T R A N S I T   C O O P E R A T I V E   R E S E A R C H   P R O G R A M

TCRP Report 13

Rail Transit Capacity

Transportation Research Board
National Research Council

Report 13

Rail Transit Capacity

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Subject Area

Public Transit

T RANSPORTATION R ESEARCH B OARD
N ATIONAL R ESEARCH C OUNCIL

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TRANSIT COOPERATIVE RESEARCH PROGRAM

The nation's growth and the need to meet mobility, environmental, and energy objectives place demands on public transit systems. Current systems, some of which are old and in need of upgrading, must expand service area, increase service frequency, and improve efficiency to serve these demands. Research is necessary to solve operating problems, to adapt appropriate new technologies from other industries, and to introduce innovations into the transit industry. The Transit Cooperative Research Program (TCRP) serves as one of the principal means by which the transit industry can develop innovative near-term solutions to meet demands placed on it.

The need for TCRP was originally identified in *TRB Special Report 213—Research for Public Transit: New Directions,* published in 1987 and based on a study sponsored by the Urban Mass Transportation Administration—now the Federal Transit Administration (FTA). A report by the American Public Transit Association (APTA), *Transportation 2000,* also recognized the need for local, problem-solving research. TCRP, modeled after the longstanding and succe Research Program, undertakes research and other technical activ in response to the needs of transit service providers. The scope of TCRP includes a variety of transit research fields including planning, service configuration, equipment, facilities, operations, human resources, maintenance, policy, and administrative practices.

TCRP was established under FTA sponsorship in July 1992. Proposed by the U.S. Department of Transportation, TCRP was authorized as part of the Intermodal Surface Transportation Efficiency Act of 1991 (ISTEA). On May 13, 1992, a memorandum agreement outlining TCRP operating procedures was the three cooperating organizations: FTA, the National Academy of Sciences, acting through the Transportation Research Board (TRB), and the Transit Development Corporation, Inc. (TDC), a nonprofit educational and research organization established by APTA. TDC is responsible for forming the independent governing board, designated as the TCRP Oversight and Project Selection (TOPS) Comm

Research problem statements for TCRP are solicited periodically but may be submitted to TRB by anyone at any time. It is the responsibility of the TOPS Committee to formulate the research program by identifying the highest priority projects. As part of the evaluation, the TOPS Comm expected products.

Once selected, each project is assigned to an expert panel, appointed by the Transportation Research Board. The panels prepare project statements (requests for proposals), select contractors, and provide technical guidance and counsel throughout the life of the project. The process for developing research problem statements and selecting research agencies has been used by TRB in managing cooperative research programs since 1962. As in other TRB activities, TCRP project panels serve voluntarily wit compensation.

Because research cannot have the desired im to reach the intended audience, special emphasis is placed on disseminating TCRP results to the intended endusers of the research: transit agencies, service providers, and suppliers. TRB provides a series of research reports, syntheses of transit practice, and other supporting material developed by TCRP research. APTA will arrange for workshops, training aids, field visits, and other activ to ensure that results are implemented by urban and rural transit industry prac

The TCRP provides a forum where transit agencies can cooperatively address common operational problems. The TCRP results support and complement other ongoing transit research and training programs.

NOTICE

Special Notice

FOREWORD

By Staff
Transportation Research
Board

This report will be of interest to transportation and rail-transit planners, designers, and operators responsible for determining the passenger-carrying capacity of rail lines for rapid rail transit, light rail transit, commuter rail, and automated guideway transit. The report provides a comprehensive description of the factors that determine rail transit capacity and easy-to-use procedures for estimating practical achievable rail transit capacity under a variety of conditions, calibrated with extensive, current, North American field data. The procedures are provided in two forms: a simple method of estimation in which rail capacity for typical or average conditions can be read from a graph based on train length and type of signal system and a more comprehensive method that allows for user control over additional variables. To assist in the more comprehensive method, a computer spreadsheet was developed in this project and is available free of charge on disk or through the Internet World Wide Web from the American Public Transit Association (APTA). A description of the spreadsheet and information on how to obtain it is provided in the Summary at the beginning of this report. Examples of applications for the rail transit capacity information found in this report include analyzing project planning and operations for new starts and extensions; evaluating transit line performance; establishing and updating service standards; assessing the capacities of new signaling and control technologies; and, estimating changes in system capacity and operations for environmental impact assessments and land-use variations.

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

Rail-transit capacity information available in TRB Special Report 209, *Highway Capacity Manual*, is based on operating experiences from the 1970s and the early 1980s. While providing broad guidelines and general approaches to determining rail transit capacity, it does not fully reflect current experience.

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

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.

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ACKNOWLEDGMENTS

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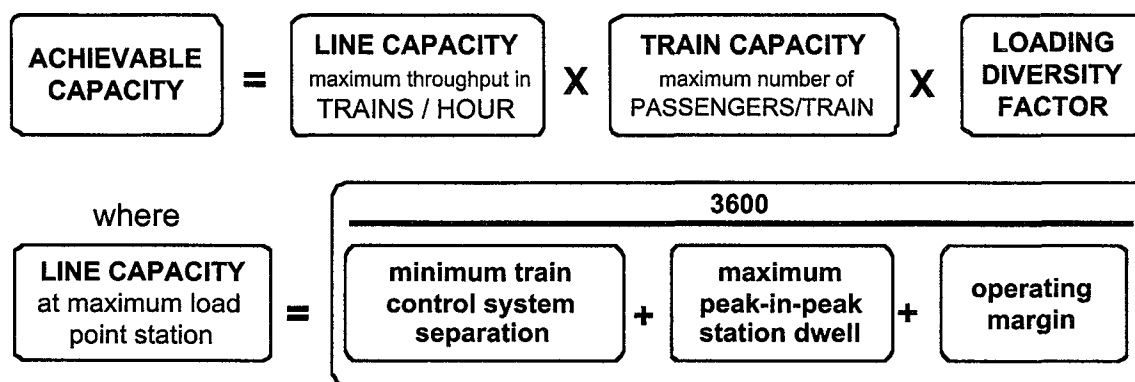
Figure S.1 Basic capacity calculation (all line capacity components in seconds)

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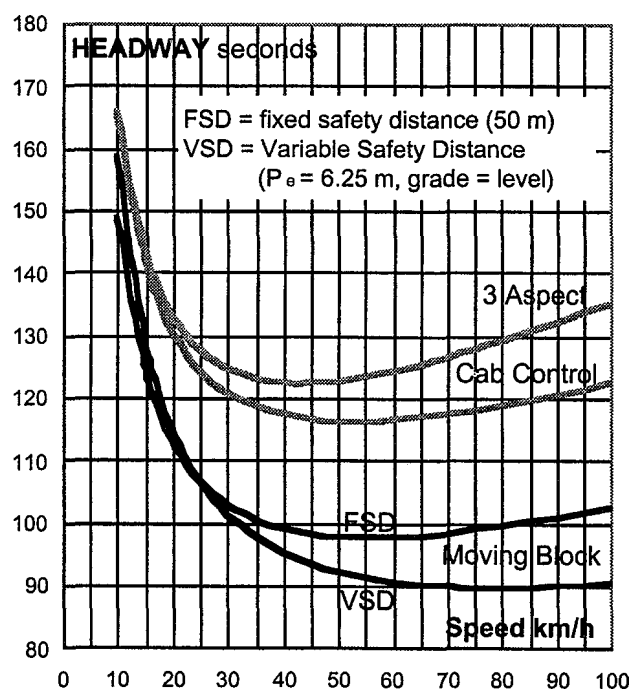
Figure S.2 Moving block headways with 45 sec dwell and 25-sec operating margin compared with conventional fixed block systems

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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 200m (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

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

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 midrange operating margin are shown in Figure S.3.

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.

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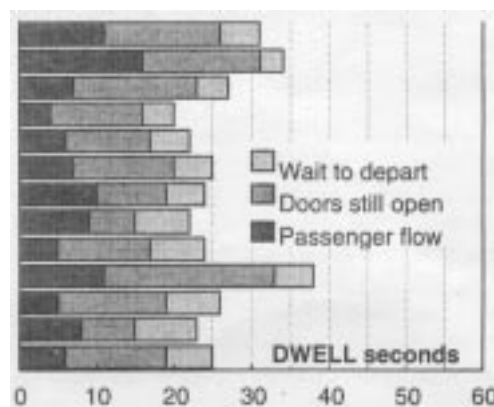
Figure S.4 Toronto Transit Commission King Station S/B dwell time components: am peak period (part) (flow time averages 31% of total dwell)

added one second per passenger on average. Light rail with lowlevel 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
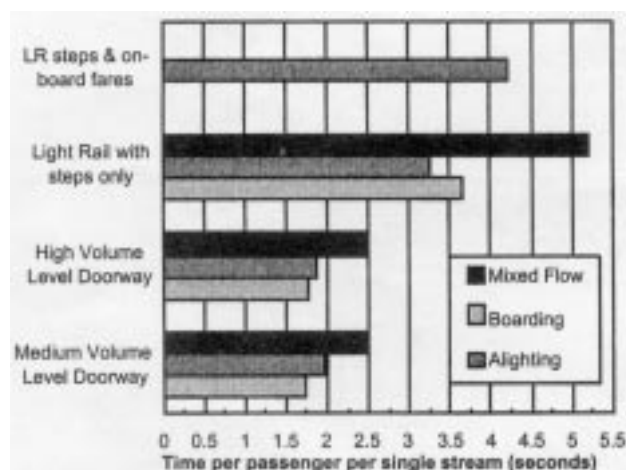
Figure S.5 Summary of rail transit doorway average flow times

Figure S.7 linear passenger loading heavy rail cars

Figure S.6 Linear passenger loading of articulated LRVs.

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

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.

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**

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.

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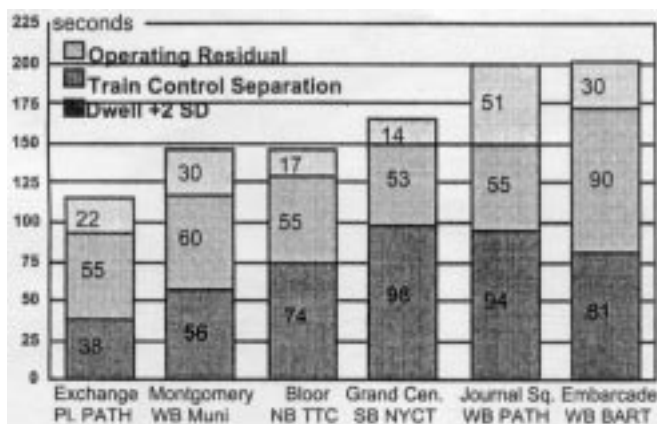
Figure S.8 Headway components of selected North American rail rapid transit systems (in seconds)

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.

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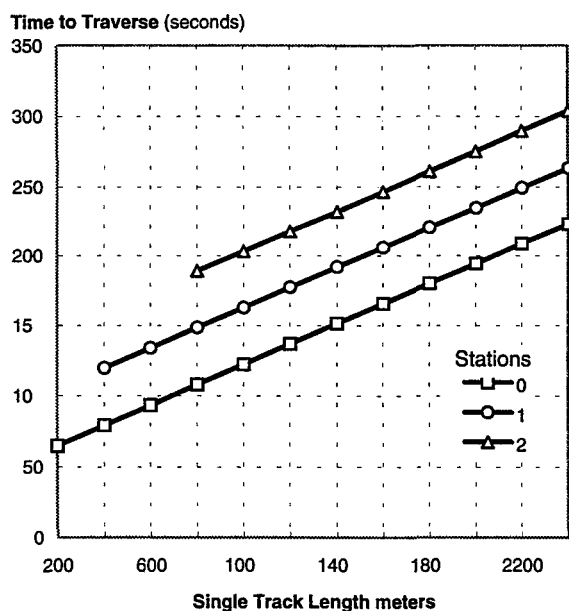
Figure S.9 Light rail travel time over single-track section.
(with a speed limit of 55 km/h and various numbers of stations train length 56 m, dwell time 20 sec, operating margin 20 sec, other data as per Table 8.2.)

Minimum train separation (seconds)
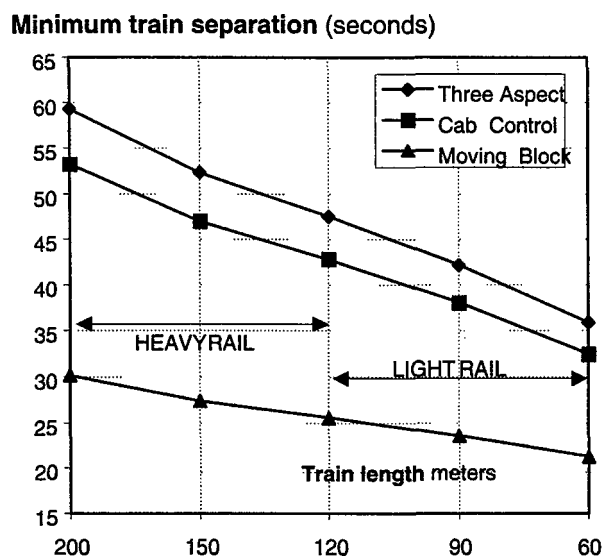
Figure S.10 Minimum train separation versus length

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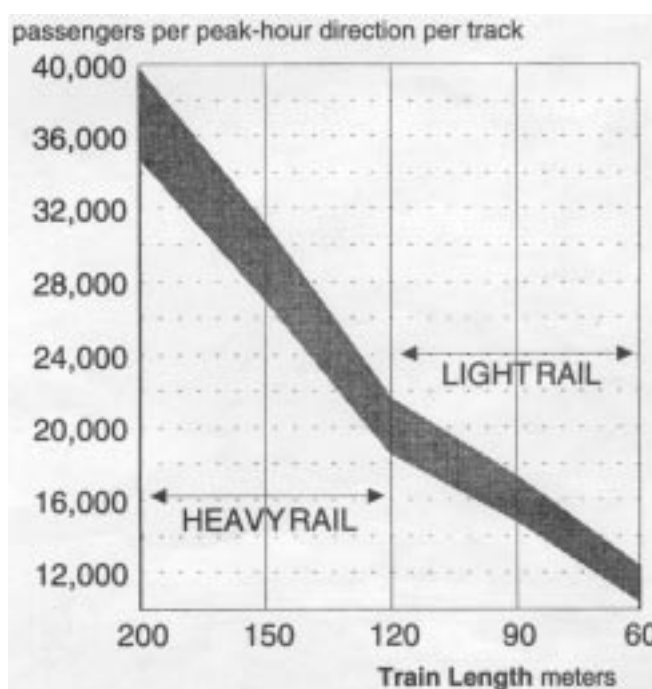
Figure S.11 Achievable capacity with a multiple-command cab-control signaling system and peak-hour average loading of two passengers per square meter for one track of a grade separated rail transit line

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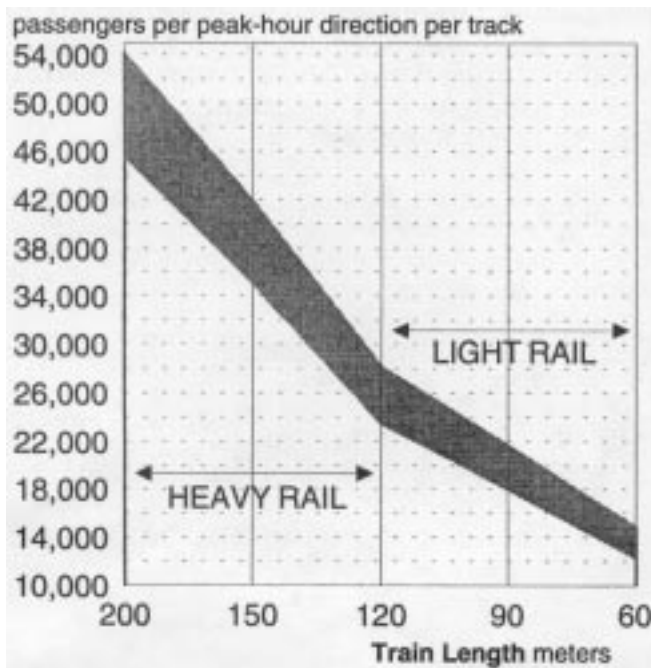
Figure S.12 Achievable capacity with a moving-block signaling system and peak-hour average loading of two passengers per square meter for one track of a grade separated rail transit line Caution: With the exception of San Francisco's Muni metro, signaled grade separated light rail lines are rarely provided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

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

rolling stock, staff and operating funds. There are few urban corridors in North America where demand requires this maximum achievable capacity.

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.

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

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.
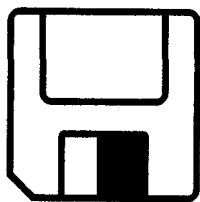
Computer Disk

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

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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.

programs for any 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: tcrapta.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

v_a = Optimum approach speed to maximum load point station

---

[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/s^2	service acceleration rate
1.3	1.3	d_s	m/s^2	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	0.0	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 secs	SD secs	n no. of samples	m+SD upper limit ONE SD	m+SD TWO SD	Operational Margin +15 sec	Operational Margin +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.

Passengers/Unit Length meters

— ◇ — Generic 23m car, 4 doors 2+2 transverse seatin
— □ — Generic 23m car, 3 doors 2+2 transverse seatin
— ○ — Generic 23m car, 4 doors longitudinal seating
— ■ — Chicago 14.6m car, 2 doors transverse seating
— ● — Vancouver 12.5m car, 2 doors mixed seating
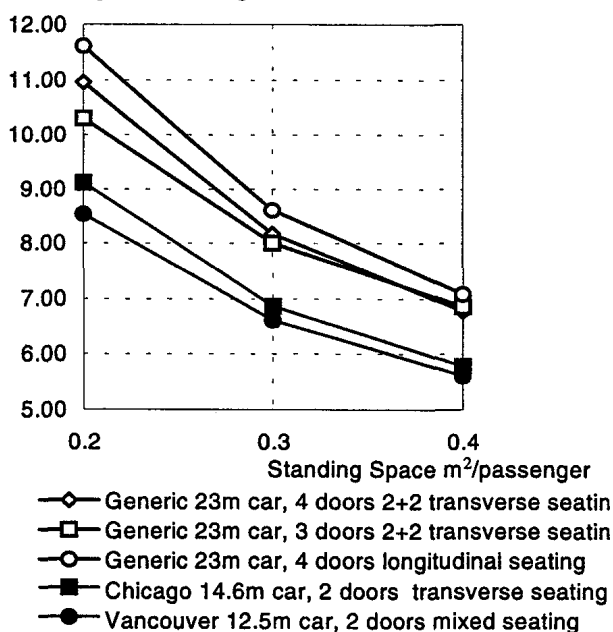
Linear passenger loading of heavy rail cars

Passengers/Unit Length meters
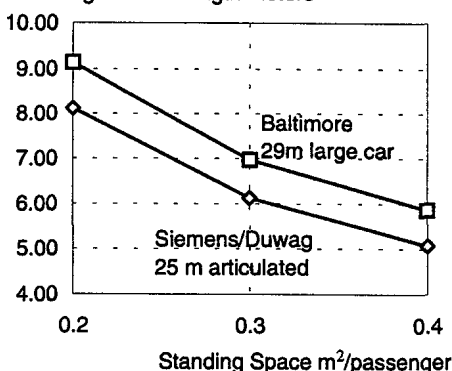
Linear passenger loading of articulated light rail cars

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.

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.

Passengers per peak hour per direction
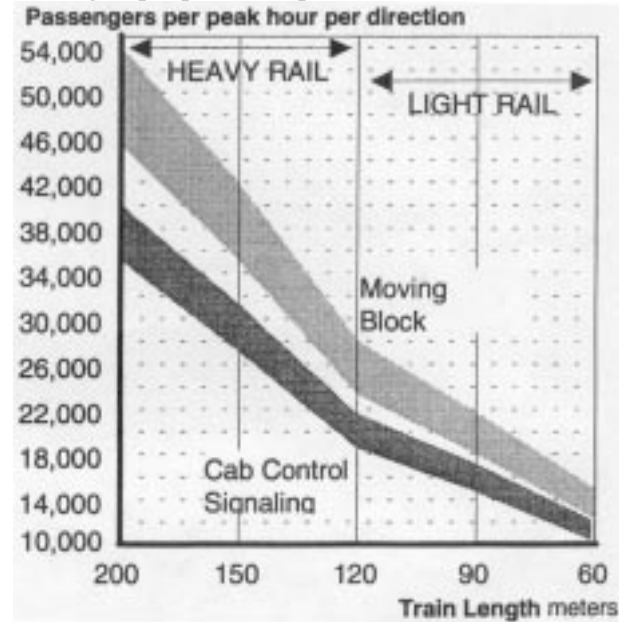
Typical maximum passenger capacities of grade-separated rail transit—exlcuding all-seated commuter rail.

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
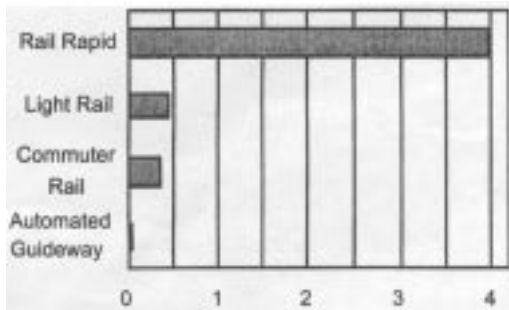
Figure 1.1 Rail transit annual passenger trips by mode (billions, Fiscal Year 1993)
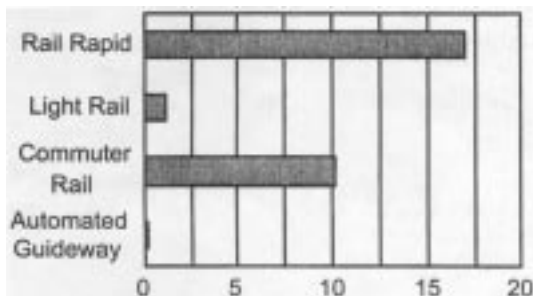
Figure 1.2 Rail transit annual passenger-kilometers by mode (billions, Fiscal Year 1993)

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

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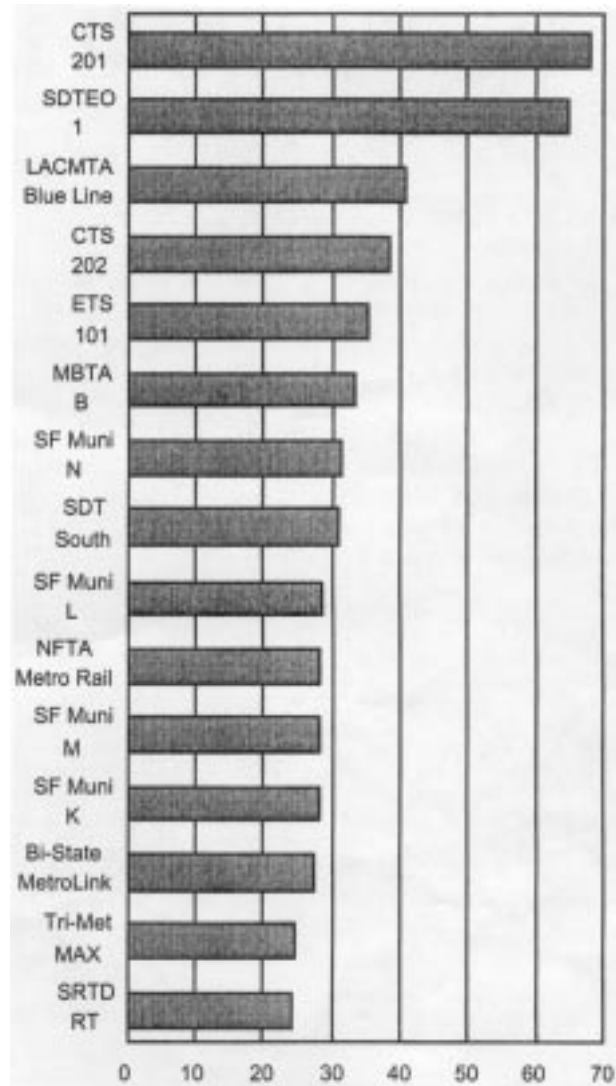
Figure 1.3 Weekday ridership for the 15 busiest North American LRT lines (thousands, Fiscal 1993)

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.

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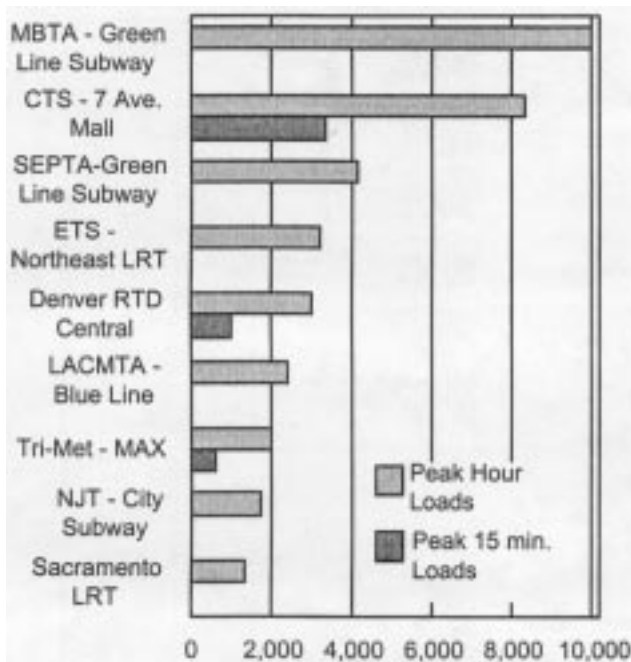
Figure 1.4 Peak-hour and peak-15-min directional flows for light rail transit trunks (passengers per hour per direction, Fiscal 1993)[3]

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

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.

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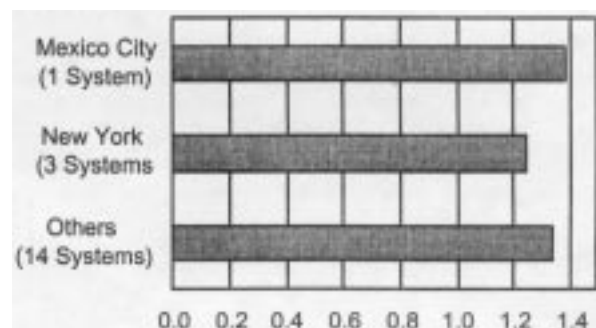
Figure 1.5 Concentration of rail rapid transit ridership (billions of annual riders, 1993 data)

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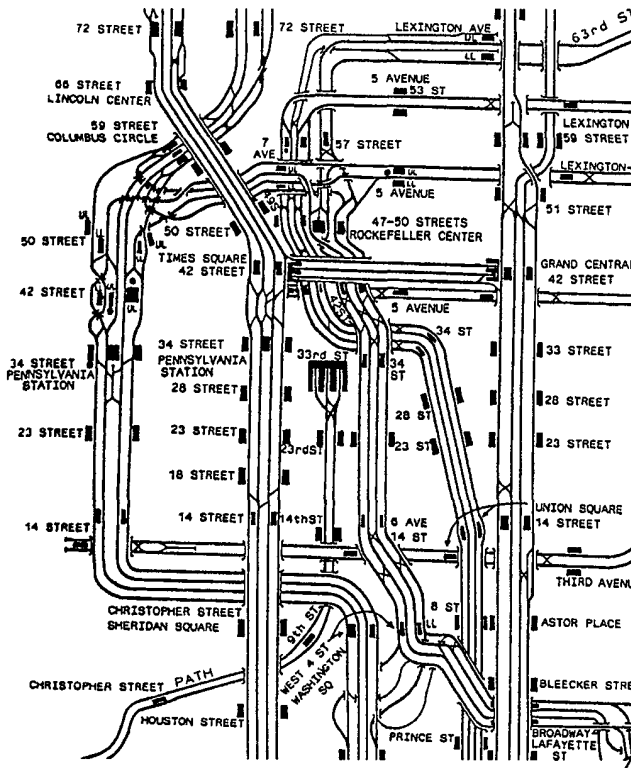
Figure 1.6 MTA-NYCT subway tracks in Midtown Manhattan[7]

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

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.

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-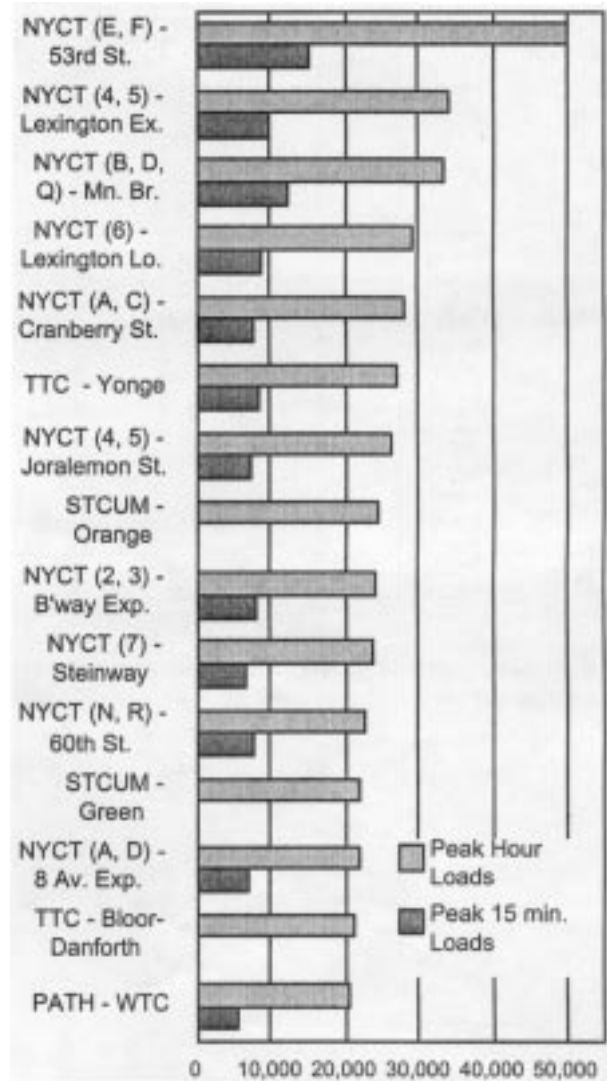track corridor operate as close as 1 min apart in the peak hours) as trains from multiple branches converge at Jamaica to continue to Manhattan.

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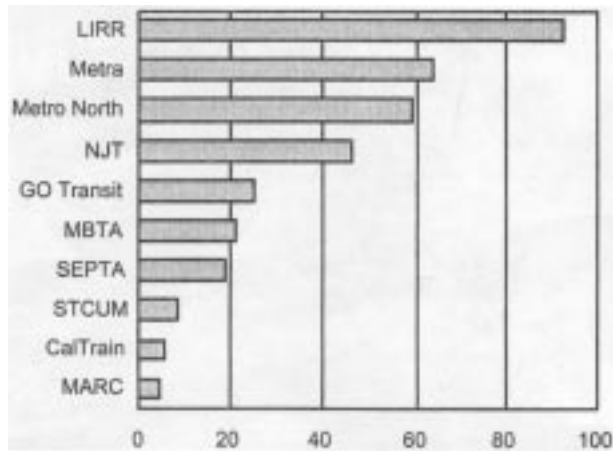
Figure 1.8 Annual ridership for the 10 busiest North American commuter rail systems (millions, Fiscal Year 1993)

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*

[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.

DESIGN CAPACITY = **LINE CAPACITY** maximum throughput in TRAINS / HOUR X **TRAIN CAPACITY** number of PASSENGER SPACES
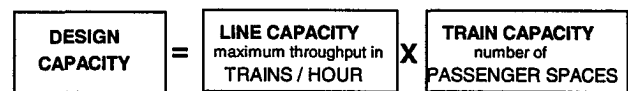
Figure 2.1 Basic design capacity expression

ACHIEVABLE CAPACITY = **DESIGN CAPACITY** X **PEAK HOUR DIVERSITY FACTOR**

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.
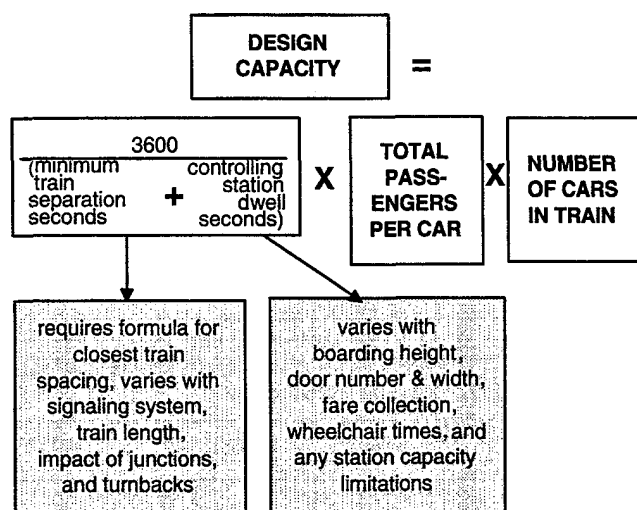
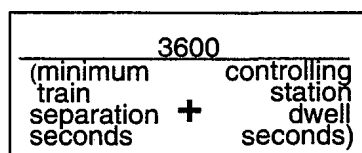**Figure 2.3 Expanded design capacity expression**

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

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

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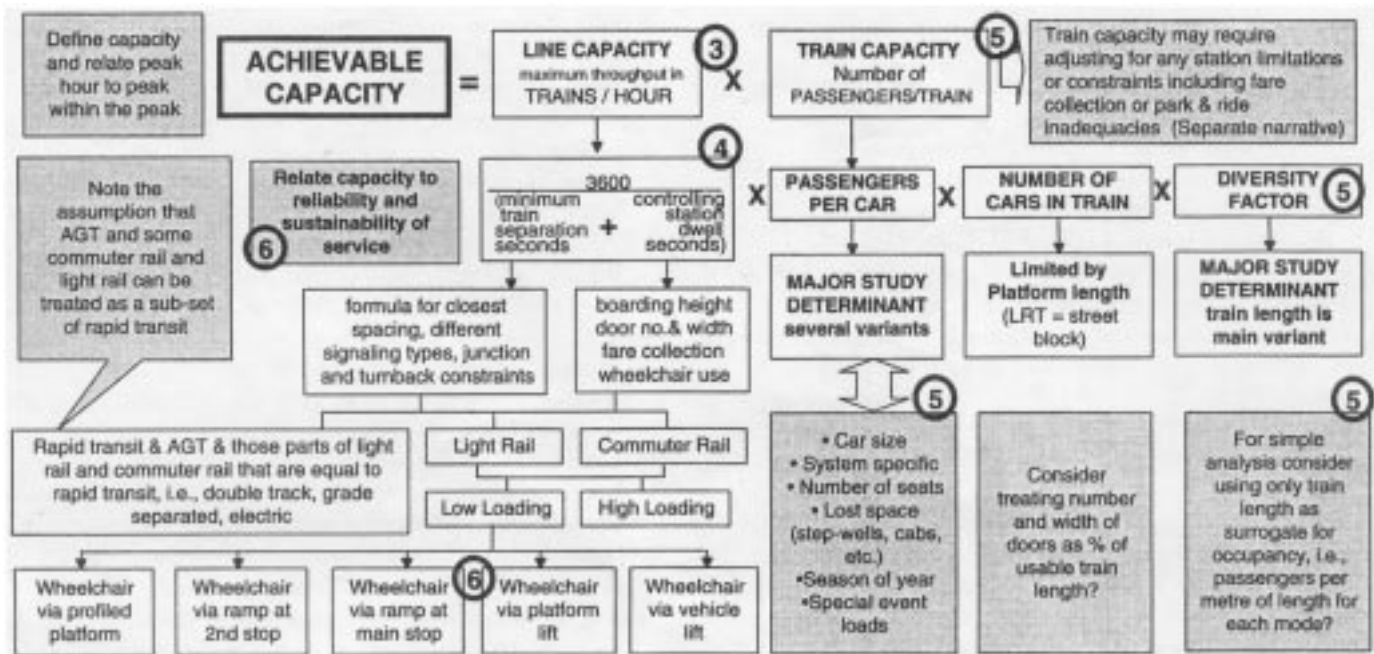
Figure 2.5 Project outline—analytic framework flowchart (Circled numbers denote the relevant report chapter)

- departures), 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 over-crowding 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 inservice 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
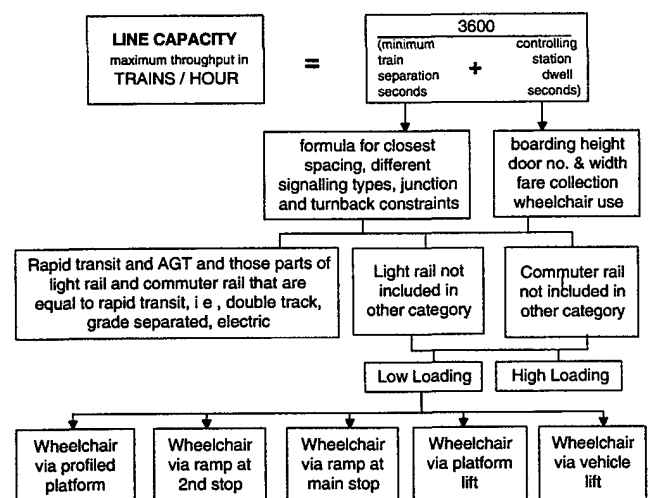

Figure 2.6 Line capacity flowchart (Not all wheelchair options apply to commuter rail)

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
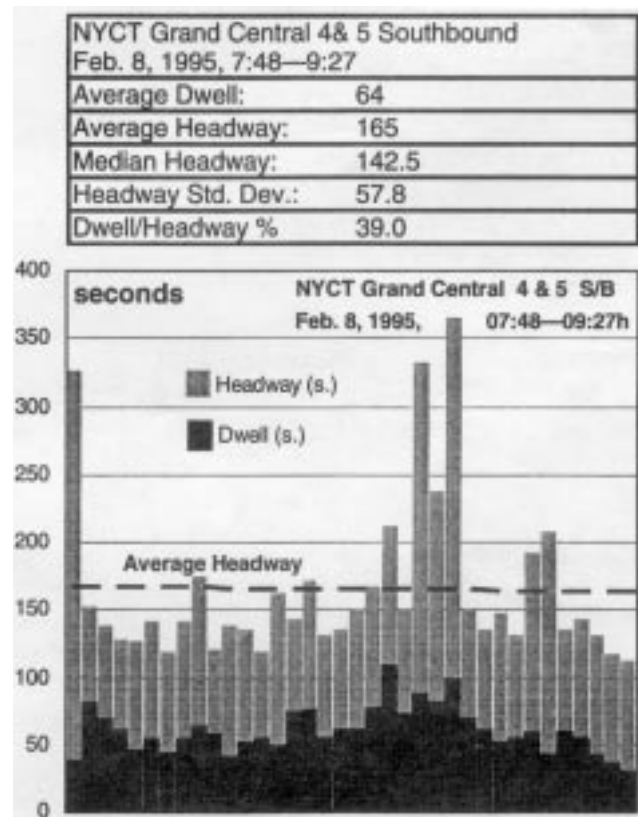

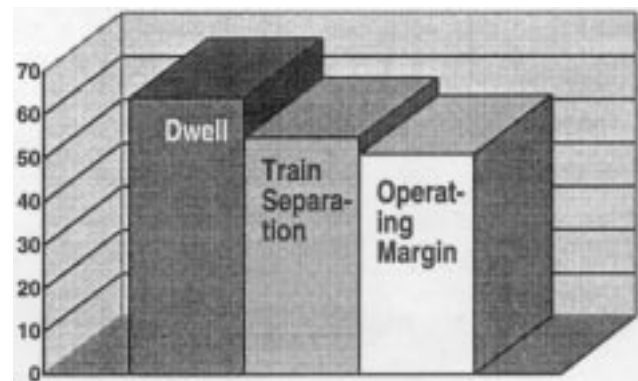**Figure 2.7 Dwell component of headway**

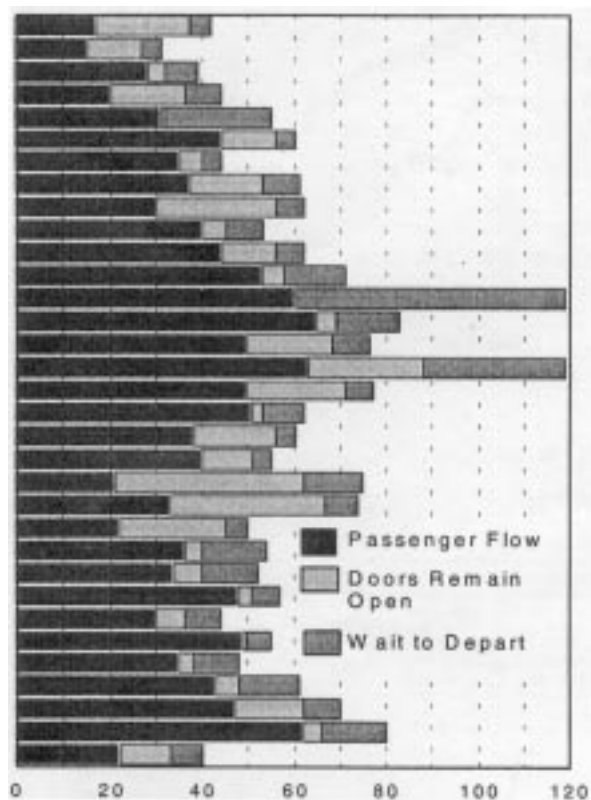**Figure 2.8 Average headway components in seconds**

14

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
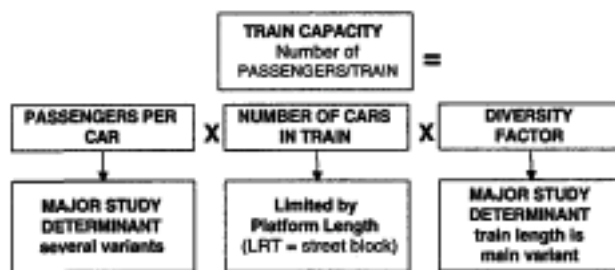number of cars, adjusted to achievable capacity case using a

Figure 2.10 Train capacity flow chart

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).

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.

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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.

- **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

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