Ridership information for systems using the proof of payment fare system (most light rail transit, some commuter rail and one rail rapid transit system) is generally derived from ticket machine revenue. Data from ride checks is used to give a ratio between fare revenue and the number of passengers riding the system. This ratio is then used to calculate ridership on a more regular basis than would be affordable with ride checks alone. A contact at BC Transit, which uses this technique, emphasized its inaccuracy.

In several cases the mailed ridership count material has contained more information than the contact indicated was available. Some contacts have also discussed their data with considerable skepticism regarding its accuracy In discussions with contacts of systems operating at or near minimum headway, the importance of station dwell times in governing headway was apparent.

Only a few systems had data for loading of individual cars in a train. Sufficient information for assessing the second level of diversity—uneven loading between cars in a train—was available for a number of rapid transit systems.

Commuter rail systems generally had the most exhaustive collections of ridership data. This is made possible by the use of conductors to collect fares and count passengers. Some agencies, however, remarked that conductor counts tended to overstate ridership in comparison with the results from dedicated ride-checking staff. Efforts to improve the accuracy of the conductor counts were being made to remedy this situation.

Most commuter rail operators were able to provide line-by-line ridership summaries along with station on/off data for all trains operated. Peak hour and peak 15-min ridership for commuter rail was generally calculated from train-by-train data.

Given the limited number of Automated Guideway Transit systems and their small size, little information could be collected regarding this mode. To supplement the information on AGT gathered during the survey, Chapter One *Rail Transit in North America* includes a table of AGT ridership data compiled from *Trans 21* data.

In summary, for the 52 systems surveyed, the ridership information indicated in Table A 2.5 is available. The commuter rail systems account for the bulk of the systems providing station on/off data.

It should also be noted that, where counts by train are available, hourly ridership and ridership by short time periods can be derived from that information if not presented separately.

Table A 2.5 Summary of available ridership information (all modes)

Information Type	Number	Percent
Counts by hour	26	43
Counts by train	36	59
Counts by short time periods	13	21
Station on/off data	11	18
Individual car counts	12	20
Ridership summary	50	82
Total number of systems	61	

A2.3 CAPACITY AND POLICIES

Much car capacity information was compiled from APTA data before the telephone survey commenced. Where possible the information was checked with other sources and agency contacts to confirm its accuracy. This data can be found in Appendix Three *Data Tabulations* to this report. Train lengths were determined from agency contacts.

Some contacts were able to provide floor plans of their cars while others indicated that these would be available if required.

A2.3.1 LOADING STANDARDS

Acceptable loading standards varied between modes and systems. Light Rail cars are generally designed to seat most passengers in the off-peak. Loading standards for rail rapid transit systems were found to vary considerably between agencies. An example of this contrast can be seen by comparing load factors between San Francisco's BART and New York's PATH. In this example, load factors are the number of passengers on the car divided by the number of seats. BART passengers are reported as accepting load factors up to 1.5 on a regular basis, although 2.5 was reached following the 1988 Loma Prieta earthquake. PATH, on the other hand, uses a load factor of 4.1 as its standard car capacity index.

Commuter rail carriers attempt to provide one seat per passenger and standing is rare although it is generally considered acceptable near the downtown terminals. The sole exception is on the Long Island Rail Road between Jamaica and Penn stations where standing loads are common in the peak hours. Agencies whose cars have 2+3 seating observed that passengers will often stand voluntarily rather than sit three to a bench.

Automated guideway transit offers an extreme alternative to the all-seated policy of most commuter rail agencies. Miami's Metro-Mover supplies only 8 seats for a car with a total capacity of 100 passengers. Such a situation is made acceptable by the short trips typical of circulator systems. While these loading levels are also common on airport AGT systems, leisure systems generally offer a seat per passenger.

A2.3.2 TRAIN LENGTH

Train length for light rail transit systems is limited by the length of street blocks in sections of street running. This is a problem not faced by the other modes with the occasional exception where commuter trains could interfere with grade crossings when stopped.

Systems handle the light rail transit block length problem in different ways. In Portland, Tri-Met is limited to running two-car trains by the short blocks in that city's downtown. SRTD in Sacramento runs four-car trains at peak hours resulting in blockage of cross-streets during station stops downtown. This is evidently made possible by a relaxed attitude on the part of the city street department. The San Diego Trolley takes still another approach and splits four-car trains in half before they enter the downtown street-running portion of the line.

A2.3.3 PASS-UPS

Few systems reported regular pass-up situations on their lines. Conditions caused by unplanned service irregularity are not included in this tabulation. New York City Transit was an exception with pass-ups reported on a regular basis. Further inquiries suggest that three of 11 NYCT trunks in Queens and Manhattan are overloaded. Pass-ups are also routine in Mexico City and occur to a lesser extent on systems in Montreal, Toronto and Vancouver.

Pass-ups were reported on four light rail transit and two commuter rail systems with none on AGT systems. However, the light rail transit and commuter rail pass-ups are atypical for these modes and the study team doubts that they are routine.

For other systems, pass-ups were often voluntary as a result of passengers waiting for less crowded vehicles. This was particularly the case at rail rapid transit stations adjacent to downtown commuter rail terminals. Washington's WMATA reported pass-ups to be a problem when commuter trains arrived at Union Station during peak hours.

In general, pass-ups were limited to stops near the edge of downtown during narrow time periods. This was the case in Edmonton where the recent light rail transit extension south to the University has boosted ridership by 50% and caused trains to become full before leaving the north edge of downtown. This may be a temporary situation.

A2.3.4 EVENT RIDERSHIP

In response to the panel's request, systems serving sports stadiums were identified and asked whether they had specific ridership figures for special events. Many agencies do keep some track of the patronage gained from such service. Most of this information is in the form of estimates of ridership and travel market share. Little information about high car loading was available although BC Transit reported loads 25% in excess of standard peak-hour maximum car capacity.

A2.3.5 RIDERSHIP/CAPACITY RATIO

Remarkably few agencies aside from commuter rail operators indicated that they regularly calculated a ridership/capacity ratio. Many calculations of this information were made while on the telephone. This ratio was more commonly available immediately from those agencies with a policy load factor.

Calculation of maximum system capacity was also often handled in the same way. Unfortunately such calculations frequently produced the current capacity of the system with the existing fleet rather than the ultimate capacity by failing to take into account increased train frequency and other possible service enhancements.

A summary of data collected on the subjects above is presented in Table A 2.6.

Table A 2.6 Summary of additional ridership and service information (all modes)

Information Type	Number	Percent
Regular Pass-ups	10	16
Event Ridership	17	28
Ridership/Capacity Ratio	21	34
Measured Dwell Times	12	20
Schedule Adherence	22	36

Commuter rail is strongly represented in the measurement of ridership/capacity ratios and schedule adherence. Both of these indicators are monitored closely by most commuter rail operators, especially when service or track usage is provided on a contract basis.

A2.4 HEADWAY LIMITATIONS

As shown in Table A 2.7, headway constraints varied by mode. One difficulty found with the answers to this question is that staff of systems not running at maximum capacity were not familiar with the *ultimate* constraints faced by their system. This concern would be particularly marked for dwell time, turnback and junction effects which would not be as evident with low service frequencies.

A2.4.1 SIGNALING

A majority of contacts (67%) reported signaling to be a major constraint on their systems. In many cases the signaling system was designed to accommodate a level of service below the maximum that could be provided given right-of-way and vehicle characteristics. Reported actual and theoretical minimum headways are shown in Table A 2.8. This allowed systems with relatively long headways to report signaling as a constraint. This is illustrated by the Edmonton light rail transit line which has already reached its minimum theoretical headway of five minutes despite operating on a largely grade-separated line with full grade crossing protection. The Calgary light rail transit system, which uses the same vehicles and has less right-of-way protection, operates every three minutes on signaled sections with higher frequencies possible on the downtown transit mall.

Table A 2.7 Headway constraints by mode (excludes those systems for which responses were not obtained)

Constraint	Light Rail Transit		Rail Rapid Transit		Commuter Rail		Automated Guideway Transit		Total	
	No.	%	No.	%	No.	%	No.	%	No.	%
Signaling	12	63	13	72	11	69	2	50	38	67
Turnbacks	3	16	5	28	2	13	0	0	10	18
Junctions	1	5	2	11	2	13	0	0	5	9
Station Approach	1	5	1	6	2	13	0	0	4	7
Single Track	6	32	1	6	3	19	1	25	11	19
Station Dwells	6	32	5	28	3	19	2	50	16	28
Other Constraints	3	16	0	0	7	44	0	0	10	18
Number of Systems	19		18		16		4		57	

Table A 2.8 Minimum headways for systems surveyed

Type	System	Minimum Headway (min:secs)	
		Operated	Theoretical
LRT	CTS	3:00	2:00
LRT	Denv. RTD	5:00	2:30
LRT	ETS	5:00	5:00
LRT	GCRTA	6:00	2:00
LRT	LACMTA	6:00	3:00
LRT	MBTA	0:45	N/A
LRT	MTA	15:00	15:00
LRT	NFTA	5:00	2:00
LRT	NJT	2:00	0:15
LRT	PAT	3:00	3:00
LRT	SCCTA	10:00	N/A
LRT	SDT	4:15	5:00
LRT	SDTEO	5:00	3:50
LRT	SEPTA	1:00	0:30
LRT	SF Muni	2:37	1:00
LRT	SRTD	15:00	15:00
LRT	STC	2:00	2:00
LRT	Tri-Met	3:00	3:00
LRT	TTC		N/A
RT	BART	3:00	2:30
RT	BCT	1:35	1:30
RT	CTA	2:45	N/A
RT	GCRTA	6:00	2:00
RT	LACMTA	6:00	3:00
RT	MARTA	8:00	1:30
RT	MBTA	3:30	3:00
RT	MDTA	6:00	3:00
RT	MTA	6:00	1:30
RT	NYCT	2:00	2:00
RT	PATCO	2:00	1:30
RT	PATH	3:00	1:30
RT	SEPTA	3:00	3:00
RT	SIR	2:00	2:00
RT	STC	1:55	1:55
RT	STCUM	2:30	2:30
RT	TTC	2:27	2:00
RT	WMATA	3:00	1:30
CR	CalTrain	5:00	5:00
CR	Coaster		N/A
CR	Conn. DOT	20:00	N/A
CR	GO Transit	10:00	10:00
CR	LIRR	3:00	3:00
CR	MARC	30:00	N/A
CR	MBTA	8:00	8:00
CR	Metra	3:00	3:00
CR	Metro-North	2:36	2:00
CR	NICTD	12:00	N/A
CR	NJT	3:30	3:30
CR	SCRRA		20:00
CR	SEPTA	5:00	5:00
CR	STCUM	10:00	9:00
CR	Tri-Rail		N/A
CR	VRE	10:00	N/A
AGT	DTC	3:30	2:30
AGT	JTA		N/A
AGT	MDTA	2:00	1:10
AGT	Morg. PRT	0:15	0:15

Notes: N/A indicates not available and/or applicable. Minimum headways for many commuter rail systems are a result of the contract with the host railroad and are not due to practical headway constraints.

On some rail rapid transit lines and light rail transit trunks headways have reached the minimum possible with the current signaling system. In these cases efforts are being made to upgrade the signaling to allow more frequent service. Even relatively recent and advanced signal systems such as those on BART and the MUNI Metro subway have reached their limits and are being replaced with more capable technology.

The shortest theoretical headways given represented the extreme ends of the spectrum. New Jersey Transit's Newark City Subway, operating PCC cars with wayside automatic block signals, was quoted as having a minimum headway of 15 sec. Such frequencies are made possible by manual operation at relatively low speeds, possibly with red signals taken as advisories, and multiple station berths. Similar conditions permit SEPTA to operate light rail vehicles 30 sec apart.

For fully signaled systems, Metro-Dade's MetroMover AGT has a minimum theoretical headway of one minute and 10 sec. A large number of rail rapid transit systems reported minimum theoretical headways of one minute, 30 sec but such frequencies are only regularly operated on BC Transit's SkyTrain. Here, trains currently operate as close as every minute and 35 sec. This is made possible with the Seltrac moving block signal system. The Morgantown PRT can operate at exceptionally close 15-sec headways thanks to the use of small vehicles and off-line stations.

The issue of light rail transit street running is related to signaling in its effects on limiting headways. The only light rail transit operation to cite street running as a headway limitation was Baltimore. Given that the current headway on the line is 15 min, it is unlikely that this is a practical problem. Traffic congestion was reported as a problem for the Toronto streetcar system but this is not a typical contemporary light rail transit operation. Also of relevance is the practice of the San Diego Trolley of splitting long trains when they enter downtown. This increases the number of trains operating on street but apparently has not caused an operational problem on the line segment governed by traffic signals.

Signaling of commuter rail systems is a very complex area given the wide variety of signal types which can be found on some of the systems surveyed. Complicating this are factors such as ownership of track by other than the operating agency and discrepancies between signaling practices between railroads. Even the two large New York commuter rail operations, Metro-North and the Long Island Railroad, reported signaling ranging from centralized traffic control (CTC) to manual block system (MBS) despite controlling almost all of their lines. In many commuter rail operations, headways are limited by the contract with the host railroad and not by the signaling system.

A2.4.2 TURNBACKS

Turnbacks were cited as a problem on five rail rapid transit systems, three light rail transit systems and two commuter rail services. Turnbacks are a common limitation when line capacity is neared or where a rapid turnaround is required to maintain schedules. The latter is the case on the Los Angeles light rail Blue line where the train operators drop back one train in order to minimize terminal time. The other light rail transit operator facing turnback difficulties is SEPTA which operates a number of high frequency routes converging on a central terminus. However, as this terminus is a loop, the delays may be more properly attributed to long dwell times resulting from passengers boarding and alighting.

Rail rapid transit agencies with intense service, New York, Boston and Vancouver, indicated turnbacks as a constraint. Staff in Los Angeles claim that the Red Line subway also faces this constraint despite long (6 min) headways.

Commuter rail contacts rarely indicated turnbacks as being a problem. This is understandable since in many cases equipment is only able to make one peak direction trip in each peak period. Agencies identifying this factor as a problem were GO Transit and New Jersey Transit. The latter stated that trains required a minimum 30-min turnaround time at New York's Penn Station before returning to service.

A2.4.3 JUNCTIONS

Junctions are a minor constraint with only five of 57 systems reporting them as limitations. The relevant rail rapid transit systems are the CTA and SEPTA. Commuter rail operators facing this difficulty are Chicago's Metra and New York's Metro-North. Other busy systems avoid this problem through the use of *flying* junctions which obviate the need for at-grade crossings. A recently installed rail/rail underpass west of Toronto's Union Station provides a relatively simple example of this technique.

A2.4.4 STATION APPROACH

This limitation was cited even less often than junctions by agency contacts with only three systems indicating difficulty. BC Transit was the only rail rapid transit system to give station approach as a problem. In this case, the station approach difficulty is a result of turnback limitations at the downtown terminus and may perhaps be better seen as a turnback problem. The two New York commuter rail operators, Long Island Railroad and Metro-North, both encounter this constraint at their large, congested Manhattan terminals.

A2.4.5 SINGLE TRACK

Single Track operation was a difficulty primarily encountered by light rail transit (32%) and commuter rail (19%) operators.

Light rail transit single track operation has been reduced in Portland, Sacramento and San Diego, through double tracking projects. San Diego has eliminated single track from its current network but the Santee extension which is under construction will feature a single track section limiting headways to 15 minutes. The new light rail transit line in Baltimore also features considerable single track operation but this route has been designed to allow double tracking in the future. Older light rail transit lines with single track running include SEPTA's Media and Sharon Hill routes.

Single track is also a problem on some of the newer commuter rail lines where passenger train service has brought substantial increases in the number of trains operated. This is the case on the Los Angeles Metrolink and San Diego Coaster services, and on the Tri-Rail line in southern Florida. A number of other commuter rail operations also reported *double* track as being a limitation. Such was the case for Maryland's MARC service on portions of Amtrak's busy Northeast Corridor Line.

A2.4.6 STATION DWELLS

Station dwells were found to be an important limitation on capacity with 28% of agencies indicating them as a headway limitation. Station dwells and related topics are discussed in section.

A2.4.7 OTHER HEADWAY CONSTRAINTS

While only 18% of all systems gave other headway constraints, 44% of commuter rail operators responded to this category. The principal reason for this is that most commuter rail systems operate on tracks owned by other railroads and so must rely on the track owner to provide pathways for commuter trains. This constraint seemed to be the strongest for the MARC and Virginia Railway Express services in the Washington DC region which have faced great resistance from the owning railroads to the operation of additional trains.

While in most cases commuter trains operate on tracks owned by freight railroads or Amtrak, Philadelphia's SEPTA also owns some track used by the freight companies. This gives SEPTA a better bargaining position for those commuter routes which operate over freight trackage. In other areas, such as Chicago and southern California, the commuter rail agencies are acquiring lightly used track from the freight railways. While this imposes a maintenance burden on the commuter rail agency, it does allow a greater priority to be accorded to the passenger service.

Two light rail transit systems reported other constraints, Toronto for extensive street running and SEPTA for delays due to electronic fare boxes. The latter factor extends dwell times and is unique to those few light rail operations with on-board fare collection.

A2.5 STATION LIMITATIONS

Table A 2.9 indicates the constraints that limit capacity at rail transit stations.

A2.5.1 FULL PARKING LOTS

By far the largest station constraint reported by systems was that of full park and ride lots. 56% of all systems noted a shortage of parking space but the response was even stronger from commuter rail systems with 81% indicating full lots. The importance of parking to ridership can often be linked to the orientation of the system towards suburban or urban customers with the former requiring more parking.

Some commuter rail systems, such as Chicago's Metra, have taken to establishing "cornfield" stations whose main purpose is to allow the construction of park and ride lots outside population centers.

A2.5.2 TICKETING LINE-UPS

Ticket purchase line-ups were generally not a problem except near month-end when monthly pass purchases are made. Pass purchase queues were especially pronounced for commuter rail systems with a number of agencies offering ticket by mail programs to reduce line-ups at stations. The San Francisco CalTrain peninsula commuter rail service offers an incentive of a 2% discount on passes sold by mail, in comparison to the service charge made by other operators.

Table A 2.9 Station constraints by mode (excludes those systems for which responses were not obtained)

Constraint	Light Rail Transit		Rail Rapid Transit		Commuter Rail		Automated Guideway Transit		Total	
	No.	%	No.	%	No.	%	No.	%	No.	%
Full Parking Lots	10	53	9	50	13	81	0	0	32	56
Ticketing Line-ups	1	5	2	11	4	25	0	0	7	12
Congested Platforms	1	5	2	11	2	13	0	0	5	9
Other Congestion	0	0	2	11	0	0	0	0	2	4
No Transfers	0	0	1	6	2	13	0	0	3	5
Transfer Cost	3	16	2	11	1	6	0	0	6	11
Safety and Security	4	21	4	22	5	31	1	25	14	25
Long Walks	5	26	5	28	4	25	0	0	14	25
Poor Access	1	5	0	0	3	19	0	0	4	7
Other Reasons	1	5	1	6	2	13	0	0	4	7
Number of Systems	19		18		16		4		57	

A2.5.3 CONGESTED PLATFORMS

Platform congestion was a relatively small problem confined to the two most heavily used rail rapid transit systems (New York and Mexico City) and the two largest commuter rail systems (Long Island and Metra.) The only light rail transit system reporting congested platforms is the STC in Mexico City, however, their light rail transit line is light rail in name only and has most of the characteristics of a rail rapid transit system.

A2.5.4 OTHER CONGESTION

Only Mexico City and New York experienced trouble with congestion at additional locations. In the case of New York, entry and exit turnstiles create congested conditions for passengers.

A2.5.5 NO TRANSFERS—TRANSFER COST

Most responses here were due to a lack of fare integration between modes and the practice of levying a surcharge for transfers. Most systems without fare integration indicated that work was being done to remedy the situation. New York's MTA is working to permit bus-subway transfers.

Another factor, particularly for commuter rail and some rail rapid transit lines, is the convenience of the downtown terminals to workplaces since a well located terminal can obviate the need for many transfers. Such is the case with PATCO's route in Center City Philadelphia.

A2.5.6 SAFETY AND SECURITY

A quarter of the systems surveyed indicated that concerns over safety and security could have an effect on ridership. These concerns were greatest on large, urban systems but were also apparent on smaller light rail transit lines (Sacramento, Edmonton) during the evening.

While most commuter rail trains were viewed as being safe, parking lot security was a major concern at many systems. This problem is also experienced on some rail rapid transit lines with one parking lot on the BART line in Oakland not filling largely as a result of security issues.

A.5.7 LONG WALKS—POOR ACCESS

A quarter of all systems reported access problems with there being very little differentiation between each mode. Some of the factors which influenced these answers included poor station location, poor station design and large park and ride lots.

A2.5.8 OTHER STATION CONSTRAINTS

Two systems reported short platforms as being limitations, the GCRTA rail rapid transit line in Cleveland and the Long Island Railroad. In the former case the platforms on the affected line segment are being lengthened to eliminate the constraint. On the LIRR station length is limited by the presence of adjacent grade crossings.

Another difficulty reported on commuter rail systems, particularly in low density areas, is a lack of feeder buses to and from stations. This is being remedied in some areas by the use of dedicated feeder buses from rail stations to important work sites.

A beneficial station effect has occurred at Trenton, NJ where SEPTA and New Jersey Transit service connect to offer travel between Philadelphia and New York. This has increased the ridership on both systems.

A2.6 DWELL TIMES

A number of factors affect rail transit dwell times. Two of the most important are platform height and method of fare collection. Wheelchair access is also of importance and this is dealt with in detail in section below. Appendix Three contains tables of these factors for each system surveyed.

As noted in Table A 2.6, only 20% of systems have dwell time data, some of which was noted as being outdated and of questionable value. Passenger flow through doors was not immediately available from any system. Car door widths have also been determined for many systems, these are included in the tabulations of Appendix Three.

Some systems were able to supply policy dwell time information. The San Diego Trolley has a policy minimum dwell of 20 seconds while Boston's MBTA has policy dwells at each of its rail rapid transit stations ranging from 15 to 30 sec. Some systems, such as Calgary's light rail transit and the TTC subway, have an enforced safety delay of a few seconds once the doors have closed before the train can move.

Dwell times on commuter rail lines ranged widely depending on car design and station usage. New Jersey Transit gave a range of 20 sec to 8 min depending on the line and station. The Long Island Railroad also operates a variety of equipment resulting in dwell times being more of a problem for conventional, low-loading, diesel-hauled trains than on electric multiple unit trains designed for rapid, high-level boarding and alighting.

A2.6.1 FARE COLLECTION

Fare collection effects on dwell times are principally a light rail transit issue although fares are collected on-board by the operator on exceptional rail rapid transit lines, as on Cleveland's Red Line. Fare collection by a conductor, as used in Chicago and on many commuter rail lines, does not affect dwell times.

Fare collection by the light rail transit operator is exclusive to the older light rail transit lines. Even here, fare collection in the Central Business District (CBD) is usually handled by station agents to ensure high passenger flow capacities. SEPTA reported that the addition of electronic fareboxes to its light rail transit fleet has also resulted in extended dwell times outside the CBD.

All new light rail transit lines, some commuter rail operators and one new rail rapid transit line have opted for the proof of payment (PoP) system which eliminates any effect of fare collection on dwells. This system is also used on the heaviest streetcar line in Toronto to allow all car doors to be used for boarding and alighting and so reduce dwells.

Seven of the rail rapid transit systems surveyed use turnstiles which accept magnetically encoded tickets and passes to speed passenger movements. The use of automated ticket vending machines (TVM's) is also becoming widespread, both in conjunction with proof of payment fare systems and as a way to speed ticket purchase for other fare systems.

A2.6.2 PLATFORM HEIGHT

Platform elevation has a considerable effect on dwells since low-level platforms necessitate the use of steps on the car to reach the passenger areas. Rail rapid transit and AGT systems universally feature high platform loading with its inherent speed advantages. Light rail transit and commuter rail systems featured both high and low level boarding, with some lines allowing both through the use of dedicated doors and/or moveable steps. The latter solution is used on the MUNI Metro network in San Francisco to allow high-capacity operation in the downtown subway and traditional street running on the surface. In the subway one door cannot be used due to the car's end taper.

A2.6.3 WHEELCHAIR EFFECTS

Wheelchair boarding and alighting can have major effects on dwell times, particularly when some form of boarding aid, such as a lift, is required. The accessibility of the systems in this study is summarized in Table A 2.10. Light rail transit and commuter rail systems use a wide variety of wheelchair access methods ranging from level loading to car and platform mounted lifts. The only light rail operation to use car-mounted lifts is the San Diego trolley, all later systems use platform lifts or special mini-high platforms which provide access to the accessible location on each train. The low-floor car, which overcomes much of the accessibility problem, is not yet in use in North America; however, Portland and Boston have ordered cars of this type.

Table A 2.10 Summary of wheelchair accessibility

Type	Accessibility			Total
	None	Partial	Full	
Light Rail Transit	6	3	10	19
Rail Rapid Transit	3	8	7	18
Commuter Rail	2	9	5	16
AGT	0	0	4	4
Total	11	20	26	57

A2.7 SCHEDULE ADHERENCE

36% of the systems surveyed (see Table A 2.6) indicated that they measure on time performance on a regular basis and it is likely that all of the commuter rail systems measure this variable, whether this was reported or not. Schedule adherence for commuter rail is important in the case of contracted service where this data can be a determinant of the fees paid to the contractor.

A2.8 COMMENTS AND RESULTS

With the survey complete, an adequate range of data; by peak hour, peak-within-the peak, individual trains and individual cars selected operators) was obtained for use in Task 5.

Although several agencies have and can make riding counts (ride-checks) available, these do not always clearly show dwell times relative to the passengers boarding and alighting, nor do they show levels of crowding in the cars and on the platforms. Such dwell time data and wheelchair boarding and alighting times were the principal areas for the field data collection requirements of Task 5.

The telephone survey achieved its goals with only a few systems not responding satisfactorily. Most agency contacts have proved to be quite helpful and accommodating. Information gathering to supplement the survey continued during the remainder of the project. The valuable contacts made during the survey were invaluable for the field data collection component of the project.

A3. APPENDIX THREE
Data Tabulations

A3.1 INTRODUCTION

This appendix compiles much of the basic information contained in the database assembled for this project. The complete database, in Microsoft Access 2.0 format, is included on the companion computer diskette to this report.

Not all the information categories listed could be determined for each operator, route, car type, etc. as a result of inadequacies in the data supplied by transit agencies and existing compilations. Particular emphasis was placed on getting as much information as possible from the major U.S. and Canadian operators.

The data used are as up-to-date as possible and were collected from agencies between April 1994 and May 1995. Data were updated where appropriate during the course of the study. As many of the basic statistics (primarily in Table A 3.1) were determined from the FTA's 1993 National Transit Database, systems which commenced operation in 1993 and later may not have complete operating statistics. This applies, for example, to Bi-State's Metrolink light rail transit line in St. Louis and the Metrolink and Coaster commuter rail services in Southern California.

A3.2 NOTES ON THE TABLES

Route ridership information was generally compiled directly from agency data. Peak-hour and peak 15-min flows were often calculated from individual train counts, particularly for commuter rail. In these cases, calculations were based on strict definitions of the time periods considered. For example, if trains were scheduled to arrive at 7:30, 8:00 and 8:30, the peak hour would be determined by the sum of the loads on either the first pair or second pair of trains, not all three. This ensures that the time interval examined does not exceed the stated interval as including all three trains would give an interval of up to 1 hour, 59 sec.

The table of trunk lines (Table A 3.4) does not include the Mexican systems; they can be found in Table A 3.3. The figures in the minimum operated headway column should be used with care, particularly for commuter rail where multiple-track lines and station approaches can allow simultaneous movements on parallel tracks.

The total car capacity figures in Table A 3.5 should also be used cautiously as each agency has its own standards for determining this value. Scheduled loading levels were used wherever possible, often based on a standing density of $4/m^2$. In some cases transit agencies provided the manufacturer's maximum stated load; often at a "crush" loading level not acceptable in regular service. Chapter Five, *Passenger Loading Levels,* discusses loading levels and provides recommendations.

Table A 3.1 Rail transit annual operating statistics

Type	System	Directional Route km	Lines	Stations	Total Vehicles	Peak Vehicles	Revenue Vehicle km (000's)	Revenue Vehicle Hours	Unlinked Trips (000's)	Total Mode Expense (000's)
AGT	DTC	4.7	1	13	12	8	797	42,720	2,519	$7,486
AGT	JTA	1.9	1	3	2	2	120	5,225	301	$681
AGT	MDTA	6.3	3	21	27	19	572	32,504	2,344	$7,639
AGT	Morg. PRT	11.6	1	5	71	65	2,027	174,000	4,800	$3,200
CR	CalTrain	247.1	1	34	93	84	5,544	110,984	5,746	$34,574
CR	Coaster	132.3	1	8	16					
CR	Conn DOT	105.6	1	7	25	13	656	9,783	274	$5,073
CR	GO Transit	426.1	7	54	322	259	2,574		25,300	$156,661
CR	LIRR	1,026.9	11	134	1,184	967	87,401	1,662,810	92,462	$620,917
CR	MARC	600.8	3	38	135	103	7,581	110,861	4,747	$32,188
CR	MBTA	852.4	11	101	337	291	25,310	533,249	21,596	$106,385
CR	Metra	1,390.8	10	224	1,034	955	50,278	960,324	64,075	$298,193
CR	Metro-North	861.5	8	118	792	696	59,973	992,747	59,119	$430,944
CR	NICTD	222.7	1	27	50	39	3,236	57,236	2,531	$22,243
CR	NJT	1,885.1	12	157	748	628	62,361	1,032,375	45,806	$334,161
CR	SCRRA	748.7	5	35	99	67	1,196	19,525	939	$18,954
CR	SEPTA	712.5	7	154	329	263	17,359	413,953	19,019	$139,786

Table A 3.1 Rail transit annual operating statistics (continued)

Type	System	Directional Route km	Lines	Stations	Total Vehicles	Peak Vehicles	Revenue Vehicle km (000's)	Revenue Vehicle Hours	Unlinked Trips (000's)	Total Mode Expense (000's)
CR	STCUM	180.2	2	31	128			104,000	8,700	$49,400
CR	Tri-Rail	213.7	1	15	31	25	3,693	57,032	2,697	$19,701
CR	VRE	260.3	2	16	69	49	1,502	26,519	1,394	$11,773
LRT	Bi-State	61.1	1	18	31					
LRT	CTS	57.6	2	31	85	72				$20,809
LRT	Denv. RTD	17.1	1	14	11	10				
LRT	ETS	22.4	1	10	37	24	2,033	1,263,282	3,458	
LRT	GCRTA	43.0	2	29	46	35	1,562	43,822	4,114	$10,838
LRT	LACMTA	69.5	1	21	54	36	4,609	149,875	11,809	$43,732
LRT	MBTA	89.9	5	10	229	194	2,332	95,823	26,704	$26,109
LRT	Metrorrey	35.4	1	17	70					
LRT	MTA	76.3	1	23	34	30	1,969	75,962	3,457	$12,463
LRT	NFTA	20.0	1	14	27	23	1,455	75,338	8,209	$12,846
LRT	NJT	13.4	1	11	22	16	1,036	41,691	2,987	$4,792
LRT	PAT	77.9	4	4	71	59	3,286	135,726	8,837	$27,445
LRT	RTA - N.O.	25.7	2		'''	21	1,116	87,316	6,440	$5,527
LRT	SCCTA	62.8	2	30	54	38	2,774	120,646	6,245	$19,602
LRT	SDT	66.8	2	36	71	59	7,133	233,774	16,504	$19,911
LRT	SDTEO		2	29	48					
LRT	SEPTA	111.5	7	8	147	107	4,630	310,105	38,066	$38,599
LRT	SF Muni	80.0	5	9	128	101	6,234	371,618	39,332	$63,043
LRT	SRTD	58.2	1	29	35	32	2,688	80,615	6,571	$15,551
LRT	STC	35.4	1	10	120	120				
LRT	STE	25.7	2	18	15					
LRT	Tri-Met	48.6	1	30	26	23	2,419	100,334	7,771	$11,676
LRT	TTC	219.5	10	3	298	222	13,123	917,658	98,788	$70,670
RT	BART	228.5	4	34	589	406	67,406	1,189,472	78,302	$203,828
RT	BCT	56.0	1	20	114	104	19,053	444,400	33,799	$31,799
RT	CTA	354.5	6	143	1,236	856	73,330	1,990,909	135,370	$282,691
RT	GCRTA	61.5	1	18	60	35	3,069	73,440	6,563	$19,903
RT	LACMTA	9.7	1	5	30	16	867	33,000	3,748	$9,239
RT	MARTA	130.0	2	29	240	160	27,254	684,655	65,005	$65,513
RT	MBTA	122.0	3	53	402	378	37,929	1,172,025	190,330	$256,188
RT	MDTA	67.9	1	21	136	76	8,609	176,358	14,818	$42,746
RT	MTA	69.5	1	12	100	48	5,723	138,581	11,114	$31,657
RT	NYCT	793.1	12	469	5,840	4,954	475,040	16,205,376	1,178,121	$2,132,926
RT	PATCO	50.7	1	13	121	102	6,861	147,030	11,232	$27,785
RT	PATH	46.0	4	13	342	282	20,656	636,967	61,815	$155,136
RT	SEPTA	122.4	2	76	376	304	24,681	732,637	94,332	$109,818
RT	SIR	46.0	1	22	64	36	2,927	85,970	5,141	$17,836
RT	STC		9	135	2,304	2,142				
RT	STCUM	122.3	4	70	759	555	64,233	2,261,000	196,984	
RT	TTC	128.2	2	60	634	510	70,889	2,267,551	311,080	$204,418
RT	WMATA	260.8	6	83	746	534	58,970	1,459,440	191,428	$313,298

Table A 3.2 Train length, loading and fare collection characteristics

Type	System	Maximum Train Length	Fare Collection Method (TVM: Ticket Vending Machine)	Platform Height	Wheelchair Access	Access Type (LRT)
AGT	DTC	2	Turnstile	High	Full	
AGT	JTA	1	Turnstile with Magnetic Tickets	High	Full	
AGT	MDTA	1	Turnstile with Magnetic Tickets	High	Full	
AGT	Morg. PRT	1	Turnstile	High	Full	
CR	CalTrain	4	Conductor	Low	None	
CR	Coaster		Proof of Payment	Low	Full	
CR	Conn DOT	10	Conductor	Low	Full	
CR	GO Transit	12	Proof of Payment	Low	Partial	
CR	LIRR	12	Conductor and TVM	High/Low	Partial	
CR	MARC	8	Conductor	High/Low	Partial	
CR	MBTA	9	Conductor	Low	Partial	
CR	Metra	11	Conductor	High/Low	Partial	
CR	Metro-North	12	Conductor and TVM	High/Low	Partial	
CR	NICTD	8	Conductor	High/Low	Partial	
CR	NJT	17	Conductor and TVM	High/Low	Partial	
CR	SCRRA	5	Proof of Payment	Low	Full	
CR	SEPTA	7	Conductor and TVM	Low	Partial	
CR	STCUM		Conductor	High/Low	None	
CR	Tri-Rail	4	Proof of Payment	Low	Full	
CR	VRE	8	Proof of Payment	Low	Full	
LRT	Bi-State	2	Proof of Payment	High	Full	High Platforms
LRT	CTS	4	Proof of Payment	High	Full	High Platforms
LRT	Denv. RTD	2	Proof of Payment	Low	Full	Mini-high Platforms
LRT	ETS	3	Proof of Payment	High	Full	High Platforms
LRT	GCRTA	2	Operator (except CBD)	Low	None	None
LRT	LACMTA	2	Proof of Payment	High	Full	High Platforms
LRT	MBTA	3	Operator (except CBD)	Low	None	None
LRT	Metrorrey	2				Unknown
LRT	MTA	3	Proof of Payment	Low	Full	Mini-high Platforms
LRT	NFTA	3	Proof of Payment	High/Low	Full	Mini-high Platforms
LRT	NJT	1	Operator	Low	None	None
LRT	PAT	2	Operator	High/Low	Partial	High Platforms
LRT	RTA - N.O.	1	Operator	Low	None	None
LRT	SCCTA	3	Proof of Payment	Low	Full	Platform Lifts
LRT	SDT	4	Proof of Payment	Low	Full	Car Lifts
LRT	SDTEO	2	Turnstile	High	None	None
LRT	SEPTA	2	Operator (except CBD)	Low	None	None
LRT	SF Muni	4	Operator (except CBD)	High/Low	Partial	Mini-high Platforms
LRT	SRTD	4	Proof of Payment	Low	Full	Mini-high Platforms
LRT	STC	6	Turnstile with Magnetic Tickets	High	Partial	High Platforms
LRT	STE		Operator	High	None	None
LRT	Tri-Met	2	Proof of Payment	Low	Full	Platform Lifts
LRT	TTC	1	Operator and Proof of Payment	Low	None	None
RT	BART	10	Turnstile with Magnetic Tickets	High	Full	
RT	BCT	4	Proof of Payment	High	Full	
RT	CTA	8	Turnstile	High	Partial	
RT	GCRTA	3	Turnstile	High	Partial	
RT	LACMTA	4	Proof of Payment	High	Full	
RT	MARTA	8	Turnstile with Magnetic Tickets	High	Full	
RT	MBTA	6	Turnstile	High	Partial	
RT	MDTA	6	Turnstile with Magnetic Tickets	High	Full	
RT	MTA	4	Turnstile with Magnetic Tickets	High	Full	
RT	NYCT	11	Turnstile	High	Partial	
RT	PATCO	6	Turnstile with Magnetic Tickets	High	Partial	
RT	PATH	8	Turnstile	High	Partial	

Table A 3.2 Train length, loading and fare collection characteristics (continued)

Type	System	Maximum Train Length	Fare Collection Method (TVM: Ticket Vending Machine)	Platform Height	Wheelchair Access	Access Type (LRT)
RT	SEPTA	6	Turnstile	High	Partial	
RT	SIR	4	Turnstile	High	Partial	
RT	STC	9	Turnstile with Magnetic Tickets	High	None	
RT	STCUM	9	Turnstile with Magnetic Tickets	High	None	
RT	TTC	6	Turnstile	High	None	
RT	WMATA	6	Turnstile with Magnetic Tickets	High	Full	

Table A 3.3 Route characteristics and ridership[1]

Type	System	Route	Length (km)	Stations	Ridership (Avg. weekday)	Peak Hour			Peak 15-minutes		
						Pass.	Trains	Cars	Pass.	Trains	Cars
AGT	DTC	People Mover	4.7	13	6,984						
AGT	MDTA	MetroMover	9.3	21	16,700						
AGT	Morg. PRT	Morgantown PRT	5.0	5	16,000	2,800					
CR	CalTrain	CalTrain	123.7	34	20,976	2,374	6	23	932	2	8
CR	Coaster	Coaster	66.2	8	1,900	600					
CR	Conn DOT	Shore Line East	52.8	7	1,100						
CR	GO Transit	Bradford	66.8	6	1,559	798	1	7	798	1	7
CR	GO Transit	Georgetown	47.3	8	8,689	3,318	3	24	1,266	1	9
CR	GO Transit	Lakeshore East	50.9	10	29,993	7,537	5	51	3,500	2	21
CR	GO Transit	Lakeshore West	63.3	12	37,157	10,091	6	62	5,265	3	31
CR	GO Transit	Milton	50.2	8	13,246	3,996	3	27	1,574	1	10
CR	GO Transit	Richmond Hill	33.8	5	4,760	1,830	3	18	830	1	6
CR	GO Transit	Stouffville	46.7	8	1,987	1,238	2	12	953	1	6
CR	LIRR	Babylon	59.4	15	68,290	12,980	14	132	4,630	4	42
CR	LIRR	Far Rockaway	34.6	17	12,890	2,780	5	36	1,440	2	16
CR	LIRR	Flatbush Terminal	15.0	4		6,490	12	86	2,230	3	22
CR	LIRR	Hempstead	32.4	15	14,110	3,200	5	36	1,490	2	16
CR	LIRR	LIC Terminal	14.5	7		120	2	11	120	2	11
CR	LIRR	Long Beach	37.7	11	20,110	5,000	6	56	2,210	2	22
CR	LIRR	Montauk	172.0	22	7,340	1,340	4	20	760	2	10
CR	LIRR	Oyster Bay	38.5	13	5,040	1,010	2	11	530	1	6
CR	LIRR	Penn Terminal	15.0	6		41,480	38	380	12,380	10	106
CR	LIRR	Port Jefferson	93.1	22	51,380	10,960	12	109	4,320	4	38
CR	LIRR	Port Washington	29.6	13	41,390	9,130	8	76	3,640	3	30
CR	LIRR	Ronkonkoma	151.8	22	39,050	8,700	6	68	3,870	3	32
CR	LIRR	West Hempstead	21.1	11	3,570	1,340	3	20	680	1	8
CR	MARC	Brunswick	119.1	17	5,539	1,789	3		702	1	
CR	MARC	Camden	58.6	12	3,138	793	3		357	1	
CR	MARC	Penn	123.3	13	10,492	2,480	4		1,027	2	
CR	MBTA	Attleboro/Stou'ton	76.6	15	21,612	4,962	4		2,732	2	
CR	MBTA	Fairmount	15.3	5	1,452	518	2		310	1	
CR	MBTA	Fitchburg	79.7	18	6,648	2,101	3		1,002	1	
CR	MBTA	Framingham	34.5	12	9,228	1,832	2		971	1	
CR	MBTA	Franklin	49.6	17	13,068	2,579	3		1,185	1	
CR	MBTA	Haverhill/Reading	53.0	14	6,604	2,096	3		842	1	
CR	MBTA	Lowell	41.1	8	7,474	1,840	3		727	1	
CR	MBTA	Needham	22.1	12	6,846	1,918	3		860	1	
CR	MBTA	Rockport/Ipswich	72.0	16	10,230	2,292	4		1,122	2	
CR	Metra	BN	60.4	27	50,082	12,848	14	101	4,196	5	34
CR	Metra	C & NW-N	83.1	26	25,549	6,126	8	44	2,230	3	16
CR	Metra	C & NW-NW	113.5	22	38,587	10,438	8	71	4,562	3	31

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[1] SEPTA commuter rail ridership data was determined from *SEPTA: Regional Rail Ridership Census 1993-94,* © SEPTA 1994.

Table A 3.3 Route characteristics and ridership (continued)

Type	System	Route	Length (km)	Stations	Ridership (Avg. weekday)	Peak Hour			Peak 15-minutes		
						Pass.	Trains	Cars	Pass.	Trains	Cars
CR	Metra	C & NW-W	57.2	17	28,592	7,739	7	57	2,667	2	19
CR	Metra	Heritage Corridor	59.9	6	1,317	677	2	6	376	1	3
CR	Metra	Milw. District -N	79.7	19	20,205	5,313	6	40	1,736	2	12
CR	Metra	Milw. District -W	64.1	23	21,273	5,833	7	44	2,359	3	16
CR	Metra	Metra Electric	65.4	49	41,024	11,292	20	100	3,288	6	30
CR	Metra	Rock Island	75.4	25	31,062	7,813	9	62	3,118	3	23
CR	Metra	South Shore	145.1	20	11,602	2,968	4	28	1,666	2	16
CR	Metra	SouthWest Serv.	40.6	9	5,862	1,957	2	15	1,075	1	8
CR	Metro-North	Harlem	124.0	36	59,675	13,377	17	138	4,820	5	47
CR	Metro-North	Hudson	119.0	29	33,461	8,541	15	88	2,619	5	28
CR	Metro-North	New Haven	168.0	39	75,656	15,282	20	158	5,191	6	55
CR	Metro-North	Waterbury Branch	52.0	8	314						
CR	NICTD	South Shore	145.0	21	11,602	2,968	4	28	1,666	2	16
CR	NJT	Atlantic City	109.3	8	1,504	222	2		120	1	
CR	NJT	Boonton Line	77.1	20	5,657	1,920	5		847	2	
CR	NJT	Main/Bergen Line	153.1	31	17,103	4,671	10		1,601	3	
CR	NJT	Montclair	20.6	6	1,239	335	2		168	1	
CR	NJT	Morris & Essex	96.9	33	25,704	4,752	13		1,952	4	
CR	NJT	N. Jersey Coast	107.4	25	37,346	6,924	7		2,965	3	
CR	NJT	Northeast Corrdr.	97.9	14	54,076	6,668	8		3,148	4	
CR	NJT	Pascack Valley	49.3	17	6,125	1,895	4		932	2	
CR	NJT	Raritan Valley	69.9	19	12,761	2,971	6		1,116	2	
CR	SCRRA	Orange County	140.4	9	2,444	859	2		542	1	
CR	SCRRA	Riverside	94.5	5	2,877	797	2		460	1	
CR	SCRRA	San Bernadino	90.6	13	4,835	1,277	2		684	1	
CR	SCRRA	Santa Clarita	124.3	8	2,632	614	2		332	1	
CR	SCRRA	Ventura County	106.6	10	2,873	769	2		449	1	
CR	SEPTA	R1	47.7	15	2,461	103	2		55	1	
CR	SEPTA	R2	75.7	33	10,142	1,444	3		553	1	
CR	SEPTA	R3	77.3	35	12,218	1,835	5		751	3	
CR	SEPTA	R5	127.0	54	26,210	3,899	6		1,622	2	
CR	SEPTA	R6	39.8	20	3,067	632	4		325	2	
CR	SEPTA	R7	73.7	27	11,524	1,314	4		739	2	
CR	SEPTA	R8	38.5	21	7,700	817	3		289	1	
CR	STCUM	Deux-Montagnes	27.2	13	10,731	2,499			875		
CR	STCUM	Dorion - Rigaud	64.4	18	11,781	3,503			1,226		
CR	Tri-Rail	Tri-Rail	107.0	15	8,065	601	1		601		
CR	VRE	Fredricksburg	86.5	11	4,605	1,188	2		858	1	
CR	VRE	Manassas	56.0	10	3,295	892	2		647	1	
LRT	Bi-State	MetroLink	30.6	18	27,055						
LRT	CTS	201 (NW-South)	19.5	22	68,000	4,950	11	33	1,840	4	12
LRT	CTS	202 (Northeast)	11.8	18	38,000	3,395	11	33	1,495	4	12
LRT	Denv. RTD	101	8.5	14	15,222	3,000			1,000		
LRT	ETS	101	13.7	10	35,000	3,219					
LRT	GCRTA	67AX (Shaker)		18							
LRT	GCRTA	67X (Van Aken)		18							
LRT	LACMTA	Blue Line	35.4	22	40,640	2,416	9	18			
LRT	MBTA	B Boston College	10.3	18	32,979						
LRT	MBTA	C Cleveland Circ.	9.3	15	12,727						
LRT	MBTA	D Riverside	21.7	24	18,421						
LRT	MBTA	E Heath St.	6.0	10	13,451						
LRT	MBTA	Mattapan	4.1	8	7,104						
LRT	Metrorrey	Metrorrey	17.5	17							

Table A 3.3 Route characteristics and ridership (continued)

Type	System	Route	Length (km)	Stations	Ridership (Avg. weekday)	Peak Hour			Peak 15-minutes		
						Pass.	Trains	Cars	Pass.	Trains	Cars
LRT	MTA	Light Rail	36.4	24	20,500						
LRT	NFTA	Metro Rail	10.3	14	28,129						
LRT	NJT	7 City Subway	8.1	11	16,871	1,769					
LRT	PAT	42L Library	13.0	48	6,649						
LRT	PAT	42S South Hills	21.0	35	20,134						
LRT	RTA - N.O.	12 St. Charles	10.6								
LRT	RTA - N.O.	Riverfront	2.6	10							
LRT	SCCTA	Light Rail	33.8	33	20,155						
LRT	SDT	East	30.0	22	12,989						
LRT	SDT	South	26.4	20	30,722						
LRT	SDTEO	1 North-South	15.5	19	65,000						
LRT	SDTEO	2 East-West	8.5	11							
LRT	SEPTA	10 Overbrook	9.5		14,494	528					
LRT	SEPTA	11 Darby	10.8		13,864	463					
LRT	SEPTA	13 Darby/ Yeadon	11.2		20,962	1,342					
LRT	SEPTA	34 Angora	8.0		15,674	1,009					
LRT	SEPTA	36 Eastwick	11.4		14,727	788					
LRT	SEPTA	100 Norristown	21.7	22	7,212	477	8		132	2	
LRT	SEPTA	101 Media	13.7	35	5,082	630	10	10	244	3	3
LRT	SEPTA	102 Sharon Hill	8.5	27	3,366	321	6	6	115	2	2
LRT	SF Muni	J Church	10.8		15,584						
LRT	SF Muni	K Ingleside	12.6		27,828						
LRT	SF Muni	L Taraval	12.7		28,451						
LRT	SF Muni	M Ocean View	14.6		27,864						
LRT	SF Muni	N Judah	11.4		31,148						
LRT	SRTD	RT	27.0	29	24,382	1,311					
LRT	Tri-Met	MAX	24.1	30	24,900	1,975	9	16	615	3	5
LRT	TTC	501 Queen	16.9		59,138	1,224					
LRT	TTC	502 Downtowner	9.7		7,737	413					
LRT	TTC	503 Kingston Rd.	9.3		2,561	327					
LRT	TTC	504 King	12.8		58,756	1,613					
LRT	TTC	505 Dundas	10.8		47,955	792					
LRT	TTC	506 Carlton	14.9		59,371	1,127					
LRT	TTC	507 Long Branch	7.8		7,003	268					
LRT	TTC	511 Bathurst	4.7		23,533	979					
LRT	TTC	512 St. Clair	7.0		29,200	1,293					
LRT	TTC	604 Harbourfront	1.8	6	9,950	520					
RT	BART	Concord/Daly City	58.6	19		7,349	8	80			
RT	BART	Fremont/Daly City	62.7	19		4,571	5	50			
RT	BART	Fremont/Rich.	58.4	18		2,004	4	24			
RT	BART	Richmond/Daly C.	44.8	19		3,713	4	40			
RT	BCT	SkyTrain	28.8	20	110,000	6,932	25	100	2,056	7	28
RT	CTA	Blue	55.1	43	122,800	9,376			2,616		
RT	CTA	Brown	18.2	28	32,750	7,051			1,848		
RT	CTA	Green	33.9	33	26,800	2,952			950		
RT	CTA	Orange	19.9	17	14,800	4,287			1,535		
RT	CTA	Purple	26.1	22	10,050	3,479			1,147		
RT	CTA	Red	34.9	33	182,350	11,533			3,601		
RT	CTA	Yellow	8.1	2	5,300						
RT	GCRTA	66X	30.8	18							
RT	LACMTA	Red	7.1	5	15,550						

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

Table A 3.3 Route characteristics and ridership (continued)

Type	System	Route	Length (km)	Stations	Ridership (Avg. weekday)	Peak Hour			Peak 15-minutes		
						Pass.	Trains	Cars	Pass.	Trains	Cars
RT	MARTA	East/West	25.8	16	71,396	2,986	8	60	926	2	12
RT	MARTA	North/South	35.7	18	117,941	5,093	8	58	1,796	3	22
RT	MBTA	Blue	9.6	12	54,000	6,389					
RT	MBTA	Orange	18.0	19	127,000	7,379					
RT	MBTA	Red	33.0	22	185,000	9,282					
RT	MDTA	Metrorail	33.1	21	46,300	3,698			1,456		
RT	MTA	Metro	22.9	12	43,000						
RT	NYCT	1, 9	23.7	38		16,991	16	160	5,398	4	40
RT	NYCT	2	41.2	49		14,052	12	120	4,585	4	40
RT	NYCT	3	29.4	34		10,524	10	90	3,107	3	27
RT	NYCT	4	33.0	27		18,084	15	150	5,200	4	40
RT	NYCT	5	40.1	40		15,975	13	130	4,600	4	40
RT	NYCT	6	24.3	38		29,175	22	220	8,648	6	60
RT	NYCT	7	15.2	21		23,369	21	231	6,318	4	44
RT	NYCT	A	54.5	61		22,526	15	136	6,638	4	40
RT	NYCT	B	33.8	46		10,715	8	80	3,614	2	20
RT	NYCT	C	36.2	47		6,611	9	72	2,151	3	24
RT	NYCT	D	41.6	42		12,377	10	80	5,513	4	32
RT	NYCT	E	24.9	20		22,530	12	120	7,884	4	40
RT	NYCT	F	43.4	49		28,554	17	136	8,210	5	40
RT	NYCT	Franklin Shuttle	2.2	5							
RT	NYCT	G	23.3	27		4,300	6	36			
RT	NYCT	42nd St. Shuttle	0.7	2		5,860		100			
RT	NYCT	H	10.7	6							
RT	NYCT	J, Z	21.4	30		13,791	13	104	4,886	4	32
RT	NYCT	L	16.3	24		12,621	13	104	3,982	4	32
RT	NYCT	M	27.5	37		3,710	8	64	1,078	2	16
RT	NYCT	N	32.6	44		11,030	11	100	3,465	3	28
RT	NYCT	Q	26.2	20		12,111	9	72	3,614	3	24
RT	NYCT	R	34.8	43		12,208	12	96	4,069	4	32
RT	PATCO	PATCO	22.9	13	41,190	7,720			2,000		
RT	PATH	Hoboken - 33rd	5.6	6	38,650	6,138	11	77	1,599	3	21
RT	PATH	Hoboken - WTC	4.8	4	55,200	8,939	13	91	3,298	4	28
RT	PATH	Journal Sq. - 33rd	9.2	8	36,600	4,763	9	63	1,484	2	14
RT	PATH	Newark - WTC	14.3	6	83,800	11,580	15	120	4,083	5	40
RT	SEPTA	Blue (Mkt - Frank)	19.6	28	193,362						
RT	SEPTA	Orange (Broad)	18.3	24	131,952						
RT	SIR	Staten Island Rly.	23.0	22	19,161						
RT	STC	1	18.8	20	1,037,726	70,700	50	450	STC provided hourly and 30 minute 2-way data. Adjusted to 1-way at 72% on heavy lines, 80% on lighter lines. The 30 minute rate is 51-59% of hourly for heavy lines, ≅ 70% on lighter lines.		
RT	STC	2	23.4	24	1,199,173	75,300	53	468			
RT	STC	3	23.6	21	940,962	63,000	53	468			
RT	STC	4	10.7	10	111,409	7,400	13	117			
RT	STC	5	15.7	13	254,224	20,700	23	207			
RT	STC	6	13.9	11	152,369	10,300	12	108			
RT	STC	7	18.9	14	241,842	18,300	20	140			
RT	STC	9	15.3	12	365,430	27,600	23	207			
RT	STC	A	17.0	10	147,374	18,100	20	120			
RT	STCUM	1 (Green)	22.1	27	369,766	21,869			7,654		
RT	STCUM	2 (Orange)	24.8	28	407,731	24,382			8,534		
RT	STCUM	4 (Yellow)	4.3	3	56,943	10,928			3,825		
RT	STCUM	5 (Blue)	9.7	12	85,555	6,360			2,226		
RT	TTC	601 B-D	27.0	31	362,811	21,050			6,598		
RT	TTC	602 Y-U-S	29.9	31	475,530	26,908	24	144	8,285	7	42
RT	TTC	603 SRT	7.2	6	38,481	3,507			1,157		

Table A 3.3 Route characteristics and ridership (continued)

Type	System	Route	Length (km)	Stations	Ridership (Avg. weekday)	Peak Hour			Peak 15-minutes		
						Pass.	Trains	Cars	Pass.	Trains	Cars
RT	WMATA	Blue	37.5	24		4,600					
RT	WMATA	Green, Inner	8.1	9		2,800					
RT	WMATA	Green, Outer	12.8	5		1,200					
RT	WMATA	Orange	42.1	26		10,700					
RT	WMATA	Red	48.9	25		11,700					
RT	WMATA	Yellow	17.1	12		4,700					

Table A 3.4 Trunk characteristics and ridership[2]

Type	System	Trunk Name	Minimum Operated Headway (minutes)	Peak Hour			Peak 15-minutes		
				Pass.	Trains	Cars	Pass.	Trains	Cars
CR	CalTrain	CalTrain	5	2,374	6	23	932	2	8
CR	GO Transit	Lakeshore East	1	9,914	8	69	4,094	3	27
CR	GO Transit	Lakeshore West	1	17,358	13	116	6,784	5	45
CR	LIRR	Jamaica - Flatbush	3	6,490	12	86	2,230	3	22
CR	LIRR	Jamaica - Penn Stn.	1	41,480	38	380	12,380	10	106
CR	MARC	Washington Union Stn.	2	4,119	9		1,694	4	
CR	MBTA	North Station	1	7,819	12		3,227	4	
CR	MBTA	South/Back Bay Stn.	1	10,330	12		3,749	4	
CR	Metra	C & NW	1	22,310	21	160	8,395	6	58
CR	Metra	Metra Electric	1	13,853	23	124	4,765	8	42
CR	Metra	Rock Island	2	7,813	9	62	3,118	3	23
CR	Metra	Union Station North	1	10,717	13	81	4,095	5	28
CR	Metra	Union Station South	1	15,433	18	122	5,374	7	45
CR	Metro-North	Park Avenue Tunnel	1	35,926	50	371	10,965	14	116
CR	NJT	Hoboken Term.	1	12,721	34		3,849	9	
CR	NJT	Newark Penn Stn.	1	15,866	21		4,932	7	
CR	SCRRA	LAUPT	1	3,608	9		1,791	4	
CR	SEPTA	Penn (30th St.)	1	8,645	23		3,487	9	
CR	SEPTA	Reading	1	6,121	19		1,990	5	
CR	STCUM	CP Windsor Station	7	3,503			1,226		
CR	STCUM	Mont-Royal Tunnel	10	2,499			875		
CR	Tri-Rail	Tri-Rail	60	601	1		601	1	
CR	VRE	VRE	10	2,080	4		1,505	2	
LRT	CTS	Northeast Line	3	3,395	11	33	1,495	4	12
LRT	CTS	South Line	2	4,950	11	33	1,840	4	12
LRT	Denv. RTD	Central	5	3,000			1,000		
LRT	ETS	Northeast LRT	5	3,219	12	36			
LRT	LACMTA	Blue Line	6	2,416	9	18			
LRT	MBTA	Green Line Subway	1.33	10,000	45	90			
LRT	NJT	City Subway	2	1,769	30	30			
LRT	SEPTA	Media - Sharon Hill	2	950	16	16			
LRT	SEPTA	Norristown High-Speed	3	477	8		132	2	
LRT	SEPTA	Subway-Surface	1	4,130	60				
LRT	SF Muni	Muni Metro	2.61						
LRT	SRTD	Sacramento LRT	15	1,311					
LRT	Tri-Met	MAX	3	1,975	9	16	615	3	5

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[2] *Ibid.*

Table A 3.4 Trunk characteristics and ridership

Type	System	Trunk Name	Minimum Operated Headway (minutes)	Peak Hour			Peak 15-minutes		
				Pass.	Trains	Cars	Pass.	Trains	Cars
RT	BART	Transbay Tube	3	14,881	17	170			
RT	BCT	SkyTrain	1.33	6,932	25	100	2,056	7	28
RT	CTA	Dearborn Subway	4	9,376	14	112	2,616	4	32
RT	CTA	State Subway	3	11,533			3,601	6	48
RT	MARTA	East/West	8	2,986	8	60	926	2	12
RT	MARTA	North/South	8	5,093	8	58	1,796	3	22
RT	MBTA	Blue	3.5	6,389					
RT	MBTA	Orange	4.5	7,379					
RT	MBTA	Red	4	9,282					
RT	MDTA	Metrorail	5	3,698					
RT	MTA	Metro	8						
RT	NYCT	14th Street Tunnel	4	10,609	13	104	3,528	4	32
RT	NYCT	53rd Street Tunnel	2	49,829	29	256	15,154	8	72
RT	NYCT	60th Street Tunnel	2	22,598	23	194	7,534	7	60
RT	NYCT	63rd Street Tunnel	4	2,331	9	72	775	2	16
RT	NYCT	8th Ave. Express	2	21,828	20	170	6,858	5	44
RT	NYCT	8th Ave. Local	1.5	8,351	12	108	2,506	3	26
RT	NYCT	Broadway Express	2	24,099	21	200	7,962	7	67
RT	NYCT	Broadway Local	3.5	16,991	16	160	5,398	4	40
RT	NYCT	Clark Street	2.5	15,073	18	171	4,873	5	48
RT	NYCT	Cranberry St. Tunnel	1.5	28,167	27	234	7,782	7	60
RT	NYCT	Joralemon St. Tunnel	2	26,236	23	230	7,305	6	60
RT	NYCT	Lexington Ave. Express	1.5	33,938	29	290	9,800	8	80
RT	NYCT	Lexington Ave. Local	2	29,175	22	220	8,648	6	60
RT	NYCT	Manhattan Bridge	0.5	33,248	25	214	12,306	9	76
RT	NYCT	Montague St. Tunnel	2	13,830	21	172	3,643	6	48
RT	NYCT	Rutgers St. Tunnel	2	12,910	14	112	3,937	4	32
RT	NYCT	Steinway Tunnel	2	23,369	21	231	6,318	4	44
RT	NYCT	Williamsburg Bridge	1.5	18,037	20	160	5,554	7	56
RT	PATCO	Ben Franklin Bridge	2	7,720			2,000		
RT	PATH	33rd St.	3	10,901	20	140	3,080	5	35
RT	PATH	World Trade Center	1.5	20,519	28	211	5,595	7	61
RT	SEPTA	Broad St. Subway	2						
RT	SEPTA	Market St. Subway	3						
RT	STCUM	1 Green	3	21,869	20	180			
RT	STCUM	2 Orange	3	24,382	20	180			
RT	STCUM	4 Yellow	5	10,928	12	72			
RT	STCUM	5 Blue	4	6,360	15	90			
RT	TTC	Bloor-Danforth	2.67	21,050	22	132			
RT	TTC	Scarborough RT	3.83	3,507	15	60			
RT	TTC	Yonge Subway	2.45	26,908	24	144	8,285	7	42
RT	WMATA	Blue/Orange	3	15,300	20				
RT	WMATA	Green/Yellow	3	7,500	20	80			
RT	WMATA	Red	3	11,700	20	120			

Table A 3.5 Rail transit car specifications

Mode	System	Car Designation	Date Built	Number in Class	Length (m)	Width (m)	Seats	Total Capacity	Doors	Door Width (m)
AGT	DTC	S-1		8	12.4	2.49	33	100	2	1.21
AGT	JTA	VAL 256	1988	2	12.8	2.64	12		2	
AGT	MDTA	C-100	1985-93	27	12.8	2.84	8	100	2	
AGT	Morg. PRT	Boeing PRT	1978-79	71	4.7	2.0	8	23	1	1.0
CR	CalTrain	California	1993	17	25.91	3.05	135		2	
CR	CalTrain	California (Cab)	1993	6	25.91	3.05	130		2	
CR	CalTrain	Gallery Cab	1985	21	25.91	3.23	139		1	
CR	CalTrain	Gallery Coach	1985-87	52	25.91	3.23	148		1	
CR	Coaster	Bi-Level	1994	16	25.91	3.0	135		2	
CR	Conn DOT	C&O 1600	1950	7	25.91	3.05	102	102		
CR	Conn DOT	C&O 1600	1950	3	25.91	3.05	66	66		
CR	Conn DOT	Comet II Mod	1991	2	25.91	3.2	131	131		
CR	Conn DOT	Comet II Mod	1991	4	25.91	3.2	118	118		
CR	Conn DOT	Comet II Mod	1991	4	25.91	3.2	130	130		
CR	Conn DOT	SPV 2000	1979	2	25.91	3.2	84	84		
CR	GO Transit	Bi-Level Cab	1983-90	42	25.91	3.0	161	302	2	
CR	GO Transit	Bi-Level Trailer	1977-91	289	25.91	3.0	162	302	2	
CR	LIRR	C-1	1990	5	25.91	3.1	190		2	
CR	LIRR	C-1	1990	5	25.91	3.1	181		2	
CR	LIRR	M-1	1972	74	25.91	3.28	122		2	
CR	LIRR	M-1	1968-71	305	25.91	3.28	118		2	
CR	LIRR	M-1	1972	74	25.91	3.28	118		2	
CR	LIRR	M-1	1968-71	305	25.91	3.28	122		2	
CR	LIRR	M-3	1985	87	25.91	3.28	114		2	
CR	LIRR	M-3	1985	87	25.91	3.28	120		2	
CR	LIRR	P-72	1955-56	38	25.2	3.18	118			
CR	LIRR	P-72	1955-56	38	25.2	3.18	123			
CR	LIRR	PP-72	1955-56	12	25.2	3.18	44			
CR	LIRR	PT-72	1955-56	36	25.2	3.18	118			
CR	LIRR	PT-72	1955-56	37	25.2	3.18	123			
CR	LIRR	PT-75	1963	28	25.2	3.2	133			
CR	MARC	Coach	1985-87	16	25.91	3.2	114			
CR	MARC	Coach	1949	2	25.91	3.05	96			
CR	MARC	Coach	1949	10	25.91	3.05	80			
CR	MARC	Coach	1992-3	11	25.91	3.2	120			
CR	MARC	Coach	1949	15	25.91	3.05	95			
CR	MARC	E/H Cab	1991	6	25.91	3.2	114			
CR	MARC	E/H Cab	1985-87	12	25.91	3.2	104			
CR	MARC	E/H Coach	1991	10	25.91	3.2	114			
CR	MARC	E/H Toilet	1991	9	25.91	3.2	118			
CR	MARC	Toilet Coach	1949	1	25.91	3.05	80			
CR	MARC	Toilet Coach	1949	5	25.91	3.05	88			
CR	MARC	Toilet Coach	1949	11	25.91	3.05	88			
CR	MBTA	BTC	1991	50	25.91	3.05	185	240	2	
CR	MBTA	BTC-1	1979	43	25.91	3.2	99	149		
CR	MBTA	BTC-1A	1987	40	25.91	3.2	127	157		
CR	MBTA	BTC-1B	1989-90	54	25.91	3.2	122	152		
CR	MBTA	BTC-3	1987-88	34	25.91	3.05	96	146		
CR	MBTA	CTC	1991	25	25.91	3.05	180	240		
CR	MBTA	CTC-1	1979	13	25.91	3.2	95	145		
CR	MBTA	CTC-1A	1989-90	52	25.91	3.2	122	152		
CR	MBTA	CTC-3	1987-88	33	25.91	3.05	94	144		
CR	Metra	CA2A, B, C	1961-65	24	25.91	3.38	156		1	
CR	Metra	CA2D	1974	14	25.91	3.38	149		1	
CR	Metra	CA2E	1978	25	25.91	3.38	147		1	

Table A 3.5 Rail transit car specifications (continued)

Mode	System	Car Designation	Date Built	Number in Class	Length (m)	Width (m)	Seats	Total Capacity	Doors	Door Width (m)
CR	Metra	CA2F	1980	7	25.91	3.51	147		1	
CR	Metra	CA2G	1980	2	25.91	3.38	147		1	
CR	Metra	CA3A, B	1959-60	49	25.91	3.51	155		1	
CR	Metra	CA3C, D, E, F	1965-68	14	25.91	3.51	155		1	
CR	Metra	CN1A, B	1965/74	26	25.91	3.18	139		1	
CR	Metra	Gallery	1994	75	25.91	3.33	140		1	
CR	Metra	Gallery	1995	98	25.91	3.33	148		1	
CR	Metra	MA3A (emu)	1971-72	129	25.91	3.2	156		1	
CR	Metra	MA3B (emu)	1978-79	36	25.91	3.2	156		1	
CR	Metra	TA2A, B, C	1961-65	57	25.91	3.23	162		1	
CR	Metra	TA2D, E, F	1974-80	125	25.91	3.23	157		1	
CR	Metra	TA3A, TB3A	1955	16	25.91	3.23	169		1	
CR	Metra	TA3B, C, D, E, F	1956-65	150	25.91	3.23	161		1	
CR	Metra	TA3G, H, I, J, K	1966-70	54	25.91	3.23	161		1	
CR	Metra	TA3L	1966-70	1	25.91	3.18	136		1	
CR	Metra	TA3L	1958	5	25.91	3.23	161		1	
CR	Metra	TN1A, D, F	1950-55	38	25.91	3.18	148		1	
CR	Metra	TN1B, C, E, G, H, I	1951-73	55	25.91	3.18	145		1	
CR	Metra	TN2A	1978	22	25.91	3.23	145		1	
CR	Metro-North	ACMU	1962	61	25.91	3.2	130			
CR	Metro-North	M-1A A	1971	89	25.91	3.2	118		2	
CR	Metro-North	M-1A B	1971	89	25.91	3.2	122		2	
CR	Metro-North	M-2 A	1973	121	25.91	3.2	118		2	
CR	Metro-North	M-2 B	1973	111	25.91	3.2	114		2	
CR	Metro-North	M-2 C	1973	10	25.91	3.2			2	
CR	Metro-North	M-3A A	1984	71	25.91	3.2	120		2	
CR	Metro-North	M-3A B	1984	71	25.91	3.2	114		2	
CR	Metro-North	M-4 A	1988	18	25.91	3.2	118		2	
CR	Metro-North	M-4 B	1988	18	25.91	3.2	114		2	
CR	Metro-North	M-4 D	1988	18	25.91	3.2	126		2	
CR	Metro-North	M-6 A	1993	16	25.91	3.2	118		2	
CR	Metro-North	M-6 B	1993	16	25.91	3.2	106		2	
CR	Metro-North	M-6 D	1993	16	25.91	3.2	126		2	
CR	Metro-North	Shoreliner	1986-91	33	25.91	3.2	118		2	
CR	Metro-North	Shoreliner	1986	45	25.91	3.2	131		2	
CR	Metro-North	SPV 2000	1981	10	25.91	3.2	109		2	
CR	NICTD	EMU-1	1982	34	25.91	3.2	93		3	
CR	NICTD	EMU-1A	1983	7	25.91	3.2	93		3	
CR	NICTD	EMU-2	1992	7	25.91	3.2	110		3	
CR	NICTD	TMU-1	1992	10	25.91	3.2	130		3	
CR	NJT	Arrow II	1974-75	35	25.91	3.2	119	149	3	
CR	NJT	Arrow II	1974-75	35	25.91	3.2	115	144	3	
CR	NJT	Arrow III	1977-78	130	25.91	3.2	119	149	3	
CR	NJT	Arrow III	1977-78	13	25.91	3.2	113	141	3	
CR	NJT	Arrow III	1977-78	87	25.91	3.2	115	144	2	
CR	NJT	Comet I	1971	9	25.91	3.2	125	156	2	
CR	NJT	Comet I	1971	32	25.91	3.2	115	144	2	
CR	NJT	Comet I	1971	106	25.91	3.2	131	164	2	
CR	NJT	Comet IA	1977/82	8	25.91	3.2	123	154	2	
CR	NJT	Comet IB	1968	15	25.91	3.2	115	144	2	
CR	NJT	Comet IB	1968	15	25.91	3.2	121	151	2	
CR	NJT	Comet II/IIA	1982-83	103	25.91	3.2	131	164	2	
CR	NJT	Comet II/IIA	1982-83	23	25.91	3.2	113	141	2	
CR	NJT	Comet IIB	1987-88	29	25.91	3.2	126	156	2	
CR	NJT	Comet IIB	1987-88	1	25.91	3.2	117	146	2	

Table A 3.5 Rail transit car specifications (continued)

Mode	System	Car Designation	Date Built	Number in Class	Length (m)	Width (m)	Seats	Total Capacity	Doors	Door Width (m)
CR	NJT	Comet IIB	1987-88	21	25.91	3.2	131	164	2	
CR	NJT	Comet IIB	1987-88	1	25.91	3.2	88	110	2	
CR	NJT	Comet III	1990-91	35	25.91	3.2	118	147	3[3]	
CR	NJT	Comet III	1990-91	11	25.91	3.2	103	129	3	
CR	NJT	Comet III	1990-91	6	25.91	3.2	108	135	3	
CR	SCRRA	Bi-Level V Modified	1992-93	59	25.91	3	148	148	2	
CR	SCRRA	Bi-Level V Modified	1992-93	31	25.91	3	145	145	2	
CR	SEPTA	JW2-C	1987	10	25.91	3.2	118		2	
CR	SEPTA	JW2-T	1987	25	25.91	3.2	133		2	
CR	SEPTA	SL II	1963	36	25.91	3.2	125		2	
CR	SEPTA	SL II	1964	17	25.91	3.2	127		2	
CR	SEPTA	SL III	1967	20	25.91	3.2	111		2	
CR	SEPTA	SL IV	1973-77	231	25.91	3.2	127		2	
CR	STCUM	Class B	1953-54	40	25.57	3.04	109		2	0.78
CR	STCUM	Gallery Cab	1970	2	25.91	3.03	154		1	2.0
CR	STCUM	Gallery Trailer	1970	7	25.91	3.03	168		1	2.0
CR	STCUM	MR90 (emu)	1994/95	29	25.91	3.05	95		3	
CR	STCUM	MR90 (trailer cab)	1994/95	4	25.91	3.05	95		3	
CR	STCUM	MR90 (trailer)	1994/95	25	25.91	3.05	95		3	
CR	STCUM	Single Level 700	1989	24	25.98	3.2	130		2	0.81
CR	Tri-Rail	Bi-Level	1988-91	15	25.91	3	162	162	2	
CR	Tri-Rail	Bi-Level III	1988	6	25.91	3	159	159	2	
CR	VRE	BTC-2	1955	17	25.91	3.05	99		2	
CR	VRE	Cab	1992	10	26.01	3.05	112		2	
CR	VRE	CTC-2	1955	4	25.91	3.05	92		2	
CR	VRE	Trailer	1992	28	26.01	3.05	120		2	
LRT	Bi-State	U2A	1992-93	31	27.28	2.67	72		4	1.3
LRT	CTS	U2, U2AC	1980-86	85	24.28	2.66	64	200	4	1.3
LRT	Denv. RTD	SD100	1993	11	29.18	2.61	64		4	1.3
LRT	ETS	U2	1978-83	37	24.28	2.66	64	161	4	1.3
LRT	GCRTA	800	1981	48	24.38	2.82	84	176	3	
LRT	LACMTA	LRV	1989-94	69	27.13	2.67	76	137	4	
LRT	MBTA	LRV Green	1986-88	100	21.95	2.69	50	112	3	
LRT	MBTA	LRV Green	1976-78	117	21.64	2.64	52	112	3	1.37
LRT	MBTA	PCC Green	1945-46	15	14.02	2.54	42		2	
LRT	Metrorrey	Monterrey LRV	1990	25	29.56	2.65	58		6	
LRT	MTA	LRV	1991-93	35	28.96	2.9	85	201	4	
LRT	NFTA	Buffalo LRV	1983-84	27	20.37	2.62	51	180	2	
LRT	NJT	PCC	1946-49	24	14.15	2.74	55	125	2	
LRT	PAT	PCC 4000	1948	16	14.02	2.54	50		2	
LRT	PAT	U3	1986	55	25.73	2.54	63	125	4	1.3
LRT	RTA - N.O.	Streetcar (St. Ch.)	1923-24	38	14.53	2.54	52		2	
LRT	RTA - N.O.	W-2	1930	3	14.63	2.74	52		1	
LRT	SCCTA	SCLRV	1987	50	26.82	2.74	76	167	4	1.56
LRT	SDT	U2	1980-89	71	24.26	2.64	64	96	4	1.3
LRT	SDT	U2A	1993	52	24.49	2.64	64	96	4	1.3
LRT	SDTEO	Guadalajara LRV	1989	16	29.56	2.65	52		4	
LRT	SEPTA	LRV (Red Arrow)	1981	29	16.15	2.69	50	96	2	
LRT	SEPTA	LRV (S-S)	1980-82	112	15.24	2.59	51	96	2	
LRT	SEPTA	N-5	1993	26	19.99	3	60	90	2	
LRT	SF Muni	LRV	1995	40	22.86	2.74	60		4	
LRT	SF Muni	SLRV	1978	100	21.64	2.69	68		3	1.37
LRT	SF Muni	SLRV	1978	30	21.64	2.69	58		3	1.37

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[3] Includes double-stream high-level center door.

Table A 3.5 Rail transit car specifications (continued)

Mode	System	Car Designation	Date Built	Number in Class	Length (m)	Width (m)	Seats	Total Capacity	Doors	Door Width (m)
LRT	SRTD	U2A	1986-91	36	24.38	2.64	60	144	4	1.3
LRT	STE	Mexico LRV	1990-91	12	29.56	2.65	46		6	
LRT	Tri-Met	Portland LRV	1983-86	26	26.51	2.65	76	166	4	1.33
LRT	TTC	A-15 (PCC)	1951	22	14.15	2.54	45	103	2	
LRT	TTC	L-1/2 (CLRV)	1977-81	196	15.44	2.59	46	102	2	
LRT	TTC	L-3 (ALRV)	1987-89	52	23.16	2.59	61	155	3	
RT	BART	A-Car (Cab)	1972-75	135	23.01	3.2	72		2	1.37
RT	BART	B-Car (Midtrain)	1972-75	305	21.34	3.2	72		2	1.37
RT	BART	C	1994-95	80	21.34	3.2	68		2	1.37
RT	BART	Single C-1	1988-90	150	21.34	3.2	64		2	1.37
RT	BCT	S-1	1984-85	114	12.4	2.49	36	80	2	1.21
RT	BCT	S-1	1991	16	12.4	2.49	30	80	2	1.21
RT	CTA	2000 A	1964	70	14.63	2.84	47	150	4	0.64
RT	CTA	2000 B	1964	70	14.63	2.84	51	150	4	0.64
RT	CTA	2200 A	1969-70	72	14.63	2.84	47	150	4	0.65
RT	CTA	2200 B	1969-70	72	14.63	2.84	51	150	4	0.65
RT	CTA	2400 A	1976-78	97	14.63	2.84	45	150	2	1.27
RT	CTA	2400 B	1976-78	97	14.63	2.84	49	150	2	1.27
RT	CTA	2600 A	1981-87	299	14.63	2.84	43	150	2	1.27
RT	CTA	2600 B	1981-87	299	14.63	2.84	49	150	2	1.27
RT	CTA	3200 (A&B)	1992	256	14.63	2.84	39	150	2	1.27
RT	GCRTA	Cleveland RT	1984-85	60	23.01	3.15	80	128	3	1.27
RT	LACMTA	HRV	1991-93	30	22.86	3.2	59		3	
RT	MARTA	CQ 310	1979	100	22.86	3.2	68	136	3	1.27
RT	MARTA	CQ 310	1979	20	22.66	3.2	64	128	3	1.27
RT	MARTA	CQ 311	1984-88	120	22.86	3.2	68	136	3	1.27
RT	MBTA	00600 Blue	1979	70	14.78	2.82	42	94		
RT	MBTA	01200 Orange	1980	120	19.81	2.82	58	132		
RT	MBTA	01400 Red	1962	86	21.18	3.18	54	160		
RT	MBTA	01500 Red	1968	24	21.18	3.1	63	160		
RT	MBTA	01600 Red	1968	52	21.18	3.1	64	160		
RT	MBTA	01700 Red	1987	58	21.18	3.05	62	160	3	1.22
RT	MBTA	01800 Red	1992	86	21.18	3.05	50	160		
RT	MDTA	Heavy Rail	1984	136	22.76	3.11	76	166	3	1.23
RT	MTA	Married Pair	1984-86	100	22.76	3.11	76	166	3	1.27
RT	NYCT	R26	1959-60	110	15.56	2.68	44	110	3	1.27
RT	NYCT	R28	1960-61	100	15.56	2.68	44	110	3	1.27
RT	NYCT	R29	1962	236	15.56	2.68	44	110	3	1.27
RT	NYCT	R30	1961-2	130	18.35	3.05	50	145	4	1.17
RT	NYCT	R32	1964-65	595	18.35	3.05	50	145	4	1.17
RT	NYCT	R33	1962-63	494	15.56	2.68	44	110	4	1.27
RT	NYCT	R33S	1962-63	39	15.56	2.68	44	110	4	1.27
RT	NYCT	R36	1963-64	424	15.56	2.68	44	110	4	1.27
RT	NYCT	R38	1966-67	196	18.35	3.05	50	145	4	1.17
RT	NYCT	R40 (SL & ST)	1968-69	396	18.35	3.05	46	145	4	1.27
RT	NYCT	R42	1969-70	392	18.3	3.05	46	145	4	1.27
RT	NYCT	R44	1972-74	278	22.77	3.05	74	175	4	1.27
RT	NYCT	R46	1975-77	752	22.77	3.05	74	175	4	1.27
RT	NYCT	R62	1984-85	325	15.56	2.68	44	110	3	1.27
RT	NYCT	R62A	1985-87	825	15.56	2.68	44	110	3	1.27
RT	NYCT	R68	1986-88	425	22.77	3.05	70	175	4	1.27
RT	NYCT	R68A	1988-89	200	22.77	3.05	70	175	4	1.27
RT	PATCO	PATCO I MP	1968	50	20.68	3.09	80	96	2	1.27
RT	PATCO	PATCO I S	1968	25	20.68	3.09	72	73	2	1.27

Table A 3.5 Rail transit car specifications (continued)

Mode	System	Car Designation	Date Built	Number in Class	Length (m)	Width (m)	Seats	Total Capacity	Doors	Door Width (m)
RT	PATCO	PATCO II	1980-81	46	20.68	3.09	80	96	2	1.27
RT	PATH	PA-1	1965	157	15.54	2.81	31	130	2	1.37
RT	PATH	PA-2	1967	44	15.54	2.81	31	130	2	1.37
RT	PATH	PA-3	1972	46	15.54	2.81	31	130	2	1.37
RT	PATH	PA-4	1986-88	95	15.54	2.81	31	130	3	1.37
RT	SEPTA	Budd E-1	1960	231	16.76	2.77	56	107	3	1.24
RT	SEPTA	Double End: B-IV	1982	49	20.57	3.09	62	180	3	1.32
RT	SEPTA	Single End: B-IV	1982	76	20.57	3.09	65	180	3	1.32
RT	SIR	R-44 "A"	1971	40	22.76	3.05	72	175	3	
RT	SIR	R-44 "B"	1971	24	22.76	3.05	76	175	3	
RT	STC	MP-66 pneumatic	1969-73	528	16.96	2.51	40	220[4]	4	1.30
RT	STC	NM-73A pneumatic	1976	99	16.96	2.51	40	220	4	1.30
RT	STC	NM-73B pneumatic	1077-79	237	16.96	2.51	40	220	4	1.30
RT	STC	NM-73C pneumatic	1979	9	16.96	2.51	40	220	4	1.30
RT	STC	NM-79 pneumatic	1981-84	527	16.96	2.51	40	220	4	1.30
RT	STC	NC-82 pneumatic	1982-83	180	16.96	2.51	40	220	4	1.30
RT	STC	MP-82 pneumatic	1982-84	225	16.96	2.51	40	220	4	1.30
RT	STC	NM-83A pneumatic	1984-85	274	16.96	2.51	40	220	4	1.30
RT	STC	NM-83B pneumatic	1986-89	225	16.96	2.51	40	220	4	1.30
RT	STC	FM-86 steel wheel	1991-92	180	16.96	2.51	40	180	4	1.30
RT	STCUM	MR-63 pneumatic	1965-67	336	16.96	2.51	40	160	4	1.30
RT	STCUM	MR-73 pneumatic	1976	423	16.96	2.51	40	160	4	1.30
RT	TTC	H1	1965-66	160	22.7	3.15	83	225	4	1.14
RT	TTC	H2	1971-72	76	22.7	3.15	83	225	4	1.14
RT	TTC	H4	1974-75	88	22.7	3.15	77	226	4	1.14
RT	TTC	H5	1977-80	137	22.7	3.15	76	226	4	1.14
RT	TTC	H6	1986-89	126	22.86	3.15	76	226	4	1.14
RT	TTC	M1	1962-63	36	22.7	3.15	84	225	4	1.14
RT	TTC	S-1	1983-86	28	12.4	2.49	30	81	2	1.21
RT	WMATA	B2000 Cam	1983	76	22.78	3.09	68	170	3	1.25
RT	WMATA	B3000 Chopper	1984	290	23.09	3.09	68	170	3	1.25
RT	WMATA	B4000 Chopper	1991-93	100	23.09	3.09	68	170	3	1.25
RT	WMATA	R1000	1976	298	23.09	3.09	80	170	3	1.25

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[4] STC (Mexico City) and STCUM (Montreal) are coincidentally adjacent listings—and the only operators of the French *metro pneumatique* system. The cars on both systems are substantially identical in dimensions, number of doors and seatings. Montreal rates total capacity at 160. Mexico City offered no such rating but loadings on the busiest line—line 3—reach 260 passengers per car. This is almost 6 passengers per m^2—by far the highest in North America. A more palatable total capacity of 220 passengers has been assigned to the Mexican fleet, less to the dimensionally identical steel-wheeled versions which experience less intense loading.