Transit Cooperative Research Program Project A-8: Rail Transit Capacity

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Before the final report is completed in late 1995, the Transit Cooperative Research Program Project A-8, Rail Transit Capacity, is summarized with emphasis on the light rail content. The project investigated and quantified the variables that affect the maximum passenger carrying capacity of rail transit in four categories: rail rapid transit (heavy rail), light rail transit, commuter rail, and automated guideway transit in North America. Light rail work constituted 45 percent of the project. A survey of existing literature; a survey of rail transit operators in Canada, Mexico, and the United States; and field data surveys determined existing capacities and capacity constraints and accumulated extensive data. Quantitative analysis, narration, and calibration to real life resulted in procedures for estimating rail transit capacity under a variety of conditions, including realistic operating margins.

In the past several decades, many developments have directly affected North American rail transit performance, vehicles, operations, and systems technologies. These developments include the extension and modernization of rail rapid transit and commuter rail systems, the introduction of the proof-of-payment fare collection system, the requirements of the Americans with Disabilities Act (ADA), and the construction of new light rail, automated guideway transit (AGT), rail rapid transit, and commuter rail systems. Consequently, data and procedures related to estimating rail transit capacity need updating. Transit Cooperative Research Program (TCRP) Project A-8, Rail Transit Capacity, is intended to do this. Results to date are summarized here.

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

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

- Conducting project planning and operations analysis for new starts and extensions,
- Evaluating transit line performance,
- Establishing and updating service standards,
- Studying environmental impacts,
- Assessing the capacities of new train control technologies,
- Estimating changes in capacity and operations over time, and

- Assessing capacity impacts in land development studies where transit provides a significant access role.

STUDY APPROACH

The study has taken a structured and methodical approach that makes maximum use of previous work and existing data, including Federal Transit Administration (FTA) Section 15 reporting (*1*).

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

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

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

From the analytic framework and data collection, quantitative analysis was carried out and calibrated, with formulas and constants determined to provide a comprehensive method for determining rail transit capacity over a wide range of variants for each of the four rail modes. A practical method of using the data and determining capacity was developed in two categories. The first is a simple method containing basic parameters with constants for major variants that reflect *typical* or *average* conditions. The second category is more complete, adding further variants including capacity adjustments for grade and line voltage.

To assist in using the results of this research, a computer disk has been prepared that contains spreadsheets into which system variables can be inserted. The results are shown both numerically and graphically. The data base, main data tabulations, and a graphic simulation of a New York three-aspect signaling system interlocking are included on the disk. (The disk, in IBM 1.44 format only, is available from Transport Consulting Limited for a nominal duplication, handling, and postage charge of $10. Reference to the explanations and detail in the report is advised. Disk programs are Microsoft Excel 5.0 and Access 2.0. Microsoft Windows and these programs, or the ability to convert from them, are required.)

RAIL TRANSIT IN NORTH AMERICA

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

The four rail modes consist of AGT, commuter rail (CR), light rail transit (LRT), and rail rapid transit (RT). Each mode is described in more detail in this chapter. Table 1 gives a condensed look at key North American statistics for each mode, and Figures 1 and 2 show annual passenger trips and passenger kilometers for the four rail transit modes.

LRT started as a development of the streetcar to allow higher speeds. LRT is characterized by its versatility

TABLE 1 Comparison of Key Modal Statistics

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

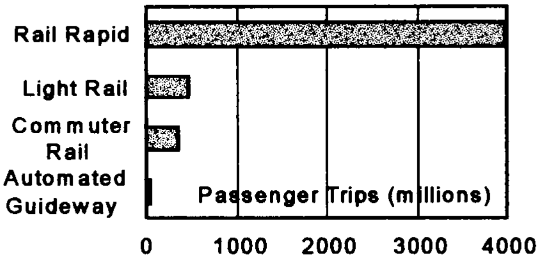


FIGURE 1 Annual passenger trips by rail transit mode.

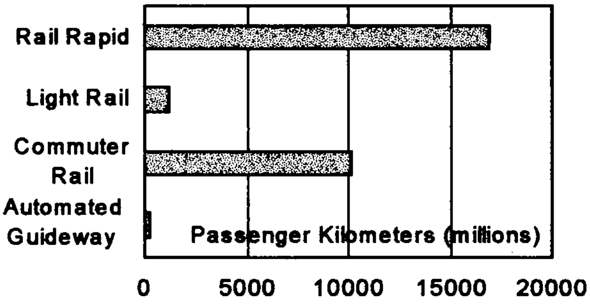


FIGURE 2 Annual passenger kilometers by rail transit mode.

of operation as it can operate separated from other traffic under the surface, at grade, on an elevated structure, or with road vehicles on the surface. Service can be operated with single cars or multiple-car trains. Electricity for traction power is taken from an overhead wire, thus eliminating the restrictions imposed by having a live third rail at ground level. (An exception is the Southeastern Pennsylvania Transit Authority's grade-separated Norristown high-speed line which uses third-rail current collection.) This flexibility helps to keep construction costs low and explains the popularity that this mode has experienced since 1978, when the first of the new North American LRT systems was opened in Edmonton.

These newer systems have adopted a much higher level of segregation from other traffic than earlier systems enjoyed. New Jersey Transit's Newark City Subway, opened in 1935, was ahead of its time in this respect, with a tunnel penetrating the downtown and few grade crossings. Segregation from motor traffic permits higher speeds, greater schedule reliability, and improved safety. Modern signal preemption and progression methods have also made on-street operation faster and more reliable.

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

There are 23 LRT systems in operation in North America (Table 2). This total includes the traditional streetcar lines in Toronto and New Orleans, because they are an integral part of their transit systems. Lines that are operated primarily for heritage and tourist purposes, such as those in Memphis and Seattle, were not included in this study.

The recent popularity of LRT is apparent in that 12 of the surveyed systems have opened since 1980. Older streetcar systems in Boston and Philadelphia survived the widespread replacement of streetcars with buses following the two world wars thanks to city-center tunnels that gave them rapid access to downtown. San Francisco's streetcars benefited from two tunnels that provide strategic routes under major hills in that city. Pittsburgh's streetcars survived for similar reasons. These older systems have been modernized with new cars and, in Pittsburgh and San Francisco, with tunnels penetrating the cities' downtowns.

TABLE 2 North American LRT Systems

Abbreviation	Lines—km	System Name—(City)
Bi-State	1—31	Bi-State Development Agency (St. Louis)
CTS	2—31	Calgary Transit
Denv. RTD	1—8	Denver Regional Transportation District
ETS	1—14	Edmonton Transit
GCRTA	2—21	Greater Cleveland RTA
LACMTA	1—35	Los Angeles County MTA
MBTA	5—51	Massachusetts Bay Transportation Authority
Metrorrey	1—18	Metrorrey (Monterrey, Mexico)
MTA	1—36	Mass Transit Administration of Maryland
NFTA	1—10	Niagara Frontier TA (Buffalo)
NJT	1—8	New Jersey Transit Corporation
PAT	2—34	Port Authority of Allegheny County. (Pittsburgh)
RTA-NO	2—13	Regional Transit Authority - New Orleans
SCCTA	1—34	Santa Clara County Transportation Authority
SDT	2—56	San Diego Trolley Inc.
SDTEO	2—24	Sistema del Tren Electrica Urbana (Guadalajara)
SEPTA	8—95	Southeastern Pennsylvania Transp. Authority
SF Muni	5—62	San Francisco Municipal Railway
SRTD	1—27	Sacramento Regional Transit District
STC	1—17	Sistema de Transporte Colectiva (Mexico City)
STE	2—15	Servicio de Transportes Eléctricos del DF (Mex. C)
Tri-Met	1—24	Tri-County Metro. Transportation Oregon (Portland)
TTC	10—96	Toronto Transit Commission

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

Ridership information collected by LRT systems is not as comprehensive as it is for other modes; many systems reported only the total number of passengers carried on an average weekday. Peak hour and peak 15-min flows were obtained for a number of systems, but these important data were not available for some of the major LRT systems, such as the San Diego Trolley. As a result, average weekday ridership for major routes is shown in Figure 3; available peak flows are shown in Figure 4. Data for the TTC's now atypical streetcar lines are not included. In some cases detailed ridership data may not be available because the system is not running near capacity, but this is not so with others, such as the busy San Francisco Muni Metro.

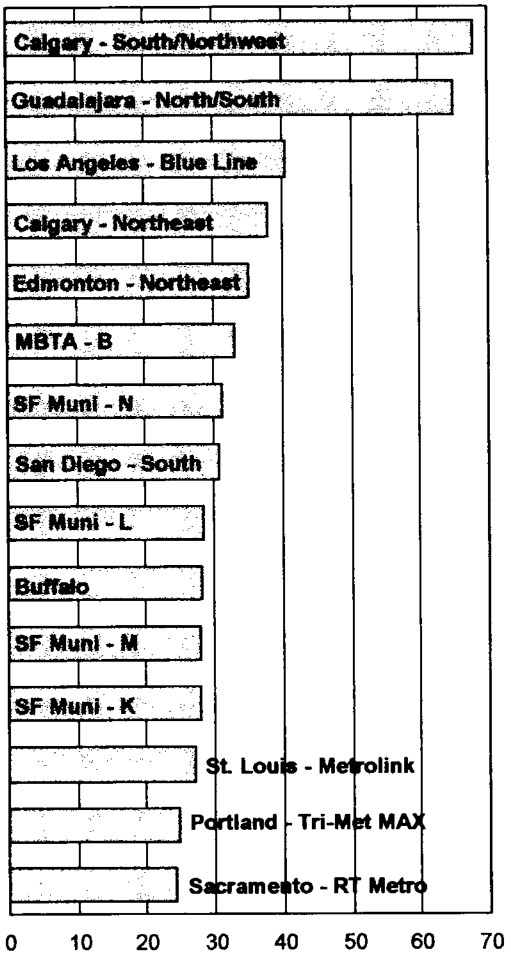


FIGURE 3 Weekday ridership for 15 busiest North American LRT lines.

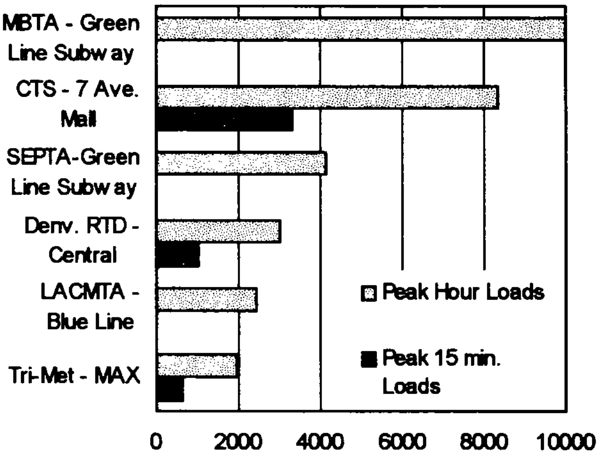


FIGURE 4 LRT peak hour and peak 15-min flows (these data were not available for many LRT systems).

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

GROUPING

After the extensive literature review and data collection, it appears clear, for the purpose of capacity analysis, that the four modes of rail transit in this study should be grouped into specific like categories based on alignment, equipment, train control, and operating practices.

The first category is fully segregated, signaled, double-track right of way, operated by electrically propelled multiple-unit trains. This is the largest category encompassing all rail transit, all noninstitutional AGT, several light rail sections—for example, the Market Street Subway in San Francisco—and several commuter rail lines on the East Coast. The minor exceptions where there are grade crossings on rail rapid transit (CTA) will be discounted. Routes with more than two tracks will be discussed relative to express, local, and skip-stop service; capacity multipliers will be suggested for a range of situations. However, unique capacity calculations for multiple-track routes are not developed. (The Morgantown AGT, the only North American example of AGT with off-line stations, is not classed as a public operation by APTA.) This category is termed "grade-separated rail" and will have subcategories for variations such as low loading, commuter rail, and AGT with short trains.

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

The third category is commuter rail other than services in the first category. This in turn will be broken down according to track ownership and control.

The fourth category is automated guideway transit. Although most AGT is a subset of the main category grade-separated rail with very short trains, the use of off-line stations (on certain systems) is unique to this mode and requires separate examination.

CAPACITY BASICS

Professor Richard Soberman in the *Canadian Transit Handbook* states: "The capacity of transit service is at best an elusive figure because of the large number of qualifications that must be attached to any measure of capacity that is adopted."

Most of the capacity calculations in the literature add constants, multipliers, reductive factors, or other methods to correlate theory with practice. In this paper, emphasis has been placed on reducing the number of qualifications and quantifying, describing, and explaining adjustments between theory and practice in determining rail transit capacity.

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

- *Design/capacity*: The maximum number of passenger spaces past a single point in 1 hr in one direction on a single track.
- *Achievable capacity*: The maximum number of passengers that can be carried in 1 hr in one direction on a single track, allowing for the diversity of demand.

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

Reference to single track is necessary as most trunk routes in New York, the Broad Street Subway in Philadelphia, and the North Side El in Chicago have four tracks, whereas certain other New York lines have sections with a third express track. (All New York three- or four-track trunks crossing the East and Harlem rivers merge into double-track tunnels or bridges.) The capacity of four-track lines is not a multiple of two single tracks and varies widely with operating practices, such as the merging and dividing of local and express services and the holding of trains at stations for local-express transfers. The result is that four tracks rarely increase capacity by more than 50 percent over a double-track line, and often less. A third express track does not necessarily increase capacity at all when restricted to the same station close-in limitations at stations with two platform faces.

Design capacity has two factors—line capacity and train capacity—and can be expressed as

$$\text{Design capacity} = \text{line capacity} \times \text{train capacity}$$

where line capacity is the maximum throughput in trains per hour, and train capacity is the number of passenger spaces.

In turn, achievable capacity can be expressed as

$$\text{Achievable capacity} = \text{design capacity} \times \text{peak-hour diversity factor}$$

The basic capacity expression can be expanded as shown in Figure 5.

$$\text{Line capacity} = 3{,}600 \div (\text{minimum train separation} + \text{controlling station dwell})\ (\text{sec})$$

This expression determines the number of trains per hour (frequency) and is the inverse of the closest or minimum headway. The relevant minimum train separation in seconds is the minimum time to approach and leave a station (i.e., the time from when a train starts to leave a station until the following train can berth at that station). This is referred to as the "close-in" time.

In determining this minimum headway, the train separation is based on "line clear" close-in, with successive green signals governing the following train. Such a headway is called noninterference. The minimum line headway is determined by the critical line condition, usually the close-in at the maximum load point station. In the *Rail Transit Survey*, 9 out of 58 responding systems cited turnbacks as a constraint: two LRT, five rail transit, and two commuter rail operators. In comparison, 34 operators cited train control limitations as a capacity constraint.

From the previous expressions the framework can be expanded to include other variables. The flow chart in Figure 6 outlines the project.

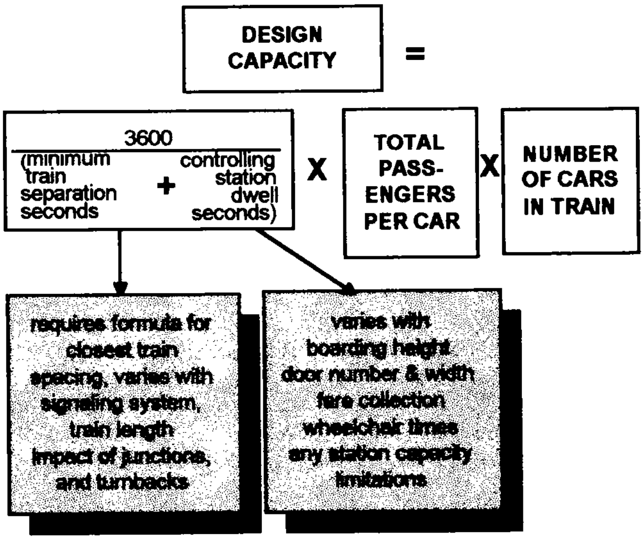


FIGURE 5 Expanded design capacity equation.

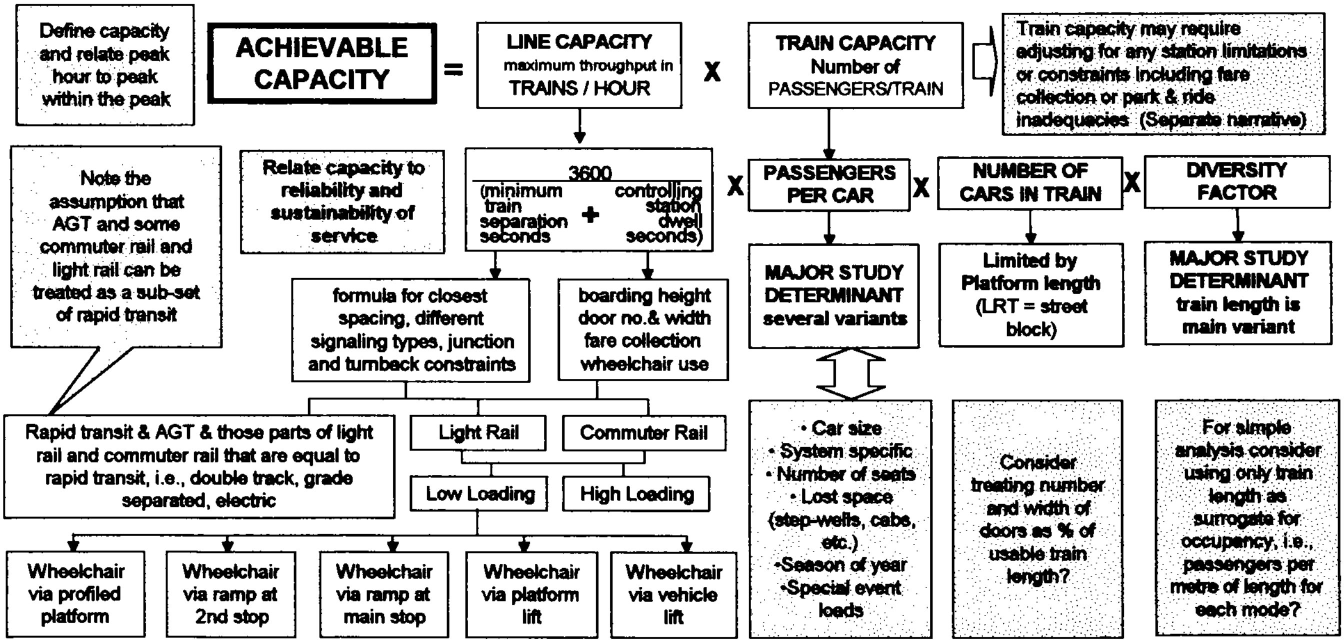


FIGURE 6 Project outline: analytic framework flow chart.

DWELL TIMES AND PASSENGER FLOW

The three constituents of headway are shown in Figure 7 and based on a heavy rail system at capacity operating 180-m-long trains with a three-aspect signaling system. The best achievable headway is 120 sec.

Dwell is the major component of headway at these close frequencies, and the operating margin is often consumed by the many small day-to-day irregularities as shown in Figure 8, where three trains have twice the average separation. This situation can worsen for light rail for which part of the operation is in mixed traffic, as shown in Figure 9 for Muni where five surface streetcar routes enter the Market Street Subway. This operation pushes the signaling system to its limits and is further hindered by the need to couple cars from individual routes into trains for operation through the subway, by constrictive turnback arrangements at Embarcadero, and by recalcitrant operating practices.

This situation is expected to improve when the new turn-back facilities are commissioned in 1998, in conjunction with a switch to a moving-block signaling system. The study found that a moving-block signaling system offers the highest throughput capabilities of all train control systems and can also provide the most sophisticated automatic train supervision.

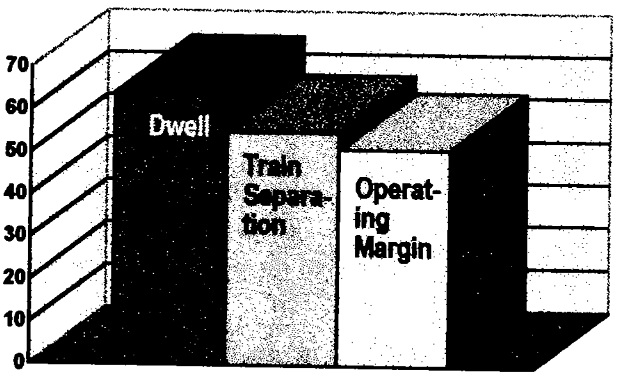


FIGURE 7 Typical headway components, in seconds.

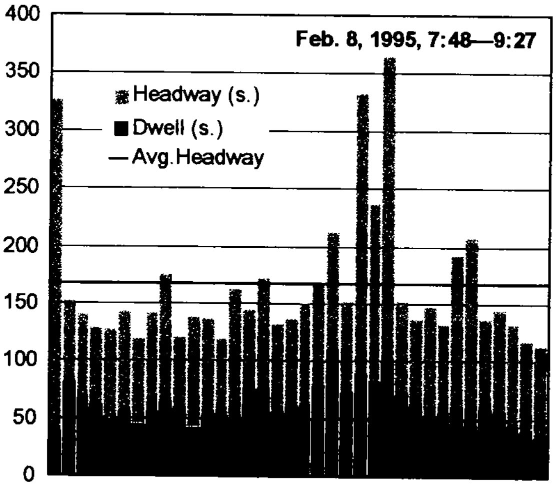


FIGURE 8 Headways, NYCT Grand Central Station.

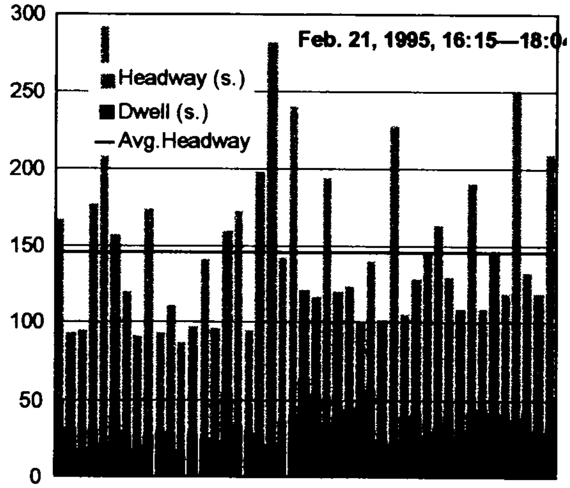


FIGURE 9 Headways with five surface lines interlaced into two multiple-car services (San Francisco Muni Metro).

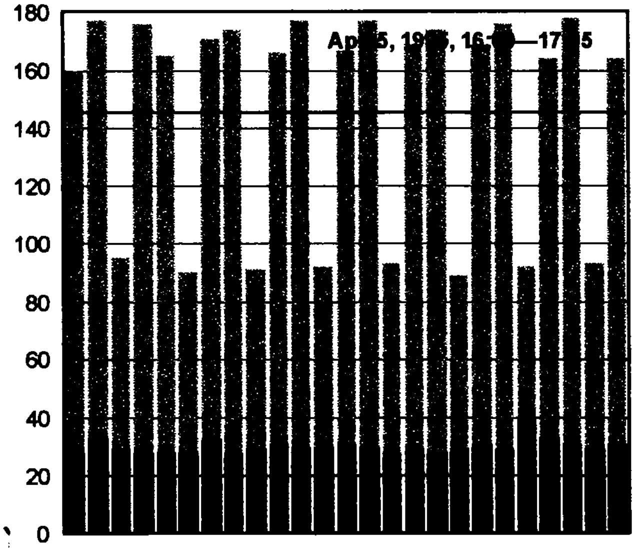


FIGURE 11 Headways with two interlaced services, BC Transit Broadway Station.

Calgary Transit, with the closest on-street headway of all U.S. and Canadian light rail systems, shows, in Figure 10, a similar smooth and regular interlacing of two services to those of BC Transit in Figure 11. This is all the more remarkable given the frequency of grade crossings on the system and the location: on-street along the downtown mall, shared with bus traffic.

The most even headways of a manually driven system in the data collection survey—limited to two to four peak periods on systems operating at or close to their maximum capacity—were those of PATH, shown in Figure 12. An impressive performance was assisted by the multiple-track terminals in Manhattan.

Automatic driving should permit a train to run close to all civil speed limits and not commence braking until the last moment, reducing train separation by 5 to 15 percent, increasing capacity by a like amount, and improving regularity. There were insufficient data to confirm this, although Figure 11 shows BC Transit's regular operation with a short-turn service integrated into regular service at a very consistent 90-sec separation. Figures 13 and 14 show the components of dwell for the

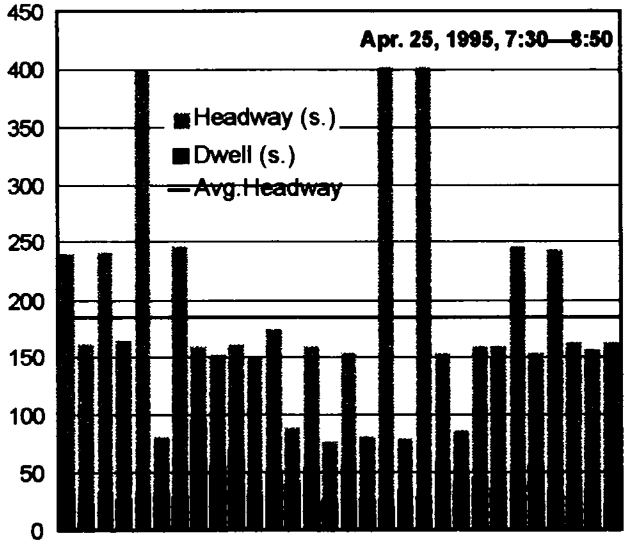


FIGURE 10 Headways, Calgary Light Rail Third Street S.W. eastbound (two services); note that headways are all multiples of 80-sec traffic light cycle.

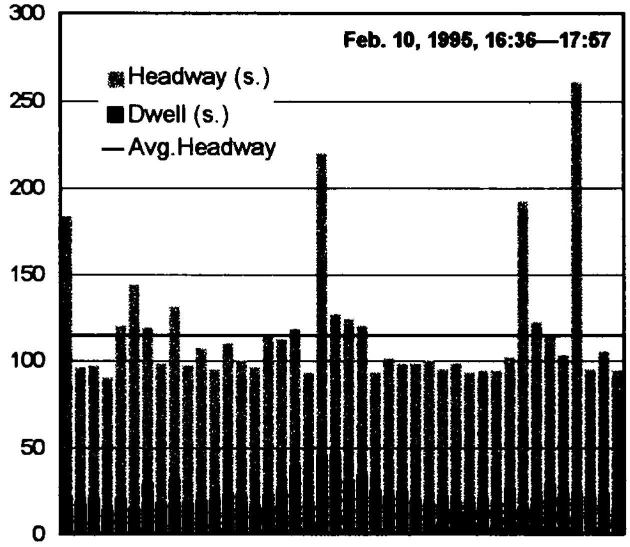
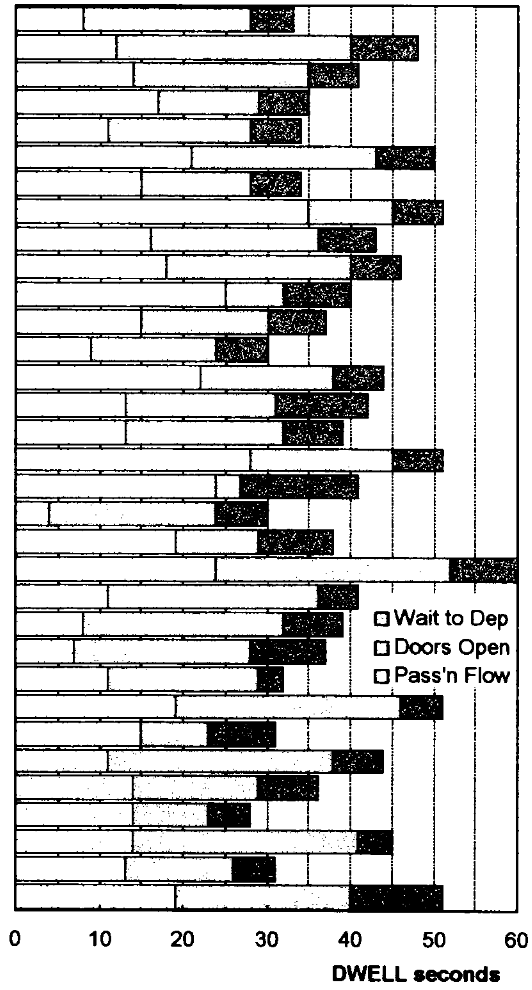
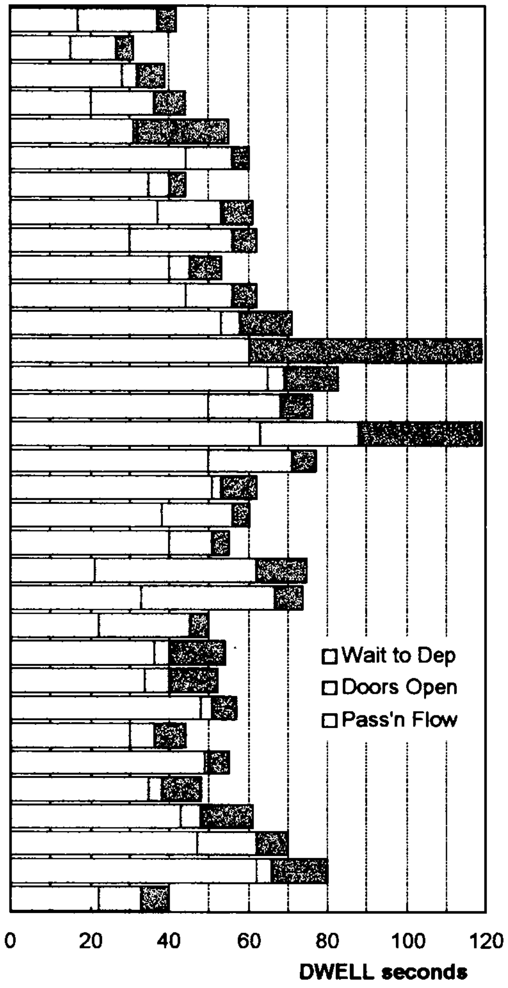


FIGURE 12 Headways, PATH Exchange Place westbound.



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

FIGURE 13 Dwell time components, BART Montgomery Station.



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

FIGURE 14 Dwell time components, NYCT Grand Central Station.

automatically driven BART versus the manually driven NYCT. On BART passenger flow times average 38 percent of the total dwell times; on NYCT passenger flow times average 64 percent of the total dwell time—almost double. Similar results were noted on other automatically driven systems. It appears that any operating gains from automatic driving are more than offset by lethargic station dwell practices.

Several light rail and heavy rail systems were notably slicker at station dwells than their counterparts, contributing to a faster, thus more economic and attractive, operation. Most automatically driven systems have sluggish station dwells in which expensive equipment and staff sit and wait long after all passenger movement has ended. Unfortunately, this torpor is extending to manually driven systems. TTC recently implemented a subway station departure delay for safety reasons. Whether this is well founded is uncertain. It dispenses with the once unsanctioned but common rail transit practice whereby the motorman would partially release the brakes, put the controller to full, and allow the door interlock circuit to initiate the departure from each station. Dwells of 8 sec were normal at quiet stations.

A companion TCRP project, Aids for Car Side Door Observation (A-3), addresses some of these issues but does not examine the overall safety of the door-platform interface or the wide differences in operating efficiency between various light and heavy rail systems. This sacred cow is one of the recommendations for future research from the A-8 project.

Given the importance of station dwells, the project examined the components of dwells shown in Figures

13 and 14. Passenger flow rates were measured under a wide variety of situations. A comprehensive statistical exercise attempted to relate the number of boarding and alighting passengers with the controlling dwell time—the longest dwell time during the peak within the peak (defined as a 15-min period) that establishes the minimum headway—and so the maximum system capacity. The process was only partly successful and is too lengthy for inclusion in this paper. A selection of the data are shown in Figure 15.

The most interesting component of these data is that passengers enter high-floor light rail vehicles faster from street level than they exit. This finding remained consistent through several full peak-period observations on different systems. Hypotheses include brisker movement going home than going to work, incentive to enter a warm dry car from wet slippy sidewalks, and easier balance ascending steps.

The A-3 report examines ways to increase capacity. These include the introduction of moving-block signaling systems and methods to reduce station dwells ranging from the design and location of platform exits to the interior design of rolling stock. JR East's Yamamoto Line in Tokyo is believed to be the world's highest-capacity two-track rail transit line. JR recently introduced high-capacity cars with longitudinal seats that are folded into the walls during the morning peak period, producing an all-standing car that is probably not appropriate for North America. Another Tokyo experiment with four stream doors is shown in Figure 16. Note the multistream line-up marks on the platform at each doorway. In combination with typical Japanese discipline, these reduce conflict between alighting and boarding passengers and help reduce the dwell time.

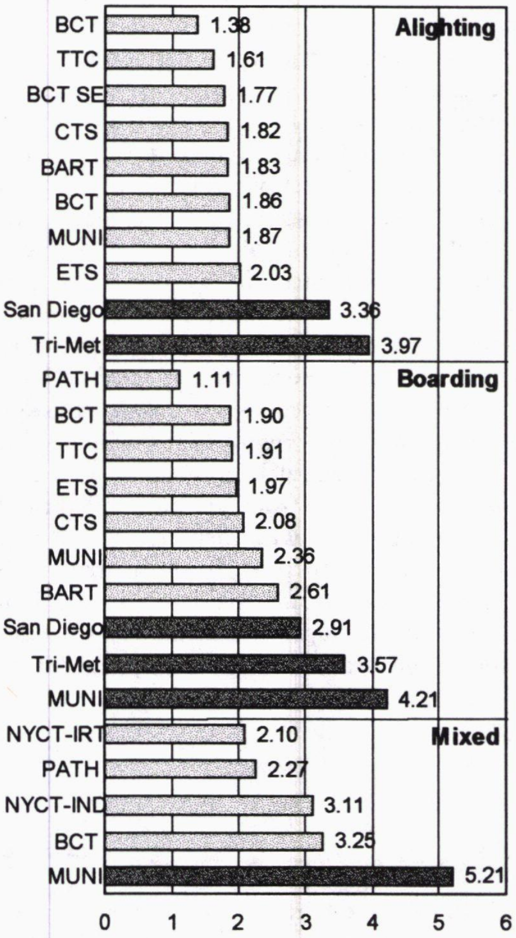


FIGURE 15 Selection of rail transit door flow rates (darker bars indicate low-level boarding with steps).

Americans with Disabilities Act

With dwell being one of the most important components of headway time, the impact of wheelchairs was studied. In addition to the modest number of field observations that could be timed, data were obtained from those few systems that have actual rather than anecdotal movement and delay times. The facts to date, though sparse, do tell a coherent story. Actual measured lift times are much shorter than many claim; they run 2 to 3 min and some are as low as 60 sec. Level wheelchair movements are generally faster than walking passengers except where the car or platform is crowded. One movement at a new San Francisco loading platform on the K Line was measured at 13 sec from doors fully opened to train moving. (This is, however, an arrangement in which the train must stop twice: once for the disabled passengers and again for the regular passengers.) An example of this loading arrangement is shown in Figure 17.

FIGURE 16 Experimental car with four-stream door, Tokyo.

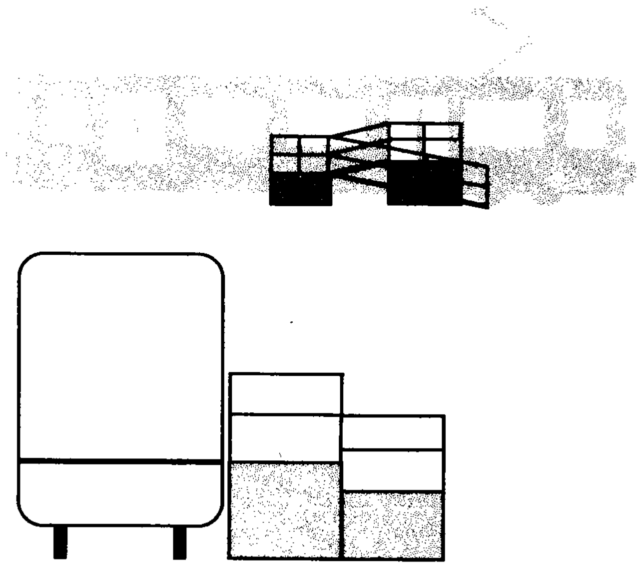


FIGURE 17 Wheelchair loading platform and ramp.

One consideration is the stratification in wheelchair use. ADA requires—and most systems already have—parallel services. The chronically disabled wheelchair user selects the parallel door-to-door paratransit service where an attendant assists with loading. This user is often unwilling or unable to negotiate curb cuts and ramps, or travel a substantial distance alone, to access a station.

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

Tentative conclusions are that with full implementation of ADA, and no more lifts on close-headway rail systems, wheelchairs generally will have little or no impact on capacity, even allowing for the rare incident causing delay, such as the front wheels becoming stuck briefly in the platform-door gap. In the interim, wheelchair lift use may cause delays, but these delays generally are on systems with long headways (6 min and more), so they have minimal impact at these levels.

For maximum capacity, high-platform loading is preferred. Dwells are reduced, and no interior car capacity is lost to the stepwells or to interior steps—a feature of high-floor cars with low-level boarding and some low-floor cars. Low-floor cars will offer much of the speed and easy access of high-platform loading. The first low-floor car to be introduced in the United States will be running in 1997 in Portland (Figure 18).

FIGURE 18 Siemens Duewag partial low-floor car, Tri-Met Portland.

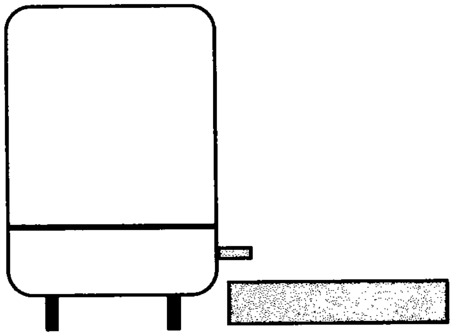


FIGURE 19 Profiled light rail platform showing slide-out or fold-down step that avoids internal steps.

Level high-floor loading may be problematic in many systems. The options range from the interior folding steps used in San Francisco to the outboard folding steps used in San Diego combined with a Manchester-style profiled platform (Figures 19 and 20). Such a platform has an intermediate height and is profiled up to a short stretch that is level with one doorway for wheelchair use. Where the street arrangement permits, the profiled platform can be raised so that its midsection, taking up most of the length, is raised one step to provide a single-step entry to most doors.

Another option to meet the ADA requirements is the separate wheelchair ramps that are used in Baltimore, Sacramento, and San Francisco, among others. In this arrangement, shown in Figure 17, a car-floor-level platform, sized for one wheelchair, is accessed by a ramp at one end, preferably the front end of each light rail stop. These are less popular with members of the physically challenged community and present a greater physical and visual intrusion into the street scene. However, there are many examples, particularly in Sacramento, of carefully integrated and relatively unobtrusive ar-

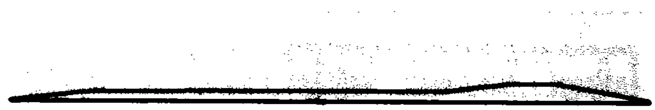


FIGURE 20 Profiled light rail platform that provides two steps into all doors except the front, which is wheelchair-accessible. All slopes maximum of 8.5 degrees to meet ADA requirements; most of platform only slightly higher than sidewalk.

rangements. These minihigh platforms have advantages over car- or platform-mounted lifts in reducing delays. The platforms also save the need for maintenance and repair of mechanical lift equipment.

CAPACITY CALCULATIONS

The other two major components in determining the capacity of a rail transit system, besides passenger flow times and station dwells, are the train separation limitation of the signaling system and the passenger capacity of the vehicles. Each of these topics has an extensive section in the TCRP A-8 report in which methodologies are developed to calculate capacity under a variety of conditions. Only the results can be briefly shown in this paper.

The minimum separation of the train control systems can be expressed by

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

where

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

(t_d and t_{om} may be combined as controlling dwell.) This equation approximates three types of train control systems:

1. Three-aspect signaling system ($B = 2.4$),
2. Multiple-command speed cab controls ($B = 1.2$), and
3. Moving block with variable safety distances ($B = 1.0$).

The passenger loading capacity of a railcar can be expressed as

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

where

V_c = vehicle capacity (peak within the peak);
L_c = vehicle interior length;
L_a = articulation length for light rail;
W_s = stepwell width (certain light rail only);
W_c = vehicle interior width;
S_{sp} = space per standing passenger = 0.2 m^2 (2.15 ft^2) maximum, 0.3 m^2 (3.2 ft^2) reasonable, or 0.4 m^2 (4.3 ft^2) comfortable;
N = seating arrangement = 2 for longitudinal seating, 3 for 2 + 1 transverse seating, 4 for 2 + 2 transverse seating, or 5 for 2 + 3 transverse seating (2 + 3 seating available only on cars 3 m wide or more; not applicable to LRT or AGT);
S_a = area of single seat = 0.4 m^2 (4.3 ft^2) for transverse or 0.35 m^2 (3.8 ft^2) for longitudinal;
D_n = number of doorways;
D_w = doorway width;
S_b = single setback allowance = 0.2 m (0.67 ft) or less;
S_w = seat pitch = 0.69 m (2.25 ft) for transverse or 0.43 m (1.42 ft) for longitudinal; and
[. . .] = expression rounded down to nearest integer (whole number).

This equation can be worked in either meters or feet. An expanded version of Equation 2 is included on the computer disk that will be available with the A-8 report. The spreadsheet calculation automatically applies the seat pitch dimension (S_w) through an "if" statement acting on the seating arrangement factor (N) using the longitudinal dimension if $N = 2$. Light rail specifics are removed automatically if the articulation length is set to 0.

An alternative approach to car capacity is based on passengers per unit length; the light rail results are shown in Figure 21. As would be expected, the wider and longer Baltimore car has proportionately higher loadings per meter of length. The almost generic Sie-

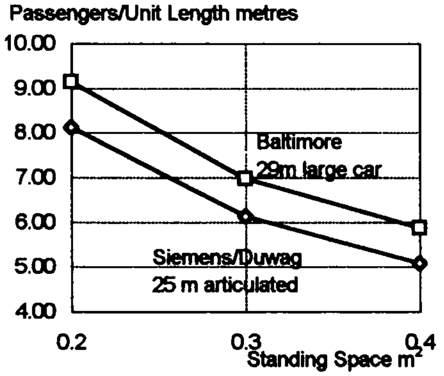


FIGURE 21 Linear passenger loading, articulated light rail vehicle.

mens Duewag car used in nine systems (with some dimensional changes) has a range of 5.0 to 8.0 passengers per meter of car length. The lower level of five passengers per meter length—with a standing space per passenger of 0.4 m^2—corresponds closely to the recommended quality loading of an average of 0.5 m^2 per passenger over the peak hour.

Equation 2 estimates vehicle capacity for the peak within the peak 15-min period. To convert to an hourly capacity, a peak-hour diversity factor must be used, expressed as

$$D_{ph} = \frac{R_{hour}}{4R_{15min}} \tag{3}$$

where

D_{ph} = diversity factor in peak hour,
R_{hour} = ridership in peak hour, and
R_{15min} = ridership in peak 15 min.

Typical values for this factor range from 0.75 to 0.90, with the upper end applicable to high-capacity heavy rail such as the NYCT Manhattan truck lines and the lower end to moderate-density light rail lines.

LIGHT RAIL SPECIFICS

Light rail has a specific chapter in the report in which the factors limiting capacity are explored. System capacity is set by the weakest link in the chain:

- Signaled private right of way,
- On-street with regular traffic signals,
- On-street with partial preemption,
- On-street with full preemption,
- Other grade crossing restrictions,
- Single-track sections, and
- Train length limitations due to block length.

Most of the newer light rail systems surveyed have signalized sections of private right of way, usually with the signaling economically designed to support a minimum headway of 3 to 4 min. In all reported cases it is this signaling system that limits the train throughput, not the on-street operation or grade crossings, with or without differing forms of preemption. Obviously, on those systems with significant lengths of single-track operation, this becomes the constraint. Overall capacity is also limited where train length is restricted by short street blocks. Splitting trains before such sections or permitting occasional longer trains to briefly block a minor street are solutions that have been used in practice.

Space precludes further summary from this study. The final report will contain a glossary, appendixes with detailed summaries of 76 capacity-related reports, and comprehensive data tabulations. Publication of the final report, subject to the review panel and Transportation Research Board approval, is anticipated for early 1996.

REFERENCE

1. Section 15 of the Urban Mass Transportation Act of 1964, as amended. *Uniform System of Accounts and Records and Reporting System.* Federal Transit Administration, U.S. Department of Transportation.

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