# A1. APPENDIX ONE
# Review of North American Rail Transit Capacity Analysis Methodologies

This appendix is the result of Task 1 of the project.

*Conduct a review of North American rail transit capacity experience and capacity analysis methodologies.*

Figures, tables and equations abstracted from the literature are not titled, numbered or indexed, but are inserted in the text, as reviewed. Those figures, tables and equations from this review that are used in the report are titled, numbered and indexed therein.

There is considerable inconsistency in use of terminology in the transit industry. In this appendix the author's terminology is used. Where this could be confusing an explanatory footnote is inserted. Similarly the author's mensuration is used with conversion to the metric units used in the report where applicable.

Inevitably in so wide a literature survey there are contradictions between reports. No attempt is made to reconcile these except where specific material is used in the main body of the report.

## A1.1 INTRODUCTION

Literature searches were carried out through BC Transit's and Transport Consulting Limited's libraries and files, and through electronic searches of the Library of Congress; University of British Columbia and University of Minnesota libraries; the transportation libraries of Northwestern University and University of California, Berkeley; and the National Technical Information Service and the Transportation Research Board's Transportation Research Information System—with listings from British and European sources, including the International Public Transport Union (UITP).

The electronic searches used multiple combinations and permutations of two or three key words:

- rail
- capacity,
- light rail
- commuter
- signaling
- public transport
- local transport—Library of Congress terminology
- transit
- rapid transit
- LRT
- AGT
- train control
- metro

The electronic search was disappointing; even with broad generic key words, such as *rail transit* alone, it failed to turn up several relevant documents known to the Principal Investigator or suggested by the Panel. In part this reveals an inadequacy in the abstracts or summaries used. In particular, multiple-paper documents and reports could not realistically cover a dozen or more papers in a 200-word (or less) abstract. One important source of rail transit information, the American Public Transit Association's Annual Rail Transit Conference, is referenced only by paper title—and then only for the past few years. Similarly, many electronic databases are recent and do not include older sources.

Mitigating these deficiencies were valuable references obtained from the initial search reports, plus reports known to the Principal Investigator or suggested by the Panel, which were read and synthesized. This process doubled the number of documents and provided some of the richest and most useful material.

A total of 381 potential documents were identified in the electronic searches. Abstracts were obtained on the 65 of these that appeared useful, resulting in 33 books and reports being obtained or ordered in hard copy. The above mentioned iterative process increased the final total to the 67 reports listed below.

The literature search and synthesis produced considerably more relevant material than had been envisaged. It served as a comprehensive source to guide and steer the project's development and evolution, and equally important, indicated deficiencies, problems and pitfalls that the project should correct or avoid.

## A1.2 LITERATURE SUMMARIES

More than 70 papers, books and reports were read and synthesized with respect to Rail Transit Capacities and Capacity Analysis Methodologies. Each item is summarized below in alphabetic order by author.

Only material relevant to TCRP A-8 study is included. *The synthesis is not intended to be a complete précis of any item.* Following most summaries is a brief commentary indicating the Principal Investigator's opinion of the material's strengths and weaknesses, and expectation of the usefulness of the material to this project.

A brief overall Summary of the literature follows as section 3 of this appendix.

**1    ABRAMOVICI, MARC**, Optimization of Emergency Crossovers and Signals for Emergency Operations in Rail Rapid Transit Systems, *APTA Rapid Transit Conference, June 1982*

**Summary:** The paper presents a methodology for determining signaling requirements and cross-over locations that will

minimize disruption from single-track working—whether due to maintenance or an emergency.

An example is given for typically spaced rapid transit crossovers, with an intermediate running time of 4 min, (approximately 3 km or 2 mi). Uni-directional signaling would reduce throughput to 33% of normal. Bi-directional signaling would permit platooning with capacity reduced to 60% of normal.

The paper provides means to calculate the restriction of singletrack working with and without intermediate stations. It shows that closer cross-over spacing can provide emergency capacity that is 80-90% of normal.

**Comment:** The straightforward methodology also permits calculations of headway for light rail with single-track sections. The report raises the issue of how much allowance capacity calculations should contain for irregular operations.

## 2 ALLE, P., Improving Rail Transit Line Capacity Using Computer Graphics, Logistics and Transportation Review, Volume 17, Number 4, University of British Columbia, Faculty of Commerce, Dec. 1981

**Summary:** The study asks the following questions: "How many trains can realistically pass a point in one hour?" "What is the impact of station dwell times on this throughput?"

The study analyses the E and F trains on the NYCTA at Queens Plaza Station, using actual dwell time data and statistical probability theory to show that, by trapping 85% of the area under the normal distribution curve, the actual dwell time will be below 75.23 sec, 85% of the time. Using this figure it concludes that a single track can support trains every 130 sec—almost identical to NYCT's throughput of 29 trains per hour (124 sec), which the agency says is saturation level.

The study's dwell time methodology is:

A 95% confidence interval for the true mean is given by:

$$\mu_{95} = \left[\overline{X} + t_{n-1}; 0.025S / \sqrt{n}\right]$$

where:  $X$ = sample mean of dwell time data
  $S$ = sample standard deviation
  $n$ = number of observations

The interval estimator for the true standard deviation makes use of the chi-square ($X^2$) distribution. A 95% confidence interval for $\delta$ is given by:

$$\delta_{95} = \frac{\sqrt{n-1}}{\chi_{n-1}}\frac{(s)}{;(.025)}, \frac{\sqrt{n-1}}{\chi_{n-1}}\frac{(s)}{;(.975)}$$

To trap 85% of the area under the normal distribution curve, the upper control limit becomes the mean plus one standard deviation. Conservatively assuming the above defined $\mu$ and $\delta$ to be the upper limits of their respective 95% confidence interval, the upper control limit for the peak-hour station dwell becomes ($\mu + \delta$).

The study observed dwell times over the morning peak hour at Queens Plaza Station from 07:30 to 08:30.

Dwell Times Used in Analysis (seconds)

| | | | | | |
|---|---|---|---|---|---|
| 45 | 30 | 25 | 30 | 35 | 125 |
| 50 | 35 | 45 | 30 | 40 | 60 |
| 40 | 45 | 45 | 40 | 30 | 35 |
| 30 | 35 | 35 | 30 | 50 | 40 |
| 40 | 75 | 35 | 40 | 35 | |

These dwell times produce a sample mean of 42.7 sec and a sample standard deviation of 18.74. (Using exact rather than the rounded data above.) The median is 37.5 and the maximum 125 sec.

The resultant upper control limit ($\mu + \delta$) calculates to 75.23 sec from this data. The throughput in trains per hour ($T_h$) becomes:

$$T_h = 3600/[M + (\mu + \delta)]$$

Where $M$ is the minimum time separation in sec provided by the three-aspect signal system on the immediate approach to the station. This is determined as $M = 55$ sec through a graphical computing process that inserts train performance and the physical location of signal block boundaries. The three restrictive signal blocks approaching the station are each 200 ft long and there are blocks at 200, 400 and 700-ft-along the platform, the latter being the departure signal for the 700-ft-long platform. This maximizes throughput by allowing a train (with yellow aspects) to enter the platform before the preceding train has completely vacated it.

The computed figure cannot be determined for other locations without access to the study program and considerable physical data on the signal system. However Barwell[R11] and Auer[R09] provide simpler means to calculate this minimum signal system time separation figure for conventional signal systems and the 55 sec can be taken as a typical figure for the common three-aspect rapid transit signal systems in North America.

**Comment:** This is a valuable paper with data and methods usable in the study to show line capacity with three-aspect signal system and variable dwell times.

The merit of this paper is that, using real life data at one of New York's heavy use stations, it produces train throughput results that are very close to actual experience without applying any of the judgment factors used in many other calculation methods to calibrate theory with practice. The disadvantage is that only one station, typical as it may be, is examined.

The main lesson is that although the average peak-hour dwell time is 43 sec, the median is 37.5 and the maximum or worst case dwell is 125 sec, the upper control limit dwell time used to calculate maximum train throughput—on a sustainable and reliable basis—is calculated to be 75 sec. This is some 74% higher than the mean, 100% higher than the median, 150% higher than the often quoted "typical" dwell of 30 sec and 40% lower than the maximum—all figures used in methods suggested elsewhere in this review.

## 3 ALLEN, DUNCAN W., Practical Limits of Single-Track Light Rail Transit Operation, *Transportation Research Record 1361, 1992: pp. 305-311*

**Summary:** The author discusses a number of assumptions applicable to light rail transit. These assumptions equate the travel

time in both directions, establish the fixed headway, and optimize the signaling for the performance of the light rail vehicles to be operated. In addition, the author assumes that the single-track occupancy direction alternates with train meets occurring every half headway. The paper then goes into considerable detail to include tolerable delay factors in the optimum design calculations.

The paper also offers some observations and opinions that a practical application of single track to light rail operations may take into account. The author notes that "several iterations or adjustments may be required to reach a satisfactory solution".

The specific assumptions and methodology are:

- vehicle performance is uniform in both directions.
- headways are fixed.
- all light rail vehicles have equal priority.
- signaling is optimized for vehicles used.
- occupation of single-track alternates by travel direction.
- meets occur every half-headway (H/2).
- length of single-track is determined by design allowances for early and late vehicles.

The amount of tolerable delay, as given in the following table, is a key factor.

| Condition | Definition |
|-----------|------------|
| B | Little or no delay in either direction |
| C | Some delays, few complete stops |
| E | All or most vehicles are delayed but traffic is still moved. |

Condition E produces a maximum occupancy time for single-track segments. This is given by:

$$T_1^E = H/2 - T_{Clear} - T_{Pass}$$

For conditions C and B, the corresponding equations are:

$$T_1^C = H/2 - T_{Crit} - T_{Pass} - T_{Clear}$$

$$T_1^B = H/2 - T_{Crit} - T_{Pass} - T_{Clear} - T_{Stop}$$

where:
$T_1^E$ = occupancy time of section
$H$ = headway
$T_{Clear}$ = signal clearance time (typical light rail value 8 sec)
$T_{Pass}$ = time for an entire vehicle to pass a control point (typical value for light rail: 3 sec)
$T_{Crit}$ = sum of expected early and late train times at meet point

A "Condition D" has been empirically derived and may give a safer, more realistic, estimate of maximum occupancy time than does Condition E. It is given by:

$$T_1^D = 0.66(T_1^C) + 0.39(T_1^E)$$

Required trackage can be determined from:

$$TK = 2.0(RK)(1.0 - T_1/H)$$

where:     $TK$ = track kilometers
$RK$ = route kilometers

**Comment:** This is an interesting paper that presents an organized but theoretical approach to determining operational throughput of single-track sections of light rail transit operations. While the author's observations may be incomplete or not apparently relevant to this project's purpose, this study may find the conditions of "tolerable delay" useful.

A potential deficiency is the paper's suggestion that single-track sections less than 500-m long are unlikely to be economic—because of the costs of special work. This is incomplete and possibly misleading. It is precisely short-single track sections that can save capital costs by squeezing light rail through an underpass or over a bridge. The high special-work (switch) costs can be avoided by use of gauntlet track. Short single-track sections can have little impact on capacity and service reliability and can often be scheduled on a random arrival, first-come first-served, basis.

## 4   AMERICAN PUBLIC TRANSIT ASSOCIATION, 1992 Transit Operating and Financial Statistics

**Summary:** Used for basic information in the study database.

## 5   AMERICAN PUBLIC TRANSIT ASSOCIATION, 1994 Membership Directory

**Summary:** Used for basic information in the study database.

## 6   AMERICAN PUBLIC TRANSIT ASSOCIATION, Equipment Roster 1993

**Summary:** Used for equipment data not in the more current and detailed rapid transit roster [R03] above. Much missing door information has been obtained in the data collection task.

## 7   AMERICAN PUBLIC TRANSIT ASSOCIATION, Roster of North American Rapid Transit Cars, 1993 Edition.

**Summary:** Used to enter rapid transit equipment dimensions, door widths and other data in the study database.

## 8   ANDERSON, J. EDWARD, Transit Systems Theory, *Lexington, 1978*

**Summary:** Anderson provides a comprehensive and analytic review of transit system theory for automated guideway transit (AGT), including spiral transition curve and super-elevation calculations, modal split modeling and analytic methods of project economic evaluation.

Two sections pertain to rail transit capacity. Chapter Two introduces the basic equations of motion and shows how to calculate performance. Jerk tolerance for standing and seated passengers is introduced showing how in initiating and ending both acceleration and braking the rate must be tapered to control jerk. This results in actual performance being lower than the simplistic performance calculation common elsewhere.

The book shows how these "transitions" together with accelerating performance limitations (whereby the initial starting rate of acceleration diminishes rapidly as the train gains speed and "follows the motor curve") result in a rate of acceleration from start to balancing (cruise) speed that will be less than half the initial acceleration—significantly so if the train is heavily loaded and/or on a grade.

A critical issue in the accurate calculation of close headways is the acceleration leaving a station and Anderson's formulas suggest that the average rate of acceleration during this period may be 20 to 30% lower than the rate often used—depending on grade, load and the power-to-weight ratio of the equipment.

In Chapter Four, Anderson shows formulas to calculate the minimum separation of trains. The most restrictive headway occurs in the approach, stop and acceleration away from the station.

$$X_{\min} = kV_{\min}^2/2a_e$$

where:    $X_{\min}$ = the minimum separation distance
      $k$ = a safety constant
      $V_{\min}$ = the speed of the trailing vehicle
      $a_e$ = the braking rate of the trailing vehicle adjusted for jerk transitions

This separation distance enables the minimum headway $H_{min}$ to be calculated

$$H_{\min} = T_c + 2T_r + T_d + 2X_{\min}/V_{\min}$$

where:    $T_c$ = time for exiting train to clear platform (or blocks), calculated in the same manner as $X_{\min}$
      $T_r$ = control and/or train operator delay and/or reaction time
      $T_d$ = station dwell time

**Comment:** Transit System Theory is a misleading title because the book deals only with AGT systems. The minimum headway calculations use a safety multiplier in calculating braking and clearance distances. This approach is less clear than adding a safety distance which can be calculated from set criteria. In the TCRP A-8 study this latter method, as outlined in Auer [R09] and Motz [R47] following, is preferred and has been used.

Anderson's Commentary on jerk limitation, transitions to braking and acceleration rates, and the rapid fall-off of the acceleration rate as a train gains speed is invaluable.

**9 AUER, J.H.,** Rail-Transit People-Mover Headway Comparison, *IEEE Transactions on Vehicular Technology, Institute of Electrical and Electronics Engineers, 1974*

**Summary:** Discusses the application of conventional block signaling to rapid transit and AGT with details of maximum train throughput under various conditions for both modes. Shows how the WMATA signaling system is designed for 75-sec minimum headways with trains of maximum length. This can be reduced to 18 sec on AGT systems—with the same *brick-wall* safety standards.

The author describes time delays that limit signaling throughput:

- train operator reaction time varies, 0 with ATO
- cab signal communication delay, 2.0 sec
- overspeed detection delay, 0.75 sec
- switch lock-to-lock time, 3.0 sec

$$MLH = 0.682K(TL + SBD + TDUD + SCBD)/CS$$

where:    MLH = Minimum Line Headway (sec)
      K = Safety Factor, must be $\geq 1$ for brick-wall standard
      TL = Train Length
      SBD = Safe Braking Distance based on runaway propulsion failure plus reduced braking factor
      TDUD = Train Detection Uncertainty Distance
      SCBD = Service Control Buffer Distance (AGT only)
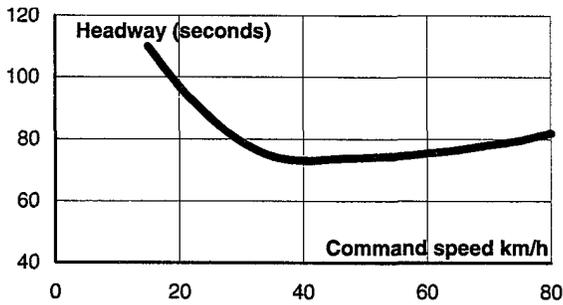      CS = Command Speed

Other equations are developed to calculate the headway on a conventional three-aspect block signaling system under a variety of conditions and assumptions, including the impact of Automatic Train Operation (ATO) and cab signals over manual operation. Cab signals can improve minimum headway by a calculated 1.7 sec at an approach speed of 50 km/h while ATO can effect a further reduction of some four sec at the same speed.

Auer shows the components in the minimum headway, at a command speed of 50 km/h, for a conventional three-aspect signaling system. The total headway of 73 sec includes a 20-sec dwell. The minimum line headways can be expressed as 53 sec plus the controlling dwell. This corresponds closely to Alle's work (R02) which suggests a three-aspect signal system with ATO can sustain a headway of 55 sec plus the upper control limit dwell time.
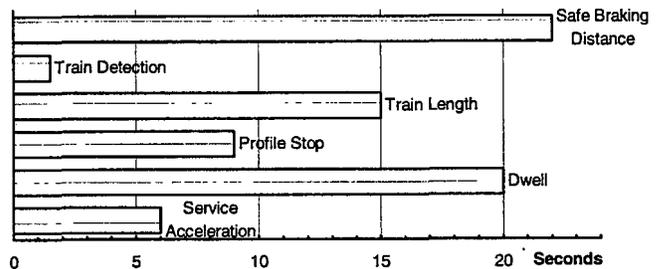


The variation of this minimum headway (73 sec) with train length is shown in the following figure.

The variation of headway with train command speed is shown below. The minimum headway is 71.2 sec at 44 km/h—including a nominal 20-sec station dwell.

Note that the command speed is the speed restriction imposed by the signal system approaching and leaving a station—not the cruise or maximum speed between stations. Typical command speeds will be in the 30 to 40 km/h range allowing a 75-sec headway—close to the optimal minimum of 71.2 sec. However where there are restrictions, approaching or leaving a station, due to special work or curves, the minimum headway can increase significantly. At a more restrictive command speed of 20 km/h, the headway increases to 100 sec. Discounting the 20-sec station dwell, this is an increase from 55 to 80 sec—45%.

**Comment:** Auer's paper provides one of the best, concise summaries of a conventional three-aspect signaling system throughput for both rapid transit and AGT. The results correspond closely to actual field data. When combined with the upper control limit dwell time calculations of Alle[R02] it suggests both simple and complete methods for the study to determine line throughput. It has been used in the study as the best representation of three-aspect signaling systems.

## 10 BARDAJI, JORDI F., Regulating Headway in Barcelona, *The Urban Transport Industries Report, Campden Publishing Limited, 1993, pp. 175-176*

Bardaji describes how automatic regulation increased the practical capacity of the Barcelona subway by 5%.

## 11 BARWELL, F. T., Automation and Control in Transport. 2nd Revised Edition *Pergamon Press Limited, 1983*

In this standard text, the late Professor Barwell covers many aspects of rapid transit operation and control. Among his many Comments are that "transport problems generally reduce to the consideration of headway at a bottleneck" and admonitions that some of the mathematical theory presented does not correspond to actual field experience without practical adjustments.

In discussing multiple-aspect signaling systems he points out that the "law of diminishing returns operates very powerfully". It is rarely economic to move beyond the typical three-aspect signaling system although four aspects have been used to increase capacity on some European high-speed inter-city railroads. In noting that track circuits were first used in 1872 and

coded circuits in 1933, he suggests that moving-block systems may take over many high speed inter-city applications where the signal system must accommodate trains of differing lengths, performance and speeds.

Barwell discusses rail junction optimization techniques and the simulation of train following behavior—particularly relevant when train spacing is perturbed. He develops the minimum train separation $S_e$ as:

$$S_e = TL + BL + 0.75V^2/aK$$

where:
- $TL$ = train length
- $BL$ = block length plus safety distance *or* block overlap plus sighting distance
- $V$ = train speed
- $a$ = braking rate
- $K$ = a safety constant

Minimum headway ($H_{min}$) is shown as:

$$H_{min} = S_e/V + \text{maximum station dwell} + \text{recovery time} + \text{reaction times}$$

**Comment:** Barwell provides a useful way to calculate the minimum train spacing for a moving block system—where theory corresponds closely with practice. However both here and in the train separation equation above, the introduction of safety factors makes the calculation subjective. Barwell's work provides methods to calculate junction constraints on capacity.

## 12 BATELLE INSTITUTE, Recommendations en vue de l'amènagement d'une installation de transport compte tenu de données anthropomètriques et des limites physiologiques de l'homme, *Geneva, 1973*

**Summary:** The relevant parts of this report deal with recommended comfort levels for many aspects of public transport vehicles, including temperature, ventilation, noise, floor slope, acceleration, rate of change of acceleration (jerk) and passenger standing density. Information is provided for three conditions, *comfortable, uncomfortable and unacceptable.*

The passenger standing density recommendations are

- comfortable      2-3 passengers per m$^2$
- uncomfortable      5 passengers per m$^2$
- unacceptable      >8 passengers per m$^2$

Details are provided on the projected body space of passengers in various situations. The most useful of these for rail transit capacity are tabulated for males.

| Situation | Projected Area m$^2$ |
| --- | --- |
| Standing | 0.13 to 0.16 |
| Standing with briefcase | 0.25 to 0.30 |
| Holding on to stanchion | 0.26 |
| Minimum seated space | 0.24 to 0.30 |
| Tight double seat | 0.36 per person |
| Comfortable seating | 0.54 per person |

## 13  BERGMANN, DIETRICH R., Generalized Expressions for the Minimum Time Interval between Consecutive Arrivals at an Idealized Railway Station, *Transportation Research, 1972 Vol. 6, pp. 327-341*

**Summary:** Bergmann's mathematical treatise explores the principal determinant in rail transit throughput—the minimum time between successive arrivals at a station.

He expands on the basic equations of motion, examining in particular limitations and effects of train approach speed, train length, and the emergency braking rate. Four expressions are developed for differing limits of these three variables.

The basic expression for minimum headway $T_{A;i/i+1}$ without limits is:

$$T_{A;i/i=1} = t_d + t_r + \frac{L_i}{V_m} + \frac{V_m}{2(D_e + D_o + A)}$$

where

$t_d$ = station dwell time
$t_r$ = emergency braking response time of following train
$L_i$ = length of leading train
$V_m$ = constant speed station approach
$D_e$ = emergency deceleration rate
$D_o$ = operational deceleration rate
$A$ = acceleration rate

Three other expressions are derived for variations or limits to approach speed, train length, and the emergency braking rate. These are plotted against approach speed to show a minimum headway of 31 sec plus station dwell at an approach speed of approximately 35 km/h (22 mph). Higher approach speeds show a linear relationship to headway when operational and emergency deceleration are equal. When emergency deceleration is higher than operational deceleration the minimum headway remains constant with approach speed.

Bergmann then compares his results with other authors before concluding that increasing the emergency deceleration rate will decrease minimum headways—with the caution that the approach is theoretical and does not take into account the effect of finite signal blocks on train separation.

**Comment:** The paper's extensive analysis is interesting in introducing the difference in minimum headways due to operational and emergency deceleration rates and showing the optimum approach speeds under various conditions. The analysis does not take into account practical limits on acceleration and deceleration with respect to passenger comfort, not does it allow for performance variations, grades or operational allowances. His calculated minimum headway of 31 sec plus dwell is applicable only to moving-block signaling systems but provides an interesting lower limit for such systems.

## 14  BERRY, RICHARD A., CERVENKA, KENNETH J. AND SU, CHANG-AN, Traffic and Light Rail Transit: Methods of Analysis for DART's North Central Corridor, *Transportation Research Record 1361, 1992: pp. 224-234*

**Summary:** This paper presents a detailed summary of the application of computer modeling of delays to automobile traffic caused by DART's (Dallas, Texas) North Central light rail line. Grade crossing methods, at-grade or grade separated, are proposed based on the effect of light rail on traffic.

**Comment:** Berry *et al.* are concerned exclusively with the effect of the light rail on general traffic flow and do not address the capacity of the light rail line itself. As such, this work is of little use to the project except to confirm other similar work that grade crossings have little, if any, impact on light rail capacity compared with the constraint of signaled sections.

## 15  BOORSE, JACK W., Blending LRT into Difficult Traffic Situations on Baltimore's Central Light Rail Line, *Transportation Research Record 1361, 1992: pp. 197-206*

**Summary:** Discusses light rail and traffic signal control for intersections with long (110-sec) cycle time. Travel time improvements are possible with sequencing. Confirms other work that suggests on-street segments with traffic control are generally less restrictive of capacity than the signal system used on segregated track sections. For example, two trains platooned through each traffic light cycle provide a throughput of 65 trains an hour—versus the 30 trains per hour of the signaling system and 8 trains an hour limit of the single-track sections.

## 16  BURGIN, EDWARD A., Light Rail Transit Signaling, *Transportation Research Board Special Report 182, 1978, pp. 119-123*

**Summary:** Overview of light rail signaling, cab controls and interlockings with breakdown of safety critical areas and nonvital areas. Details Muni's original Market Street light rail subway cab control signaling with the three codes for 16, 43 and 80 km/h and automatic overspeed braking that occurs at 3.2 km/h over the set limit. (This signaling is now being replaced by a moving-block system to increase capacity.)

## 17  BUSHELL, CHRIS., Jane's Urban Transport Systems, *Jane's Information Group Ltd., UK, 1989*

**Summary:** A comprehensive reference to rail transit systems.

## 18  CALLAN, DENNIS R., Toronto Transit Commission's 90 Second Headway Study: Getting More Out of Existing Infrastructure, *APTA Rapid Transit Conference, Vancouver 1990*

**Summary:** See reviews [R61] and [R68] on which this paper is based.

**19 CANADIAN URBAN TRANSIT ASSOCIATION**, Canadian Transit Handbook, 2nd Edition, Chap. 8—Capacity, *Canadian Urban Transit Association. and the Roads and Transportation Association of Canada, Toronto, 1985*

**Summary:** This work gives a broad-ranging introduction to the subject of transit capacity. Capacity is cited as being an "*elusive figure.*" Both rail and bus modes are covered in easily comprehensible language.

The chapter deals with the following determinants of capacity: loading standards, headways and signaling, dwell times and vehicle performance. The paper closes with a table of design flows for selected transit modes.

Full utilization of capacity is limited to short periods of time. Capacity is an elusive figure which is determined partly by the level of service (speed, degree of crowding) desired. The handbook defines three terms relating to capacity:

- volume      =      actual flow
- demand      =      potential flow
- capacity      =      possible flow

A basic equation for determining capacity is given. Units are passengers per hour.

$$Capacity = Q = fnp = \frac{60np}{h} \qquad (1)$$

$$Capacity = Q' = \frac{p\,\overline{V}n'}{2L} \qquad (2)$$

where:   $h$ = headway (minutes)
       $f$ = frequency (units per hour)
       $n$ = number of vehicles per transit unit
       $p$ = passengers per vehicle

The author states that capacity is determined by a number of factors which can be readily grouped into categories as follows:

**1. Vehicle Characteristics**
- fleet size
- maximum number of vehicles per transit unit
- vehicle dimensions
- seating configuration
- number and location of doors
- maximum speed
- acceleration and deceleration rates

**2. Right of Way Characteristics**
- cross-section design
- degree of separation from other traffic
- intersection design (at-grade or separated)
- horizontal and vertical alignment

**3. Stop Characteristics**
- stop spacing
- on-line or off-line (latter allows passing stopped vehicles)

- fare collection method
- high- or low-platform loading
- length of platforms
- turnaround facilities at terminals

**4. Traffic Characteristics**
- volume and nature of other traffic (for shared right-of-way)
- cross-traffic at intersections (at-grade)

**5. Method of Headway Control**
- type of control separation standards for safety.

The report states that the permissible level of passenger crowding on transit vehicles is an important determinant of capacity. Standing densities of 0.1 m$^2$ per passenger have been observed in some cities but a value of between 0.2 and 0.7 m$^2$ per passenger is more typical in North America.

Passenger behavior is also important in determining loading standards as loading in cars and trains tends to be uneven. Allowing passengers to travel between cars through end doors can help even loading on a train. Irregular densities in cars can be caused by passengers congregating around doors, stanchions and the like.

Minimum headway is determined by the degree of separation from other traffic, the method of headway control, and by dwell time effects. Most rail transit modes other than streetcars have "controlled" headways. For streetcars, the maximum frequency is around 120 units per hour in mixed traffic. However, at this frequency the service quality is reduced due to poor service reliability. At such frequencies the traffic lane used by transit essentially becomes a transit-only lane by default. A more realistic maximum frequency would be 60 units per hour in mixed traffic or 75 units per hour on an exclusive right-of-way.

Headways are governed by the type of signaling system. With automatic train operation (ATO), door control and initiation of acceleration remain under manual control. Automatic train control (ATC) fully automates all aspects of train operation and allows full driverless operation with possible throughput increases.

The minimum headway for a block-signaled line can be determined from:

$$h' = T = \frac{L}{V} + \frac{KV}{2d} + \frac{V}{2a} + t$$

where:   $h'$   =   minimum headway(s)
       $T$   =   station dwell time (s)
       $L$   =   train length (m)
       $V$   =   operating speed (m/s)
       $d$   =   deceleration (m/s$^2$)
       $a$   =   acceleration (m/s$^2$)
       $t$   =   reaction time (s)
       $K$   =   safety factor

A common value of $h'$ for lines signaled for minimum headway is 90 sec. Sustained headways of 120 to 130 sec are more common and allow for peak station delays. Headways of dieselelectric commuter rail service tend to be on the order of 10 to 12 min to allow for grade crossings, longer braking distances and mixed use of the rail line.

Average speed depends upon vehicle characteristics, traffic, stop separation and dwell times. It is given by the following equations:

$$\overline{V} = \frac{S}{T + \dfrac{S}{V} + \dfrac{V}{2a} + \dfrac{V}{2d}}$$

where:    $S$ = stop spacing in meters

If $S$ is not constant then:

$$\overline{V} = \frac{L}{\dfrac{L}{V} + k\left(\dfrac{V}{2a} + \dfrac{V}{2d}\right) + \sum_{i=1}^{k} T_i + r}$$

where:    $k$ = number of stops
$r$ = terminal time to turnaround (sec)
$L$ = route length (m)

The main vehicle independent factors governing average speed are dwell times and stop separation. For wide stop separation, maximum speed is the most important vehicle characteristic, while acceleration and deceleration rates are more important with narrow stop separation. Acceleration and deceleration values also partly regulate safe following distances. A value of 1.25 m/s$^2$ is reasonable for these characteristics.

Dwell times are controlled by the following factors:

- number of passengers boarding and alighting
- method of fare collection
- number of loading positions
- high/low level car entry and exit
- door arrangement and number
- seating arrangement

Typical ranges for on-board fare collection, low loading equipment are 2–3 sec per boarding passenger and 1.5–2.5 sec for each alighting passenger.

The chapter closes with a discussion of comparative design flows and a table of capacities for various transit modes. Two key points are that service quality and reliability are compromised at the upper limits of design capacity, and that design flows are generally only reached for short periods. Some sample hourly capacities for the various modes are:

Streetcars, mixed traffic ............................... 6,060  pphd
Streetcars (2 cars) exclusive lanes ............ 15,150 pphd
Commuter rail, bi-level ............................ 13,750 pphd
LRT, articulated cars ................................ 24,300 pphd
Rail Rapid Transit ..................................... 43,000 pphd

**Comment:** The chapter gives a broad ranging introduction to the subject of transit capacity. It discusses full capacity as limited to short periods of time because of practical peak service considerations. These are covered in considerable detail with regard to vehicle characteristics, right-of-way characteristics, and methods of operational control. In addition, the chapter covers the effect on capacity of passenger loading standards, and on the physical and control limitations on headway for various transit modes. The chapter closes with a comprehensive view of expected capacities for urban transit.

**20    CELNIKER, STEPHEN, and TERRY, E. WAYNE,** Trolley Priority on Signalized Arterials in Downtown San Diego, *Transportation Research Record 1361, 1992: pp. 184-188*

**Summary:** The trolley priority signaling system in downtown San Diego was altered in 1990 as a result of the original system's inadequacy following increases in San Diego Trolley services. The original pre-emption mechanism gave light rail vehicles full priority at all intersections. With more frequent light rail service, this resulted in excessive delays to pedestrian and vehicular traffic crossing streets used by the light rail. A lack of an allowance for light rail trains traveling in the opposite direction and a tendency to fail further high-lighted the need for improved signaling.

The replacement system integrates light rail operations into the downtown traffic signal progression system. This allows the light rail trains to travel unimpeded from one station to the next in a "green window". In theory, all waiting for signals is done as dwell time at stations. In the morning peak, some trains must leave stations after the "green window" has passed but while the nearest signal is still permissive. This allows the following train to enter the station but results in the first train waiting between stations.

**Comment:** The installation of an improved trolley priority signaling system has improved light rail travel times in Centre City San Diego. A capacity limitation created by the uni-directional nature of the earlier signal system has been removed.

**21    DELAWARE RIVER PORT AUTHORITY**, 90 Sec Headway Feasibility Study, Lindenwold Line, *Delaware River Port Authority, January 1973*

**Summary:** To accommodate proposed new branches, methods were examined to decrease headways on the inner (Camden - Philadelphia) portion of the PATCO line to 90 sec. The analysis shows that this headway can be achieved by a combination of adjusting block boundaries and both increasing and reducing speeds—increasing speeds where speed limits (curves) increase the critical station close-in time, reducing those speeds that produce *limiting* safe braking distances.

To mitigate the cost and inconvenience of increased travel time, options were presented to increase the assured braking rate and reduce the braking system reaction time within the capabilities of adhesion and the existing slip-slide detection and control—specifically the overspeed control reaction time—which applies the brakes if the non-vital speed governor fails.

The report states "Braking distance is one of the most important factors in the calculation of minimum headways because it determines minimum safe train separation." A train must always

be separated from the train ahead, or end-of-line bumping block, by at least the worst case stopping distance plus safety margins—termed the *safe braking distance*—a function of speeds, curves, grades, braking rate, available adhesion and the reaction times of on-board and wayside train control equipment.

PATCO uses automatic train operation with full automatic driving. On this equipment the worst case reaction time occurs when the speed governor fails just before receiving a lower speed code with the train already close to the overspeed limit. This worst case failure assumes the train is under full power until the vital overspeed protection system intercedes and applies braking. In a worst case, such emergency braking assumes the failure of one set of braking equipment (independent for each truck) on the shortest consist.[1]

A separate analysis examined changes necessary to accommodate 90 sec headways in the downtown turnback. To achieve this involved a combination of reducing the terminal approach speed, relocating the terminal scissors cross-over from behind to in front of the station and extending the tail tracks behind the station.[2] This had the added benefit of decreasing turn-around time, in part compensating for increased running times elsewhere.

The analysis in this report was based, in part, on the separately summarized paper: Weiss, David M., and Fialkoff, David R., *Analytic Approach to Railway Signal Block Design,* Transportation Engineering Journal, February 1974.

**Comment:** This report provides useful information on providing higher capacity by reducing headways with track circuitbased automatic train operation. The thorough, yet concise, description of *safe braking distance*, and its constituent components, is applicable to many rapid transit systems.

## 22 DEMERY, LEROY W., Jr., Supply-Side Analysis and Verification of Ridership Forecasts for Mass Transit Capital Projects, *American Planning Association Journal, Summer 1994*

**Summary:** Demery's paper deals extensively with the difference—and often confusion—between the *demand for* and the *supply of* service on rail transit.

> *... peak-period capacity is not an issue in most United States and Canadian cities ... ... observed peakpoint loads outside New York, Montreal and Toronto are well below the theoretical capacity of the heavyrail and light-rail modes.*

[1] Reviewer's Note: The worst case safe braking distance (sometimes called the safety distance) is calculated from the worst case reaction time assuming the heaviest passenger load, plus any possible snow and ice load, tail wind (if any), steepest applicable down grade, adhesion limits, and partial brake system failure. Note that the terminology *worst case* is misleading. The truly worst case would be a total braking failure. In these analyses *worst case* means *reasonable failure situations.* Total brake failure is not regarded as a realistic scenario on modern rail transit.

[2] Reviewer's Note: The report recommended extending the underground tail tracks by 125 ft. The possible alternate of energy absorbing train arrestors was not discussed.

Four supply-side parameters are defined:

- Peak traffic share (PTS) (passengers per peak-hour direction as a percentage of weekday ridership)
- Vehicles per hour
- Passengers per vehicle
- Average weekday ridership (AWR)

The relationship between these four parameters is expressed as:

$$(AWR) \times (PTS) = (Veh/hr) \times (Pass/veh).$$

Following further discussions of the supply-side, the report details the relationship between average weekday and peak-hour ridership, citing data from many cities to show a North American range of 9 to 24 percent with a mean of 15 percent.

The maximum service that a fixed-guideway transit facility can supply or "field" is stated to be a function of maximum train length and maximum frequency of service, with the former determined by platform length and the latter by the train control system. Other factors are stated to be vehicle performance, maximum speed between stations, average dwell times at stations and other operating considerations.

The report tabulates average peak-hour occupancy derived from data between 1976 and 1990.

| City | Passengers/m² of Gross Floor Space |
|------|------------------------------------|
| New York | 2.6 into CBD |
| Chicago | 1.5 into CBD |
| Philadelphia | 1.3 into CBD |
| Boston | 2.0 into CBD |
| San Francisco | 1.2 - 1.9 |
| Washington | 0.9 - 2.0 |
| Atlanta | 1.4 - 1.6 |
| Toronto | 1.8 - 2.4 |
| Montreal | 2.6 - 3.2 |

The report discusses capacity limitations on recent light rail lines as they relate to the signaling system, single track sections and maximum train length.

| City | Max. train length | Closest headway |
|------|-------------------|-----------------|
| Buffalo | 4 | 5.0 minutes |
| Pittsburgh | 2 | 3.0 minutes |
| Portland | 2 | 5.0 minutes |
| Sacramento | 4 | 15.0 minutes |
| San Diego[3] | 4 | 7.5 minutes |

[3] Demery states the maximum train length in San Diego's Centre City is 3 cars and that the four-car trains have a car added or removed at the 12th and Imperial station. Other sources state that four-car trains are broken into 2 two-car trains to move through city streets.

Demery discusses three reasons why vehicle loadings fall "far short" of the theoretical levels.

- Maximum peak-period demand occurs over intervals of 15 to 20 min (quoted as the "sub-peak" rather than peak-within-the-peak).
- As the number of standing passengers increases, loading and unloading times also increase, extending dwells and reducing schedule adherence.

- Outside the largest, most congested urban areas, the level of crowding that transit passengers appear willing to tolerate falls well short of theoretical "design" or "maximum" vehicle capacity.

After brief reference to different vehicle lengths and widths, Demery suggests that, for the purpose of capacity calculations, an upper plausible limit for vehicle occupancy is 150 passengers per car with occupancy higher than 100 unlikely to occur outside, New York, Boston, Montreal and Toronto. *"Long before crowding levels ... reached New York levels, prospective passengers would choose to travel by a different route, by a different mode, at a different time, or not at all."*

The report tabulates and compares daily and peak-hour ridership and passengers per vehicle for 19 New York CBD trunks for 1976 and 1991, as abbreviated below:

| New York Location | Average passengers per car in peak hour | | Change 1976-1991 15 years |
| --- | --- | --- | --- |
| | 1976 | 1991 | |
| IRT Lexington Exp. | 155 | 138 | -10.97% |
| IRT Lexington Local | 147 | 112 | -23.81% |
| IRT Lexington JT | 132 | 149 | 12.88% |
| IRT Broadway Exp. | 152 | 125 | -17.76% |
| IRT BroadwayLocal | 104 | 95 | -8.65% |
| IRT Broadway CT | 98 | 137 | 39.80% |
| IRT Flushing | 116 | 115 | -0.86% |
| IND Queens | 200 | 195 | -2.50% |
| IND 8th Exp. | 146 | 128 | -12.33% |
| IND 8th Local | 91 | 74 | -18.68% |
| IND 8th CT | 148 | 134 | -9.46% |
| IND 6th RT | 91 | 99 | 8.79% |
| BMT Astoria | 129 | 108 | -16.28% |
| BMT Canarsie | 138 | 113 | -18.12% |
| BMT Jamaica | 103 | 139 | 34.95% |
| BMT Man. Bridge | 136 | 119 | -12.50% |
| BMT Montague | 106 | 101 | -4.72% |
| PATH WTC | 79 | 112 | 41.77% |
| PATH 33rd | 91 | 91 | 0.00% |
| Average | 124.4 | 120.2 | -3.30% |
| Median | 129 | 115 | -10.85% |

The report then makes a case that ridership forecasts are prepared with little or no reference to supply-side parameters and that ridership will be below forecast when the delivered service frequency is below initial plans—often because too few cars were purchased or there are inadequate operating funds—or the line was not designed or signaled to accommodate the frequencies used in initial forecasts.

Ridership figures can be misleading in cities with free downtown zones. In Pittsburgh 20% of use is short trips in the free zone.[4]

Ridership can increase without additional peak-hour supply due to spreading periods of peak demand, a rise in off-peak and reverse-peak use, and/or a willingness of passengers (and prospective passengers) to tolerate higher levels of crowding.

The report states that effective capacity—or likely maximum ridership—falls well below the routinely quoted capacity figures

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[4] Reviewer's Note: The percentage is lower in Pittsburgh and Portland and higher in Calgary (30%).

such as 30,000 to 50,000 passengers per peak hour direction for heavy rail and 10,000 to 30,000 for light rail. It also says rail transit ridership stabilizes when peak-period vehicle occupancy reaches the point where prospective riders are no longer willing to board—often at a point well below that implied by the phrase "full standing load".

**Comment:** The gist of Leroy Demery's recent report deals with the relationship between the *demand for* and the *supply of* service on rail transit and is not relevant to this study. However there are numerous useful insights on the issue of capacity. One is the caution with respect to ridership data from the four light rail systems that have CBD free zones. Another is the relatively low average loading density in the peak hour on all US and Canadian systems in the range of 0.9 to 3.7 passengers per $m^2$ with the highest outside New York, Boston, Toronto and Montreal being 2.3 passengers/$m^2$.

The tabulation of average peak hour loadings per vehicle in New York in 1976 and 1991 shows an 11 per cent decline in the median over 15 years. Despite a few lines showing increases, many others—deemed, now and then, to be saturated or at capacity—have lower loading densities. This would suggest an expectation of better standards and Demery comments clearly that new rail transit systems in cities with palatable transport alternatives will not achieve these densities—and if they reduce service levels to increase vehicle loadings, as appears to be the case on several systems, then riders will go elsewhere.

This suggestion has significant implications for a study of future capacity based on existing and past ridership.

## 23 ENVIRODYNE ENGINEERS, INC., Metro-North Speed and Capacity Improvement Study. Tasks 1 to *5 US Department of Transportation, Urban Mass Transportation Administration, 1989*

**Summary:** The volumes in this series summarize the major locations on the Metro-North rail system where capacity is constrained. The key limitations include the following: interlocking locations and layout, lack of grade-separation at junctions, inadequate number of tracks, and short platform lengths. The Port Jervis line faces an additional problem of competition with freight trains for track access.

The capacity at each of the locations studied is given in combinations of the number of express and local trains which could be operated given current and future conditions. Generally, express operations allow a higher throughput of trains since there are no station stops during which time the track is occupied. A particular problem is in finding pathways for local trains which stop in more than one of the express zones as the current track configuration is often not designed for this. The provision of more local trains between zones is necessitated by the growing suburb to suburb travel market.

**Comments** These reports outline specific instances of many of the general capacity constraints faced by commuter rail operators. An emphasis on conclusions reached, rather than the

simulation methodology used, restricts the usefulness of these studies for general application.

## 24 EUROPEAN CONFERENCE OF MINISTERS OF TRANSPORT, Report of the 38th Round Table on Transport Economics - Scope for the Use of Certain Old-Established Urban Trans. Techniques, *Transport Capacity, OECD, Paris, 1979, pp. 24-25*

**Summary:** Provides a European aspect to capacity with the following list for maximum capacity by mode:

| Mode | Trains/hour | Passengers/ hour/direction |
|---|---|---|
| Metro (heavy rail) | 40 | 40,000 |
| Expres stram (light rail) | 46 | 21,000 |
| Tram (streetcar) | 54 | 12,500 |

**Comment:** The passenger capacity figures can be misleading because they do not indicate consistent length or loading density. The maximum number of trains per hour reflects European practice and is higher than similar North American data.

## 25 FOX, GERALD D., Light Rail/Traffic Interface In Portland: The First Five Years, *Transportation Research Record 1361, 1992: pp. 176-183*

**Summary:** Fox summarizes the use of railway crossing gates, traffic signals and stop signs to control grade-crossings on TriMet's 24.3 km light rail line in Portland. Signaling of the line is also dealt with peripherally. The majority of the line is operated on sight with 11.3 km of private right-of-way being governed by automatic block signals (ABS).

A description of traffic signal pre-emption techniques is given, ranging from wayside push-buttons to the Philips Vetag inductive loop system. Installation of the latter system allowed the addition of two intermediate stations to the line while maintaining the same overall travel time.

The principal traffic control lessons learned from Tri-Met's initial light rail line are:

- Use conventional traffic signal equipment for public familiarity and ease of maintenance.
- Do not give motorists more information than they need because it only causes them confusion.
- Controlling traffic movements is generally more effective than prohibiting them. Motorists tend to ignore prohibitions but are more receptive to controls.
- Light rail construction often involves lengthy street closures which alter traffic flows. Such adjustments in traffic flow can continue after construction is complete, so reducing conflicts between light rail and vehicular traffic.

**Comment:** This paper updates previous work by the author on this subject with practical experience gained from five years of operation. It addresses a number of ways of reducing light rail travel time through traffic signal pre-emption and shows that with careful traffic engineering neither road not light rail capacity is reduced by the grade crossings—at the headways and specific circumstances of the Portland system.

## 26 GILL, D.C., and GOODMAN C.J., Computer-based optimisation techniques for mass transit railway signalling design, *IEE Proceedings-B, Vol. 139, No. 3, May 1992*

**Summary:** This recent British paper compares and presents analytic treatment of the capacity of fixed-block, multi-aspect cab control and transmission based train control systems before suggesting that the many nuances are beyond analytic methods and require computer simulation.

The authors state that, in addition to the major headway components of station close-in time plus station dwell, a margin must be added to allow for small delays and variations in train performance. They suggest an allowance of 15-20 sec and use the term *minimum service headway* when this margin is included, or *signal headway*[5] when it is not.

Increases in line capacity require either increases in train length or increases in positional resolution by creating shorter block sections, possibly with an increase in either the number of visual aspects or the number of automatic train protection codes—or the introduction of a moving-block signaling system.

Theoretical minimum headway (between stations), H, is defined as:

$$H = \frac{v}{2b} + \frac{l}{v}$$

where
$v$ = velocity
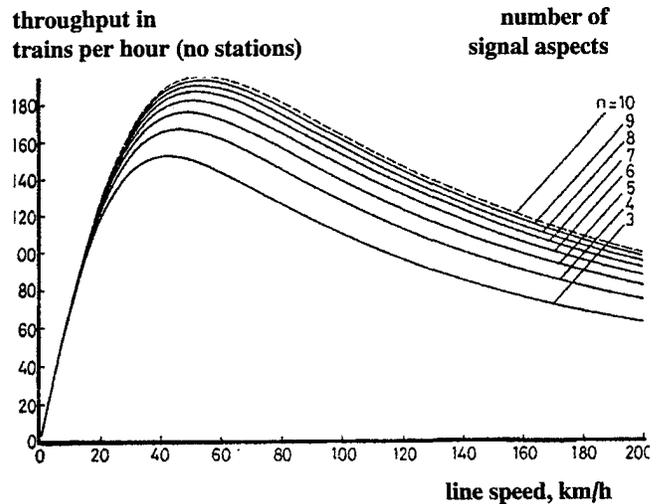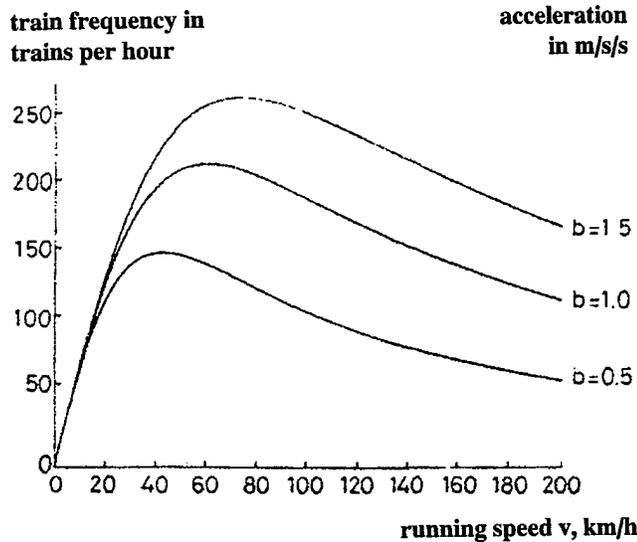$b$ = deceleration
$l$ = train length

Maximum train frequency, F, is 3600/H, setting dF/dv to zero produces the speed ($v_{op}$) for the closest headway)

$$v_{op} = \sqrt{(2bl)}$$

As capacity is proportional to train length and inversely proportional to headway—itself a function of train length, the above equations can be merged to show that *capacity is a function of the square root of train length.*

At the optimal running speeds in the above figure, train frequencies range from 150 to 260 per hour without station stops or with off-line stations. With station stops the typical maximum practical train throughput is a much reduced 20 to 30 trains per hour. As these high throughputs (between stations) are not required, block lengths can be extended away from stations with considerable cost saving and no impact on throughput.

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[5] Reviewer's Note: CAUTION. Other authors rarely include station dwell in the definition of signal headway.

**train frequency in trains per hour**     **acceleration in m/s/s**



running speed v, km/h

**throughput in trains per hour (no stations)**     **number of signal aspects**



line speed, km/h

On conventional rail transit systems with stations theoretical headway calculations must take into account the time a train takes to decelerate from line speed, stop at the platform and accelerate out. With simplifying assumptions, Bergmann[6] shows that the theoretical minimum headway $H_{min}$ is given by:

$$H_{min} = \frac{v_m}{b} + t_r + t_w + \sqrt{\left(\frac{2l}{a}\right)}$$

where
$v_m$ = maximum velocity
$t_r$ = ATO equipment response delay
$t_w$ = station dwell time
$a$ = acceleration
$b$ = deceleration
$l$ = train length

Under typical rail transit conditions, with a 140 m (460 ft) train and a 30-sec dwell, this equation gives a minimum headway of 70-sec plus any operational margin.

Bergmann also derives the optimal line speed for maximum throughput as:

$$V_{op} = \sqrt{\frac{2ab_s b_e l}{ab_s + ab_e + b_s b_e}}$$

where
$b_s$ = minimum service deceleration
$b_e$ = inimum emergency deceleration

Under typical rail transit conditions this equation gives an optimal line speed of 37 km/h. The authors specifically note that this is the station approach speed and does not preclude higher inter-station speeds.

The paper then analyzes the improvements in headways which are possible by increasing the number of visual signalling aspects or the number of automatic train protection codes. The results, shown below, support their conclusion of diminishing returns and indicate the optimum line speed approaching a station of approximately 40 km/h.

The paper then adjusts Bergmann's work to add allowances for jerk limits into and out of acceleration and deceleration, grades and curves—specifically in station approaches and safety distance adjustments. The equations are complex and still require assumptions for train control and vehicle equipment response or reaction time, driver reaction time (if any) station dwell time, an operations allowance or margin, reduction in the nominal acceleration rate as speed increases and fluctuations in traction power voltage (and hence train performance) as trains accelerate in each specific supply section.

Recommendations are made that computer simulation is the preferred approach, combining a train performance program with a signal layout design program. To compensate for such refinements as traction voltage fluctuation and jerk, such programs should be run at increments of 0.1 sec. The paper points out that programs do not necessarily take coasting into account.[7]

The results of such computer simulations are provided for the following typical rail transit conditions:

| | |
|---|---|
| train length | 140 m (460 ft) |
| maximum speed | 80 km/h (50 mph) |
| aspects | 4 |
| reference speeds | 80.0, 69.5, 53.3, 0.0 km/h |
| service braking | 1.0 m/s/s (m/s$^2$) |
| emergency braking | 1.3 m/s/s (m/s$^2$) |
| minimum jerk rate | 0.75 m/s/s/s (m/s$^3$) |

The resulting minimum headway was 74.8 sec plus dwell time and an operational allowance. A 30-sec dwell and a 15-sec operational allowance would produce a headway of 120 sec. The programs were run for a moving-block signaling system under the same conditions. The close-in headway was reduced to 43.9 sec, producing a minimum headway of 89 sec—leading to the

[6] BERGMANN, D.R.: *Generalized expressions for the minimum time interval between consecutive arrivals at an idealized railway station. Transportation Research 1972, Vol. 6, pp. 327-341.*

[7] Reviewers Note. Coasting is a period when neither power nor braking is applied. It is required by some operators as an energy conserving measure and is often omitted in peak periods when the maximum system performance is required. While coasting increases running time between stations—and hence decreases system capacity with a given vehicle fleet size—it should not affect the *minimum service headway* (other than by causing minor increases in supply voltage).

conclusion that, under typical conditions, a moving-block signaling system can increase line capacity by 33%.

**Comment:** Gill and Goodman's lengthy paper provides the most detailed analysis of train control system throughput in the reviewed literature. Despite the analysis accommodating nuances such as jerk and multiple equipment and driver reaction times, ignored in most other work, there are still many variables that are best accommodated by computer simulation.

The initial analyses of throughput without station stops appear somewhat academic but allow the determination of any inter station speed controls or speed limits. Such restrictions may reduce throughput with stations only if they reduce the station approach speed below the optimum 37 km/h (23 mph). Otherwise inter station speed controls or speed limits only reduce running times and impose the economic penalty of requiring additional vehicles to serve a given passenger demand.

The results show *minimum service headways* that are longer than most other work reviewed, even with station dwells only estimated. The comparison of conventional multiple aspect signaling systems and moving-block signaling systems is valuable.

### 27 GRAHAM, IAN R., Optimizing Headways on an Automated Rapid Transit System: The SkyTrain Experience, *American Public Transit Association, Rapid Transit Conference, Vancouver, B.C., 1990*

**Summary:** Describes how the use of moving block train control with sophisticated Automatic Train Supervision allows close matching of supply to demand by varying headways second by second through each peak period.

**Comment:** Provides useful information on the relationship of peak-within-the peak to average peak-hour demand. Data show the loading standard difference between normal operation and after delays where standing passenger density increases from a mean of 2.8 per $m^2$ to 5 per $m^2$.

### 28 GRAY, GEORGE E., and HOEL, LESTER A., Public Transportation Planning, Operations and Management, *Prentice-Hall Inc., 1979*

**Summary:** Comprehensive transit textbook with chapters by individual authors.

Professor Vukan Vuchic's Chapter 4 defines transit modes and various terms, offering the following capacity ranges.

| Mode | passengers per peak hour direction |
|---|---|
| Light Rail | 6,000 - 20,000 |
| Rapid Transit | 10,000 - 40,000 |
| Regional Rail | 8,000 - 35,000 |

William Vigrass in Chapter 5 cites planned and actual maximum capacities for selected examples. Muni's light rail metro is designed for 9,000 passengers per peak-hour direction.

The NYCTA sets crush loading standards at 255 passenger per 18 m car—a density of 5 per $m^2$. This makes the maximum capacity of a ten-car train on a single track—with a signaling throughput of 30 trains an hour—some 76,500 passengers per peak hour direction. Such a capacity is not realistic, however, as it is based on the crush capacity of the cars.

John Fruin in Chapter 10 shows that the shoulders of the 95th percentile male occupy 0.14 $m^2$, and that unavoidable contact between standees occurs at a space occupancy of 0.26 $m^2$. Space requirements in free standing lines or platform waiting areas are 0.5 to 1.0 $m^2$ per person.

**Comment:** Fruin's work is valuable in discussing the preferred and minimum space per standing and per waiting passenger.

### 29 HOMBURGER, WOLFGANG S., Urban Mass Transit Planning, *The Institute of Transportation and Traffic Engineering, Univ. of California, 1967*

**Summary:** A comprehensive course text with examples of actual rail system capacities. Useful table, albeit with out-dated data, of peak-within-the-peak relationships (data from various sources).

| Location | Trains/ hour | 15-20 min rate | Full hour | % short term over full hour |
|---|---|---|---|---|
| IND Queens | 32 | 71,790 | 61,400 | +17% |
| IND 8th Av. Ex. | 30 | 69,570 | 62,030 | +12% |
| IRT Lexington. Av. | 31 | 50,700 | 44,570 | +14% |
| IRT Express. | — | 38,520 | 36,770 | +5% |
| TTC Yonge | 28 | 39,850 | 35,166 | +13% |
| Chicago | — | 14,542 | 10,376 | +40% |

**Comment:** The ratio of peak hour to peak-within-the-peak capacity is an important part of TCRP A-8's approach to Rail Transit Capacity. The above table has been extended, recompiled with current data, and disaggregated by mode in the study—which designates this ratio as the *first level of diversity*.

### 30 JACOBS, MICHAEL., SKINNER, ROBERT E., and LERNER, ANDREW C., Transit Project Planning Guidance—Estimate of Transit Supply Parameters, *Transportation Systems Center, US Department of Transportation, Oct. 1984*

**Summary:** Chapter 4 deals with the estimation of capacities, with many data from sources referenced elsewhere in this study. The chapter cites level-loading doorway flow at 1.5 to 2.0 sec per person per door lane with low-loading light rail increasing to 1.5 to 2.5 sec per person per door lane unloading and 2.0 to 8.0 sec per person per door lane boarding—the higher figures relating to train operator fare collection.

The following factors in train headway are listed:

- braking rate (with adjustment for any grade)
- maximum speed
- train length
- block length
- train control delays
- type of signaling
- dwell times

North American platform lengths ranged from 70 to 213 m. The closest European light rail headways at low speeds is quoted in the range of 37 to 58 sec, North American range is quoted at 90 to 120 sec with the possibility of down to 40 sec.

A comprehensive section on vehicle space per passenger suggests that gross vehicle area is the most practical data to use. While 53% of U.S. rapid transit lines enjoyed rush hour loadings of 0.5 m$^2$ per passenger or better, the following data were offered. (compiled from two separate tables from different sources, average of 58 routes):

| Criteria | Passenger/area | Mean |
|---|---|---|
| Max. practical (NY) | 6.0 /m² | 6.0 |
| Typical rapid transit | 2.2 - 3.6 /m² | 2.9 |
| Crush rapid transit | 2.6 - 5.4 /m² | 3.8 |
| Design rapid transit | 1.4 - 4.0 /m² | 2.6 |
| Design light rail | 2.3 - 4.0 /m² | 3.3 |
| Actual light rail | 2.9 - 5.7 /m² | 4.0 |
| To avoid contact | 3.8 - 4.5 /m² | 4.1 |
| Unconstrained | 1.2 - 2.7 /m² | 2.0 |

The report is one of the few to discuss the diversity of standing densities within a car—higher in doorways/vestibules, lower in aisles and at car ends (unless the car has end doors). The report includes extensive references, tables of data and a glossary.

**Comment:** As one of the most comprehensive compilations of loading standards, this has been useful to the project.

## 31 JANELLE, A., POLIS, M.P., Interactive Hybrid Computer Design of a Signaling System for a Metro Network: *IEEE Transactions on Systems, Man and Cybernetics, 1980*

This comprehensive computer modeling approach looks at how to obtain the maximum train throughput in designing a three-aspect signaling system for rapid transit. Although specific to Montreal's rubber tired Metro, the approach is adaptable to any three-aspect signaling system.

The model makes use of the repetitive nature of rapid transit operations and assumes Automatic Train Operation that regulates speed and controls station stopping. Block ends are assumed fixed at station platform ends and interlockings, and a train separation of two blocks is maintained at all times. The model adjusts other block lengths to maximize throughput using the following relationship among travel time, block length and capacity.

The basic modeling equation is:

$$T_j = T(x_{j+3} - TL_{max}) - T(x_j)$$

with the constraint

$$T_j \leq T_D \text{ for all } j$$

where:
| | | |
|---|---|---|
| $j$ | = | block number |
| $T_i$ | = | block cycle time |
| $x_i$ | = | block length of controlling joint |
| $x_{i+3}$ | = | block length of controlled joint (3 blocks downstream from the controlling joint) |
| $T_{max}$ | = | maximum train length |
| $T_D$ | = | desired headway (less dwell) |

The model showed that the block lengths could be defined for nine car trains (162 m) to permit a headway of 83 sec, plus station dwell of 37 sec, for the design total of 120 sec, this is down from the initial Montreal design standard of 150 sec.

**Comment:** An interesting and comprehensive approach to optimizing the throughput of a conventional three-aspect signaling system without overlays.

## 32 KLOPOTOV, K., Improving the Capacity of Metropolitan Railways *UITP, 40th International Congress, The Hague, 1973*

**Summary:** Klopotov's report is derived from questionnaires sent to 38 international rapid transit systems, three-quarters of which stated they were working to increase capacity.

The percentage of peak-hour passengers that are seated ranges from 12.5% in Tokyo to 70% in Liverpool (PATH 30%, SEPTA 55%). (Systems with a 100% seated policy are excluded.) Average peak-hour loading density varies widely:

| Group | pass/m² |
|---|---|
| Some European and most North American | 2.0 - 3.0 |
| Some European systems and New York | 3.1 - 5.0 |
| Most European large cities | 5.1 - 6.0 |
| Large Soviet and Japanese systems | 7.1 - 8.0 |

Controlling station dwell to increase capacity shows that 54% of the systems surveyed have four double doors per car side, each in the range of 1.2 to 1.4-m wide with the great majority close to 1.4 m. Door opening and closing times range from 1.0 to 4.5 sec with most in the 2- to 3-sec range. Brief mention is made of the Paris Metro's dwell control method of closing off platform entry as a train approaches and Copenhagen's method which is to start opening the doors before a train has come to a full stop.

A common dwell reduction feature is doorway setbacks so that standing passengers do not block the flow. 71% of surveyed systems had setbacks of 200 mm or more.

Most systems had sustained peak-hour headways at or greater than 120 sec with the exception of Tokyo (110 sec), Leningrad and Philadelphia Market-Frankford (105 sec), Paris (95 sec),

PATH (90 sec) and Moscow (80 sec) The latter required an expensive move from a two- or three- aspect to four-aspect signaling system.

Methods employed or planned to increase capacity ranged from decreasing seating space to removing cabs from all but the end cars, with the most common approach being new or improved signaling to reduce headways.

Signaling changes including adding automatic train operation and automatic train supervision, using more realistic safety distances, adjusting block lengths or adding blocks. Where station capacity was a limitation, improvements were suggested to increase passenger flow to and from platforms. These included separating entry and exit flows and operating escalators at higher speeds. While most escalators in the United States run at 0.46 m/s, 0.6 to 0.75 m/s is used occasionally in Canada and frequently in Europe with certain former Soviet bloc cities doubling flows with speeds of 0.75 to 0.9 m/s.

**Comment:** Although outdated, this report presents comprehensive information on rail transit capacity, unfortunately diminished by the poor translation and editing from Russian. Russian and Japanese rapid transit systems achieve the highest capacity in the world by a combination of very close headways and high densities of standing passengers.

Several countries show that close headways can be operated reliably and (when adjusted for North American loading levels) provide an upper limit to rapid transit capacity.

## 33 KOFFMAN, D., RHYNER, G. and TREXLER, R., Self-service Fare Collection on the San Diego Trolley, *US Department of Transportation, 1984*

**Summary:** Chapter 3—*Transit Operations* provides a comparison of dwell times between light rail in San Diego and Boston. In both cities observers with stop watches rode the light rail lines counting and timing passengers entering and leaving each car, along with the number of passengers remaining on-board. Data was collected at all stations in San Diego and in three sets for Boston: fare free (station collection) zones (two routes) and inbound cars with train operator fare collection.

The model used multiple regression analysis with loading time (dwell time) as the dependent variable and total on, total off, total on-board as the independent variables. (The San Diego model included zero-one variables to represent whether there was any boarding or alighting activity at a stop.) The coefficients of these variables include the extra time needed in San Diego for the first boarding or alighting passenger who operate the doors themselves. (Similar variables were tested in Boston but, as could be expected, performed poorly).

After testing a variety of variables, including various powers, exponentials, logarithms and interaction terms, a linear model produced the best results. The only non-linear terms which improved any models were the squares of ons and offs in San Diego. These made "only a minor improvement and were not used as they have no physical interpretation, may be due to

errors in the data collection process and make the comparison between the two cities difficult."

The result was a two part loading model with one linear relationship for passengers movements from zero to one and another linear relationship for all passengers movements above one.

Only the San Diego model results are shown below.

| San Diego | Intercept | Any Ons | Any Offs | Tot.Ons |
|---|---|---|---|---|
| Coefficient | 8.14 | 1.91 | 1.12 | 0.67 |
| Std. Error | (.54) | (.43) | (.45) | (.04) |
| Student's t | (15.0) | (4.4) | (2.5) | (17.4) |
| Prob (coeff=0) | <.0001 | | | |

| | Total Offs | On-Board | R² | Std. Err. |
|---|---|---|---|---|
| Coefficient | 0.59 | 0.034 | .43 | 5.4 |
| Std. Error | (.04) | (.007) | | |
| Student's t | (14.9) | (4.8) | | |
| Prob. (coeff=0) | <.0001 | | | |

Note that data is excluded from terminal stations and train operator relief points, dwell times are from first door open to last door shut and excludes time when the door is open without any passenger activity.

Finally, a composite model was developed using the constant and zero-one coefficients from the San Diego model and the remaining coefficients from the Boston inbound model.

$$\begin{aligned}
\text{Loading Time} = 7.76 &+ (1.91) \text{ (Any Ons):} \\
&+ (1.12) \text{ (Any Offs):} \\
&+ (3.12) \text{ (Cash Ons):} \\
&+ (1.94) \text{ (Non-cash Ons):} \\
&+ (1.61) \text{ (Offs):} \\
&+ (0.87) \text{ (Passengers on-board):}
\end{aligned}$$

The 95% confidence interval is ± 2 sec, computed from the estimated variances and co-variance's in each component model. The report shows that without self-service fare collection the San Diego running times would increase from the then 42 min, to 47 to 48 min.

**Comment:** Chapter 3 provides a comparison of loading times between San Diego MTDB's self-service fare collection system and that part of the MBTA's Green Line where on-board train operator collection is used. The methodology and data provide useful information for use in estimating light rail station dwells with low loading.

## 34 KORVE, HANS W. and WRIGHT, PATRICK M., New Standards for Control of At-Grade Light Rail Transit Crossings, *Transportation Research Record 1361, 1992: pp. 217-223*

**Summary:** There is very little consistency of traffic control devices used on American light rail lines. Variation can be found not only between, but also within systems. Korve and Wright outline the need for an American standard system of traffic control devices and the efforts of an Institute of Transportation Engineers committee to create such a standard.

**35    KORVE, HANS W.** Traffic Engineering for Light Rail Transit, *Transportation Research Board Special Report 182, 1978, pp. 107-114*

**Summary:** Korve provides an alternative definition of light rail and shows that light rail road crossings can be separated in space or time, detailing control options for the latter.

Stop signs are acceptable for grade crossings with traffic < 5,000 vehicles/day and light rail > every 5 min. Total preemption is feasible down to 2-min light rail headways with multiphase traffic signals and cross-traffic as high as 25,000 vehicles/day. On inter-connected traffic signals, progression can be adjusted to favor light rail. Where possible, light rail stop placement can be arranged to enhance progression speed.

The report contains acceleration and braking curves for modern light rail vehicles and shows various methods to accommodate traffic turning left across median light rail tracks.

**Comment:** The report shows that light rail grade crossings should rarely impact line capacity as good engineering can ensure that a train can move through a grade crossing on each light cycle—and, in certain circumstances (limited train length), a platoon of two trains per cycle. This condition permits a throughput of 60 to 120 trains per hour, well beyond the capacity of any signaling system on other sections of a typical light rail line.

However, such throughput will impose delays which can be minimized (or eliminated) with properly timed progression and coordinated station placement—but only in one direction. Progression timing can be adjusted to favor the peak direction.

**36    KRAFT, W. H.,** and **BERGEN, T. F.,** Evaluation of Passenger Service Times for Street Transit Systems. *Transportation Research Record 505, Transportation Research Board, Washington DC 1974*

**Summary:** Kraft analyzed 1500 entry and exit observations to derive an expression for passenger loading times, using the method of least squares. All were on surface vehicles, disaggregated by type of fare payment, time of day and by the following types of flow.

- all passengers boarding
- all passengers alighting
- mixed flows

The results show linear relationships with distinct differences for elderly, handicapped and commuter passengers. Off-peak passenger times were more leisurely. The applicable results for low-loading streetcar (light rail) with exact fare, and double-doors were:

**Boarding Only Time = 3.4 + 0.9(ons)**
Data sets = 7
Coefficient of Determination = 0.64
Standard error of estimate = 0.90

**Boarding and Alighting Time = -4.0 + 2.0(ons)**
$1 \leq$ (offs) $\leq 8$ and $6 \leq$ (ons) $\leq 13$
Data sets = 5
Coefficient of Determination = 0.94
Standard error of estimate = 1.50

**Comment:** The wide variation in results from city to city, vehicle to vehicle and mode to mode suggest caution in developing a general equation for dwell times. Kraft comments that platform congestion could increase alighting times but provides no data to substantiate this.

There are several deficiencies in this report which has been quoted in several other papers. As such, the report is of little value to the study other than to suggest caution in system to system comparisons.

**37    KUAH, GEOK K.** and **ALLEN, JEFFREY B.,** Designing At-Grade LRT Progression: Proposed Baltimore Central Light Rail, *Transportation Research Record 1361, 1992: pp. 207-216*

**Summary:** Kuah and Allen analyze the effect of modifying the traffic signal progression in downtown Baltimore to allow the light rail service on Howard Street to benefit from progressive signaling. Computer modeling of the proposed changes shows a 10% increase in downtown traffic flows.

**Comment:** The paper does not directly address capacity but does provide information on the related issue of light rail signaling on city streets. It is interesting that the current signaling is not mentioned as a capacity limitation.

**38    KYOSAN ELECTRIC MFG. CO., LTD.** Total Traffic Control System—TTC, *Yokohama, Japan, 1986*

**Summary:** Many Japanese electric railways, typically a cross between rapid transit and commuter rail, operate intensive service. This report describes the track layout, signaling system and operations of one of the busy two-track lines in the suburbs of Tokyo.

The Keio Teoto Electric Railway has a two-track main line between Keio-Hachioji and Shunjuku. Four branches merge into this line and many trains continue through into central Tokyo via joint running with the subway system. There are 49 stations and a total of 63 route kilometers.

The Keio Teoto Electric Railway operates 30 trains in the peak hour over a single track, combining four levels of express, semi-express and local service. This frequency is made possible by four platform and off-line platform stations, where faster trains pass local trains, and an Automatic Train Supervision system. The signaling system is a relatively conventional three-aspect block system.

**Comment:** This manufacturer's description shows how commuter rail capacity can be increased with multi-track stations,

precision operation and the assistance of a computerized automatic train supervision system.

## 39 LANG, A SCHEFFER, and SOBERMAN, RICHARD M., Urban Rail Transit: Its Economics and Technology, *MIT Press, 1964*

**Summary:** Lang and Soberman's book on rail transit economics and technology is reportedly the first since Dooliitle's treatise of 1916. Three sections relate to the A-8 rail transit capacity project.

Parts of Chapter Three, Stations, deal with the interaction of train and station design with dwell times. Loading time is dependent on the distribution of passengers along the platform, the ratio of total door width to car length and the number of boarding passengers. Obtaining a uniform distribution of passengers along the platform is desirable but difficult, particularly so when crowded platforms impede flows in the rush hour.

Sufficient entries and exits to adequately sized platforms are necessary and must be evenly spaced for best distribution. Passageway flow rates of up to 100 passengers per minutes per meter of width are quoted (30 per minute per foot). Downward stairs reduce this flow by some 25%, upward stairs by 40%. These flow rates diminish when crowding exceeds 4 persons per square meter (0.4 square feet per person).

In Chapter Four, Rail Transit Vehicles, Section 4.5 Car Capacity and Dimensions discusses seating provision relative to compromises between capacity and comfort. Suggesting that all rapid transit cars are substantially similar in width, the report equates passengers per square foot versus the percentage seated. This ranges from 0.3 passengers per square foot with 50% seated to 0.6 passengers per square foot with 15% seated. This is then translated into passengers per Linear Foot of Train, as shown below. The maximum vehicle capacity is 4 passengers per linear foot—approximately 2.5 square feet per passenger.
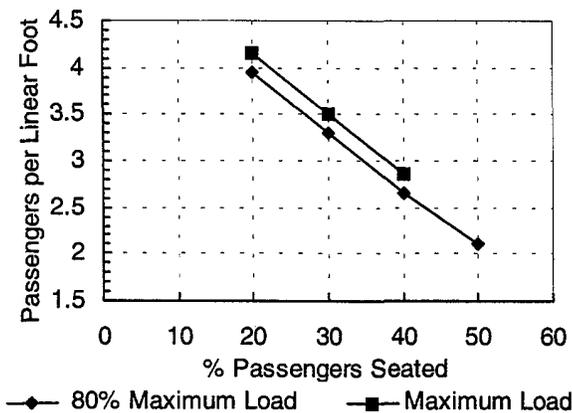


The authors also discuss the importance of ease of ingress and egress, recommending minimum distances between seats and doorways and discouraging three abreast seating. Comfort levels are discussed relative to smoothness of operation and the issue of supply and demand. Where systems are oversubscribed and few attractive alternate forms of transportation are available, high levels of crowding will be tolerated. Where systems wish to attract passengers, higher comfort levels, i.e., less crowding, are desirable.

Chapter Five of this text deals entirely with capacity. Capacity is calculated as the number of trains per hour multiplied by train length and the passengers per linear foot from the above graph. Using the mathematics of Appendix A the minimum headway is expressed as:

$$h = T + \frac{L}{V} + \frac{V}{2a} + \frac{5.05V}{2d}$$

where
- $h$ = headway (s)
- $L$ = total train length (ft)
- $T$ = station stop time (s)
- $V$ = maximum train speed[8] (ft/s)
- $a$ = rate of acceleration (ft/s$^2$)
- $d$ = rate of deceleration (ft/s$^2$)

Applying this equation at a maximum approach (close-in) speed of 32 km/h (20 mph) and a dwell of 40 sec produces the following optimum headways for different train lengths, and capacity in passengers per peak-hour direction. These use a vehicle loading of 3.1 passengers per linear foot with average acceleration (a) of 3.0 mph/s (1.33 m/s$^2$) or 2.0 mph/s (0.89 m/s$^2$)

| Train Length (m/ft) | 120/400 | 150/500 | 180/600 |
|---|---|---|---|
| Minimum Headway | 75 secs | 79 secs | 83 secs |
| Capacity (a=3.0) | 60,600 | 72,400 | 83,200 |
| Capacity (a=2.0) | 44,600 | 55,100 | 65,000 |

Appendix A, Some Considerations of Minimum Headway, develops the above minimum headways with equations for wayside signals and theoretical minimum headways and minimum headways with automation.

The theoretical minimum headway is expressed as

$$h = T + 2\sqrt{\frac{L}{a}}$$

The minimum headway with cab signals, assuming the following train stops behind the preceding train before entering the station is

$$h = T + 2\sqrt{\frac{L + s}{a}} + r$$

For a completely automated system

$$h = T + 2\sqrt{\frac{L}{a}} + c$$

where
- $h$ = headway (s)
- $L$ = total train length (ft)
- $T$ = station stop time (s)
- $a$ = rate of acceleration (ft/s$^2$)
- $s$ = safety distance (ft)
- $r$ = operator reaction time (s)
- $c$ = communication time (s)

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[8] Reviewer's Note: The maximum train speed, in feet per second, is the maximum speed in the final approach to the station—not the maximum speed between stations.

**Comment:** In one of the earliest modern texts on rail transit Lang and Soberman have provided a succinct yet thorough outline of capacity issues. Their calculations, regarded by the authors as conservative, tend to show passenger volumes higher than would be regarded as practical—due to their use of dwell times of 30 to 40 sec—which do not take into account an allowance for irregular running.

## 40 LEVINSON, HERBERT S., and HOEY, WILLIAM E. Some Reflections on Transit Capacity *Proceedings of the International Symposium on Highway Capacity, Karlsruhe, July 1991*

**Summary:** The authors comment that "transit capacity is far more complex than highway capacity." They show that train headway is the sum of dwell time plus the reaction time, braking time, acceleration time and time to clear the station.

They caution that "*because actual capacities may vary in a way that cannot actually be described in a formula ... capacities obtained by analytical methods must be cross-checked against operating experience...*"

The study cites the historic high train throughput on the Chicago Loop with visual rules (70 trains per hour) versus the maximum NYCTA throughput on a three-aspect signaling system of 35 trains per hour, achieved by use of "key-by" procedures. Similar historic experience has shown streetcar throughput on a single track of up to 145 cars per hour.

The same general (transit, all modes) capacity formula is shown as in the ITE *Transportation Planning Handbook* below.

**Comment:** A useful general paper which repeats the cautions necessary in an analytic approach.

## 41 LEVINSON, HERBERT S., Capacity Concepts for Street-Running Light Rail Transit, *Australian Road Capacity Conference 1994*

**Summary:** The report compares historic streetcar service capacities of up to 150 cars per track per hour with current services that reach 96 cars per track per hour (Hong Kong) and a passenger volume up to 8,500 passengers per peak hour direction (Calgary).

On-street light rail capacity is related to the loading and unloading times at the busiest stop, train length and traffic signal cycles. Train length is limited to the shortest city block. Dwell time is related to the loading level (platform height) and fare collection system.

Basic capacity is defined with a simplified version of the formula in the same author's *Chapter 12 Capacity in Transportation Planning,* of the *Transportation Planning Handbook.*

The formula for trains per hour per direction with signalized intersections is given as:

$$C_p = \frac{(g/C) \cdot 3{,}600R}{(g/C)D + t_c}$$

where:

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

Passenger spaces per car, needed in this equation to determine capacity, are suggested at an occupancy level of two passengers per m$^2$, compared with a crush load of 4 per m$^2$.

The results quote a maximum capacity of 40 to 45 trains per track per hour at level of service "E,"[9] reducing to 36 to 40 trains when variations in arrival and dwell times are considered—equivalent to 10,000 to 13,500 passengers per peak-hour direction with trains 46 to 69 m long.

System planning based on level of service "D" is recommended. The following table extract shows light rail capacities in trains per track per hour at level of service "D", with 23-m long cars, a typical 50% green cycle ratio, an R of 0.80, a station clearance time of 5 sec per 25 m of train, and a further reduction to 80% of maximum capacity.

| Dwell Time | 1 car | 2 car | 3 car | 4 car |
|---|---|---|---|---|
| 20 secs | 48 | 41 | 36 | 32 |
| 30 secs | 41 | 36 | 32 | 29 |
| 40 secs | 36 | 32 | 29 | 26 |
| 50 secs | 32 | 29 | 26 | 24 |
| 60 secs | 29 | 26 | 24 | 22 |

Mention is made of the possibility that two single-car trains may be able to berth in a station simultaneously—doubling the capacity. Train spill back[10] is discussed and two recommendations made:

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[9] Levinson, Herbert S, Chapter 12 Urban Mass Transit Systems, Transportation Planning Handbook,

[10] Failure of a train to clear an intersection within the green cycle.

- The length of trains should not exceed the street block length.
- There should be no more that one train every other block to reflect variations in arrival and dwell times, suggesting that there should not be more than one train every other signal cycle where blocks are less than 122 m.

These recommendations result in a design capacity of 30 trains per hour for 60-sec cycles, reducing to 20 for 90-sec cycles and 15 for 120-sec cycles. The equivalent capacity, based on a 30-sec dwell time, ranges from 4,500 to 10,000 passengers per peak-hour direction for two-car trains to 6,000 to 13,500 for three-car trains.

The report concludes with a list of useful planning guidelines.

- dwell times should be minimized by using cars with high platforms or low floors, multiple doors and fare prepayment.
- Green time for trains should be maximized.
- Exclusive lanes should be provided
- Routing patterns should minimize the number of on-street turns
- Central area junctions should be kept to a minimum.

**Comment:** This recent paper adds to the substantial transit capacity work by author Levinson with information on light rail on-street operation. It contributes useful information to the study.

The "one train every two light cycles" provides a basis for the "simple" capacity calculations and conveniently coincides with the typical maximum frequency on signaled segregated track of 30 trains per hour—although several new U.S. light rail lines are only signaled for 17 trains per hour. (3.5-min headways). The spill back situation has been investigated in the study and the more detailed calculations can be used to help determine dwell times and to analyze junction clearance and turnback times.

**42   LEVINSON, HERBERT S.,** Chapter 5 Urban Mass Transit Systems, *Transportation Planning Handbook, Institute of Transportation Engineers, Prentice Hall, 1992*

**Summary:** The author provides a comprehensive outline of transit services with definitions and extensive data tables. Characteristics and capacities are shown for numerous transit vehicles, including some performance curves and formulas to calculate performance.

Figures 5.10 and 5.11 show the relationship between maximum speed, station spacing and average speed is documented and a tabulation[11] shows one second per passenger per lane for level boarding and alighting and 1.7 sec for low-level (light rail) alighting.

A table of *Factors Influencing Transit Capacity,* derived from the *Highway Capacity Manual* and *Canadian Transit Handbook* is the most comprehensive in the literature.

[11] Table 5.16 Average Boarding and Alighting Intervals for Transit Vehicles

**FACTORS INFLUENCING TRANSIT CAPACITY**
(* non-rail factors removed or adjusted)

1. **Vehicle Characteristics**
   a. Number of cars in train
   b. Car dimensions
   c. Number and configuration of seats
   d. Number, location, width and actuation of doors
2. **Rights of Way Characteristics**
   a. Number of tracks
   b. Degree of separation from other traffic
   c. Intersection design
   d. Horizontal and vertical alignment
   e. Route branching and junctions
   f. Turnaround conditions at terminals
3. **Stop Characteristics**
   a. Spacing
   b. Dwell Time
   c. Design (on-line or off-line)
   d. Platform height (high or low level boarding)
   e. Number and length of loading positions
   f. Method of fare collection
   g. If on-board fares, type of fare
   h. Common or separate areas for boarding or alighting passengers.
   i. Passenger accessibility to stop
4. **Operating Characteristics**
   a. Service types* (express, local)
   b. Layover and schedule adjustment practices
   c. Time losses to obtain "clock headways" or crew reliefs
   d. Regularity of arrivals at a given stop
5. **Passenger Traffic Characteristics**
   a. Passenger distribution among major stops
   b. Passenger concentration and interchange at major stops
   c. Peaking of traffic (peak-hour factors)
6. **Street Traffic Characteristics**
   a. Volume and nature of traffic (on shared right-of-way)
   b. Cross traffic at intersections (where at grade)
   c. Curb parking practices
7. **Method of Headway Control**
   a. Automatic or by train operator
   b. Policy spacing between trains (* or safety distance)

**Comment:** A wealth of information. The above table and certain performance information has been used in developing the Analytic Framework.

**43   LEVINSON, HERBERT S.; ROBINSON, CARLTON, C.** and **GOODMAN, LEON,** Chapter 12 Capacity in Transportation Planning, *Transportation Planning Handbook, Institute of Transportation Engineers, Prentice Hall, 1992*

**Summary:** Chapter 12 follows the more general information of Chapter 5 to present a wide range of capacity information with material synthesized from many sources.

The general equation for capacity of a transit line is given as:

$$C_p = \frac{3,600nSR}{(D + t_c)}$$

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and for light rail with controlled intersections:

$$C_p = \frac{(g/C) \cdot 3,600nSR}{(g/C)D + t_c}$$

where:
- $C_p$ = passengers per hour per track
- $t_c$ = clearance between successive cars or trains, in sec
- $D$ = dwell time at the major stop on the line under consideration, in sec
- $n$ = number of cars in train
- $R$ = reductive factor to compensate for dwell time and arrival time variations (0.833 suggested in text for maximum theoretical capacity for buses, 0.89 in later rail-specific references)
- $g$ = traffic light green time, in sec
- $c$ = traffic light cycle length, in sec

Various passenger load factors are shown based on a percentage of seats. Loading standards A through F (crush) are tabulated. The suggested "schedule design capacity" is 2.8 to 3.3 passengers per m$^2$, 25% below the "crush" capacity. The peak-hour factor is discussed for 15-min peak-within-the-peak. A range of 0.70 to 0.95 is suggested, approaching 1.0 in large metropolitan areas. Diversity of loading between cars of a train is mentioned but only limited data is provided.

Specific capacity for rapid transit is shown as:

$$\frac{Passengers}{Hour} = \frac{Trains}{Hour} \times \frac{Cars}{Train} \times \frac{Seats}{Car} \times \frac{Passengers}{Seat}$$

or

$$\frac{Passengers}{Hour} = \frac{Trains}{Hour} \times \frac{Cars}{Train} \times \frac{Floor\ Area\ per\ Car}{Area\ per\ Passenger}$$

Numerous examples are given of actual capacity with rapid transit maximums ranging from Hong Kong's 81,000 passengers per peak hour direction to NYCT's 53rd Street tunnel at 54,500 in 1982, down from 61,400 in 1960. The calculated maximum "attainable" for 10 car trains every 120 sec is shown as 57,300 passengers per peak hour direction after a 15% reduction for unequal passenger distribution.

Historic streetcar or light rail volumes are shown reaching 10,000 passengers per peak hour direction in North America. Three articulated light rail vehicles are calculated to handle up to 17,000 passengers per peak hour direction, with 35 trains per hour and a density of 3.25 passengers per m$^2$.

Commuter rail in North America is shown as achieving 15,500 passengers per peak hour direction with 15 trains per hour per track (LIRR). Comparable European capacities can reach 28,520 passengers per peak hour direction with 30 trains per hour. As a result, several European cities signal and operate commuter rail in a manner equivalent to rapid transit. (The lower volume is due to the common commuter rail policy of a seat per passenger.)

**Comment:** An outstanding and comprehensive report.

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## 44    LIN, TYH-MING and WILSON, NIGEL H.M., Dwell Time Relationships for Light Rail Systems, *Transportation Research Record 1361, 1992: pp. 287-295*

**Summary:** Lin and Wilson make a detailed analysis of dwell time determinants at two stations on the subway portion of the Massachusetts Bay Transportation Authority's Green Line light rail. Both linear and non-linear models are used to explain the dwell time data with the latter being only slightly more effective. Data for one- and two-car trains were analyzed separately so exposing a considerable difference in contributing factors according to train length.

The linear equations giving the best fit to the data as a whole are reproduced below.

For one-car trains:

$$DT = 9.24 + 0.71 * \text{T}_{\text{ONS}} + 0.52 * \text{T}_{\text{OFFS}} + 0.16 * \text{LS}$$

This gives an $R^2$ value of 0.62.
For two-car trains:

$$DT = 13.93 + 0.27 * \text{T}_{\text{ONS}} + 0.36 * \text{T}_{\text{OFFS}} + 0.0008 * \text{SUM}_{\text{ASLS}}$$

This gives an $R^2$ value of 0.70.

where:
- $DT$ = Dwell time(s)
- $\text{T}_{\text{ONS}}$ = Total boarding passengers
- $\text{T}_{\text{OFFS}}$ = Total alighting passengers
- $LS$ = Number of departing standees
- $\text{SUM}_{\text{ASLS}}$ = Sum of ($\text{T}_{\text{OFFS}}$)*(arriving standees) +($\text{T}_{\text{ONS}}$)*(departing standees)

The constant term for two-car trains in the equations is larger but the lower multipliers give a lower marginal dwell time for boarding compared with one-car trains. Note that the effect of crowding on the cars (the last term in the equations) is much lower for two-car trains. There is also evidence that the effect of crowding may cause a non-linear increase in dwell time during congested periods.

The paper closes with a brief discussion of the service implications of variable dwell times. Uneven dwell times cause uneven loading in a self-perpetuating cycle. Mixing different train lengths on the same service is likely to cause uneven loading.

**Comment:** While the information given by Lin and Wilson is specific to Boston's Green Line, the basic form of their equations and conclusions is likely applicable elsewhere. As such, this paper is a valuable reference in discussions of dwell times and their effects on capacity.

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## 45    MEDVECZKY, GEORGE. Hub-Bound Travel 1991, *New York Metropolitan Transportation Council 1992*

**Summary:** Comprehensive statistics on transit and vehicular movements in Manhattan. Cordon counts provide peak-point passengers on trunk lines. Additional New York cordon counts

for the study were acquired directly from MTA - New York City Transit.

## 46     MILLER, E. J. and BUNT, P. D., Simulation Model Of Shared Right-of-Way Streetcar Operations, *Transportation Research Record 1152 1987: pp. 31-41*

Miller and Bunt introduce the reader to a computer program designed to simulate streetcar operation on the *501 Queen* line in Toronto, Ontario. The number of inputs to the model is exhaustive and includes a directly proportional relationship between standee numbers and boarding passenger service times.

**Comment:** Much of the effort expended in the program is in creating a routine for explaining the short-turning of cars to assist in determining the best way to increase service regularity and capacity on the Queen line. As traditional streetcar service is only a small part of the capacity study, this report is of limited value.

## 47     MOTZ, D., Attainable Headways using SELTRAC, *Alcatel Canada, Toronto, September 1991 (Proprietary Report—only non-confidential data used for the A-8 study)*

**Summary:** Seltrac was one of the first transmission-based moving-block signaling systems. It is now in its fifth generation and is used in five North American locations. It is currently being installed on the Muni Metro light rail subway to increase throughput.

The system is based on the "brick-wall stop safety criteria" and allows trains to operate at the closest possible spacing with separation defined as the normal braking distance plus a safety distance. Braking distance is a readily determined or calculated figure for any system. The safety distance is less tangible, being comprised of a calculated component adjusted by agency policy. In certain systems this safety distance is a fixed quantity; however, the maximum throughput is obtained by varying the safety distance with speed and location.—and where different types of equipment are operated, by equipment type.

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

- system reaction time
- brake actuation time
- speed
- train load (mass)
- grade
- emergency braking rate
- normal braking rate
- train to track adhesion
- an allowance for partial failure of the braking system

The paper shows safety distances in "worst case failure situation" for the London Underground's new Jubilee Line that could be as long as 190 m for a fully loaded train at maximum speed (90 km/h) on a maximum down grade (5%).

In contrast, the constant safety distance used on the Seltrac equipped rapid transit system in Vancouver is 50 m, in part due to the better assured emergency braking provided by magnetic track brakes.

The paper describes the simulation of other capacity constraints at junctions, turnback and terminal stations, including situations with late trains, to show that a throughput of 36 trains per hour can be sustained with a train irregularity (behind schedule) of up to 60 sec.

**Comment:** It is not usually appropriate to reference a proprietary paper that is not available in the public domain. However, this is the only known source that explains and derives the safety distance for a moving-block-signaling system with conventional rapid transit equipment.

As such it sets the upper limit of throughput that could be achieved on any existing or new rapid transit whether that system uses Seltrac or one of the other moving-block signaling systems that have recently entered the market, including French and British systems and the recently announced BART/Hughes Aircraft development.

In principle, a moving-block signaling systems allows headways to decrease from the optimum with a three- aspect signaling system of 55 sec plus dwell to 25 to 35 sec plus dwell. However, at such closer headways, constraints at junctions and terminals and the issue of irregular operation become increasingly critical. (Note that the "worst case" braking rate used in the report is relative and does not assume total braking failure but rather no electric braking and partial air brake failure—retaining 75% of normal braking ability.)

The paper does not comment on the safety distance selected by the London Transport management or the regulatory authority (the United Kingdom Railway Inspectorate) as a result of this study, but it is possible that it is less than the 190 m calculated.

Moving-block signaling systems, constraints and recovery issues are fully discussed in the study. The data in the paper have been used to set a range of safety distances that, in conjunction with the maximum dwell time, establishes the minimum headway on both moving-block signaling systems and conventional multiple-aspect signaling systems.

## 48     NEW YORK CITY TRANSIT AUTHORITY, Rapid Transit Loading Guidelines, *April 1992*

**Summary:** This policy paper gives the loading and service standards which have been applied, with minor modifications, to the New York subway system since 1987. The guidelines provide for slightly more space per passenger than those in effect until 1986. Modifications have allowed for a relaxation in the nonrush hour passenger loading guideline to allow for the operation of short trains.

The loading guidelines were established from test loadings of different car types, loading surveys of revenue service at the

peak load point and comparisons with the policies of other rail transit operators. Additional concerns such as passenger comfort, dwell time effects, uneven loading within trains, and an allowance for "slack" capacity in the event of service irregularities and fluctuations in passenger demand were also considered. A rush hour standard of 3 sq ft per standing passenger (3.6 passengers per m$^2$) was generated from this work. The policy recognizes that this condition is only to be met at the maximum load point on a route and so is effective for only a short time and small portion of the overall route. For comparison, the agency's calculations of the maximum capacity of each car type are based on 6.6 - 6.8 passengers per m$^2$.

The graph below compares the loading standards of a number of systems.



Scheduled Loading Guidelines
Passengers per square meter
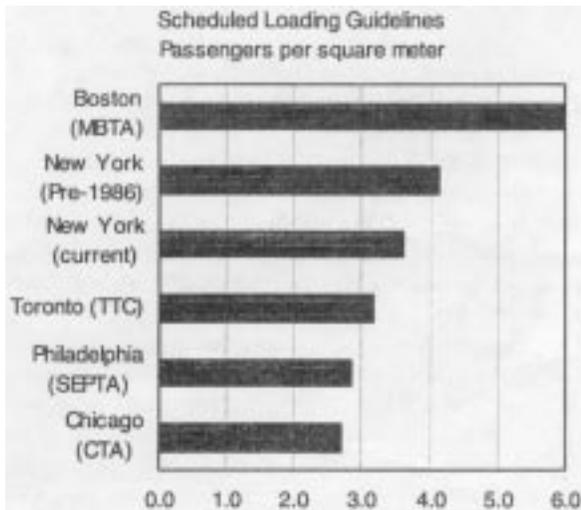
Standards for loading in the non-rush hours are substantially more generous with a seated load at the maximum load point being the general standard. If this would require headways of four minutes or less, or preclude operation of short trains, a standard of 125% of seated capacity applies. This consideration of passenger comfort also extends to rush hour service on lines where the headway is longer than 4 min. In these cases a sliding scale is used to ensure lower standing densities on routes with longer headways, as shown in the following graph.



New York Loading Guidelines
(passengers per square meter)
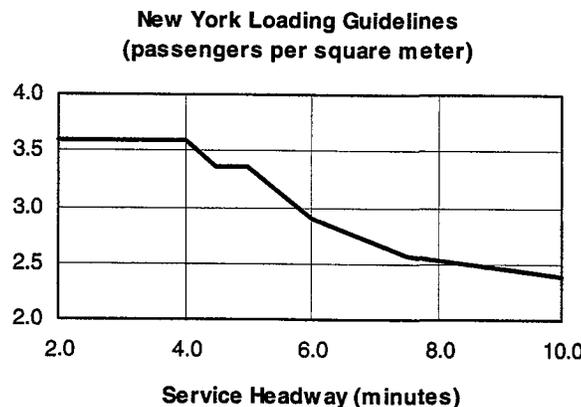
Minimum headways for each day and service period were also developed with the results shown in the following table:

| Schedule | Time Period | Minimum Headway |
|---|---|---|
| Weekday | Rush hours | 10 minutes |
| Weekday | Midday | 10 minutes |
| Weekday | Evening | 12 minutes |
| Saturday | Midday | 10 minutes |
| Saturday | Evening | 12 minutes |
| Sunday | All Day | 12 minutes |
| All days | Midnight | 20 minutes |

The application of these guidelines resulted in a 6.4% increase in weekday train miles, a minor increase (0.3%) on Saturdays and a 1.0% decrease on Sundays.

**Comment:** This useful paper gives a look at how loading standards are developed and their effects. It confirms the importance of considering the effects on dwell times when creating loading standards. The need to give passengers with access to alternative transportation a comfortable ride is also given importance with the variable loading standards applied to less frequent rush hour and non-rush hour services.

**49    O'BRIEN, W., SCHNABLEGGER, J.** and **TEPLY, S.,** Control of Light Rail Transit Operations in Edmonton, *Transportation Research Board Special Report 182, 1978, pp. 115-118*

**Summary:** This paper gives a pre-opening report on the control of light rail and traffic on the Edmonton, Alberta Northeast light rail line. The signal blocks on the light rail are stated to be 1-km long which places a severe constraint on capacity. The authors place emphasis on the need to maintain consistent service on the outlying portion of the light rail line in order to ensure proper utilization of the downtown tunnel. This is achieved with light rail pre-emption of the nine grade crossings on the line. Grade crossing signals and gates are integrated into the signal controllers of adjacent intersections to ensure smooth traffic flow and prevent queuing on the rail tracks.

**Comment:** This report supports other literature information that signaling systems, not grade crossings, are generally the capacity constraints on light rail systems.

**50    PARKINSON, TOM E.,** Passenger Transport in Canadian Urban Areas, *Canadian Transport Commission, Ottawa 1971*

**Summary:** The Principal Investigator's 1971 report quotes maximum rapid transit volumes from sources referenced elsewhere in this review. The ratio for the peak-within-the-peak is discussed for both a 5-min and 20-min flow level. The report looks briefly at the difference between theoretical and practical maximum capacities for rail transit and the headway reductions possible with automatic train operation.

**Space per passenger (square meters)**
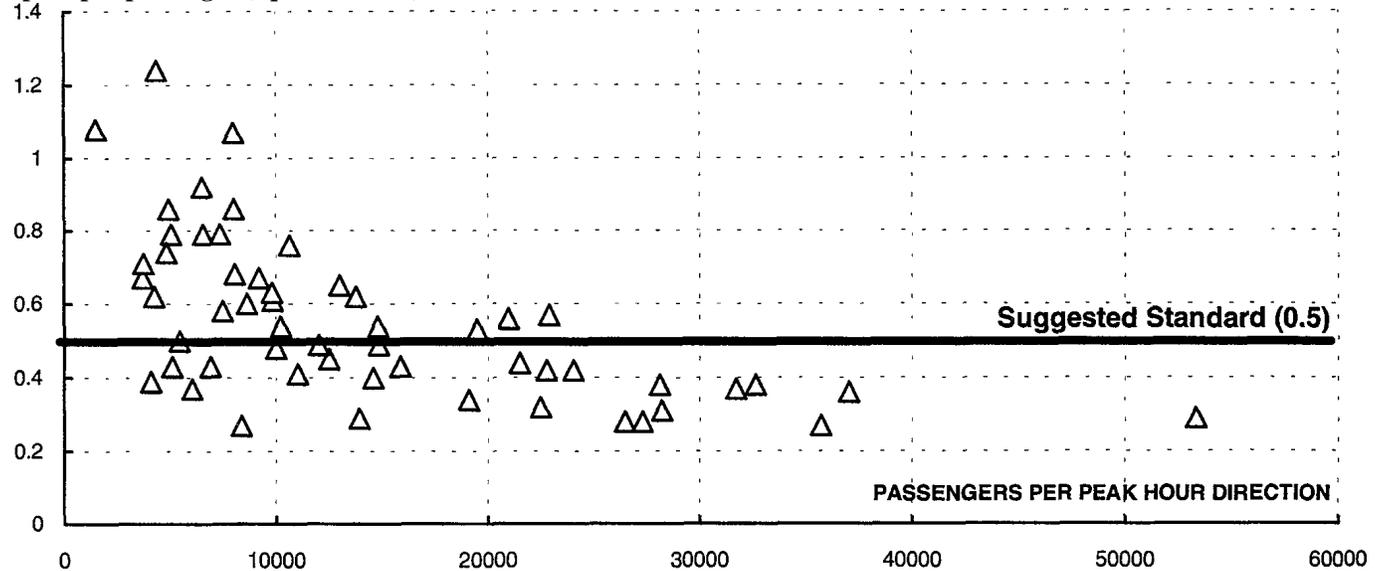


**Comment:** This study is one of a small number that suggest higher throughput with automatic train operation compared to manually driven systems.

## 51 PUSHKAREV, BORIS S., ZUPAN, JEFFREY M., and CUMELLA, ROBERT S., Urban Rail In America: An Exploration of Criteria for Fixed-Guideway Transit, *Indiana University Press, 1982*

**Summary:** Pushkarev et al. use a unique approach to rail transit, discussing the number of rail transit tracks (65) that enter CBD's in the USA and Canada; of which 38 operate in the peak hour with the luxury of more than 0.5 $m^2$ of space per passenger. Only 6 "tracks" operate at system capacity, 5 in New York and one in Montreal. The authors point out that in the United States outside New York, no rail system operates at more than 33% of nominal system capacity.

Data compilations and presentations are numerous and have been cited and reproduced elsewhere. The relationship between peak hour volumes, space per passenger and theoretical capacity of lines in the United States is shown. The first two data sets are illustrated below:

The report suggests using "gross vehicle floor area" as a readily available measure of car occupancy and applies the following quality of service standards:

- ADEQUATE—0.5 $m^2$ provides comfortable capacity per passenger space
- TOLERABLE WITH DIFFICULTY—0.35 $m^2$ lower limit in North America with "some touching"
- TOTALLY INTOLERABLE—0.2 $m^2$ least amount of space that is occasionally accepted

The report discusses two of the three types of occupancy

diversity—*peak-within-the-peak* and *uneven loading between cars of a train.*

The book states that the physical capacity of a rapid transit line is "frequently misunderstood" but is basically controlled by:

1. Policy determination
2. Car Width
3. Platform Length
4. Minimum operational headway

Car width can be assigned to two groups: narrow-2.5 to 2.8 m (generally old systems — IRT, PATH, SEPTA Market-Frankford, Montreal, Chicago and Boston) and wide-3.05 to 3.20 m (IND, SIRT, SEPTA Broad Street, Cleveland, Toronto—and all newer systems). Platform length ranges from 70 m (Boston, currently being extended) to 213 m (BART). The authors comment that minimum operational headway must be sustainable reliably and has three major components:

- type of signaling
- complexity of route
- dwell times

They cite the common limit of 30 trains per hour with the typical three-aspect signaling system and state that in practice this is lower if there are merges but can be increased with careful and precise operation, as for example, with the NYCT's 33 trains an hour on the Flushing Line or the 38 on PATH's World Trade Center line—made possible only by the multiple track terminal. The highest routine frequencies in the world (on a two-track system with on-line stations and no junctions) are the 40 trains an hour of the Moscow Metro. However, AGT can operate at closer headways using off-line station as shown in the 15-sec and 18-sec headways in Morgantown and Dallas-Fort Worth.

The report has only minor content on light rail quoting Pittsburgh PCC car headways of 23.5 sec with on-sight operation

and SEPTA's 29 sec with block signals on the Market street subway at a reasonable schedule speed of 20 km/h. This is achieved by allowing train operators to pass red signals, operating on-sight, and with multiple station berths (4).

The authors discuss performance in terms of installed power per tonne, suggest 80 km/h as a suitable maximum speed which should be achieved in 25 sec—but takes 60 sec in a few cases where old, under-powered equipment is still in service. They address some confusion in defining average speeds and use the terms:

*Schedule Speed* is the net average operating speed without terminal layover time. *Gross Average Operating Speed* adds terminal layover time.

**Comment:** Pushkarev, Zupan and Cumella's book is one of the most comprehensive, readable and complete treatises on North American rail transit. It uses principally new data, specifically acquired for the book, presented with outstanding clarity and exceptional graphics.

The section on headways is perceptive, introducing one of the factors not mentioned elsewhere in the literature—that capacity is heavily dependent on policy—ranging from New York with 290 passengers per car (crush load) through Washington with service specified for an average of 170 passengers per car to BART with a policy of 90 in a larger car—but not currently achieved. The authors clearly indicate that passenger loading densities of the older subway systems will not be accepted on new North American systems.

## 52 RADWAN, A. E., and HWANG, K. P., Preferential Control Warrants of Light Rail Transit Movements, *Transportation Research Board State-of-the-Art Report 2, Light Rail Transit: System Design for Cost-Effectiveness, 1985: pp. 234-240*

**Summary:** Radwan and Hwang attempt to quantify the delay caused to light rail and general traffic by the use of light rail traffic signal pre-emption. The following version of Webster's delay model was used in their research:

$$d = 9/10 \left\{ \left[ \frac{c(1 - \lambda)^2}{2(1 - \lambda x)} \right] + \left[ \frac{x^2}{2q(1 - x)} \right] \right\}$$

where:
- $d$ = average delay per vehicle on the particular intersection approach
- $c$ = cycle time
- $\lambda$ = proportion of the cycle that is effectively green for the phase under consideration (g/c)
- $q$ = flow
- $s$ = saturation flow
- $x$ = degree of saturation

The authors have endeavored to create a model that does not discriminate against the transit mode; as most comparisons based on intersection level of service do. As a result, their model assesses both the delay and savings experienced by road vehicles and the light rail trains.

Their findings showed that, for a two-phase intersection with no left turns, the overall intersection gain due to signal preemption is linearly proportional to light rail volume. For a three-phase intersection with an exclusive light rail phase almost no intersection gain was observed. In the case of a three-phase intersection with an exclusive left-turn phase "it was found that there is an optimum main-arterial volume at which the overall intersection gain is maximum for a given constant left-turn volume."

**Comment:** While providing some interesting results, the model used in the study has some faults which may have biased the results. The most important of these are assuming an overly optimistic car occupancy of 1.4 and light rail volumes of 40-50 trains per hour. This level of light rail service is far beyond that operated on North American lines running at-grade with signal pre-emption.

The study does not mention that at-grade light rail capacity is limited by grade-crossings.

## 53 RAINVILLE, WALTER S., and HOMBURGER, WOLFGANG S., Capacity of Urban Transportation Modes, *Journal of the Highway Division, American Society of Civil Engineers, 1963*

**Summary:** The late Walter Rainville was Chief of Research for the then American Transit Association (now APTA) and was noted for his no-nonsense approach. In the transit section of this paper he defines:

> **Effective transit capacity =**
> **Vehicles per hour × Passengers per vehicle**

The paper then lists typical fully loaded capacities of rapid transit cars 35 years ago, the number of trains per hour (20 to 32) and a range of actual capacities. The paper points out that in theory a two-track rapid transit system could be built to handle 90,000 passengers per peak-hour direction whereas in practice the maximum in the country, then, was the NYCTA IND 6th and 8th Avenue expresses at 71,790.

Rainville discusses peak-hour loading diversity and shows an average for heavy volume lines in New York and Toronto of 87.6 (peak hour/peak-within-the-peak rate), an exceptional 95.6 for the NYCTA 7th Avenue line and the lower figure of 72.9 for less heavily loaded lines in other cities.

**Comment:** The now historic data in this, and other references, provides an insight into the maximum capacity of rail transit in an era when ridership and loading levels were higher.

## 54 RICE, P., Practical Urban Railway Capacity—A World Review, *Proceedings of the 7th International Symposium on Transportation and Traffic Theory. Kyoto*

**Summary:** Rice's long paper combines two diverse areas. The first is a survey of the headways, capacities and commercial

speeds of 53 urban railway systems throughout the world based on available published data. The second is an analysis of minimum headways that expands on the work of Lang and Soberman [R39] and Bergmann [R13] to compensate for reduced acceleration as a train increases speed

- coasting between stations
- closely spaced stations that result in a station approach below the optimal speed for minimum headways[12]
- the distance a train must move out of a station before the following train receives signal clearance to enter

The survey shows three[13] systems that operate 40 trains per hour, thirteen systems that operate 30 to 36 trains per hour and twelve that operate 24 to 27 trains per hour on a single track. The highest quoted capacity is 72,000 passengers per peak-hour direction per track, three systems quote capacity between 60,000 and 70,000. All other systems (49) show capacities below 50,000 passengers per peak-hour direction per track. The data shows that the 53 rail transit systems have a mean route length of 14.6 km and a mean overall station spacing of 1.1 km.

Rice analyzes a typical station to station run of 1.6 km (1 mi) with modern rail transit equipment. Constant acceleration to the point where station braking must commence produces a theoretical run time of 89 sec. However as the speed of a train increases acceleration tapers off—ultimately to zero—as the train *moves along the motor performance curve.* Using a typical performance curve results in a practical station to station time to 111 sec—25% higher.

Adding the maximum realistic level of coasting increases travel time by a further 9 sec to 120 sec—an 8% increase with an estimated energy saving of 23%.[14]

Rice also tabulates performance and capacity data for the 53 systems. The overall mean normal service braking rate is 1.14 $m/s^2$, the mean emergency braking rate is 1.51 $m/s^2$ and the mean initial acceleration rate is 1.12 $m/s^2$. The overall mean design maximum speed is 79.4 km/h (50 mph). The overall mean packing density is 3.61 passengers per square meter.

The headway equations that are developed contain constraints for conditions where the optimal approach speed cannot be obtained due to coasting practices (or to speed control), due to tapering of the initial acceleration, and due to any run out distance from a station—a distance that a train must cover before the following train receives.

Rice acknowledges the importance of dwell time in determining the minimum practical headway—and the difficulty in estimating the dwell time. He quotes a dwell time in sec for a *heavy departure load* at

Dwell = 17.5 + 0.55(number of passengers per double door)

and for a *medium departure load* at

Dwell = 13 + 0.49(number of passengers per double door)

Only limited results of applying the numerous equations derived in the report are shown. The most significant are (for a 1.6 km station to station run):

- the optimum approach speed for typical rolling stock is 32 km/h (19 mph) which produces a headway of 80.4 sec with a nominal 30-sec dwell
- headways increase at approach speeds above and below this optimum. For example at 50 km/h (31 mph) the headway increases to 86 sec, a 7.5% decrease in capacity; at 20 km/h (12.5 mph) the headway increases an identical amount to 86 sec
- removing the adjustments due to the tapering of the acceleration curve results in a linear acceleration decreasing the headway to 80.1 sec, a 0.4% improvement. (0.6% improvement without considering the dwell)

**Comment:** Rice, in attempting to accommodate performance and station spacing nuances in train performance has added considerable complexity to the calculations and imposed several conditions. The results do not seem to justify the complexity. There are few conditions of station spacing, (or speed control) and train performance where an optimal approach speed of 32 km/h (19 mph) cannot be achieved. Using actual motor characteristics rather than assuming linear acceleration only changes the calculated headway by 0.4%. The calculation of the actual impact of this improvement is valuable.

Despite the added complexity several assumptions have still to be made, for example driver and equipment reaction time, and the use of the very variable emergency braking rate, rather than the service braking rate, to determine minimum separation times is unusual. This higher braking rate and a lower estimate of reaction time than other workers (2 sec) may explain why Rice's calculated minimum headway of 50 sec plus dwell—for a three-aspect fixed-block system with typical train lengths and performance—is lower than the 55 sec typical of other work.

The largest deficiency, considering the elaborate analysis, is that no allowance is made for schedule recovery to avoid any headway interference.

## 55    SCHUMANN, JOHN W., Status of North American LRT Systems: 1992 Update, *Transportation Research Record 1361, 1992: pp. 3-13*

**Summary:** This paper provides a concise overview of recent North American light rail developments. Future plans of systems are also outlined. Seven tables are used to gather together many of the basic statistics for U.S. and Canadian light rail systems operating in 1992. A brief section also discusses the interest in low-floor light rail cars shown by many transit agencies.

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[12] This constraint would be the same is speed controls were used that limit the optimal approach speed.

[13] The three closest headway systems (40 trains per hour) are quoted as Moscow, PATH and NYCT. As NYCT operates no more than 30-32 trains per hour on its heaviest trunk routes the data are suspect. It may be that the information relates to the theoretical throughput of the signaling system rather than actual trains operated.

[14] The calculation of energy consumption is not specified and probably does not take into account power other than traction use. i.e. hotel load power, the bulk of which is for heating or air conditioning. On systems with weather extremes—most East coast systems—the hotel load can be as high as the traction load cutting the coasting savings in half.

**Comment:** Schumann provides a useful but brief summary of some of the aspects of light rail which are relevant to this project. The information in the tables may be directly useful or form a base to seek more current data. The introduction of low-floor cars will have effects on capacity as a result of reduced dwell times through faster passenger movements and better accessibility to the mobility impaired.

## 56   SONE, SATORU, Squeezing Capacity out of Commuter Lines, *Developing Metros, Railway Gazette International 1990.*

**Summary:** Professor Satoru of the University of Tokyo gives a broad outline of many of the factors limiting rail transit capacity. Station dwells are introduced as the key factor in determining capacity. The minimum practical headway on an uncomplicated line is around 40 sec plus dwell time at the busiest station plus the time needed for a train to move its own length from a standing start. Even with an infinitesimally short dwell time, the minimum headway is thus at least 50 to 60 sec.

One method of reducing overall line headway is to have some trains by-pass lightly used stations or to use an A/B stopping pattern where lighter stations are served by either the A or B services with heavier locations and transfer points being served by both.[15] Dwell times at AB stations are still a major limitation on headway. Commuter rail services with complex stopping patterns are often able to be more flexible than rail rapid transit and so trains can be scheduled to pass through relatively busy outlying stations when other services are provided.

An even passenger distribution on board the trains is important to ensure that maximum use is made of the rolling stock. Station design can be used to create an even distribution of passengers throughout the train. This can be achieved by designing cross-platform transfers, and distributing platform entrances and exits along the length of the platform and varying their locations at different stations. Stub-ended termini are a particular problem which can, at least, be partially improved by adding platform access at the outlying ends of the platforms.

Additional platforms can be used to reduce dwell times by allowing boarding on one side of a train and alighting on the other. Throughput can also be increased with additional track by converting side platforms to island platforms and running alternate trains on either side of the platform. This is a much more economical solution than adding a parallel main line.

Junctions can be improved with grade separation or by shifting the interchange function to a major station nearby with excess platform capacity.

The city terminus is a common limiting station on rail transit lines. Creating run-through stations by linking terminus stations is an excellent, albeit expensive, solution. Building a loop giving direct access to all platform tracks is another successful way of increasing station throughput. Allowing higher speed approaches to stub-end stations by extending the station tracks a short safety distance beyond the platforms is also possible in some cases. Double-decking is another effective but expensive

station improvement. Train schedules can also be adjusted to increase throughput. Three main categories can be defined:

- All trains stop at each station.
- Fast trains over-take slower ones at four-track stations.
- Each train serves all stations in a zone then runs express to the city terminus.

The first pattern works best with less than 10 stations of similar traffic generation. The second is effective with a large homogeneous system but does not give the higher number of fast trains near the central hub which is desirable on a radial system.

The last pattern (3) is ideal for branching, radial commuter lines since it gives high capacity and fast journeys. Passengers traveling between intermediate stations may be inconvenienced by the need to change trains but their numbers are small.

A number of Japanese examples of capacity increases are given. Several of these are of running trains of similar service characteristics in succession in a practice commonly known as "platooning". In one case the first train leaves 130 sec before the second, stops at one additional station and arrives at the terminus 90 sec before its slightly faster counter-part. The double-track Seibu Railway, which operates such patterns, runs 30 trains into its Tokyo terminus in the morning peak hour and has plans to add three additional trains. This is despite the terminus being stub-ended with only three full length tracks.

Care must be taken when increasing capacity to ensure that additional ridership does not simply create another choke-point at stairs or passageways.

Future capacity increases will likely require the use of offline stations, on-board switching, and train-to-train safety control or collision avoidance technologies.[16] Off-line stations can only be practical where the platform loop track is long enough to allow acceleration and deceleration to take place off the main line. Headway improvements may, however, be marginal since a train approaching a facing points switch must be able to stop short if the switch has failed in mid-position. On-train switching equipment could remove this restriction with more development.

**Comment:** This paper presents a comprehensive overview of the factors restricting the upper limits of rail transit capacity. It gives useful examples of capacity increases obtained on several Japanese rail transit services—several of which have both the highest train, and highest passenger, densities in the world

## 57   STRAUS, PETER., Light-Rail Transit: Less Can Mean More, TRB Special Report No. 182, Light-Rail Tran: Planning and Technology. 1978: pp. 44-49

**Summary:** Mr. Straus makes a strong argument for keeping the "light" in light rail transit and resisting the temptation to build light rail lines to rapid transit standards. A particularly interesting

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[15] The AB skip stop system was used extensively on the Chicago Transit Authority's rail lines until 1995.

[16] Reviewer's Note: Essentially a moving-block signaling system.

table showing capacities of various light rail alignment options is reproduced here.

| Right of way option | Passengers per hour |
|---|---|
| Exclusive subway | 20,000 to 30,000 |
| Exclusive aerial | 20,000 to 30,000 |
| Exclusive grade-separated surface | 20,000 to 30,000 |
| Semi-exclusive: median or side of road | 10,000 to 20,000 |
| Separated but in-street surface | 10,000 to 20,000 |
| Mixed-traffic surface operation | 5,000 to 10,000 |

Another relevant point made in the article is that higher speeds can lead to reduced capacity because of the need for longer following distances. Mention is also made of the faster boarding possible with high-level platforms, as found in the Muni Metro subway[17]. The use of low level platforms (with moveable steps on the cars) on the surface maintains the flexibility and simplicity of light rail operation elsewhere on the system.

## 58    SULLIVAN T. J., New York City Transit New Technology Signals Program Status Report, *MTA New York City Transit Division of Electrical Systems, APTA Rapid Transit Conference, Sacramento, June 1994*

**Summary:** NYC Transit's existing train control system is an automatic fixed block wayside signal system. Virtually all track circuits are single rail. Much equipment dates to the original installation and has a high failure rate and maintenance costs. Following the 1992 14th Street derailment, a $14 million speed protection system is being installed at 31 priority locations.

A 5-year, $1 million study of train control systems has concluded with broad support for Communications-based signaling—also referred to as transmission-based or moving-block signaling. The principal attribute is continuous two-way communication and control, increased safety, increased functionality, and lower life cycle costs.

A survey of signaling technology around the world showed numerous advantages for moving-block signaling systems, including increases in capacity. Other advantages include improved schedule adherence, reduced power consumption and the inherent ability to operate in both direction on any track with full automatic control.

The report discusses the issue of adapting the traditional failsafe signaling concept to the equivalent, but different, safety standards of computer based controls. Despite concerns, and resistance to the introduction of new technology in train control, many rail transit operators have selected moving-block signaling systems, including London Transport and Stockholm Transit. An overlay track-circuit system, SACEM, with some moving-block attributes, has increased train throughput on the Paris RER line A. The report describes the selection and successful operation of moving-block signaling systems by eight other rail transit operators in North America and Europe.

The report expresses concern with acquisition of a single proprietary system. The market for moving-block signaling systems has been dominated by one company for two decades. However all the signaling suppliers contacted had or were developing moving-block systems. NYC Transit intends to work with the international signal industry, to seek an engineering partner and to use a development-driven approach to test and select moving-block signaling systems. Sullivan expresses hope that this process will develop a standard for such systems and that NYC Transit will have more than two suppliers to ensure competition and the lower costs that moving-block signaling systems have the potential to deliver.

**Comment:** The strong endorsement of moving-block signaling systems by two of the world's largest rail transit operators, MTA New York City Transit and London Transport indicates that this technology and its multiple advantages has become acceptable.

## 59    TABER, JOHN and LUTIN, JEROME, Investigating the Potential for Street Operation of Light Rail Transit, Transportation *Research Board Special Report 182, 1978: pp. 161-166*

**Summary:** While using data collected in 1973, this paper has some interesting figures of delay for streetcars in Toronto. Traffic signals were found to cause 50% of the delays to streetcars while passenger service (boarding) times accounted for 40%.[18] Delays caused by traffic congestion were only 3.3% of the total. On the St. Clair line boarding delays accounted for only 27% of total delay. This is believed to be a benefit of the extensive use of island stops on this route.

## 60    TAYLOR, P. C., LEE, L. K. and TIGHE, W. A., Operational Enhancements: Making the Most of Light Rail, *Transportation Research Board Special Report 221, 1989: pp. 578-592*

**Summary:** This mis-titled work summarizes the efforts to minimize the effects of the Los Angeles Blue Line light rail on roadway capacity. This is achieved by varying the priority given to the light rail trains according to road traffic volumes. During peak traffic periods, the light rail is accorded a lower signaling priority to prevent disruption of motor traffic. At off-peak hours, the light rail can be allowed greater priority with minimal impact on motor traffic.

**Comment:** At the 6-min headways under consideration, the light rail is seen as limiting road capacity and not the reverse. Reducing priority for light rail at peak hours—when it is most needed—is negative. It reflects badly on the traffic engineering process whereby the number of vehicles, rather than the number of people, moved is prioritized.

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[17] Reviewer's Note. In the subway the double front door is not used due to the large gap created by the tapered car end.

[18] Reviewer's Note. The latter figure has no doubt dropped since the adoption of an exact fare policy.

**61    TIGHE, W. A.** and **PATTERSON, L. A.,**
Integrating LRT into Flexible Traffic Control Systems, Transportation Research Board State-of-the-Art Report 2, Light Rail Transit: System Design for Cost-Effectiveness, 1985: pp. 213-220

**Summary:** Tighe and Patterson offer a general discussion of integrating light rail into vehicular traffic signaling. Their ideas are then applied to the Woodward corridor in Detroit, and the Guadalupe corridor in Santa Clara County, Different solutions are offered in each case to reflect the specific alignment characteristics.

For the Woodward Corridor, the light rail is proposed to run in the exceptionally wide median of Woodward Avenue. This allows the use of two-phase traffic signals (i.e. no left turns permitted) at all intersections since the median can be used to create U-turn bays between intersections. Cars wishing to turn left are able to use a combination of right-turns and U-turns to achieve the same result. Intersection spacing is such that the light rail can easily run with the progressive signaling at cross-streets while pre-empting the U-turns when required.

In the Guadalupe corridor example, the medians of North First Street and Tasman Drive are of a more conventional width making the U-turn arrangement impractical. Instead, multiple phase traffic signal controllers with a total of up to 16 phases (some of which can run concurrently) will be used to accommodate heavy volumes of turning traffic. The degree of light rail pre-emption will be variable so as not to unduly hinder automobile flows at peak times. During off-peak periods a greater degree of pre-emption will be permitted.

**Comment:** The omission of any mention of a reduction of light rail capacity due to less than full signal pre-emption in this paper indicates that, at the headways under consideration (4 - 6 minutes), pre-emption is not necessary for providing sufficient light rail capacity.

**62    TOPP, R. M.,** Improving Light Rail Transit Performance in Street Operations: Toronto Case Study, *Transportation Research Board State-of-the-Art Report 2, Light Rail Transit: System Design for Cost-Effectiveness, 1985*

**Summary:** The Queen streetcar line in Toronto, ON experiences service irregularities due to extremely heavy use (75,000 passengers per day) and a lack of transit priority. This paper summarizes some of the operational problems of the route and details the results of two studies aiming to solve them. Key to improving the service on the route is a reduction in the number of unscheduled short-turns required to maintain headways and capacity on the central portion of the line.

One approach was solely to look at operational adjustments which would improve service reliability. Passenger service time was found to take 12 - 18 percent of total travel time. Signal and queue delays accounted for 13 - 15 percent of total travel time. Suggestions included extending running times, increasing the

service gap required to initiate a short-turn, adding scheduled short-turns, and using larger, articulated vehicles.

The second approach was to study ways of improving service through the use of transit priority measures such as pre-emptive signaling. In some cases this could simply mean re-timing the traffic signals to improve general traffic flow.

**Comment:** This is one of few papers to address the operational problems of a traditional streetcar service in mixed traffic with no priority measures.[19] The speed of the service and number of cars required is heavily affected by the current conditions.

**63    TORONTO TRANSIT COMMISSION**, Yonge-University-Spadina Improved Headway Study, Final Report *Toronto Transit Commission, December 1988*

**Summary:** This staff report, based on studies by consultants Trans mode and Gibbs and Hill, examines a range of options to increase capacity on the TTC's Yonge-University-Spadina (YUS) subway.

In 1988 the Yonge subway south of Bloor was close to its rated capacity of 34,000 passengers per peak hour direction.[20] This capacity is based on maximum length six-car trains, 140-m (450-ft) long, operating at headways of 130 sec (28 trains per hour).

The Yonge subway, opened in 1953, was the first new postwar subway in North America. It uses a conventional three aspect color light signaling system based on track circuits designed for 120-sec headways (30 trains per hour), on the basis of station dwells of no more than 30 sec. Actual dwells at the major Bloor-Yonge interchange station of 45 sec prevent undisturbed operation of more than the 28 trains per hour.

Analysis of downtown developments had indicated a future demand, on this critical section of the subway, increasing by 33% to 45,000 passengers per peak hour by the year 2011.

A detailed analysis of the signaling system confirmed that the Bloor station dwell was the only bottleneck preventing 120-sec headways. However if the signaling system was upgraded for closer headways other bottlenecks would appear, particularly the Finch turnback used by all trains. (At the other end of the line a short-turn divided the turnbacks between two stations, so avoiding any restrictions.)

The study examined three signaling improvements that would progressively reduce headway. The first option made minor signal adjustments in the vicinity of Bloor station to permit 122-sec headways. The second set of improvements to signaling reduced the headway to 112 sec but required a major reconstruction of the Bloor station to ensure dwell times within 30 sec, and changes to the terminal at Finch.[21]

The third improvement was to replace the signaling system

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[19] The Toronto Transit Commission has recently managed to obtain priority for streetcars on sections of its network.

[20] Ridership has decreased in the last few years.

[21] A fourth option that would permit a 105-sec headway required extensive modifications to the existing signaling system and was discarded as impractical.

with automatic train operation that would permit 90-sec headways—again with a major reconstruction of the Bloor station and both terminals.

|  | Option 1 | Option 2 | Option 3 |
|---|---|---|---|
| Minimum Headway | 122 secs | 112 secs | 90 secs |
| Capacity in ppphd | 36,400 | 38,800 | 48,400 |
| Capacity Increase | 10.7% | 14.1% | 42.3% |
| Bloor Dwell | 45 secs | 30 secs | 30 secs |
| Implementation | 1 year | 4 years | 8 years |
| Signaling Cost | $1M | $8M | $134M |
| Bloor Station Cost | -- | $120M | $120M |
| Turnback Costs | -- | $35M | $99M |
| Vehicle, Power & Yard Costs | $36M | $78M | $515M |
| TOTAL | $37M | $241M | $868M |
| Cost /10% capacity increase | $35M | $171M | $204M |

Each option required additional vehicles and the yard expansions to accommodate them. The results are summarized above with cost estimates in millions of 1988 Canadian dollars.

The study showed that the most cost effective way of reducing dwells at Bloor station was to widen the station and add a Centre platform so that trains could simultaneously open doors on both sides.

Terminal changes involved extending the tail tracks and adding a second pocket track so that peak period trains could reverse behind rather than in front of the station. The improved headways could not be accommodated by using the scissors crossover ahead of the station due to the wide track separation dictated by the center platform and the resulting high traverse time.

**PROPOSED TERMINAL CHANGES (Not to Scale)**

| Original Crossovers | Original Pocket | New pocket & tail tracks |
|---|---|---|



The study did not evaluate the considerable operating cost repercussions. All options required additional crews to permit a set-back operation at the terminals while the first two options imposed speed controls that reduced the average system speed, increasing vehicle and crew requirements. Option Three's automatic train operation offered the significant potential saving of reducing train crews from two to one.

Implementation of Options Two and Three was lengthy and difficult as changes had to be made while the subway was operating, work being restricted to limited hours, even with proposed early closing each night.

The study also reviewed alternate methods of increasing capacity. Widening vehicle doors was suggested as a way to reduce dwells. An increase of 22 cm (9 in.) to a total width of 1.37 m (4.5 ft) was proposed. This was not practical on existing cars but may be implemented on future car orders.

Adding a short (50 ft) car to each train would be possible within the existing platform length of 152 m (500 ft). This would increase capacity by 11% while concurrently reducing dwell time by an estimated 12%. The costs was estimated at $47 million.

**Comment:** The TTC's capacity problem stems from a failure to operate the Bloor-Danforth subway as originally planned. A wye junction at Bay/St. George was designed so that each alternate Bloor-Danforth train ran downtown via the University subway—avoiding the need for passengers to physically transfer to downtown trains. This operation was abandoned after a six month trial in 1966 as uneven train arrivals made the merge difficult. The uneven arrivals were primarily due to the lack of any intermediate timing points on the long cross-town Bloor-Danforth subway.

Twenty years after the subway opened, intermediate timing points (dispatch signals) were added. By this time the University subway had been extended along Spadina and the wye operation was no longer feasible. 30% of Yonge subway's peak-point passengers and 48% of the University subway's peak-point passengers transfer from the Bloor-Danforth subway.

The study offers valuable information on capacity limitation and upgrade alternatives. The possibility of operating 7 car trains of existing cars does not seem to have been considered. Such a consist would extend beyond the station platform but all doors would be (just) within the platform—automatic train operation would be desirable or necessary to achieve the required berthing accuracy.[22] There is no supporting evidence that widening doors would reduce dwells. Information elsewhere suggests that the 1.15 m (3.75 feet) wide door, while narrower than normal for heavy rail vehicles, supports two streams of passengers and that little gain would be achieved until the doorway is sufficiently wide for three streams.

The addition of automatic train operation and rebuilding Bloor station appear to be the only way to meet future passenger demand. This would be easier, cheaper and faster using a transmission based signaling system (moving-block), avoiding the difficult, potentially service disruptive, changes to the existing signaling equipment. Transmission based signaling systems have been selected by MTA-NYCT and London Transport as the most practical way to upgrade or replace existing conventional signaling systems. This omission from the study is all the more surprising considering that the TTC already operates a transmission based signaling system on the Scarborough line,—an extension to the Bloor-Danforth subway.

**64 TORONTO TRANSIT COMMISSION**, Yonge-University-Spadina Improved Headway Study, Signaling Report *Toronto Transit Commission, December 1988*

**Summary:** This staff report, based on studies by consultants Trans mode and Gibbs and Hill, expands on the signaling system options required to increase the capacity of the TTC's Yonge-University-Spadina subway described in *Yonge-University-Spadina Improved Headway Study, Final Report* (above).

**65 TRANSPORTATION RESEARCH BOARD**, Collection and Application of Ridership Data on Rapid Transit Systems, Synthesis of Transit Practice, *Washington DC, 1991*

**Summary:** A comprehensive account of rapid transit data collection practices. The report comments on the generally low

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[22] The transmission based automatic train control on the TTC's Scarborough line achieves stopping accuracy ± 8 cm (3 inches).

technology approach that is mainly devoid of any field survey design or sampling techniques. Toronto is an exception using optical readers to enter field data into the computer. Several systems are starting to use electronic registers in the field.

Indications of accuracy are not quantified but the report infers that most operators achieve the FTA Section 15 requirements in passenger counts of accuracy within 10% at the 95% confidence level. Toronto and Atlanta claim accuracy to within 5%. NYCT states its checkers cannot monitor heavily loaded trains and at a certain (unspecified) level of crowding just mark such cars as crush loaded. NYCT also estimates that its exit counts are light by 15%.

On-board counts vary widely with the NYCT's Rapid Ride-check being among the most comprehensive, measuring: actual arrival time; alighting passengers; boarding passengers; passenger load leaving; actual departure time and scheduled departure time.

**Comment:** Provides a useful indication of the data collection process and probably accuracy level. NYCT offers possibility for a detailed dwell time analysis from the large quantity of Rapid Ridecheck data but actual NYCT peak counts and any loading diversity within a train is tainted by the lack of actual checker counts on crush loaded cars.

## 66 TRANSPORTATION RESEARCH BOARD, Gray, Benita, editor. Urban Public Transportation Glossary, *1989*

**Summary:** A comprehensive glossary used with the APTA glossary and definitions from several summarized reports, to compile the rail transit capacity specific glossary in this report.

## 67 TRANSPORTATION RESEARCH BOARD, Highway Capacity Manual, *Special Report 209, 1989*

**Summary:** This much referenced report devotes a modest space to rail transit capacity. It tabulates observed peak hour capacities in the United States and Canada, suggesting that peak 15- to 20-min volumes are about 15% higher. Typical maximum train throughput is suggested at 30 with reference to higher levels—PATH's 38 trains per track per hour and the CTA's 78 (prior to the use of a cab control signaling system on the elevated loop.)

The formula for rapid transit capacity is the same as shown above in Levinson. Suggested loading levels for capacity calculations are, level "D", an average of 5 sq ft per passenger $(0.46m^2)$.[23] The resulting suggested maximum capacity for two-track rapid transit lines is 18,000 to 30,000 passengers per peak-hour direction.

The formula for light rail capacity is also shown above in Levinson[R42]. The resulting suggested maximum capacity for two-track light rail lines with three-car articulated light rail vehi-

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[23] Reviewer's Note. Much the same as the 0.5 m$^2$ of Pushkarev (reviewed above)—particularly when Pushkarev's use of gross vehicle floor area is taken into account.

cles is 11,000 to 13,000 passengers per peak hour direction. (30 to 35 trains per hour) at level of service "D". This range increases to 17,500 to 20,000 passengers per peak hour direction at passenger service level "E" with 0.3 m$^2$/passenger.

**Comment:** The simple set of capacity information and calculations derived in this study are expected to be a suitable replacement for the Highway Capacity Manual's rail transit capacity section.

## 68 US DEPARTMENT OF TRANSPORTATION FEDERAL TRANSIT ADMINISTRATION Characteristics of Urban Transportation Systems, Revised Edition, *1992*

**Summary:** Contains many tabulations of rail transit information including a compiled range of rapid transit passenger space occupancies.

- seated passengers          0.28 - 0.46 m$^2$
- standing passengers        0.22 - 0.26 m$^2$
- crush loading              0.17 m$^2$

A list of AGT car capacities has been used in the AGT data table. Examples of dwell times are higher than used by many other examples in this literature survey.

| Location | Mean dwell times-secs | Standard deviation |
|---|---|---|
| NYCTA Lexington Avenue | 53 | 17 |
| CTA Evanston | 42 | 14 |
| MBTA Green Line | 58 | 24 |
| Milw. Road commuter rail | 19 | 6 |

**Comment:** The values for seated floor occupancy and for commuter rail dwell appear low.

## 69 US DEPARTMENT OF TRANSPORTATION, National Transportation Statistics, *Annual Report, Sept., 1993*

**Summary:** A comprehensive tabulation of transportation statistics with limited general information on urban transit.

## 70 VANTUONO WILLIAM C. Signaling and Train Control, High-Tech for High Capacity. *Transit Connections, September 1994*

**Summary:** This magazine article discusses advanced train control systems relative to a need to increase capacity. Communication based[24] signaling systems in use and under development are summarized.

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[24] AUTHOR'S TERMINOLOGY. Communication based signaling systems are also called transmission based or moving-block systems. As not all communication or transmission based signaling systems are moving block the A-8 report will use moving-block signaling system to avoid confusion.

Pointing out that moving-block signaling systems have been in use in Europe and Vancouver, Canada for several years the author discusses the selection of the Seltrac system for San Francisco's MUNI resignaling and an unspecified similar system for the modernization on New York's subway lines. It comments that other US rail systems are expected to follow New York's lead, quoting NYCT "after an intensive study and international peer review, communications based technology is the best, most cost-effective system for our purposes".

The article describes moving-block signaling systems from nine suppliers[25]:

- General Railway Signal—ATLAS ®™
- Union Switch & Signal—MicroBlok ®™
- AEG Transportation Systems—Flexiblok ®™
- Alcatel Canada—SELTRAC ®™
- Harmon Industries—UltraBlock ®™
- Siemens Transportation Systems
- Matra Transport—METEOR ®™, SACEM ®™, MAGGALY ®™
- CMW (Odebretch Group Brazil)
- Morrison Knudsen (with Hughes and BART)

**Comment:** One of the most comprehensive and current descriptions of moving-block signaling system. The only known system omitted is that of Westinghouse Brake and Signal (UK) currently being installed on a portion of London Transport's Underground.

The article is somewhat optimistic, claiming possible headway reductions to 60 sec. It also steers around the considerable industry controversy related to moving-block systems in which the hardware based fail safe features of conventional signaling are replaced by a software equivalency. Until NYCT announced the selection of a transmission based system, several of the above manufacturers were vociferously opposed to the software based train control systems (despite some of them offering software controlled interlockings).

## 71    VUCHIC, VUKAN R., Urban Public Transportation Systems and Technology, *Prentice-Hall Inc., 1981*

**Summary:** Professor Vuchic's comprehensive text devotes 70 pages to capacity, introducing some unique definitions and taking an approach that defines two capacities: $C_w$—way capacity and $C_s$—station capacity. Maximum offered line capacity $C$ is defined as the minimum of way or station capacity.

$$C_s = \frac{3600(n)(C_v)}{h_{s\,min}} \cdot \left|\frac{C_s}{sps\,/\,h}\right| \frac{n}{veh\,/\,TU} \left|\frac{C_v}{sps\,/\,veh}\right| \frac{h}{\sec\,/\,TU}$$

where:  $n$   = numbers of vehicle per Train Unit
$C_v$   = Passenger spaces per vehicle
$h_{s\,min}$ = minimum headway (station)

The vehicle capacity (passenger spaces per vehicle) is shown as:

$$C_v = m + \frac{\xi A_g - A_l - m\rho}{\sigma} \cdot \left|\frac{m}{seats\,/\,veh}\right| \frac{A}{m^2} \left|\frac{\rho,\sigma}{m^2\,/\,space}\right| \frac{\xi}{1}$$

where:  $\xi$  =  vehicle floor area loss factor for walls
$A_g$  =  gross vehicle floor area
$A_l$  =  vehicle floor area used for cabs, stairwells and equipment
$m$  =  number of seats
$\rho$  =  floor area per seat
$\sigma$  =  floor area per standing passenger

Suggested values for space per seat are 0.30 to 0.55 m$^2$, for space per standee 0.15 to 0.25 m$^2$. Operating capacity, $C_o$, is defined as:

$$C_o = C_{one\,hour} < C$$

The scheduled line capacity utilization factor, $\delta$, is defined as:

$$\delta = \frac{C_o}{C}$$

The capacity utilization coefficient[26] $\alpha$ is defined as:

$$\alpha = \frac{P}{C_o}$$

where:  $P$ =  number of passengers transported past a point in one hour

Professor Vuchic develops the concept of *Linear Vehicle Capacity* $\Pi$

$$\Pi = C_v/l'$$

where:  $l$ = length of vehicle

Suggested values of $\Pi$ are 7.0—8.5 for light rail vehicles and 8.0—10.0 for heavy rail cars. The maximum way capacity $C_w$ is developed as:

$$C_w = \frac{3600nC_v}{(nl' + s_o)\,/\,v + t_r = Kv\,/\,2b}$$

where:  $s_o$ = safety separation
$t_r$ = reaction time[27]
$K$ = safety factor
$v$ = train speed
$b$ = braking rate

Ten different safety regimes from Friedrich Lehner (1950) are introduced.[28] Using the above equation for way capacity and the brick-wall scenario, Vuchic calculates the way capacity for BART at 185 trains per hour and 350 trains per hour for 2 car articulated light rail vehicles.

The book then develops a station capacity equation incorporating dwell times. Station capacity is shown to be 1/4 to 1/7th of

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[25] Reviewer's Note. Several of these moving-block signaling systems are under development and it will be some years before they are proven in service.

[26] Reviewer's Note The capacity utilization coefficient is more commonly called the *load factor.*)

[27] Reviewer's Note: Operator and equipment reaction time for manual trains, equipment (brake) time only for automatic train operation.

[28] Reviewer's Note: Only one is accepted in North American rapid transit, namely the brick wall scenario with a service braking rate

way capacity. The theoretical throughput and optimum speed is shown as:

| Train | Speed km/h | Passengers per peak hour direction |
|---|---|---|
| 10 car rapid transit | 44.7 | 90,000 |
| 6 car rapid transit | 32.0 | 56,000 |
| 2 car articulated LRT | 22.5 | 30,000 |

Suggested practical capacities are 15,000 to 20,000 passengers per peak-hour direction for light rail and 55,000 to 65,000 passengers per peak hour direction for rapid transit.

The Yamanote Line in Tokyo is referenced as possible the highest capacity line with 165,000 passengers per peak-hour direction on four tracks. Actual examples of minimum headways and capacities are tabulated. Streetcars are shown to have operated historically at headways down to 23 sec on street and 30 sec on segregated tracks. Signaled light rail has demonstrated headways down to 27 sec.[29]

Rail rapid transit headways as low as 70 sec are shown in the Soviet Union with 90 sec the closest operated elsewhere. Vuchic's mathematical analysis of capacity concludes with extensive comments on the relation ship between theoretical and practical capacities of transit modes:

- Capacity is not a single fixed number but is closely related to system performance and level of service.
- Operation at capacity tends to "strain" the system to its maximum abilities and does not represent a desirable condition.
- There is a significant difference between design capacity and the number of persons transported during one hour.
- Theoretical capacities are often quite different from practical capacities.
- Way capacity is a different concept from station capacity, station capacity always governs line capacity.
- There can be friction between boarding and alighting passengers that impacts dwell time calculations.

**Comment:** Professor Vuchic develops by far the most comprehensive mathematical treatise of rail transit operation and capacity. As with other mathematical treatments, the difference between theory and practice is difficult to reconcile or quantify.

The concept of passenger capacity per linear unit of a train has merit and is developed in the study.

Except possibly for automated guideway transit with off-line stations, the use of "way capacity" has little relevance and produces dubious results. It is difficult to see the value of a line without stations and questionable whether such a line could throughput the calculated 185 BART trains per hour or 350 light rail trains per hour.

The book acknowledges this and states that station stops are the capacity constraint on rail transit systems. In calculating the clearance times for these station stops dwell times are poorly dealt with and several factors are omitted—particularly issues

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[29] Reviewer's Note: With multiple berth stations and without automatic train stops to allow operators to proceed through red signals on a *line of sight* basis.

of a train's initial acceleration diminishing rapidly, speed limits and/or grades entering and leaving stations, braking transition times (jerk limitation) and worst case braking conditions due to either equipment failures or adhesion limitations.

Other sources (Alle[R02] on dwell times, Auer[R09] on minimum headways and Motz[R47] on safety distances) provide methods to calculate minimum headways that include better treatments of dwell time and incorporate factors not considered in this book.

## 72 WALSHAW, J. R., LRT On-Street Operations: The Calgary Experience, Transportation Research Board State-of-the-Art Report 2, *Light Rail Transit: System Design for Cost-Effectiveness, 1985. pp. 221-226*

**Summary:** This paper describes the operation of the 7th Avenue transit mall in Calgary, AB. In the peak hour, 176 trains and buses use the mall. Light rail headways were expected to be reduced from 5 min to 2.5 min with the opening of the Northeast Line in 1985. Light rail operation benefits from a progressive signaling system that keeps signal delays down to 7-8 % of mall travel time.

**Comment:** The paper provides useful information with respect to buses and light rail sharing a right-of-way.

## 73 WEISS, DAVID M., and FIALKOFF, DAVID R., Analytic Approach to Railway Signal Block Design, *Transportation Engineering Journal, February 1974*

**Summary:** This paper describes computer based methods to design a fixed-block signaling system for high capacity rail lines. Five programs were developed.

1. A passenger station dwell time program using information on passenger traffic, number and size of doors, distribution of passengers on the platform and train and the ratio of boardings to alightings.
2. 1A train performance simulator that produces train speed, time and location based on a line's grades and curves and on the train's traction performance.
3. A braking distance program that utilizes braking rates, jerk limitation and reaction times. This program calculates the worst case stopping distance plus safety margins—termed the *safe braking distance*—a function of speeds, curves, grades, braking rate, jerk rates, available adhesion and the reaction times of car-borne and wayside train control equipment. The exactness of the *safe braking distance* calculation contributes to higher capacity and eliminates the need for additional margins to be added—termed *ignorance factors*.
4. A minimum headway program utilizing the outputs from the above three programs.
5. 1A graphical plotting program.

A composite schematic of the final output is shown below:
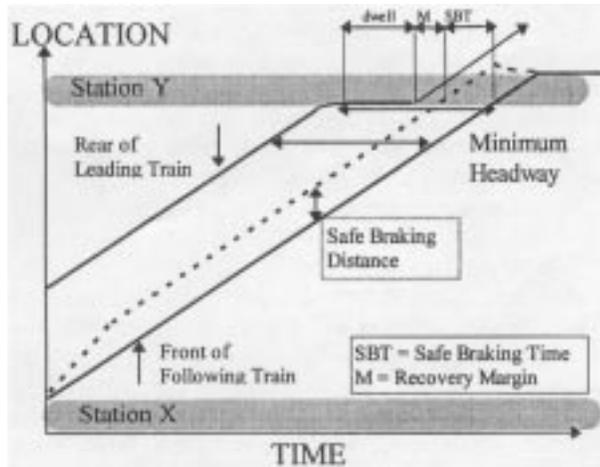


NOTE *Recovery margin is operationally desirable but not essential.*

The paper describes the selection of cab signal speed commands, locating signal block boundaries and the development of the optimum train design profile.

An appendix calculates the value of train speed which minimizes headway as:

$$MT = \frac{V}{2B} + N + \frac{L}{V}$$

where

| | | |
|---|---|---|
| $MT$ | = | minimum headway in sec |
| $V$ | = | constant train velocity |
| $B$ | = | constant braking rate |
| $N$ | = | brake application reaction time |
| $L$ | = | train length |

Differentiating this equation relative to V shows that for minimum headway:

$$V = \sqrt{2BL}$$

Substituting this optimum value of velocity back into the minimum headway equation results, relative to two trains traveling at a constant speed, in an expression for minimum headway that is independent of velocity:

$$MH = \sqrt{\frac{2L}{B} + N}$$

The authors warn that trains do not usually maintain constant velocity and that the factors influencing braking distance are continually changing, making the calculation of minimum headways more complex. In most situations it is the station stop times that determine the minimum headway—not the speed between stations.

**Comment:** This paper provides a useful and concise outline of signaling system optimization. In most cases the minimum headway is the station stop time, comprising the sum of the close-in time, dwell time and recovery margin. The paper shows that the braking distances that establish the close-in time can be approximated by quadratic functions of train velocity.

Braking distances cause large headways at high speeds—where between station maximum speeds may become the limiting factor in minimum headway. However the time to travel a train length—critical to the close-in time—will blow up hyperbolically at low speeds. "*In between lies a speed or profile that will optimize headway.*"

The paper tantalizingly offers a method to equate passenger volume with dwell times but offers no details.

## 74 WILKINS, JOHN D., and BOSCIA, J. F., Considerations For Effective Light Rail Street Operation, *Transportation Research Board State-of-the-Art Report 2, Light Rail Transit: System Design for Cost-Effectiveness, 1985: pp. 195-202*

**Summary:** Wilkins and Boscia outline their views on designing light rail for on-street operation. Some portions are relevant to capacity issues.

- Throughput is lower but this can be partially offset by train operation.
- Dwell times are longer with low platforms unless self-service fare collection and safety islands are used.
- Average speed is reduced because of pedestrian and vehicle interference.

**Comment:** The paper provides indications of capacity limitations with on-street light rail operation.

## 75 WILSON, NIGEL H. M., MACCHI, RICHARD A., FELLOWS, ROBERT E. and DECKOFF, ANTHONY A., Improving Service on the MBTA Green Line Through Better Operations Control, *Transportation Research Record 1361, 1992: pp. 296-304*

**Summary:** Wilson *et al.* examine the operational control system of the MBTA Green Line light-rail system in Boston in this paper. Particular attention is paid to methods of maintaining even headways, such as short-turning, express running and deadheading, in order to maintain as even a service as possible.

The existing operating practice relies on the intuition of inspectors stationed in the subway stations to decide the action to be taken to maintain service. Interestingly, all the correctional methods described are applied in the downtown portion of the line, not the outlying branches. The actions of the inspectors were examined by the authors and found to be generally beneficial to reducing passenger travel time. The researchers also created a correctional decision making routine for each line which is based on the preceding and following headways for each train. A different routine is required for each line given the discrete riding patterns on the individual branches. This framework would take much of the guess work out of dispatching and further reduce the number of deleterious dispatching decisions.

Determining the following headway is not possible with the current manual train supervision methods but this problem will be more readily corrected with utilization of the recently installed Automatic Vehicle Identification (AVI) system for field dispatching. While the AVI system does not automatically calculate preceding and following headways, the authors argue that modification of to the AVI system could enable automatic headway calculation and so make correctional actions still more effective.

**Comment:** This paper examines the operational control of the busiest light rail system in the United States. The discussions of maintaining even headways are highly relevant to the provision of capacity on any rail transit line. As the authors point out, their work is especially applicable to the light rail systems in Philadelphia and San Francisco which, like Boston, have multiple surface lines funneling into a downtown tunnel trunk line.

**76    YOUNG J.A.,** Passenger Comfort in Urban Transit Vehicles, *Ontario Ministry of Transportation and Communications, 1976*

**Summary:** Contains useful tables:

- transit seat dimensions for several rail systems
- detailed car dimensions
- chart of ratio of door openings to car length
- transit vehicle entry step heights
- transit vehicle door flow rates

Useful recommendations on optimal door widths, aisle widths and interior designs. Data on car lighting, noise and vibration levels are not relevant to the TCRP A-8 study.

**Comment:** The seat data should allow the development of a North American rapid transit average which could avoid the complexity of determining floor space used by seats on a system by system basis. Equating the total door width along the side of a car as a percentage of the car's length and relating this percentage to boarding and alighting flows has merit.

# A1.3 REVIEW SUMMARY

The literature review of North American Rail Transit Capacities and Capacity Analysis Methodologies has produced a wealth of information, data and methodologies.

## A1.3.1 BASICS AND CAUTIONS

Several authors caution that there is no absolute determination of rail transit capacity, that capacity is subject to many variants which can change from mode to mode and system to system. There are several cautions concerning the accuracy of ridership information, particularly with respect to individual car counts under crowded conditions.

There is general agreement that the definition of rail transit capacity is the number of passengers that can be carried past a single point, in a single direction, in a single hour. Many authors discuss the relationship between peak hour and peak-within-the-peak capacity, others concentrate on the latter short term capacity. This results in an overstatement of a full hour's capacity.

One author argues that a case can be made that the peak-within-the-peak is the actual maximum capacity of the system and, if there were an adequate supply of passengers, that rate could be sustained for a full hour.[30] Several authors discuss this issue of supply versus demand, both with respect to capacity and in two cases with respect to the quality of service. Here the argument is that if service is provided that exceeds demand, the level of crowding will decrease and more passengers may be attracted.

A valuable input on this topic is the suggestion that new rail transit systems must move away from providing service based on the loading levels of older systems. If their goal is to attract riders then the quality of service must be improved. Three papers peripherally mention that this was the original goal of BART—that all passengers have a seat—subsequently lost to the realities of operating economics.

## A1.3.2. INFLUENCING FACTORS

The literature clearly indicates the two major factors that, multiplied together, determine rail transit capacity. The first is line capacity, the throughput of trains per hour, the second is train capacity.

Line capacity is a function of two major factors, each of approximately equal weight. One is the time between a train starting from a station and the next train berthing at that station. This is a function of the train control system, both the type of system and the design of that type. For example the conventional three aspect signaling system can be designed for a minimum station separation of 55 sec, but is often, particularly for light rail, designed for longer separation times which require fewer blocks and lower capital and maintenance costs.

The literature introduces several minor factors that influence line capacity. These include speed limits at station approaches and exits and the rapid fall off of the acceleration rate as a train gains speed. Three authors state that automatic train operation can increase throughput within a range of 5 to 15%. None provide data to support this proposition. Many of the discussions on line capacity fail to consider constraints due to junctions or turnbacks. Where such limitations are discussed it is invariably without the detailed analysis that has been applied to the headway limitation at stations. Several papers indicated that the maximum or average speed of trains between stations is a factor in capacity. This is only true when a finite quantity of rolling stock is taken into account.

The second major factor pertaining to line capacity is the station dwell time. This is extensively dealt with in 26 papers, listed in the framework chapter, section 3.6.5. Suggestions range

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[30] Reviewer's Note: This argument glosses over the practice of several operators who insert one or more trains to handle the peak-within-the-peak demand, then remove them at the end of their run as the system cannot reliably sustain that number of trains over a longer period.

from using average or typical dwells in the 20- to 30-sec range, to a detailed methodology to calculate an upper control limit based on measured dwells over a peak hour at the busiest station.

The relationship between passenger movements and dwell times is a component of most dwell discussions. Those that included analysis concluded, without exception, that linear regression provided the most suitable fit for both rapid transit and light rail with high and with low loading. Three references improved the data fit by including the number of passengers onboard a car as a variable. One study used multiple regression and showed a small improvement in data fit with the variable of on-board passengers to the power of 2.0 or 2.5. One paper evaluated a variable to account for passenger actuated doors on the San Diego Trolley.

The literature contained many references to train or car capacity, methods of calculation based on net floor area, gross floor area and length of train, and examples of loading levels throughout North America. One paper contains useful information on capacity variations with different door and interior arrangements.

Although the literature had an abundance of information on these three major factors, train control throughput, dwell times and train or car capacity with one exception it was mainly silent on the fourth major capacity issue—policy. While this is a difficult area to analyze it can have a massive impact on capacity. Suggestions that new rail lines should be based on all passengers with a seat can reduce capacity, as normally defined, by a factor of three or four. In effect such policy issues are the most important of the four main rail transit capacity factors.

## A1.3.3 GROUPING

The literature generally dealt clearly and specifically with the different modes, rapid transit, light rail, commuter rail and automated guideway transit. It became clear that for the purpose of capacity calculations the modes were better grouped by the types of operation. These groups are defined and presented in the framework chapter, section 3.3.

## A1.3.4 LIGHT RAIL SPECIFICS

No fewer than 37 of the reviewed papers dealt specifically with light rail. In particular the issue of traffic engineering for shared right-of-way and grade crossings was extensively covered. Capacity issues on lines without full grade separation broke the literature into two groups. One group indicated that capacity was rarely an issue as the demand for service under such situations was far below the train headways that could be provided.

Other work suggested that capacity on lines with grade crossings was effectively limited to one train per traffic signal cycle.[31] Another suggested that where train length approached the street block length, one train every second traffic signal cycle was more realistic.

## A1.3.5 STATION CONSTRAINTS

Beyond two unsuccessful attempts to equate dwell times with the level of crowding on station platforms there was little discussion in the literature on the impact of station constraints on capacity. This is not unreasonable as most of the station constraints impact the number of people using that station, that is the demand, not the capacity of the rail transit line.

## A1.3.6 CONCLUSIONS

The literature has produced a wealth of information, methodologies and data so aiding this project to maximize its use of existing information and data.

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[31] Reviewer's Note: Papers that dealt with traditional streetcar operation suggested much higher throughputs—reaching as high as two or occasionally three single cars per cycleor over 100 cars per hour.

# A2. APPENDIX TWO
# Rail Transit Survey

This appendix is the result of Task 3 of the study.

*Survey rail transit services in North America to determine system characteristics and factors that influence and constrain capacity.*

The survey was carried out in June and July 1994. Data have been updated using 1993 FTA Section 15 reporting contained in the 1993 National Transit Database, published in 1994.

## A2.1 INTRODUCTION

### A2.1.1 PURPOSE OF SURVEY

A telephone survey of North American rail transit systems was conducted to determine the availability of existing ridership data, capacity and capacity constraints from each system. The opportunity was also taken to ask other relevant questions regarding line and station constraints, dwell times, signaling systems, and other issues of relevance to the A-8 study. Table A 2.1 through Table A 2.4 show the systems surveyed by mode. The Vancouver SkyTrain and Toronto Scarborough RT lines are included in the rail rapid transit category as they are not typical of automated guideway transit in ridership and route characteristics.

### A2.1.2 SURVEY METHODOLOGY

Letters were sent to the CEO or General Manager of each agency in mid April, 1994 requesting the designation of a contact person. 22 responses were received from 43 letters. Contact persons from non-responding agencies have been obtained by telephone query. Multiple mode systems often required separate contacts for each mode or division.

As a result of the principal investigator's work on a light rail system in Mexico City, English speaking contacts were obtained for four of the five Mexican rail systems and complete data acquired for two systems. Limited data was obtained for a third system. The remaining two systems were dropped after three telephone calls failed to get responses. Basic information and annual ridership was obtained from other sources to enable complete survey listings.

A questionnaire was developed from a relational database derived from APTA data and the initial analytic framework, showing each system and mode. System and vehicle data, including car dimensions has been incorporated in this database. The questionnaire was tested with a series of initial telephone interviews. It was not satisfactory and numerous changes resulted. A sample of the final questionnaire, completed for the Washington Metropolitan Area Transit Authority, is attached.

The survey itself was conducted in June and July 1994 with each system answering the same 24 questions. The same one page survey was used for all modes to ensure consistency in the study. For multi-modal systems, a separate questionnaire was completed for each mode. A few mode-specific questions were included to deal with unique aspects of particular modes, such as passenger actuation of light rail transit doors. Emphasis was also placed on determining the accessibility of each system to the mobility impaired and the resulting effects on service quality and capacity. When possible, ridership reports, car details and timetables were obtained. Information gathered from this survey was used to update and expand the database in preparation for the remainder of the study.

A variable in the survey was the level of interest and knowledge shown by the contacts. Many were enthusiastic to talk about their system and volunteered additional useful information. Other staff members were more restrained and only dealt with questions asked directly. In numerous cases the contact requested that the questionnaire be faxed to allow additional staff people to assist in answering the questions. Others wished to answer the questionnaire in written form to ensure accuracy. Project staff met these requests with some reservations as voice communication can convey nuances and useful asides which are not readily given in short written answers.

**Sample Telephone Survey**

## TCRP A-8   DATA QUESTIONNAIRE

| RT | System ID: **54** |
|---|---|
| **Washington Metropolitan Area TA** | |
| 600 Fifth Street NW | |
| Washington DC 20001 | |
| Telephone:202-962-1251   Date      June      9th | |
| Fax:  202-962-1133    Time | |
| Contact: | Mr. Larry Levin |
| Position: | Rail Analyst |
| Department: | Rail Services |

| | |
|---|---|
| Directional Route Miles | 156.2 |
| Number of Through Routes | 5 |
| Number of Stations | 67 |
| Total Vehicles | 664 |
| Peak Vehicles | 442 |
| Unlinked Passenger Trips | 188,252,916 |
| Passenger Miles | 966,860,097 |
| Revenue Vehicle Miles | 36,035,610 |
| Revenue Vehicle Hours | 1,498,740 |
| Total Operating Expense | $268,900,000.00 |
| Fare Collection System | Turnstile Mag Tick. |
| Platform loading height | High |
| Wheelchair accessibility | Full |

DATA FROM APTA AND OTHER SOURCES 1991/1992

1. Do you have individual route peak point ridership data by hour ☑ by trains ☑ by short time periods ❏ how many ___ mins?
   Do you have riding counts (ride-checks) ☑ **2-4/month**
   *On systems with 4-car or longer trains.* Do you have individual car counts for peak hours at the peak points on one or two representative days?
   ☑_____

2. Do you issue ridership statistics or a summary? ☑ Can you send us this as a starting point? ☑ *Offer address, fax number.*

3. No of cars in trains? **2-4-6** _____

4. Are there any stations on the system which regularly experience pass-ups? ❏ Which route and station(s) _____
   **sometimes at Union after commuter train arrives**
   _____

5. Do you serve stadiums? ☑ have any event ridership? ❏ notice higher densities? ☑ _____

6. Do you have any station constraints that reduce ridership?
   Full parking lots ❏ _____ Ticketing line ups ❏
   Long walks ❏ _____Congested platforms ❏
   Other congestion ❏ _____ Safety/security issues ❏
   No transfers ❏ _____ Poor access ❏
   Transfer cost ❏ _____ Other reasons ❏
   **Not really, some may apply i.e. walks** _____

7. Do you calculate the maximum capacity of the system in passengers per peak hour direction?
   How? **170 × no. of cars**

8. What is the full peak-hour capacity of your cars? seats **68 / 80** standing total **170** *Use end of form if different car types.*
   Is this determined by a formula? ❏ **by experience** _____
   Is this an agency policy? ❏ _____
   Do you have any folding seats ❏ _____

9. Do you have any published standards or policies you can send us? ☑ **policy headway of 6 mins in peak** _____

10. Do you measure the ratio of ridership to capacity? ❏ _____

11. What type of signaling system is used? _____
    **3 aspect cab signals with ATO** _____

12. What is the closest headway scheduled? **2 mins _____ 00 secs**

13. What is the theoretical closest? _____ **1 mins30 secs**

14. What limits the closest headway? Station Dwells ☑
    Turnbacks ❏ _____ Signaling ☑
    Station Approach ❏ _____ Single track ❏
    Junctions ❏ _____ Other ❏
    **occasional turnback problems** _____

15. Is driving manual ❏ or Automatic Train Operation ☑ If ATO is manual driving allowed or practiced ☑? **once a week/driver** _____

16. *If not tabulated above* Type of fare collection system?
    **Cubic stored value, being upgraded** _____

17. *If not tabulated above* Wheelchair accessible ❏? Type? _____

18. We are trying to relate stations dwells with passenger volume and door width to passenger flow per second. Do you have information on maximum station dwells, number of passengers entering and exiting a train versus stopped time.
    ❏ _____
    **Contact rail superintendent Tom Ferer 962-2760 may have some dwell data** _____

19. *Only for systems at or close to minimum headway.* We are interested in schedule adherence at close headways. Do you have peak hour, peak point information ❏? _____
    **Not to level you seem to want** _____

20. *Only for heavy volume systems if there is no dwell data.* Later this year we may want to time dwells in the peak period at peak-point stations. Would this be possible? How should we set it up?
    **Probably** _____

21. *Only for LRT* Are car doors passenger actuated ❏? _____
    Does this cause any delays ❏ _____
    Do you have any data on such delays ❏ _____

22. *Only if accessible.* How many wheelchairs are carried each day ___, each month _____? Line

by line _____? Is there data on any delays so caused? ❏ **contact Avon Mackel 962-1083 for use data (Task 5)** _____

23. *Only where no APTA data (not CR)* Do you have dimensioned floor plans of major car types in order to determine number of seats, area for standing passengers and door widths? ❏ ____

24. **Further Notes and Comments**
   **Both Rohr (80 seats) and Breda (68 seats) are deemed to have same peak capacity of 170**

**and counts support this compares with manufacturers rated crush capacity of 220-230 respectively 2 min. headway from 2 6 min. services plus inserted extra train(s)** _____
**Possible dwell time survey location** _____
**Follow up wheelchair data in Task 5** _____
**Very helpful & informative** _____
_____

Use other side of form for more comments or information

**Table A 2.1 Light rail systems surveyed**

| System Name | Abbreviation | Directional Route km | Lines | Stations | Unlinked Passenger Trips (1993) |
|---|---|---|---|---|---|
| Bi-State Development Agency (St. Louis) | Bi-State | 61.2 | 1 | 18 | 7,920,000 |
| Calgary Transit | CTS | 57.6 | 2 | 31 | 32,614,900 |
| Denver Regional Transportation District | Denv. RTD | 17.1 | 1 | 14 | |
| Edmonton Transit | ETS | 22.4 | 1 | 10 | 3,458,000 |
| Greater Cleveland Regional Transit Authority | GCRTA | 43.0 | 2 | 29 | 4,113,683 |
| Los Angeles County Metropolitan Transit Authority | LACMTA | 69.5 | 1 | 21 | 11,809,196 |
| Mass Transit Administration of Maryland | MTA | 76.3 | 1 | 23 | 3,457,361 |
| Massachusetts Bay Transportation Authority | MBTA | 89.9 | 5 | 10 | 26,703,669 |
| Metrorrey (Monterrey, Mexico) | Metrorrey | 35.0 | 1 | 17 | 19,200,000 |
| New Jersey Transit Corporation | NJT | 13.4 | 1 | 11 | 2,986,781 |
| Niagara Frontier Transportation Authority (Buffalo) | NFTA | 20.0 | 1 | 14 | 8,209,120 |
| Port Authority of Allegheny County (Pittsburgh) | PAT | 77.9 | 4 | 4 | 8,837,078 |
| Regional Transit Authority - New Orleans | RTA - N.O. | 25.7 | 2 | | 6,440,087 |
| Sacramento Regional Transit District | SRTD | 58.2 | 1 | 29 | 6,571,393 |
| San Diego Trolley Incorporated | SDT | 66.8 | 2 | 36 | 16,504,499 |
| San Francisco Municipal Railway | SF Muni | 80.0 | 5 | 9 | 39,331,872 |
| Santa Clara County Transportation Auth. (San Jose) | SCCTA | 62.8 | 2 | 30 | 6,245,385 |
| Servicio de Transportes Eléctricos del DF (Mexico) | STE | 25.7 | 2 | 18 | |
| Sistema de Transporte Colectiva (Mexico) | STC | 35.4 | 1 | 10 | 48,746,500 |
| Sistema del Tren Eléctrico Urbano (Guadalajara) | SDTEO | 47.9 | 2 | 29 | 64,000,000 |
| Southeastern Pennsylvania Transportation Authority | SEPTA | 111.5 | 7 | 8 | 38,065,812 |
| Toronto Transit Commission | TTC | 219.5 | 10 | 3 | 98,788,000 |
| Tri-Met of Oregon (Portland) | Tri-Met | 48.6 | 1 | 30 | 7,770,651 |

**Table A 2.2 Rail rapid transit systems surveyed**

| System Name | Abbreviation | Directional Route km | Lines | Stations | Unlinked Passenger Trips (1993) |
|---|---|---|---|---|---|
| BC Transit (Vancouver) | BCT | 56.0 | 1 | 20 | 33,799,000 |
| Chicago Transit Authority | CTA | 354.5 | 6 | 143 | 135,369,734 |
| Greater Cleveland Regional Transit Authority | GCRTA | 61.5 | 1 | 18 | 6,563,270 |
| Los Angeles County MTA | LACMTA | 9.7 | 1 | 5 | 3,748,200 |
| Mass Transit Administration of Maryland | MTA | 42.8 | 1 | 12 | 11,114,213 |
| Massachusetts Bay Transportation Authority | MBTA | 122.0 | 3 | 53 | 190,329,524 |
| Metro-Dade Transit Agency (Miami) | MDTA | 67.9 | 1 | 21 | 14,817,894 |
| Metropolitan Atlanta Rapid Transit Authority | MARTA | 130.0 | 2 | 29 | 65,005,000 |
| MTA - New York City Transit | NYCT | 793.1 | 12 | 469 | 1,178,121,493 |
| Port Authority Trans-Hudson Corp. (New York/NJ) | PATH | 46.0 | 4 | 13 | 61,814,595 |
| Port Authority Transit Corporation of Pa. and NJ | PATCO | 50.7 | 1 | 13 | 11,232,302 |
| San Francisco Bay Area Rapid Transit District | BART | 228.5 | 4 | 34 | 78,301,800 |
| Sistema de Transporte Colectiva (Mexico City) | STC | 314.6 | 9 | 135 | 1,387,324,600 |
| Southeastern Pennsylvania Transportation Authority | SEPTA | 122.4 | 2 | 76 | 94,332,492 |
| MTA - Staten Island Railway (New York) | SIR | 46.0 | 1 | 22 | 5,141,005 |
| Soc. de transport de la Comm. urbaine de Montréal | STCUM | 122.3 | 4 | 70 | 196,984,213 |
| Toronto Transit Commission | TTC | 152.4 | 2 | 60 | 311,080,000 |
| Washington Metropolitan Area Transit Authority | WMATA | 260.8 | 6 | 83 | 191,428,020 |

**Table A 2.3 Commuter rail systems surveyed**

| System Name | Abbreviation | Directional Route km | Lines | Stations | Unlinked Passenger Trips (1993) |
|---|---|---|---|---|---|
| Connecticut Department of Transportation | Conn. DOT | 105.6 | 1 | 7 | 274,021 |
| GO Transit (Toronto region) | GO Transit | 426.1 | 7 | 54 | 25,300,000 |
| Mass Transit Administration of Maryland | MARC | 600.8 | 3 | 38 | 4,747,380 |
| Massachusetts Bay Transportation Authority | MBTA | 852.4 | 11 | 101 | 21,595,853 |
| Metropolitan Rail - Chicago | Metra | 1,390.8 | 10 | 224 | 64,074,627 |
| MTA - Long Island Railroad | LIRR | 1,026.9 | 11 | 134 | 92,462,000 |
| MTA - Metro-North Railroad | Metro-North | 861.5 | 8 | 118 | 59,119,405 |
| New Jersey Transit Corporation | NJT | 1,885.1 | 12 | 157 | 45,806,216 |
| North County Transit District (San Diego) | Coaster | 132.3 | 1 | 8 | |
| Northern Indiana Commuter Transportation Dist. | NICTD | 222.7 | 1 | 27 | 2,531,169 |
| San Mateo County Transit District (San Francisco) | CalTrain | 247.1 | 1 | 34 | 5,745,654 |
| Southeastern Pennsylvania Transportation Authority | SEPTA | 712.5 | 7 | 154 | 19,018,730 |
| Southern California Regional Rail Auth. (Metrolink) | SCRRA | 748.6 | 5 | 35 | 939,456 |
| Soc. de transport de la Comm. urbaine de Montréal | STCUM | 180.2 | 2 | 31 | 8,700,000 |
| Tri-County Commuter Rail Authority (Miami) | Tri-Rail | 213.7 | 1 | 15 | 2,697,456 |
| Virginia Railway Express | VRE | 260.3 | 2 | 16 | 1,394,419 |

**Table A 2.4 AGT systems surveyed**

| System Name | Abbreviation | Directional Route km | Lines | Stations | Unlinked Passenger Trips (1993) |
|---|---|---|---|---|---|
| Detroit Transportation Corp. | DTC | 4.6 | 1 | 13 | 2,518,916 |
| Jacksonville Transportation Authority | JTA | 1.9 | 1 | 3 | 301,478 |
| Metro-Dade Transit Agency (Miami) | MDTA | 6.3 | 3 | 21 | 2,343,571 |
| West Virginia University | Morg. PRT | 11.6 | 1 | 5 | 4,800,000 |

# A2.2 RIDERSHIP INFORMATION

## A2.2.1 COLLECTION AND AVAILABILITY OF RIDERSHIP INFORMATION

Ridership data collected from agencies is presented in Appendix Three *Data Tabulations.* Not all information categories requested are included in the appendix and reference may be made to the files on the computer disk for categories not appearing in the tables in the appendix.

Ridership information for systems using the proof of payment fare system (most light rail transit, some commuter rail and one rail rapid transit system) is generally derived from ticket machine revenue. Data from ride checks is used to give a ratio between fare revenue and the number of passengers riding the system. This ratio is then used to calculate ridership on a more regular basis than would be affordable with ride checks alone. A contact at BC Transit, which uses this technique, emphasized its inaccuracy.

In several cases the mailed ridership count material has contained more information than the contact indicated was available. Some contacts have also discussed their data with considerable skepticism regarding its accuracy In discussions with contacts of systems operating at or near minimum headway, the importance of station dwell times in governing headway was apparent.

Only a few systems had data for loading of individual cars in a train. Sufficient information for assessing the second level of diversity—uneven loading between cars in a train—was available for a number of rapid transit systems.

Commuter rail systems generally had the most exhaustive collections of ridership data. This is made possible by the use of conductors to collect fares and count passengers. Some agencies, however, remarked that conductor counts tended to overstate ridership in comparison with the results from dedicated ridechecking staff. Efforts to improve the accuracy of the conductor counts were being made to remedy this situation.

Most commuter rail operators were able to provide line-by-line ridership summaries along with station on/off data for all trains operated. Peak hour and peak 15-min ridership for commuter rail was generally calculated from train-by-train data.

Given the limited number of Automated Guideway Transit systems and their small size, little information could be collected regarding this mode. To supplement the information on AGT gathered during the survey, Chapter One *Rail Transit in North America* includes a table of AGT ridership data compiled from *Trans 21* data.

In summary, for the 52 systems surveyed, the ridership information indicated in Table A 2.5 is available. The commuter rail systems account for the bulk of the systems providing station on/off data.

It should also be noted that, where counts by train are available, hourly ridership and ridership by short time periods can be derived from that information if not presented separately.

**Table A 2.5 Summary of available ridership information (all modes)**

| Information Type | Number | Percent |
| --- | --- | --- |
| Counts by hour | 26 | 43 |
| Counts by train | 36 | 59 |
| Counts by short time periods | 13 | 21 |
| Station on/off data | 11 | 18 |
| Individual car counts | 12 | 20 |
| Ridership summary | 50 | 82 |
| Total number of systems | 61 | |

# A2.3 CAPACITY AND POLICIES

Much car capacity information was compiled from APTA data before the telephone survey commenced. Where possible the information was checked with other sources and agency contacts to confirm its accuracy. This data can be found in Appendix Three *Data Tabulations* to this report. Train lengths were determined from agency contacts.

Some contacts were able to provide floor plans of their cars while others indicated that these would be available if required.

## A2.3.1 LOADING STANDARDS

Acceptable loading standards varied between modes and systems. Light Rail cars are generally designed to seat most passengers in the off-peak. Loading standards for rail rapid transit systems were found to vary considerably between agencies. An example of this contrast can be seen by comparing load factors between San Francisco's BART and New York's PATH. In this example, load factors are the number of passengers on the car divided by the number of seats. BART passengers are reported as accepting load factors up to 1.5 on a regular basis, although 2.5 was reached following the 1988 Loma Prieta earthquake. PATH, on the other hand, uses a load factor of 4.1 as its standard car capacity index.

Commuter rail carriers attempt to provide one seat per passenger and standing is rare although it is generally considered acceptable near the downtown terminals. The sole exception is on the Long Island Rail Road between Jamaica and Penn stations where standing loads are common in the peak hours. Agencies whose cars have 2+3 seating observed that passengers will often stand voluntarily rather than sit three to a bench.

Automated guideway transit offers an extreme alternative to the all-seated policy of most commuter rail agencies. Miami's Metro-Mover supplies only 8 seats for a car with a total capacity of 100 passengers. Such a situation is made acceptable by the short trips typical of circulator systems. While these loading levels are also common on airport AGT systems, leisure systems generally offer a seat per passenger.

## A2.3.2 TRAIN LENGTH

Train length for light rail transit systems is limited by the length of street blocks in sections of street running. This is a problem

not faced by the other modes with the occasional exception where commuter trains could interfere with grade crossings when stopped.

Systems handle the light rail transit block length problem in different ways. In Portland, Tri-Met is limited to running two-car trains by the short blocks in that city's downtown. SRTD in Sacramento runs four-car trains at peak hours resulting in blockage of cross-streets during station stops downtown. This is evidently made possible by a relaxed attitude on the part of the city street department. The San Diego Trolley takes still another approach and splits four-car trains in half before they enter the downtown street-running portion of the line.

## A2.3.3 PASS-UPS

Few systems reported regular pass-up situations on their lines. Conditions caused by unplanned service irregularity are not included in this tabulation. New York City Transit was an exception with pass-ups reported on a regular basis. Further inquiries suggest that three of 11 NYCT trunks in Queens and Manhattan are overloaded. Pass-ups are also routine in Mexico City and occur to a lesser extent on systems in Montreal, Toronto and Vancouver.

Pass-ups were reported on four light rail transit and two commuter rail systems with none on AGT systems. However, the light rail transit and commuter rail pass-ups are atypical for these modes and the study team doubts that they are routine.

For other systems, pass-ups were often voluntary as a result of passengers waiting for less crowded vehicles. This was particularly the case at rail rapid transit stations adjacent to downtown commuter rail terminals. Washington's WMATA reported pass-ups to be a problem when commuter trains arrived at Union Station during peak hours.

In general, pass-ups were limited to stops near the edge of downtown during narrow time periods. This was the case in Edmonton where the recent light rail transit extension south to the University has boosted ridership by 50% and caused trains to become full before leaving the north edge of downtown. This may be a temporary situation.

## A2.3.4 EVENT RIDERSHIP

In response to the panel's request, systems serving sports stadiums were identified and asked whether they had specific ridership figures for special events. Many agencies do keep some track of the patronage gained from such service. Most of this information is in the form of estimates of ridership and travel market share. Little information about high car loading was available although BC Transit reported loads 25% in excess of standard peak-hour maximum car capacity.

## A2.3.5 RIDERSHIP/CAPACITY RATIO

Remarkably few agencies aside from commuter rail operators indicated that they regularly calculated a ridership/capacity ratio. Many calculations of this information were made while on

**Table A 2.6 Summary of additional ridership and service information (all modes)**

| Information Type | Number | Percent |
|---|---|---|
| Regular Pass-ups | 10 | 16 |
| Event Ridership | 17 | 28 |
| Ridership/Capacity Ratio | 21 | 34 |
| Measured Dwell Times | 12 | 20 |
| Schedule Adherence | 22 | 36 |

the telephone. This ratio was more commonly available immediately from those agencies with a policy load factor.

Calculation of maximum system capacity was also often handled in the same way. Unfortunately such calculations frequently produced the current capacity of the system with the existing fleet rather than the ultimate capacity by failing to take into account increased train frequency and other possible service enhancements.

A summary of data collected on the subjects above is presented in Table A 2.6.

Commuter rail is strongly represented in the measurement of ridership/capacity ratios and schedule adherence. Both of these indicators are monitored closely by most commuter rail operators, especially when service or track usage is provided on a contract basis.

# A2.4 HEADWAY LIMITATIONS

As shown in Table A 2.7, headway constraints varied by mode. One difficulty found with the answers to this question is that staff of systems not running at maximum capacity were not familiar with the *ultimate* constraints faced by their system. This concern would be particularly marked for dwell time, turnback and junction effects which would not be as evident with low service frequencies.

## A2.4.1 SIGNALING

A majority of contacts (67%) reported signaling to be a major constraint on their systems. In many cases the signaling system was designed to accommodate a level of service below the maximum that could be provided given right-of-way and vehicle characteristics. Reported actual and theoretical minimum headways are shown in Table A 2.8. This allowed systems with relatively long headways to report signaling as a constraint. This is illustrated by the Edmonton light rail transit line which has already reached its minimum theoretical headway of five minutes despite operating on a largely grade-separated line with full grade crossing protection. The Calgary light rail transit system, which uses the same vehicles and has less right-of-way protection, operates every three minutes on signaled sections with higher frequencies possible on the downtown transit mall.

**Table A 2.7 Headway constraints by mode (excludes those systems for which responses were not obtained)**

| Constraint | Light Rail Transit | | Rail Rapid Transit | | Commuter Rail | | Automated Guideway Transit | | Total | |
|---|---|---|---|---|---|---|---|---|---|---|
| | No. | % | No. | % | No. | % | No. | % | No. | % |
| Signaling | 12 | 63 | 13 | 72 | 11 | 69 | 2 | 50 | 38 | 67 |
| Turnbacks | 3 | 16 | 5 | 28 | 2 | 13 | 0 | 0 | 10 | 18 |
| Junctions | 1 | 5 | 2 | 11 | 2 | 13 | 0 | 0 | 5 | 9 |
| Station Approach | 1 | 5 | 1 | 6 | 2 | 13 | 0 | 0 | 4 | 7 |
| Single Track | 6 | 32 | 1 | 6 | 3 | 19 | 1 | 25 | 11 | 19 |
| Station Dwells | 6 | 32 | 5 | 28 | 3 | 19 | 2 | 50 | 16 | 28 |
| Other Constraints | 3 | 16 | 0 | 0 | 7 | 44 | 0 | 0 | 10 | 18 |
| Number of Systems | 19 | | 18 | | 16 | | 4 | | 57 | |

**Table A 2.8 Minimum headways for systems surveyed**

| Type | System | Minimum Headway (min:secs) Operated | Theoretical |
|---|---|---|---|
| LRT | CTS | 3:00 | 2:00 |
| LRT | Denv. RTD | 5:00 | 2:30 |
| LRT | ETS | 5:00 | 5:00 |
| LRT | GCRTA | 6:00 | 2:00 |
| LRT | LACMTA | 6:00 | 3:00 |
| LRT | MBTA | 0:45 | N/A |
| LRT | MTA | 15:00 | 15:00 |
| LRT | NFTA | 5:00 | 2:00 |
| LRT | NJT | 2:00 | 0:15 |
| LRT | PAT | 3:00 | 3:00 |
| LRT | SCCTA | 10:00 | N/A |
| LRT | SDT | 4:15 | 5:00 |
| LRT | SDTEO | 5:00 | 3:50 |
| LRT | SEPTA | 1:00 | 0:30 |
| LRT | SF Muni | 2:37 | 1:00 |
| LRT | SRTD | 15:00 | 15:00 |
| LRT | STC | 2:00 | 2:00 |
| LRT | Tri-Met | 3:00 | 3:00 |
| LRT | TTC | | N/A |
| RT | BART | 3:00 | 2:30 |
| RT | BCT | 1:35 | 1:30 |
| RT | CTA | 2:45 | N/A |
| RT | GCRTA | 6:00 | 2:00 |
| RT | LACMTA | 6:00 | 3:00 |
| RT | MARTA | 8:00 | 1:30 |
| RT | MBTA | 3:30 | 3:00 |
| RT | MDTA | 6:00 | 3:00 |
| RT | MTA | 6:00 | 1:30 |
| RT | NYCT | 2:00 | 2:00 |
| RT | PATCO | 2:00 | 1:30 |
| RT | PATH | 3:00 | 1:30 |
| RT | SEPTA | 3:00 | 3:00 |

| Type | System | Minimum Headway (min:secs) Operated | Theoretical |
|---|---|---|---|
| RT | SIR | 2:00 | 2:00 |
| RT | STC | 1:55 | 1:55 |
| RT | STCUM | 2:30 | 2:30 |
| RT | TTC | 2:27 | 2:00 |
| RT | WMATA | 3:00 | 1:30 |
| CR | CalTrain | 5:00 | 5:00 |
| CR | Coaster | | N/A |
| CR | Conn. DOT | 20:00 | N/A |
| CR | GO Transit | 10:00 | 10:00 |
| CR | LIRR | 3:00 | 3:00 |
| CR | MARC | 30:00 | N/A |
| CR | MBTA | 8:00 | 8:00 |
| CR | Metra | 3:00 | 3:00 |
| CR | Metro-North | 2:36 | 2:00 |
| CR | NICTD | 12:00 | N/A |
| CR | NJT | 3:30 | 3:30 |
| CR | SCRRA | | 20:00 |
| CR | SEPTA | 5:00 | 5:00 |
| CR | STCUM | 10:00 | 9:00 |
| CR | Tri-Rail | | N/A |
| CR | VRE | 10:00 | N/A |
| AGT | DTC | 3:30 | 2:30 |
| AGT | JTA | | N/A |
| AGT | MDTA | 2:00 | 1:10 |
| AGT | Morg. PRT | 0:15 | 0:15 |

**Notes:** N/A indicates not available and/or applicable. Minimum headways for many commuter rail systems are a result of the contract with the host railroad and are not due to practical headway constraints.

On some rail rapid transit lines and light rail transit trunks headways have reached the minimum possible with the current signaling system. In these cases efforts are being made to upgrade the signaling to allow more frequent service. Even relatively recent and advanced signal systems such as those on BART and the MUNI Metro subway have reached their limits and are being replaced with more capable technology.

The shortest theoretical headways given represented the extreme ends of the spectrum. New Jersey Transit's Newark City Subway, operating PCC cars with wayside automatic block signals, was quoted as having a minimum headway of 15 sec. Such frequencies are made possible by manual operation at relatively low speeds, possibly with red signals taken as advisories, and multiple station berths. Similar conditions permit SEPTA to operate light rail vehicles 30 sec apart.

For fully signaled systems, Metro-Dade's MetroMover AGT has a minimum theoretical headway of one minute and 10 sec. A large number of rail rapid transit systems reported minimum theoretical headways of one minute, 30 sec but such frequencies are only regularly operated on BC Transit's SkyTrain. Here, trains currently operate as close as every minute and 35 sec. This is made possible with the Seltrac moving block signal system. The Morgantown PRT can operate at exceptionally close 15-sec headways thanks to the use of small vehicles and offline stations.

The issue of light rail transit street running is related to signaling in its effects on limiting headways. The only light rail transit operation to cite street running as a headway limitation was Baltimore. Given that the current headway on the line is 15 min, it is unlikely that this is a practical problem. Traffic congestion was reported as a problem for the Toronto streetcar system but this is not a typical contemporary light rail transit operation. Also of relevance is the practice of the San Diego Trolley of splitting long trains when they enter downtown. This increases the number of trains operating on street but apparently has not caused an operational problem on the line segment governed by traffic signals.

Signaling of commuter rail systems is a very complex area given the wide variety of signal types which can be found on some of the systems surveyed. Complicating this are factors such as ownership of track by other than the operating agency and discrepancies between signaling practices between railroads. Even the two large New York commuter rail operations, Metro-North and the Long Island Railroad, reported signaling ranging from centralized traffic control (CTC) to manual block system (MBS) despite controlling almost all of their lines. In many commuter rail operations, headways are limited by the contract with the host railroad and not by the signaling system.

## A2.4.2 TURNBACKS

Turnbacks were cited as a problem on five rail rapid transit systems, three light rail transit systems and two commuter rail services. Turnbacks are a common limitation when line capacity is neared or where a rapid turnaround is required to maintain schedules. The latter is the case on the Los Angeles light rail Blue line where the train operators drop back one train in order to minimize terminal time. The other light rail transit operator

facing turnback difficulties is SEPTA which operates a number of high frequency routes converging on a central terminus. However, as this terminus is a loop, the delays may be more properly attributed to long dwell times resulting from passengers boarding and alighting.

Rail rapid transit agencies with intense service, New York, Boston and Vancouver, indicated turnbacks as a constraint. Staff in Los Angeles claim that the Red Line subway also faces this constraint despite long (6 min) headways.

Commuter rail contacts rarely indicated turnbacks as being a problem. This is understandable since in many cases equipment is only able to make one peak direction trip in each peak period. Agencies identifying this factor as a problem were GO Transit and New Jersey Transit. The latter stated that trains required a minimum 30-min turnaround time at New York's Penn Station before returning to service.

## A2.4.3 JUNCTIONS

Junctions are a minor constraint with only five of 57 systems reporting them as limitations. The relevant rail rapid transit systems are the CTA and SEPTA. Commuter rail operators facing this difficulty are Chicago's Metra and New York's Metro-North. Other busy systems avoid this problem through the use of *flying* junctions which obviate the need for at-grade crossings. A recently installed rail/rail underpass west of Toronto's Union Station provides a relatively simple example of this technique.

## A2.4.4 STATION APPROACH

This limitation was cited even less often than junctions by agency contacts with only three systems indicating difficulty. BC Transit was the only rail rapid transit system to give station approach as a problem. In this case, the station approach difficulty is a result of turnback limitations at the downtown terminus and may perhaps be better seen as a turnback problem. The two New York commuter rail operators, Long Island Railroad and Metro-North, both encounter this constraint at their large, congested Manhattan terminals.

## A2.4.5 SINGLE TRACK

Single Track operation was a difficulty primarily encountered by light rail transit (32%) and commuter rail (19%) operators.

Light rail transit single track operation has been reduced in Portland, Sacramento and San Diego, through double tracking projects. San Diego has eliminated single track from its current network but the Santee extension which is under construction will feature a single track section limiting headways to 15 minutes. The new light rail transit line in Baltimore also features considerable single track operation but this route has been designed to allow double tracking in the future. Older light rail transit lines with single track running include SEPTA's Media and Sharon Hill routes.

Single track is also a problem on some of the newer commuter rail lines where passenger train service has brought substantial

increases in the number of trains operated. This is the case on the Los Angeles Metrolink and San Diego Coaster services, and on the Tri-Rail line in southern Florida. A number of other commuter rail operations also reported *double* track as being a limitation. Such was the case for Maryland's MARC service on portions of Amtrak's busy Northeast Corridor Line.

## A2.4.6 STATION DWELLS

Station dwells were found to be an important limitation on capacity with 28% of agencies indicating them as a headway limitation. Station dwells and related topics are discussed in section.

## A2.4.7 OTHER HEADWAY CONSTRAINTS

While only 18% of all systems gave other headway constraints, 44% of commuter rail operators responded to this category. The principal reason for this is that most commuter rail systems operate on tracks owned by other railroads and so must rely on the track owner to provide pathways for commuter trains. This constraint seemed to be the strongest for the MARC and Virginia Railway Express services in the Washington DC region which have faced great resistance from the owning railroads to the operation of additional trains.

While in most cases commuter trains operate on tracks owned by freight railroads or Amtrak, Philadelphia's SEPTA also owns some track used by the freight companies. This gives SEPTA a better bargaining position for those commuter routes which operate over freight trackage. In other areas, such as Chicago and southern California, the commuter rail agencies are acquiring lightly used track from the freight railways. While this imposes a maintenance burden on the commuter rail agency, it does allow a greater priority to be accorded to the passenger service.

Two light rail transit systems reported other constraints, Toronto for extensive street running and SEPTA for delays due to electronic fare boxes. The latter factor extends dwell times

and is unique to those few light rail operations with on-board fare collection.

# A2.5 STATION LIMITATIONS

Table A 2.9 indicates the constraints that limit capacity at rail transit stations.

## A2.5.1 FULL PARKING LOTS

By far the largest station constraint reported by systems was that of full park and ride lots. 56% of all systems noted a shortage of parking space but the response was even stronger from commuter rail systems with 81% indicating full lots. The importance of parking to ridership can often be linked to the orientation of the system towards suburban or urban customers with the former requiring more parking.

Some commuter rail systems, such as Chicago's Metra, have taken to establishing "cornfield" stations whose main purpose is to allow the construction of park and ride lots outside population centers.

## A2.5.2 TICKETING LINE-UPS

Ticket purchase line-ups were generally not a problem except near month-end when monthly pass purchases are made. Pass purchase queues were especially pronounced for commuter rail systems with a number of agencies offering ticket by mail programs to reduce line-ups at stations. The San Francisco CalTrain peninsula commuter rail service offers an incentive of a 2% discount on passes sold by mail, in comparison to the service charge made by other operators.

**Table A 2.9 Station constraints by mode (excludes those systems for which responses were not obtained)**

| Constraint | Light Rail Transit | | Rail Rapid Transit | | Commuter Rail | | Automated Guideway Transit | | Total | |
|---|---|---|---|---|---|---|---|---|---|---|
| | No. | % | No. | % | No. | % | No. | % | No. | % |
| Full Parking Lots | 10 | 53 | 9 | 50 | 13 | 81 | 0 | 0 | 32 | 56 |
| Ticketing Line-ups | 1 | 5 | 2 | 11 | 4 | 25 | 0 | 0 | 7 | 12 |
| Congested Platforms | 1 | 5 | 2 | 11 | 2 | 13 | 0 | 0 | 5 | 9 |
| Other Congestion | 0 | 0 | 2 | 11 | 0 | 0 | 0 | 0 | 2 | 4 |
| No Transfers | 0 | 0 | 1 | 6 | 2 | 13 | 0 | 0 | 3 | 5 |
| Transfer Cost | 3 | 16 | 2 | 11 | 1 | 6 | 0 | 0 | 6 | 11 |
| Safety and Security | 4 | 21 | 4 | 22 | 5 | 31 | 1 | 25 | 14 | 25 |
| Long Walks | 5 | 26 | 5 | 28 | 4 | 25 | 0 | 0 | 14 | 25 |
| Poor Access | 1 | 5 | 0 | 0 | 3 | 19 | 0 | 0 | 4 | 7 |
| Other Reasons | 1 | 5 | 1 | 6 | 2 | 13 | 0 | 0 | 4 | 7 |
| Number of Systems | 19 | | 18 | | 16 | | 4 | | 57 | |

## A2.5.3 CONGESTED PLATFORMS

Platform congestion was a relatively small problem confined to the two most heavily used rail rapid transit systems (New York and Mexico City) and the two largest commuter rail systems (Long Island and Metra.) The only light rail transit system reporting congested platforms is the STC in Mexico City, however, their light rail transit line is light rail in name only and has most of the characteristics of a rail rapid transit system.

## A2.5.4 OTHER CONGESTION

Only Mexico City and New York experienced trouble with congestion at additional locations. In the case of New York, entry and exit turnstiles create congested conditions for passengers.

## A2.5.5 NO TRANSFERS—TRANSFER COST

Most responses here were due to a lack of fare integration between modes and the practice of levying a surcharge for transfers. Most systems without fare integration indicated that work was being done to remedy the situation. New York's MTA is working to permit bus-subway transfers.

Another factor, particularly for commuter rail and some rail rapid transit lines, is the convenience of the downtown terminals to workplaces since a well located terminal can obviate the need for many transfers. Such is the case with PATCO's route in Center City Philadelphia.

## A2.5.6 SAFETY AND SECURITY

A quarter of the systems surveyed indicated that concerns over safety and security could have an effect on ridership. These concerns were greatest on large, urban systems but were also apparent on smaller light rail transit lines (Sacramento, Edmonton) during the evening.

While most commuter rail trains were viewed as being safe, parking lot security was a major concern at many systems. This problem is also experienced on some rail rapid transit lines with one parking lot on the BART line in Oakland not filling largely as a result of security issues.

## A.5.7 LONG WALKS—POOR ACCESS

A quarter of all systems reported access problems with there being very little differentiation between each mode. Some of the factors which influenced these answers included poor station location, poor station design and large park and ride lots.

## A2.5.8 OTHER STATION CONSTRAINTS

Two systems reported short platforms as being limitations, the GCRTA rail rapid transit line in Cleveland and the Long Island Railroad. In the former case the platforms on the affected line

segment are being lengthened to eliminate the constraint. On the LIRR station length is limited by the presence of adjacent grade crossings.

Another difficulty reported on commuter rail systems, particularly in low density areas, is a lack of feeder buses to and from stations. This is being remedied in some areas by the use of dedicated feeder buses from rail stations to important work sites.

A beneficial station effect has occurred at Trenton, NJ where SEPTA and New Jersey Transit service connect to offer travel between Philadelphia and New York. This has increased the ridership on both systems.

# A2.6 DWELL TIMES

A number of factors affect rail transit dwell times. Two of the most important are platform height and method of fare collection. Wheelchair access is also of importance and this is dealt with in detail in section below. Appendix Three contains tables of these factors for each system surveyed.

As noted in Table A 2.6, only 20% of systems have dwell time data, some of which was noted as being outdated and of questionable value. Passenger flow through doors was not immediately available from any system. Car door widths have also been determined for many systems, these are included in the tabulations of Appendix Three.

Some systems were able to supply policy dwell time information. The San Diego Trolley has a policy minimum dwell of 20 seconds while Boston's MBTA has policy dwells at each of its rail rapid transit stations ranging from 15 to 30 sec. Some systems, such as Calgary's light rail transit and the TTC subway, have an enforced safety delay of a few seconds once the doors have closed before the train can move.

Dwell times on commuter rail lines ranged widely depending on car design and station usage. New Jersey Transit gave a range of 20 sec to 8 min depending on the line and station. The Long Island Railroad also operates a variety of equipment resulting in dwell times being more of a problem for conventional, lowloading, diesel-hauled trains than on electric multiple unit trains designed for rapid, high-level boarding and alighting.

## A2.6.1 FARE COLLECTION

Fare collection effects on dwell times are principally a light rail transit issue although fares are collected on-board by the operator on exceptional rail rapid transit lines, as on Cleveland's Red Line. Fare collection by a conductor, as used in Chicago and on many commuter rail lines, does not affect dwell times.

Fare collection by the light rail transit operator is exclusive to the older light rail transit lines. Even here, fare collection in the Central Business District (CBD) is usually handled by station agents to ensure high passenger flow capacities. SEPTA reported that the addition of electronic fareboxes to its light rail transit fleet has also resulted in extended dwell times outside the CBD.

All new light rail transit lines, some commuter rail operators and one new rail rapid transit line have opted for the proof of payment (PoP) system which eliminates any effect of fare

collection on dwells. This system is also used on the heaviest streetcar line in Toronto to allow all car doors to be used for boarding and alighting and so reduce dwells.

Seven of the rail rapid transit systems surveyed use turnstiles which accept magnetically encoded tickets and passes to speed passenger movements. The use of automated ticket vending machines (TVM's) is also becoming widespread, both in conjunction with proof of payment fare systems and as a way to speed ticket purchase for other fare systems.

## A2.6.2 PLATFORM HEIGHT

Platform elevation has a considerable effect on dwells since lowlevel platforms necessitate the use of steps on the car to reach the passenger areas. Rail rapid transit and AGT systems universally feature high platform loading with its inherent speed advantages. Light rail transit and commuter rail systems featured both high and low level boarding, with some lines allowing both through the use of dedicated doors and/or moveable steps. The latter solution is used on the MUNI Metro network in San Francisco to allow high-capacity operation in the downtown subway and traditional street running on the surface. In the subway one door cannot be used due to the car's end taper.

## A2.6.3 WHEELCHAIR EFFECTS

Wheelchair boarding and alighting can have major effects on dwell times, particularly when some form of boarding aid, such as a lift, is required. The accessibility of the systems in this study is summarized in Table A 2.10. Light rail transit and

**Table A 2.10 Summary of wheelchair accessibility**

| Type | Accessibility | | | Total |
|---|---|---|---|---|
| | None | Partial | Full | |
| Light Rail Transit | 6 | 3 | 10 | 19 |
| Rail Rapid Transit | 3 | 8 | 7 | 18 |
| Commuter Rail | 2 | 9 | 5 | 16 |
| AGT | 0 | 0 | 4 | 4 |
| Total | 11 | 20 | 26 | 57 |

commuter rail systems use a wide variety of wheelchair access methods ranging from level loading to car and platform mounted lifts. The only light rail operation to use car-mounted lifts is the San Diego trolley, all later systems use platform lifts or special mini-high platforms which provide access to the accessible location on each train. The low-floor car, which overcomes much of the accessibility problem, is not yet in use in North America; however, Portland and Boston have ordered cars of this type.

# A2.7 SCHEDULE ADHERENCE

36% of the systems surveyed (see Table A 2.6) indicated that they measure on time performance on a regular basis and it is likely that all of the commuter rail systems measure this variable, whether this was reported or not. Schedule adherence for commuter rail is important in the case of contracted service where this data can be a determinant of the fees paid to the contractor.

# A2.8 COMMENTS AND RESULTS

With the survey complete, an adequate range of data; by peak hour, peak-within-the peak, individual trains and individual cars selected operators) was obtained for use in Task 5.

Although several agencies have and can make riding counts (ride-checks) available, these do not always clearly show dwell times relative to the passengers boarding and alighting, nor do they show levels of crowding in the cars and on the platforms. Such dwell time data and wheelchair boarding and alighting times were the principal areas for the field data collection requirements of Task 5.

The telephone survey achieved its goals with only a few systems not responding satisfactorily. Most agency contacts have proved to be quite helpful and accommodating. Information gathering to supplement the survey continued during the remainder of the project. The valuable contacts made during the survey were invaluable for the field data collection component of the project.