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Transport Research Support

PUBLIC TRANSPORT CAPACITY ANALYSIS PROCEDURES FOR DEVELOPING CITIES

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Transport Research Support

The Transport Research Support program is a joint World Bank/ DFID initiative focusing on emerging issues in the transport sector. Its goal is to generate knowledge in high priority areas of the transport sector and to disseminate to practitioners and decision-makers in developing countries.

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Several procedures and tables in this report were adapted from the *Transit Capacity and Quality of Service Manual*, published by the Transportation Research Board, Washington, DC.

1 INTRODUCTION

The introduction of urban rail transit and high performance/quality/capacity bus transit **systems** throughout the world has dramatically improved the mobility of residents of cities in which they operate. Rail systems are known for their ability to transport up to 100,000 passengers per track per hour per direction. In some cases, integrated bus systems like BRT are viewed as an affordable, cost-effective alternative to them. In fact, the capacities of these systems, with a maximum practical capacity of about 25,000-35,000 for two lanes, 10,000-15,000 for one, exceeds the number actually carried on many urban rail transit systems. At present, there are over 50 cities in the developing world which have implemented some type of integrated bus system referred to as "Bus Rapid Transit" or BRT in the US and Canada, or "Bus with a High Level of Service, or BLHS in France. While there is not a universally accepted definition of such a system its primary attributes are that it be a physically and operationally integrated system with frequent service, operation entirely or partially in a dedicated right of way, physical elements and service design appropriate to the market and operating environment, off-board fare collection and other appropriate ITS applications and strong, pervasive system identity. The development of such rail and bus systems has been most notable in cities where high population density and limited automobile availability results in high transit ridership density along major transit corridors.

A considerable impediment to improving the performance of these systems and developing new high-quality systems in developing cities is the limited availability of appropriate transit system planning and design analysis tools. Specifically, there is no central source of public transport planning and operations data and analysis procedures for rail and high capacity bus services specifically tailored for the conditions of the developing world. Fortunately, a large number of current rail and bus systems provide a large base of experience from which to develop relationships between system design factors and performance.

For nearly 60 years, an active community of researchers and practitioners, primarily in the United States, have developed and sustained the *Highway Capacity Manual* (HCM). This document, which is published by the Transportation Research Board (TRB) of the U.S. National Academy of Sciences provides a consistent set of procedures to assess both the throughput capacity of various elements of a highway system and also some measure of the traveler's perception of quality.

A counterpart volume for public transport was developed in 1999 through the support of the TRB. The *Transit Capacity and Quality of Service Manual* (TCQSM) is now in its second printing with an update to be published in 2011. The development model for the manual is comparable to that of the HCM. Each year, volunteer panelists select of a number of studies and contractors are selected to complete specific scopes of work. At approximately 10 year intervals the body of research conducted since the previous update is assembled and a new volume is published. While the document does not represent a standard, it has become the main set of procedures to conduct capacity analyses and quality of service determinations.

The TCQSM contains both procedures and data tables to assist in transit capacity and quality of service analysis. The data tables summarize empirical observations of US and Canadian practice. They provide default values for initial transit system design or operations analysis. For many applications, particularly estimating the capacity of mechanical systems such as escalators, the default US values may be satisfactory. However, there are a number of other transportation system elements where US practice may have limited applicability. There are several reasons for this. Among them are:

- Transit vehicle characteristics such as door numbers, sizes and placement, floor height, acceleration capability, interior configuration and fare collection methods are different.
- Some transit operating conditions such as transit passenger vehicle loads, general traffic volumes and vehicle mixes, including two-wheelers, in developing countries are outside of the range of typical North American practice. Specifically, the high volume of two and three wheeled vehicles in the traffic mix can influence transit capacity.
- Transit passengers, pedestrians and motorists have behavioral differences from North American and other developed countries specifically in their tolerance for crowded conditions. This results in higher design loading standards.

- There are some unique traffic regulatory and engineering practices which are particular to North American practice such as right turn on red traffic signals.
- High pedestrian volumes at intersections, beyond the range of most North American experience, can affect overall vehicle flow and therefore transit vehicle flow.
- Specific measures of the pattern of travel demand over the day (e.g., peaking characteristics) may vary in different countries.
- More widespread use of bus rapid transit (BRT) systems in developing countries and much more heavily used urban rail systems provides a rich data set from which to extrapolate findings to other cities.

1.1 OBJECTIVES

The objectives of this work are:

- To provide a technical resource for transit planners and designers in developing cities in their public transport capacity and performance analysis work irrespective of mode. Specifically, to develop databases and analytical procedures, modeled on those in the TCQSM that will enable practitioners in the developing world to analyze existing systems and services and/or plan new ones This volume includes appropriate data tables and case studies of the application of selected capacity and service quality analysis procedures using data collected and/or appropriate to developing city conditions.
- To provide a basic technical resource for academics and researchers to use in their capacity building and research activities

As such, the document and its procedures will be incorporated into the curricula of the World Bank's urban transport capacity building program and serve as a resource for the capacity building efforts of the Bank's partners.

1.2 AUDIENCES

It is expected that the primary audience for this document are public transport planning and design practitioners, academics and researchers in developing countries. Secondarily, it serves the same functions for academics and researchers and to a certain extent, practitioners in the developed world.

1.3 APPLICATIONS

This document is useful for both planning, design and systems analysis purposes. The tables and procedures from this document can enable a transportation system planner to scale each element of a rail or an enhanced bus transportation system to the design passenger load for the system. In this context, it is assumed that a transportation system of known required passenger capacity is to be planned and/or designed. The exhibits in this manual will enable each component to be appropriately scaled to meet that requirement. This report identifies those elements which limit overall capacity as the traveler enters uses and departs from the transportation system. For example, in a typical bus rapid transit or light rail system, there are a number of "bottlenecks" (running ways/intersections, station platforms, turnstiles (if applicable) vehicles, etc.) which can limit the overall capacity. In essence, the overall system capacity is the minimum of the capacity of each of system element.

Alternatively, the procedures can be used to analyze the performance of existing transit systems and provide techniques to estimate the effects of changes such as vehicle size, stop configuration and service patterns on the capacity of the system and hence the quality of service offered to its customers. This is particularly useful in planning for increased service utilization at some time in the future. The procedures will enable the assessment of a variety of measures to meet a target system capacity.

1.4 Using the Manual

This manual supplements the *Transit Capacity and Quality of Service Manual* with information assembled for cities in developing countries. It is useful in addressing two basic types of capacity analysis – one assessing the performance of an existing transit line or system and the other in planning for a new facility.

Assessing performance of an existing facility includes:

- analyzing travel times and delay,
- analyzing observed bus queues at principal stations (stops) and congested intersections,
- identifying overcrowded vehicles and stations, and
- identifying car-bus-pedestrian conflicts and delays at critical locations

Assessing future conditions includes:

- determining vehicle requirements for anticipated future peak demands
- providing sufficient number of vehicles to avoid overcrowding, and
- designing rights-of-way and junctions (where permitted) and stations to accommodate needed bus, rail and passenger flows.

The techniques for assessing bus rapid transit systems differ from those from a rail system. Therefore, each is discussed separately.

The specific factors of the transit services that influence capacity included in this work, irrespective of mode are:

1. ***Running way capacity*** including the role of safe separation distance, signal/control systems and junctions and turnarounds.
2. ***Platform capacity*** including allowance for circulation, waiting space, number size and location of platform ingress/egress channels
3. ***Facility access elements*** including doorway and corridor widths, turnstiles and other barrier gates
4. ***Fare collection systems*** including staffed fare booths and ticket vending machines
5. ***Level changing systems*** including capacity of elevators, escalators and stairs
6. ***Vehicle design elements*** including consist lengths, interior configuration, doorway number, locations and widths.
7. ***Passenger loading standards*** which include the design occupancy level for vehicles and stations.

The report has a section on facility emergency evacuation analysis in the discussion of platform capacity to assure adequate life safety in the event of fire or other event.

1.5 MANUAL ORGANIZATION

Subsequent chapters of this guide are as follows:

Chapter 2 gives general guidelines pertaining to transit capacity and quality of service. It contains some underlying concepts and principles.

Chapter 3 sets forth bus system capacity guidelines and estimating procedures.

Chapter 4 contains rail rapid transit capacity guidelines

Chapter 5 contains guidance on rail and bus stations

There are a number of appendices which discuss data collection procedures and offer some sample analyses. After the discussion for each analytical procedure, there is a numerical problem which applies the concept to actual practice.

2 TRANSIT CAPACITY, QUALITY, SERVICE AND PHYSICAL DESIGN

A good understanding of the interrelationship among capacity, resource requirements and design in transportation operations is necessary to assess how changes in transit design characteristics influence service quality, the user's perception of value of service. This section sets forth basic transit capacity concepts, identifies the factors that influence capacity and shows how capacity relates to quality of service and costs. It establishes the policy and planning framework for the chapters that follow.

2.1 TRANSIT CAPACITY

Transit capacity deals with the movement of **both** people and vehicles. It is defined as the number of people that can be carried in a given time period under specified operating conditions without unreasonable delay or hazard and with reasonable certainty.[1]

Capacity is a technical concept that is of considerable interest to operators, planners and service designers. There are two useful capacity concepts – stationary capacity and flow capacity. Scheduled transit services are characterized by customer waiting at boarding areas and traveling in discrete vehicles along predetermined paths. The waiting area and the vehicle itself each have a stationary capacity measured in persons per unit of area. Transit services also have a flow capacity which is the number of passengers that can be transported across a point of the transportation system per unit of time. While this is usually thought of as the number of total customers per transit line per direction per hour, flow capacity can be measured for other elements of the system including corridors, fare turnstiles, stairs, elevators and escalators.

2.2 KEY FACTORS INFLUENCING CAPACITY

The capacity of a transit line varies along a route. Limitations may occur along locations between stops (way capacity), at stations and terminals (station capacity) or at critical intersections or junctions where way capacity may be reduced (junction capacity). In most cases, station capacity is the critical

[1] Source: Transit Capacity and Quality of Service Manual.

constraint. In some stations, junctions near stations may further reduce capacity.

The key factors which influence capacity include the following:

- the type of right-of-way (interrupted flows vs. uninterrupted flows),
- the number of movement channels available (lanes, tracks , loading positions, etc.),
- the minimum possible headway or time spacing between successive transportation vehicles,
- impediments to movement along the transit line such as complex street intersections and "flat" rail junctions,
- the maximum number of vehicles per transit unit (buses or rail cars),
- operating practices of the transit agency pertaining to service frequencies and passenger loading standards, and
- long dwell times at busy stops resulting from concentrated passenger boardings and alightings, on-vehicle fare collection and limited door space on vehicles

The equations and guidelines shown in table 2.1 show how these factors can be quantified. Further details are shown in subsequent sections.

TABLE 2-1: SUMMARY OF TRANSIT VEHICLE AND PASSENGER CAPACITY ESTIMATE

$$\frac{\text{People per channel}}{\text{Per berth per hour}} = \frac{3600}{\text{headway}} \times \frac{\text{green}}{\text{cycle}} \times \frac{\text{passengers}}{\text{vehicle}} \times \frac{\text{vehicles}}{\text{unit}} \qquad \text{(Eq. 2.1)}$$

$$\text{Minimum headway (h)} = \frac{\text{green}}{\text{cycle}} \times \left(\text{dwell time} + \underbrace{\text{dwell time variance} + \text{clearance time}}_{\textit{operating margin}}\right) \qquad \text{(Eq.2.2)}$$

Source: H. Levinson

Passengers per unit depends on vehicle size and internal configuration, passengers per unit and agency policy on the number of people per vehicle. This policy can be approximately represented as total passengers per seat times the number of seats. Alternatively, a better approximation would be the passengers per meter of vehicle length times train length. An even better approximation would be to add the number of seats to the vehicle floor area available for standees divided by an occupancy standard of passengers per unit of area, the latter varying by type of service, e.g., commuter rail versus downtown people mover, commuter bus versus CBD circulator.

Service frequency is normally governed by the peak demands at the maximum load section. Then it is necessary to assess if and how this demand can be accommodated at the critical constraint that governs capacity along a transit line. The critical capacity limitations normally occur at the points of major passenger boarding, alighting and interchange, outlying terminals, key junctions and (for surface transit), congested intersections.

Some guidance on service design to increase capacity are enumerated below:

- A simple route structure usually results in higher capacities and better service reliability. There is less passenger confusion at stations, impacting dwell times for both bus and rail systems and less bus-on-bus congestion. Accordingly, especially for rail rapid transit, branching should be avoided (or at least kept to a simple branching of two lines)
- Stop and station dwell times should be kept to a minimum by providing off-vehicle fare collection and level entry of buses and rail cars.
- Dispersal patterns of station boardings and alightings generally permit higher capacities than situations where passenger movements are concentrated at a few locations.
- "Crush" passenger loads should be avoided wherever possible since they may increase station dwell times, reduce service reliability and, in the end, reduce passenger throughput.
- Various analytical methods provided bases form estimating vehicle and passenger capacity. However, these results should be cross-checked with actual operating experience.
- Peak ridership estimate: transit capacity analysis should be based on a peak 15 minute flow rate. This normally occurs during the morning and evening rush hours. However, sometimes there are noon hour and weekend peaks.
- Use peak 15 minute passenger flow rather than peak hour flow rates since ridership demand is not uniform over an entire peak period. Fifteen minute flow rates can be obtained by direct measurement. Commonly a peak hour factor is often used. This factor represents the ratio of the hourly observed passenger volume to the peak 15 minute period time 4. It is a measure of the dispersion of riders about the peak period.
- The appropriate design volume for transit systems should be the peak 15 minutes since designing for the average over the peak hour will result in operationally unstable service during peak intervals within the peak period which have a disproportionate share of travel.
- In some large urban areas, there is little variation in ridership over the peak period. This suggests that the ridership is constrained by capacity. Where possible, increased capacity should be provided.

2.2.1 THEORETICAL VS. PRACTICAL OPERATING CAPACITY

One of the most important capacity considerations is to distinguish between maximum theoretical or crush capacity and practical operating capacity, also called schedule design capacity). A transit vehicle may have an absolute "maximum" capacity usually referred to as the crush load. This commonly the capacity cited by vehicle manufacturers. The absolute capacity assumes that all space within the vehicle is loaded uniformly at a specified passenger density and that occupancy is uniform across all vehicles throughout the peak period, a condition that rarely happens in practice. Similarly a rail line or a bus system operating in an exclusive right of way may have a theoretical minimum headway (time between two successive vehicles) based on station dwell times, vehicle propulsion characteristics and safety margins. From these characteristics, the theoretical maximum capacity measured as vehicles per hour per direction can be determined. However, random variations in dwell times, caused by such things as diminished boarding and alighting flow rates on crowded trains, reduces the maximum or theoretical line capacity.

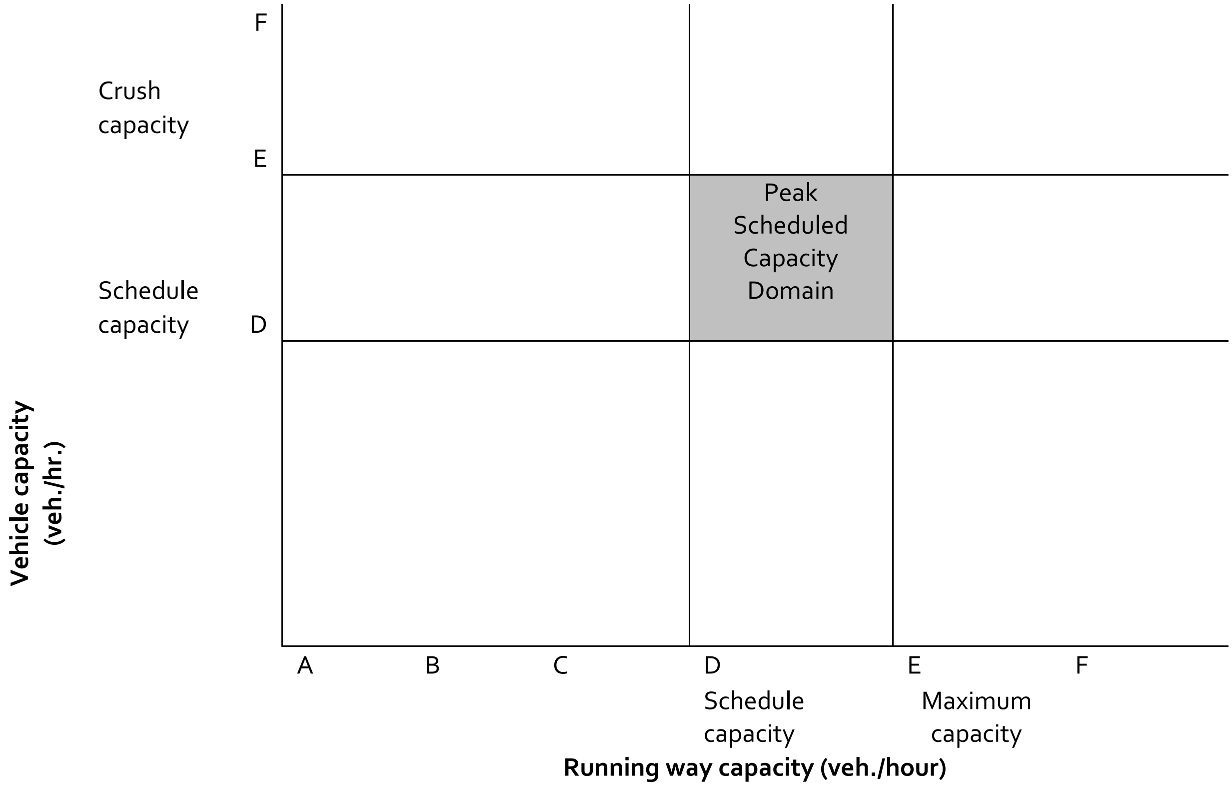
Operation at maximum capacity strains the system and should be avoided. They result in serious overcrowding and poor reliability. Therefore, **scheduled design** capacities should be used. This capacity metric takes into consideration spatial and temporal variation and still results in some but not all transit vehicles operating at crush capacity.

Further, the arriving patterns of passengers and vehicles at transit stops during peak periods may result in some vehicles having lower than capacity loads particularly if there is irregularity in the gap between successive arriving vehicles. Finally, there can be a "diversity of loading" for parts of individual vehicles (e.g., in partial low-floor LRT vehicles or buses with internal steps) and among vehicles in multi-vehicle consists such as heavy rail trains.

Error! Reference source not found. below illustrates the relationship between schedule and crush capacity of passengers on vehicles and scheduled track or running way capacity. The person capacity is the product of the two, which is represented by the areas of a rectangle between the origin and a specific vehicle and track capacity. In both cases, the practical operating capacity is less than the maximum capacity. The shaded area represents the likely range of rush hour conditions.

This report recommends methods of achieving practical transit capacity during normally encountered operating conditions. Where capacity is influenced by a measure of dispersion of some characteristic such as stop dwell time or vehicle headway, this is also noted. For example, line capacity is usually influenced by both the mean and distribution of dwell times at the critical stop along the line. At higher levels of dispersion of dwell times around the mean, capacity diminishes in a predictable way.

TABLE 2-2 MAXIMUM AND SCHEDULE CAPACITY



The user is cautioned against designing a transit service in which the capacity is just sufficient enough to meet expected peak passenger volumes. Transit operations are characterized by various random events, many of which are not in the direct control of operators particularly in bus operations. Operating at or near capacity leaves the operator little margin to respond to such events without substantial service disruption.

The purpose of measuring capacity is not just to provide a measure of system capability to transport passengers but also to provide some insight into the effect of service and physical design on customer service quality. When the demand for a service exceeds its schedule design capacity, service quality deteriorates either due to overcrowding on vehicles or at station platforms or diminished ability of customers to board the next arriving transport vehicle since it is already fully loaded, increased dwell times and hence decrease revenue speeds. A more useful measure of service performance than capacity from the customer perspective is the comfort level on vehicles which is usually a function of the ratio of customers to vehicle capacity or available space per passenger.

2.3 QUALITY OF SERVICE

In contrast with capacity, which is largely a technical and quantitative concept, quality of service on the other hand is a more qualitative concept. It represents the value to the passenger of the service provided. Quality can be measured by customer response to a number of service characteristics. In only a few cases, however, do actions taken by transit operators (e.g., smoother acceleration/deceleration, more gradual turning on rail systems and smoother bus maneuvering) translate directly into a measurable change in some service characteristic valued by customers. For example, increasing the skill of drivers through better training does not readily convert to an improved perception of quality. On the other hand, larger vehicle sizes and shorter waiting times at bus or rail stops due to more frequent service directly result in measureable changes in service attributes valued by passengers.

Two service attributes of value to customers can be influenced by the design decisions of transportation operators. These are comfort (related to operating and physical factors) and operating speed. Comfort is a function of the relationship between demand (over which an operator usually has little control) to capacity (over which an operator has considerable control). Service speed is more than just the maximum vehicle speed. It represents the total travel time of the passenger trip including waiting time at the boarding stop, passenger service times at downstream stops, time lost at intersections or decelerating and accelerating and getting into and out of stations, and time actually in motion. The service planning and design elements of a transit system (vehicles, stations, service frequency, operating practices etc.) will influence both speed and comfort. This document shows through analysis of empirical data, the relationship between service inputs and customer quality.

Service quality measurement can be portrayed as a letter level in the range of A through F, with A representing a high quality and F a low quality. For the attribute of passenger comfort, level of service A represents a very non-congested condition and F, a level associated with very limited movement within vehicles and platforms. Each of the letters represents a specific range of densities measured in person per square meter. Owing to cultural differences throughout the world, there are varying levels of tolerance or acceptability for standee and seating densities. As a result, the class intervals of the densities associated with each of the letter attributes will vary among cities throughout the world. For passenger speed, a measure of distance per time (i.e., kilometers per hour) is most appropriate.

Another service attribute valued by passengers is reliability, the variation in travel times (or speed) between trips or between days. This is a more complex attribute than comfort and speed. Poor reliability is the result of randomness in certain transit system operating processes. In high frequency services, where passengers arrive randomly at stops, the customer waiting time when arrivals between vehicles are uniform is one-half of the headway. However, when this uniform interval is disrupted by factors such as intersection delay, or variability in time spent at bus stops, the average waiting time is increased. The time variability at stops and in the case of buses – at intersections, also results in variations in the travel times of customers already on the vehicle. While some factors that introduce randomness are beyond the control of transit operators, variation in time can be minimized through better service design, scheduling practices and street operations management. Traffic signal priority, exclusive bus lane enforcement, more efficient fare collection, better station design and headway based scheduling are examples of such measures.

Poor reliability has consequences for both customers and operators. A service with poor day-to-day requires riders to add buffer time to their planned departure time to account for the probability of late arrivals of buses and trains and variation in travel speeds. As such, a more reliable service, all other things being equal has value to customers. Reliability also has an effect on in-vehicle passenger comfort. Variation in the headway of scheduled vehicles results in irregular loading patterns of vehicles and diminishes effective capacity. On high frequency bus services, particularly where scheduled headway is nearly the same as the traffic signal cycle length at critical intersections, there is a tendency for buses to bunch and travel in platoons. Grade separated transit generally has better reliability than transit vehicles subject to street traffic interference.

While this does not diminish the theoretical capacity, it does reduce the practical or effective capacity. This is because with headway intervals longer than the scheduled headway, the number of customers arriving at a stop between successive buses will exceed the design arrival rate for some of the buses, resulting in overcrowding,

Conversely, vehicles arriving at intervals shorter than the design headway will be underloaded. This load imbalancing deteriorates customer service quality and operators add vehicles to compensate for this. Further, reliability has another impact on operating costs. "Schedule recovery" time must be build into vehicle and crew schedules so that delays do not accumulate over the course of a peak period or day.

These result in the need for more vehicles to provide the same service frequency and capacity. improvements in reliability also result in reductions in "schedule recovery time" and hence on the number of vehicles/drivers and mechanics required to carry a given number of people. For the purposes of this report, procedures to improve reliability such as reduction of dwell time variability, will be introduced not only so that reliability itself can be improved but also as a means of improving comfort levels and reducing operating costs.

The importance of service quality in transit capacity analysis cannot be overstated. Transit operators should be mindful that the urban transportation marketplace is mode competitive. While it might be technically possible to design a service using a loading standard of 7 or 8 passengers per square meter, a number of customers will find that level intolerable and will seek alternate means of travel including walking (in the case of short distance trips), riding with someone else, riding taxis or purchasing a motorcycle or car. Accordingly, such loading standards should be thought of as interim measures until higher capacity at lower crowding can be achieved.

2.4 RELATIONSHIP BETWEEN CAPACITY, QUALITY AND COST

Transit production cost is rarely discussed in the context of transit capacity since conventional thinking holds that capacity and cost are related in a linear fashion. That is, doubling capacity requires doubling production cost. The interrelationship is actually far more complex. A key determinant of practical or effective capacity is variability in such things as interarrival times of scheduled vehicles and dwell times at stops. While some of these are random variation over which the transit operator has little control, some strategies such as traffic signal priority and all-door loading of buses through off-board fare collection can reduce variability and thereby positively increase capacity.

Actions to reduce variability also reduce passenger wait time, improve travel speeds and reduce transit operating costs. The following are specific examples:

- Dwell time variability results in headway variation, reduced effective capacity due to vehicle bunching and increased customer wait time. The reduced effective capacity (discussed in section 3.5 for buses) results in adding more vehicles to produce the required capacity.
- Dwell time and intersection time variability result in variability in travel times between transit terminals. To assure timely departure of the next trip to which the bus or train is assigned, additional time in the schedule must be added. In order to maintain a specific headway, more vehicles must be assigned to the service.

3 BUS SYSTEM CAPACITY

3.1 INTRODUCTION

Bus rapid transit (BRT) systems are increasing in importance and use in cities throughout the developing world. They can be implemented quicker than rail rapid transit and may cost substantially less even in total life cycle cost terms. They can also serve as a precursor to future rail systems.

This chapter provides guidelines for estimating the capacity of BRT lines. It overviews existing operational experience, describes the design and operating factors that influence capacity, sets forth procedures for estimating bus vehicles and passenger capacities and presents additional analyses related to bus operations, service quality and capacity.

BRT, in contrast with rail rapid transit operates in a variety of environments. It may run on segregated, fully grade separated running ways, e.g., in reserved freeway lanes railroad rights of way, or in arterial street median busways or single or dual curbside bus lanes. Sometimes, buses may have to operate in mixed traffic environment. From a capacity perspective, operation through traffic signal controlled environments is common.

3.2 OPERATING EXPERIENCE

There is a growing body of information on the number of buses and people carried by BRT lines. Examples of the peak-hour, peak direction passengers carried by high-capacity bus systems in the developing world are shown in **Error! Reference source not found.**.

3.3 BUS SERVICE DESIGN ELEMENTS AND FACTORS

The specific factors that influence capacity are as follows. This report treats each of the elements of bus transit service independently and provides empirical data on the effect of the design elements on service capacity and quality They are:

1. ***Running way type and configuration*** including degree of segregation, service location (curb lanes vs. median lanes), the number of lanes (e.g., passing lanes at stations) and in the case of curb lanes, access to the second lane for passing buses, intersection spacing, and traffic

engineering features like signal programs (e.g., cycle length and number of phases). The availability of space for terminal operations also influences capacity.

2. ***Intersection characteristics*** including traffic signal cycle lengths and phases, signal priority vehicle turning movements, near side vs. far side vs. mid block stops.

TABLE 3-1: HOURLY PASSENGER VOLUMES OF HIGH CAPACITY BUS TRANSIT SYSTEMS IN THE DEVELOPING WORLD

Region	City	Peak Volume (pphpd)*
Asia	Ahmedabad	3,000
	Beijing	4,100
	Guanzhou	25,000
	Hangzhou	6,600
	Jakarta	4,000
	Jinan	3,600
	Seoul	6,700
Latin America	Belo Horizonte	16,000
	Bogota	45,000
	Curitiba	14,000
	Mexico City	9,000
	Porto Alegre	26,100
	Sao Paulo	20,000
	Quito	8,000
Africa	Lagos	10,000

*pphpd – passengers per hour per direction

1. ***Fare collection*** system elements including location of fare payment, (on-board vs. off-board) complexity of fare structure and fare media employed (cash, cards etc.)

2. ***Bus design*** factors including vehicle length, seating configuration, floor height, door numbers and width, location and size characteristics

3. ***Bus boarding area*** factors such as bus stop length and width, number of berths, approach to assignment of multiple routes to boarding berths, availability of passing lanes and platform height in relation to floor height.

4. ***Service design factors*** including service frequency, route structure, operation of multiple routes or branches on a corridor and serving stations, vehicle platooning and station spacing

5. ***Policy factors*** such as enforcement of parking restrictions at stops and along the running way, encouragement of multi-door boarding and alighting and passenger loading standards.

These elements are discussed separately and the effect of changes on service quality and capacity is augmented with empirical tables. Essentially, the capacity of a route in passengers per period per direction is a product of the running way capacity (vehicles per hour per direction) and the vehicle capacity (passengers per vehicle). **Error! Reference source not found.** illustrates how the design decisions affect the components of system capacity.

TABLE 3-2: TRANSIT DESIGN ELEMENTS AND THEIR EFFECT ON CAPACITY

		Running Way Capacity			
		Time at Stops	**Time at Intersections**	**Time Moving**	**Vehicle Capacity**
Vehicle Characteristics					
	Vehicle size (length)				X
	Seating configuration/Aisle width	X			X
	Floor height, number of internal steps	X			X
	Door location and size	X			
	Acceleration./Deceleration rates				
Stop Characteristics					
	Platform height	X			
	Number of loading berths	X			
	Platform size	X			
	Berth assignment to routes	X			
	Number of entry/exit channels	X			
Fare Collection Characteristics					
	On board/off board	X			
	Fare media	X			
	Fare structure complexity	X			
Running Way Characteristics					
	Speed limit			X	
	Stop spacing	X			

	Passing capability	X			
	Pedestrian behavior			X	
Other policies					
	Lane enforcement			X	
	Loading standard				X
	Traffic law enforcement				
Intersection characteristics					
	Traffic signal cycle times and splits		X		
	Phases		X		
	Turn restrictions		X		
	Pedestrian flows and behavior		X		

3.4 OVERVIEW OF PROCEDURES

Error! Reference source not found. and **Error! Reference source not found.** illustrate procedures for assessing the capacity of existing and proposed BRT lines respectively. These tables also show ways of increasing vehicle capacity.

TABLE 3-3: CAPACITY ASSESSMENT OF EXISTING BRT LINE

Data Collection – Critical Stop

1. For each major stop determine the mean dwell time and dwell time standard headway standard deviation.
2. Identify the critical stop. This is the one with the maximum of the mean dwell time plus two standard deviations.
3. Determine the peak period passenger boarding and alighting rate and magnitude at the critical stop.
4. Determine the probability (failure rate) of a bus entering the critical station without a stopping place available to board passengers.

Data Collection – Critical Intersection

1. Determine pedestrian crossing volume per peak period that conflicts with right turning vehicles in the bus lane. (curb lane only)
2. Determine right turning vehicle movements from bus lane (curb lane only) during the same period
3. Identify the green time for turns and traffic signal cycle time.
4. Identify if there are major bus-auto or bus-pedestrian conflicts

Data Analysis

1. Determine the capacity at the critical bus stop. (Section x.x)
2. Determine capacity at critical intersection. (Section x.x)

Estimate Future Volumes

1. Estimate future passengers
2. Establish bus frequency
3. Determine conflicting right hand turns

Capacity Expansion Estimate

1. Determine if capacity expansion is necessary over the planning horizon
2. Determine required capacity expansion by year

Assess Capacity Expansion Alternatives for Stops

1. Change service frequency and stopping patterns; add stops, assign different routes to different stops
2. Change vehicle capacity; dispatch bus "platoons", also known as convoys
3. Change stop configurations (berths and access)
4. Improve reliability (reduce headway variance)
5. Reduce dwell time (e.g. through fare collection practice changes)
6. Reduce dwell time variance

Assess Capacity Alternatives for Intersections (curbside bus lane)

1. Increase green time for buses and right hand turns
2. Introduce pedestrian crossing phase
3. Prohibit right and/or left turns
4. Segregate right turns from bus lane
5. Change cycle length

Assess Capacity Alternative for Running Ways

1. Introduce traffic signal priority
2. Reduce clearance time by making second land available for buses

TABLE 3-4: CAPACITY ASSESSMENT OF A PROPOSED BRT LINE

Develop a Proposed Running Way

1. Degree of separation between buses and cars
2. Develop passing opportunities at stops
3. Determine traffic signal controls at stops and major intersections
4. Determine spacing and location of passenger boarding stops

Initiate a Proposed Service Design

1. Develop service frequency
2. Identify trip patterns
3. Propose vehicle size and type
4. Propose fare collection system (on board, off board)
5. Develop a passenger loading standard

Data Collection – Critical Stop

1. Estimate expected passenger loading per time period at each stop.
2. Estimate on-board load after bus leaves each stop.
3. Estimate expected dwell time and dwell time variance at each stop
4. Identify the critical stop for planning purposes.
5. From the initial estimate of bus frequency, determine the probability. (failure rate) of a bus entering the critical station without a place available to board Passengers

Data Collection – Critical Intersection

1. Determine pedestrian crossing volume per peak period which conflicts with right turning vehicles in the proposed bus lane. (curb lane only)
2. Determine right turning vehicle movements from bus lane (curb lane only)
3. Identify the green time for right hand turns and cycle time.

Data Analysis

1. Determine the capacity at the critical bus stop. (Section x.x)
2. Determine capacity at critical intersection. (Section x.x)

Estimate Future Volumes

1. Passengers
2. Bus frequency
3. Conflicting right hand turns

Assess Adequacy of initial Plan

1. Determine if passenger flow at critical stop can be maintained
2. Determine if vehicle flow through critical intersection can be maintained.

Assess Capacity Expansion Alternatives for Stops

1. Change service frequency
2. Change vehicle capacity
3. Change stop configurations (berths and access)
4. Improve anticipated reliability (reduce headway variance)
5. Reduce anticipated dwell time

6. Reduce anticipated dwell time variance

Assess Capacity Alternatives for Intersections (curbside bus lane)

1. Increase green time for buses and right hand turns
2. Introduce pedestrian crossing phase
3. Prohibit right turns
4. Segregate right turns from bus lane

Assess Capacity Alternative for Running Ways

1. Introduce traffic signal priority
2. Reduce clearance time by making second land available for buses

Both sets of procedures underscore the need to reduce the number of and dwell time at stops.

3.5 OPERATION AT BUS STOPS

Computing the capacity of a bus route operating in an exclusive right of way is conceptually straightforward. It is essentially the product of the number of vehicles which can be processed through a critical point on the route and the number of passenger spaces of each vehicle during the peak period of passenger demand.

Where the buses operate under uninterrupted (ideal) flow conditions, as along grade separated busways or on freeways, the capacity per station or stop is essentially 3,600 seconds divided by the time spent per stop multiplied by the number of effective loading positions (berths). When buses stop at signalized intersections, less time is available for bus movement. In both cases, the stop processing time includes the waiting time to reach a vacant berth, the dwell time needed to board and discharge passengers, the clearance time between successive vehicles and time to re-enter the traffic stream as needed. In some cases, conflicts between right turning traffic and pedestrians may limit the capacity of the curb lanes.

The delay in waiting for a vacant berth is a function of dwell time distribution, number of berths at the stop and whether or not buses have the ability to overtake other buses at stops to access vacant loading berths. Boarding/discharging dwell time is a function of vehicle, passenger demand and fare collection methods. Clearance time depends on the availability of the adjacent lane (exclusively for buses or not) and the traffic volume and dispersion of traffic gaps on the adjacent lane.

The distribution of dwell times at the critical stop[2] in a transit system can limit the number of vehicles per hour that can pass through the station. Accordingly, measures that reduce the dwell time or dwell time variation can

[2] The critical stop is the one in which the mean plus two standard deviations of the dwell time is maximum.

improve system capacity and the quality of service to customers. The individual factors that govern bus operations at stops are described below followed by a discussion of incorporating these factors together to estimate stop capacity.

An operating margin must be introduced in estimating station capacity. This is a buffer time to allow for random variation in dwell time. An operating margin allows for dwell time variability without disrupting scheduled operating.

Another design attribute must be accounted for in berth or stop calculations is the "failure rate." This is defined as the percentage of the time that a bus or train will approach a stop and not find a berth available. This is a particularly important concept for on-street bus and tram operations with stops on the far side of intersections. If the failure rate is too high, transit vehicles will tend to "spill back" through the respective intersection, causing undue congestion for vehicle flows in the perpendicular direction. This has been an issue for a number of busway applications in China (Kunming, Shijiazhuang).

3.5.1 BERTH (STOP) CAPACITY UNDER SIMPLE CONDITIONS

3.5.1.1 LOADING BERTH DYNAMICS AND CAPACITY

For this discussion, it is assumed that there is a single route serving the bus stop so that passengers can select any arriving bus to travel to their destination and further there is a single boarding location at the bus stop. Given the variation in arrival rates of buses and the dwell (service) times of buses, there is a possibility that an arriving bus will not be able to immediately access the stop. If the arrival and service time distributions are know with any precision, the probability of delay due to bus berths being occupied, referred to as the failure rate, can be computed. Transit planners can reduce this rate by reducing the mean or variability of the service time, increasing the headway or reducing the headway variance. Alternatively, the number of bus berths can be increased.

The operating margin (t_m) is defined as:

$t_m = s\,Z = c_v\,t_d\,Z$ (Eq. 3.3)

Where,

t_m = operating margin (sec)

s = standard deviation of dwell times

Z = the standard normal variable corresponding to a specific failure rate (one-tailed test)

c_v = coefficient of variation (standard deviation/mean) of dwell time; and

t_d = average dwell time (sec).

The table below shows the z-statistic value associated with certain failure rates.

TABLE 3-5: Z-STATISTIC ASSOCIATED WITH STOP FAILURE RATES

Acceptable Failure Rate	Z -statistic
1%	2.326
5%	1.645
10%	1.282

There is a tradeoff between the failure rate and the berth capacity. A high operating margin is required to assure that the failure rate is tolerable. One method is to specify a failure rate and through actual observation of mean and standard deviation of dwell time, estimate the capacity of the stop. At reasonable failure rates, this value represents the practical sustainable capacity. The maximum theoretical capacity will occur at a failure rate which may be unacceptably high.

3.5.1.2 BERTH CAPACITY WITH UNINTERRUPTED FLOW

The capacity of a bus berth in vehicles per hour can be estimated by the following equation:

$$B = 3600/(t_d + t_m + t_c) \qquad \text{(Eq. 3.1)}$$

Where,

B = berth capacity in buses per hour

t_d = mean stop dwell time

t_m = operating margin

t_c = clearance time, (the time for stopped buses to clear the station, minimum separation between buses, and time to re-enter the traffic stream

3.5.1.3 CAPACITY FOR STOPS NEAR SIGNALIZED INTERSECTIONS

The maximum flow capacity at a bus stop near a signalized intersection in vehicles per hour is:

$$B_l = 3600(g/C)/(t_d(g/C) + t_m + t_c) \qquad \text{(Eq. 3.2)}$$

Where,

B_l = buses per berth per hour

g = green time at stop

C = cycle time at stop

t_d = mean stop dwell time

t_c = clearance time, the time to re-enter the traffic streams defined above

t_m = operating margin

The capacity of a bus stop in buses per hour is shown in **Error! Reference source not found.** below. This table shows values for average dwell times from between 10 and 80 seconds and a range of coefficient of variation between .3 and .6. In all cases, a maximum allowable failure rate of 5% was assumed. These estimates should be adjusted downward for flow interrupted by traffic control devices by the ratio g/C

TABLE 3-6: BUS BERTH CAPACITY (UNINTERRUPTED FLOW) FOR A STATION WITH A SINGLE BERTH

	Dwell Time Coefficient of Variation	
Dwell Time Mean (sec.)	0.3	0.6
10	144	120
20	90	72
30	65	51
40	51	40
50	42	32
60	36	27
70	31	24
80	27	21
90	24	19

Table entries are in buses per berth hour

Source: Transit Capacity and Quality of Service Manual

Actual US experience shows considerable scatter in observed coefficients of variation. TCRP Report 26[3] indicates that the coefficients decreases as the overall dwell time increases. Coefficients between 40% and 60% were representative of dwell times of 20 seconds or more but tend to underestimate variability when mean dwell times are lower.

An issue arises when the critical bus stop requires more than one loading berth to meet the capacity requirement. If buses are able to pass each other, then the capacity of the stop, measured in vehicles per hour, will increase almost linearly with the number of berths. However, if the bus stop does not permit

[3] St. Jacques, K.R. and Levinson, H. S. TCRP Report 26, Operational Analysis of Bus Lanes on Arterials, TRB, national Research Council, Washington, DC 1997.

buses to pass each other, then the efficiency of successive berths beyond the first will be diminished. That is, doubling the number of berths will not double the effective capacity. Simulation studies, augmented by empirical data found the following relationships (**Error! Reference source not found.**) between the number of berths and the capacity of the multi-berth stop.

Some cities, especially in South America, provide bypass lanes around stations on median arterial busways. The service pattern should be analyzed. The capacities should be computed for the busiest stop for each group of buses. For example, if stop A can accommodate 80 buses per hour and stop B can accommodate 100 buses per hour, the system capacity would be the sum assuming that different buses serve each stop.

TABLE 3-7: ACTUAL EFFECTIVENESS OF BUS BERTHS

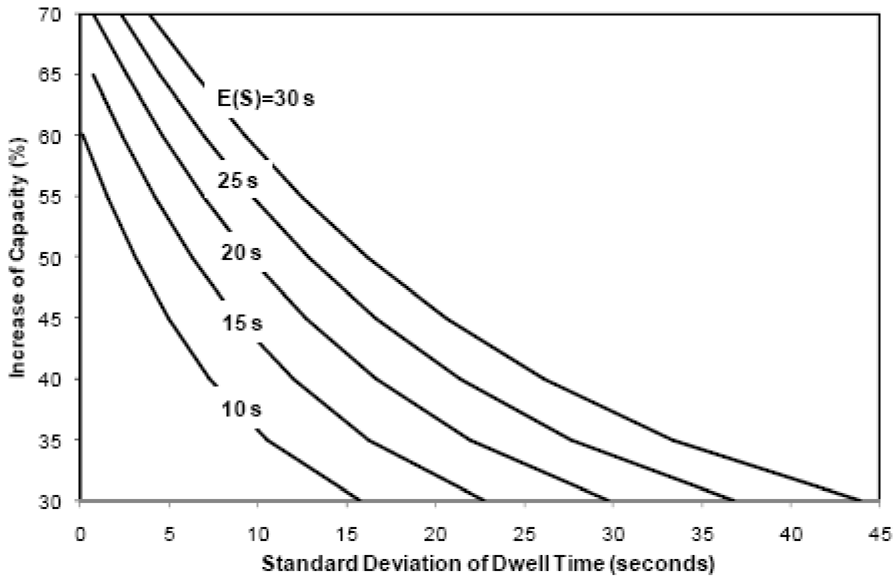
	On-Line Station		Off-Line Station	
Number of Berths	Effectiveness of Berth	Total Effectiveness* of all Berths	Effectiveness of Berth	Total Effectiveness* of all Berths
1	1.0	1.00	1.00	1.00
2	.75	1.75	.85	1.85
3	.70	2.45	.80	2.65
4	.20	2.65	.65	3.25
5	.10	2.75	.50	3.75

*Ratio of the capacity of the number of berths to a single berth.

(Source: Research Results Digest 38, Operational Analysis of Bus lanes on Arterials, Transportation Research Board.

Using observed data from Barcelona, Spain, Estrada et al., (2011) determined that the incremental capacity of a second loading berth was a function of the standard deviation of dwell time and developed the chart below to assess this value.

FIGURE 3-1INCREMENTAL CAPACITY OF A SECOND BUS BERTH:



Source: Estrada et al., (2011)

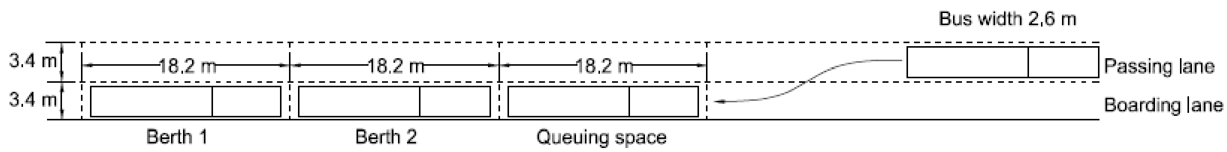
Example: A transit route at the critical stop has a mean dwell time of 30 seconds with a coefficient of variation of 0.3. Compute the capacity of the system in vehicles per hour if 3 bus bays are provided. Note that there are no passing lanes at the bus stop.
Capacity of single stop berth = 87
Effectiveness of first three berths (on-line) = 2.45
Capacity of 3 bus berths (on line) = 87 * 2.45 =213 buses per hour

3.6 BUS BERTH CAPACITY IN MORE COMPLEX SERVICE CONFIGURATIONS

The US transit capacity manual has procedures for determining the increase in capacity with successive berths at a bus stop. The operating system for this analysis assumes that each arriving bus accesses the first vacant berth and that buses can board and discharge customers at any berth. In cases where the stop serves multiple routes, passengers must observe the location of arriving buses in order to board the proper vehicle.

In several circumstances outside of the US, the service operating system is quite different. Transmilenio in Bogota is a case in point. The Transmilenio running way consists of two lanes in each direction and buses are able to pass each other in most circumstances. Most of the stops are served by several routes. The routes are partitioned into route groups and the group is assigned to a single berth. A plan view of a typical station is shown in **Error! Reference source not found.** below. Note that some stations have two or three such modules.

FIGURE 3-2: PLAN VIEW OF TRANSMILENIO BUS STATION



In the figure berth 2 has a queuing space behind it in the boarding lane. Boarding and discharging is not done in the queuing space. The queuing space can be accessed from the bypass lane. The set of routes assigned to berth 1 is distinct from the routes assigned to berth 2.

In order to present a set of tools to analyze this and other situations, a set of simulation models was developed to determine the capacity of the following four configurations:

Single loading berth – no queuing space

Single loading berth – queuing space for one bus

Dual loading berth – no queuing space

Dual loading berth – queuing space for one bus

Capacity was defined for several acceptable failure rates including (5%, 10% and 25%) with the failure rate being defined as the probability that an arriving bus will not be able to enter either a vacant berth or a queuing space. Other variables in each of these assessments included mean service time with values of 20, 20, 40, 50, 60 and 75 seconds[4]. The final two input variables were service time variability and arrival rate variability. To simplify the assessment, these two variables were staged as either high or low. Definitions are shown in the table below.

TABLE 3-8: SERVICE VARIABILITY LEVELS

Input	Level	Definition
Service time variability	Low	CV* = 0.4 times mean service time
	High	CV = 0.8 time mean service time
Headway variability	Low	CV = 0.4 times mean headway
	High	CV = 0.8 time mean headway

* Coefficient of variation = standard deviation/mean

[4] The term service time is used in these calculations. Service time includes the dwell time (time the bus is stopped) as well as the safe separation time between successive vehicles – about 12 seconds.

This analysis resulted in the development of 8 tables – two for each of the four service domains described above and the presence or absence of a traffic signal at the station. These are shown in tables 3-22 through 3-29. A summary table appears in **Error! Reference source not found.** These tables require relatively little data collection effort to estimate station capacity. On high volume BRT services, mean service times can be obtained with about an hour's worth of observations. A similar length of time would enable a determination of low or high values of service time and headway variability. These data are for articulated (18m) buses. Non-articulated (13 m) buses are likely to increase capacity slightly since the time for the bus to clear the station is about 5 seconds less. Conversely, a bi-articulated bus takes 7-8 seconds to clear the station.

The determination of an acceptable failure rate is more complex. In cases where some buses bypass certain stops, the inability of buses serving the stop to access either the berth or the queuing area may result in blocking through buses. In such cases a low failure rate of about 10% is suggested. In high volume cases, a high failure rate may result in a queue which may not dissipate for a long time, perhaps as much as several minutes. The photograph (**Error! Reference source not found.**) below shows a long queue at a TM stop. Fortunately, this dissipated within 2 minutes.

TABLE 3-9: TRANSMILENIO STATION (BOGOTA) WITH LONG QUEUE

TABLE 3-10: BUS BERTH CAPACITY (UNINTERRUPTED FLOW) FOR A STATION WITH A SINGLE BERTH

				Mean Service Time (sec.)				
Case	**Berths**	**Queue Space**	**Traffic Signal***	**30**	**40**	**50**	**60**	**75**
1	1	Yes	Yes	60	45	35	25	25
2	1	Yes	No	60	50	40	25	25
3	1	No	Yes	35	30	25	20	15
4	1	No	No	45	40	30	20	15
5	2	Yes	Yes	80	55	40	40	35
6	2	Yes	No	80	65	50	45	35
7	2	No	Yes	60	50	40	30	25
8	2	No	No	80	65	50	35	30

Table entries are capacities in vehicles per hour with a failure rate of 10% with moderate service time variation and moderate headway variation. In this table, dwell time includes time to enter the stop, and time to depart the stop. This is about 15 seconds.

* If yes, green to cycle time ratio is 0.5

3.7 STOP DWELL TIMES AND PASSENGER BOARDING TIMES

The procedures described above require using the mean and distribution of stop dwell times as inputs to determine bus berth capacity. The common method of estimating stop dwell time is through observation of the passenger flow at the critical door multiplied by the boarding or alighting time per passenger. The boarding and alighting rates per passenger are a function of variables such as method of fare payment, bus floor height relative to platform height and level of crowding already on the bus. These can be determined through actual observation.

Error! Reference source not found. below illustrates a range of reported observations of transaction time per passenger for bus systems. These entries assume a single boarding and alighting stream per doorway.

TABLE 3-11: PASSENGER SERVICE TIMES (SEC./PASS.)

Situation	**Observed Range**	**Suggested Default**
Boarding		
Pre-payment*	**2.2-2.8**	**2.5**
Single ticket or token	**3.4-3.6**	**3.5**
Exact change	**3.6-4.3**	**4.0**
Swipe or dip card	**4.2**	**4.2**
Smart card	**3.0-3.7**	**3.5**

Alighting		
Front door	**2.6-3.7**	**3.3**
Rear door	**1.4-2.7**	**2.1**

** includes no fare, bus pass, free transfer, pay on exit and off-board payment rear door boarding.*
Add 0.5 sec./pass to boarding times when standees are present.
Subtract 0.5 sec./pass from boarding times and 1.0 sec./pass. from front-door alighting times on low floor buses.
Source: Transit Capacity and Quality of Service Manual

The stop dwell time is also influenced by customer discipline and operating practices. With on-board driver-controlled fare collection, boarding customers enter through the front door and ideally exit through the rear door. In practice, however, several passengers exit through the front door. This delays boarding passengers and sometimes extends dwell times. The critical door capacity calculation must take this into account.

Off board or conductor-controlled fare collection allows for multiple door boarding and alighting and can reduce stop dwell times.

The common method for estimating dwell time requires as an input the expected value and distribution of number of boarding passengers at each stop. This is captured in the following equation:

$$t_d = P_a t_a + P_b t_b + t_{oc} \qquad \text{(Eq. 3.4)}$$

where:

t_d = average dwell time;

P_a = alighting passengers per bus through the busiest door (p);

t_a = alighting passenger service time (pass./sec.);

P_b = boarding passengers per bus through the busiest door (p);

t_b = boarding passenger service time (pass./sec.); and

t_{oc} = door opening and closing time.

Example: At a busy bus stop with off-board fare collection, the design number of boardings is 12 and the design number of alightings is 14. There are two single stream doors, and customers use each equally for boardings and alighting. Assume door opening and closing time is 2 seconds. Compute the expected dwell time for this stop.

$t_d = P_a t_a + P_b t_b + t_{oc}$

$= (6 * 3.3) + (7 * 3.3) + 2 = 45$ seconds

Fernandez et al (2007) proposed a formulation for dwell times using data from TranSantiago. Two models were calibrated – one for BRT trunk buses and the other for feeder buses. On the BRT buses passenger fares were collected through contactless smart cards through the front door. The feeder fares were collected through conventional fare technology.

For the BRT routes, the model was of the form:

$t_d = 9.32 + \max_{j=door}((2.05 + .88d_1)B_j + (3.32 – 1.93d_2)A_j$

where,

t_d	=	dwell time
d_1	=	dummy variable = 1 if boardings > 40, 0 otherwise
B_j	=	boardings through door j
d_2	=	dummy variable = 1 if alightings > 15, 0 otherwise
Aj	=	alightings through door j

Loosely interpreted, there is a 9.3 second time for door opening and closing. For each boarding customer, the time is 2.05 seconds unless the boardings at the stop exceed 40. Similarly the discharge rate is 3.32 seconds per customer unless the discharge rate exceeds 15, in which case the rate reduces by 1.93 second per customer. For the feeder routes, the model was

$t_d = 8.04 + \max_{j=door}((3.82 + .88d_1)B_j + (3.32 – 1.93d2)A_j$

where,

d_1	=	dummy variable = 1 if boardings <5, 0 otherwise
d_2	=	dummy variable = 1 if alightings > 25, 0 otherwise

These models have reasonably good explanatory power with the R^2 (the proportion of variation in dwell times explained by the model) being 0.84 and 0.72 for the trunk and feeder buses respectively. Additional research in this area is warranted, particularly in determining the effect of crowded buses on dwell time.

Predictive models of dwell time which use boarding and alighting data have limited utility in the planning and design of new services since travel demand forecasting models do not explain boardings and alightings by individual trip. Further, in high capacity bus rapid transit systems, the mean dwell time is more a function of the physical design of station and vehicle elements such as doorway width, fare collection scheme and the difference in height between the bus floor and the boarding platform. Some limited data on dwell time of the high capacity bus rapid transit service in Bogota, Colombia is shown in

Error! Reference source not found. below. The Transmilenio system has high floor buses, level loading platforms at stations, off-board fare collection and articulated buses with three loading doors each capable of accommodating two parallel boarding streams. This mode of operation was designed specifically to minimize mean dwell time.

TABLE 3-12: STOP DWELL TIME – BOGOTA TRANSMILENIO

Stop	Time Period	Mean (sec.)	Standard Deviation (sec.)	Coefficient of Variation
Calle 100	AM Peak	24	17	0.71
	PM Peak	22	14	0.64
Calle 72	AM Peak	19	15	0.79
	PM Peak	20	10	0.50

Source: Transmilenio, SA

3.8 CLEARANCE TIME

Clearance time must be considered when buses need to re-enter traffic stream from curb-side stop. Clearance time has three components. (1) the time for a bus to leave the berth, (2) the time needed before the next bus arrives and (3) the time separation needed to re-enter the traffic stream. US experience has found that total clearance times are roughly 15 to 20 seconds. The first two components require about 10 seconds. The third component is necessary when buses must change lanes. The amount of re-entry time ranges up to 15 seconds depending on the hourly traffic volumes in the adjacent lane. (See **Error! Reference source not found.**)

With curbside lanes and high bus traffic volumes, passing a bus in one of the bus berths is necessary. This is more likely to happen where there are a number of routes assigned to the bus lane. In some instances, (Madison Avenue, New York City) the second lane from the curb is a bus lane that reduces the re-entry time. In cases where the adjacent lane is not exclusive, the re-entry time can be estimated from the table below. Yield to bus laws can reduce this re-entry time.

The exit time is estimated at 5 seconds for a 13 meter bus and about 10 seconds for an articulated bus. This clearance time (exit plus re-entry time) should be added to the dwell time to compute the total time associated with boarding and discharging passengers at the stop.

TABLE 3-13: RE-ENTRY TIME

Adjacent Lane Volume (veh/hr)	Average Re-entry Delay (sec)
100	1
200	2
300	3
400	4
500	5
600	6
700	8
800	10
900	12
1000	15

Source: Transit Capacity and Quality of Service Manual

3.9 CALCULATION PROCEDURE

Bus stop capacity calculations are straightforward. The formula below shows the effect of boarding time and clearance time and the effective capacity of multiple berth bus stops. Essentially the computation procedure is to find the product of the effective number of loading areas and the capacity per loading area. The formula is generalized for a near side bus stop at a signalized intersection. For a midblock, far side or unsignalized intersection where the bus lane is in the major travel direction, g/C would be equal to one.

$B_s = N_{el}B_l = N_{el} * (3600*(g/C))/(t_c + t_d(g/C) + Zc_vt_d)$ (Eq. 3.5)

Where,

B_s = bus stop capacity (bus/h)

B_l = individual loading area bus capacity (bus/h)

N_{el} = number of effective loading areas

3,600 = seconds per hour

g/C = green time ratio (effective green time to total signal cycle time)

t_c = clearance time (s)

t_d = mean dwell time (s)

Z = standard normal variable corresponding to a desired failure rate (one-tailed test)

c_v = coefficient of variation of dwell times

Example: Compute the capacity of a bus stop with two in-line berths where the average dwell time is 40 seconds with a coefficient of variation of 0.3 and the g/C ratio is 0.5. Assume 500 cars per hour in the adjacent lane and the tolerable failure rate is 5%.

$B_s = N_{el}B_l = N_{el}\ (3600*(g/C))/(t_c + t_d(g/C) + Zc_vt_d)$

$N_{el} = 1.75$
$g/C = 0.5$
t_c = 5 seconds (from table x) plus 10 seconds equal 15 seconds
t_d = 40 seconds
$c_v = 0.3$
Z = 1.645 (one-tailed z-statistic associated with 5% failure rate)

$B_s = 1.75*\ ((3600 * .5)/(15 + (40 * 0.5) + (1.645*0.3*40)) = 46$ buses per hour

3.10 VEHICLE PLATOONING

The methods of capacity analysis in the previous sections assume there is a single route operating within the BRT corridor and the service design includes constant service intervals within time periods. There are conditions where a different operating pattern is in place and alternate methods of capacity analysis should be considered for vehicle platooning and multiple routes in the corridor.

Vehicle platooning (operation of "virtual bus trains") is an operating system in which two vehicles move in tandem along a busway. These can be either on the same route or different routes. The advantage of such a scheme is increased capacity where capacity is constrained by stop dwell time and stops have multiple loading berths. Platooning can also reduce the probability of bunching because the headway to provide the same capacity is longer and irregular vehicle arrivals are a lower proportion of the total arrival interval. Platooning can also fa-cilitate signal priority because the number of priority events will be reduced. Finally, platooning can also obviate the need for a passing lane at BRT stops.

If there are two routes in the two bus platoon, the operating scheme may be either a constant sequence (i.e. Route A is always the first bus in the platoon.) or random sequence. If both routes start at a common terminal, the constant sequence is more easily attained. The benefit of constant sequencing is that customers can wait at specific locations on the loading platform since the bus for their destination will consistently arrive at that location. With random sequencing, customers have to reposition themselves when buses arrive causing dwell times to increase and reducing capacity. Through the use of intelligent transportation system technology, the sequence can be made known ahead of time. However, some passenger confusion will remain even if such measures are implemented.

At signalized intersections, it may be difficult to maintain the platoon without some ITS application such as traffic signal priority or use of "count down" clocks to ensure that the entire platoon can proceed through a green phase. For the purpose of capacity analysis the following analytical technique is offered.

This is an extension of the generalized capacity equation for vehicles at stops. The number of effective loading areas for platooned operation (N_{el}) is estimated to be 1.85 for two-bus platoons.

$B_s = N_{el}B_l = N_{el}3{,}600(g/C)/(t_c + t_d(g/C)+Zc_vt_d)$ (Eq. 3.6)

Where,

B_s = Bus stop capacity (buses/hour)

B_l = Individual loading area bus capacity

N_{el} = Number of effective loading areas = 1.85 for platooned arrival of two buses

3,600 = seconds per hour

g/C = green time ratio (ratio of effective green time to cycle time. This equals 1.0 for unsignalized intersections)

t_c = clearance time (sec.)

t_d = mean dwell time (sec.) (This is the dwell time associated with the route with the highest number of passenger transactions in cases where the platoon serves two routes.)

Z = standard normal variable corresponding to desired failure rate (one tail) ; and

c_v = coefficient of variation of dwell time

Example: Compare the capacity in vehicles per hour of a two berth bus stop with platooning and non-platooing of arriving buses if the dwell time mean is 30 seconds and the standard deviation is 10 seconds. Assume a 5% permitted failure rate, a non-signalized intersection and a 10 second clearance time.

Platooned arrival:

Note: c_v = standard deviation/mean

Therefore, c_vt_d = standard deviation

$B_s = N_{el}B_l = N_{el}3{,}600(g/C)/(t_c + t_d(g/C)+Zc_vt_d)$

$=(1.85 * 3600)/(20 + 30 (1) + (1.645 * 10)) = 100$ *buses per hour*

Non platooned arrival (no passing):

$B_s = N_{el}B_l = N_{el}3{,}600(g/C)/(t_c + t_d(g/C)+Zc_vt_d)$

$=(1.75 * 3600)/(20 + 30 (1) + (1.645 * 10)) = 95$ *buses per hour*

Table 3.11 provides some typical values of bus capacity at a stop with multiple berths. In the table the assumed failure rate is 5% and the clearance time is 10 seconds.

TABLE 3-14: STOP CAPACITY FOR MULTIPLE BERTH STOPS AT VARIOUS DWELL TIME LEVELS

		Bus Berths				
Dwell Time (sec.)	Coefficient of Variation of Dwell Time	1	2	3	4	5
20	0.3	93	162	204	255	278
20	0.6	76	132	166	208	227
30	0.3	68	118	149	186	203
30	0.6	54	95	119	149	163
40	0.3	53	93	117	146	160
40	0.6	42	74	93	116	127

Table entries are in buses per hour

Source: Calculations based on Transit Capacity and Quality of Service Manual

3.11 VEHICLE CAPACITY

There is considerable diversity in the size, capacity and configuration of transit buses among cities in the developing world. Only full size buses suitable for bus rapid transit (BRT) services are considered here. **Error! Reference source not found.** below shows a range of typical bus sizes in Pakistan.

TABLE 3-15: TYPICAL BUS MODELS IN PAKISTAN

Manufacturer	Model	Floor Height	Length (m)	Seating Capacity	Standing* Capacity
Ashok Leyland	222	High	10.9	50	20
	Articulated bus	High	16	52	20
Volvo	8700	Low	12	40	N/A
	8700	Low	13.5	45	N/A
	8700	Low	15	53	N/A
	8700	High	12	53	N/A
	8700	High	13.5	55	N/A
Tata	STAR ULF	Ultra low	12	27	35
	STAR LF	Low	12	44	35

* Manufacturer's estimate

A generally applicable approach to the estimation of bus capacity is:

Vehicle Capacity = # seats + area available for standing/area per standee (set as a standard)

For planning purposes, the standee density standard would be the amount of space each standee would be assigned to allow an acceptable level of crowding across an average peak hour. For "crush" design purposes, the density would correspond to the peak fifteen minutes. In either case, this is a policy standard that reflects social norms and available resources. It also reflects the type of service provided and the nature of the market. The longer that people must stand (e.g., for on long distance CBD-oriented commuter services), the more space generally assigned to each standing passenger

Typical standards for urban bus and rail services are shown in **Error! Reference source not found.** below.

TABLE 3-16: URBAN BUS AND RAIL LOADING STANDARDS

Place of Application	Typical Number of Standees per Square Meter
EU	**4-5**
US, Canada	**3-4**
Latin America BRT	**6-8**
Asia	**8-10**

A generalized formula for the capacity of a bus given its geometry, door and seating configuration and acceptable loading standard is as follows:

$$V_c = \frac{(L-1)*(W-0.2) - (0.5 D_n W_s D_w)}{S_{sp}} + (1 - S_a/S_{sp}) N \frac{((L-1) - D_n(D_w + 2S_h))}{S_w}$$

Where,

V_c = Total vehicle capacity (seats plus standees)

L = Vehicle length (m)

W = Vehicle width (m)

D_n = Number of doorways

W_s = Doorway setback (m)

D_w = Doorway width (m)

S_a = Area of single seat (m^2) [0.5 m^2 for transverse, 0.4 m^2 for longitudinal]

S_{sp} = Standing space per passenger

N = Vehicle arrangement

[2 for 2 seats/row, 3 for 2 + 1 seats/row, 4 for 2 + 2 seats/row, 5 for 2 + 3 seats/row]

S_w = Seat pitch [0.69 m for transverse, 0.43 m for longitudinal]

S_b = Single set-back allowance (additional space for storing open door) [0.2 m]

Error! Reference source not found. below shows typical capacities for a range of bus types (single unit, articulated and bi-articulated) and loading standard. In each case, the assumed number of doors is 2 for single unit, 3 for articulated and 4 for bi-articulated buses. The first table is for transverse seating, while the second is for longitudinal (peripheral) seating.

TABLE 3-17: BUS VEHICLE CAPACITY

Transverse Seating			
Bus type	**single**	**articulated**	**bi-articulated**
Doorways	**2**	**3**	**4**
Length (m)	**13**	**20**	**25**
Standees/sq. m.			
4	80	126	160
5	87	137	174
6	94	148	188
7	101	158	203
8	109	169	217

Longitudinal Seating			
Bus type	**single**	**articulated**	**bi-articulated**
Doorways	2	3	4
Length (m)	13	20	25
Standees/sq. m.			
4	86	136	172
5	97	153	194
6	108	170	217
7	120	188	239
8	131	205	262

The passenger capacity of a bus depends on its seating configuration and the allowable loading design standard. The use of low-floor buses complicates the analysis since in low floor buses, vehicle wheel wells and internal stairs reduce passenger capacity.

As in other discussions about capacity, these estimates are maximum theoretical capacity which should be adjusted downward to allow for variation in demand through the peak hour, diversity of loading within vehicles and non-uniformity of the headway.

3.12 PASSENGER CAPACITY OF A BUS LINE

The passenger capacity of a bus route can be estimated by multiplying the bus (vehicle) capacity at the busiest stop by the scheduled design capacity of the vehicle used. Results should be compared with actual data for a similar route in the same city.

Thus, if 90 articulated buses per hour are accommodated at the busiest boarding point, and the schedule design capacity is 100 passengers, the line could carry about 9,000 passengers per hour. Since many BRT lines have passing opportunities at stations (or there are dual bus lanes), this capacity would be doubled for dual berths. Note that busy BRT lines in cities carry 20,000 people per hour in the peak direction of travel. The line capacity calculation is illustrated below:

$$C = VN_{el}B_l = VN_{el} * (3600*(g/C))/(t_c + t_d(g/C) + Zc_vt_d) \quad \text{(Eq. 3.8)}$$

Where,

C = line capacity in passengers per hour

V = vehicle scheduled capacity

B_l = individual loading area bus capacity (bus/h)

N_{el} = number of effective loading areas at critical stop

3,600 = seconds per hour

g/C = green time ratio (effective green time to total signal cycle time)

t_c = clearance time (s)

t_d = mean dwell time (s)

Z = standard normal variable corresponding to a desired failure rate (one-tailed test)

c_v = coefficient of variation of dwell times

Example: Compute the line capacity of a bus line with three in-line berths at the critical stop where the average dwell time is 200 seconds with a coefficient of variation of 0.3 and the critical g/C ratio is 0.6. Assume a 10 second clearance time and the tolerable failure rate is 5%.

$B_s = VN_{el}B_l = N_{el} (3600*(g/C))/(t_c + t_d(g/C) + Zc_vt_d)$
V = 80 passengers
N_{el} =2.45 (from table 3.x)
g/C = 0.5
t_c = 10 seconds
t_d = 20 seconds
c_v = 0.3
Z = 1.645 (one-tailed z-statistic associated with 5% failure rate)

C = 80* 2.45* ((3600 * .6)/(10 +(20 * 0.5)+ (1.645*0.3*20))=14,100 passengers per hour

3.13 Transit Operations At Intersections

While the throughput capacity of a bus transit route is usually limited by the operation at the critical stop, the capacity can also be constrained by traffic operations at critical intersections. This may happen in cases where there is considerable intersection interference from other vehicles making left or right turns, pedestrians and bicyclists, low green to cycle time ratios in the direction of bus travel, or where the bus service operates on the minor approach of an intersection. On curbside bus lanes, the traffic conflict occurs when right turning cars and trucks occupy the bus lane, and are impeded by crossing pedestrians in the direction of travel of the bus. In median bus lanes, there is generally no comparable conflict since normal design practice is to have signal controlled left turns in a distinct lane from the exclusive bus lane. Transit intersection capacity is also influenced by the location of any bus stops at the intersection.

3.13.1 Curb Lane Operation

Traffic conflicts at signalized intersections can impede bus movements when the green per cycle time is limited and/or when right turns from or across the bus lane conflict with through buses. The delay can constrain bus capacity where right turn volume conflicts with heavy pedestrian movements. The result is reduced capacity in the curb or interior bus lane.

3.13.1.1 Screening for Right Turn Conflicts

The impact of pedestrian-right turn conflicts on curb bus lane capacity may call for restricting the right turns, or possibly grade separating the conflicting pedestrian movement. A simple method to assess these effects is set forth in TCRP Report 90 Bus Rapid Transit Implementation Guidelines. A more detailed method is available in the Transit Capacity and Quality of Service Manual at page 4-48.

The simplified method assumes each pedestrian channel takes a specified time to cross the area in which there is a conflict with right turns; in effect, each pedestrian delays each right turn by this time. The time lost can be estimated by weighing the time per pedestrian by the number of pedestrians and right turns per signal cycle. The green time which is lost due to pedestrian-right turn conflicts can then be approximated by the following equation:

$\Delta t = rpt_s/L$ (Eq. 3.9)

Where,

Δt = green time to be gained per cycle,

r = right turns/cycle (peak 15 minutes)

p = conflicting pedestrians/ cycle (peak 15 minutes)

t_s = time per pedestrian (e.g. 3 or 4 seconds), and

L = number of pedestrian channels in crosswalk (e.g., 1 to 4)

The lost time per cycle is deducted from the green time per cycle. If the remaining effective green time is less than 25% of the cycle time, then the turn conflicts will not impede operation of the curbside bus lane.

Estimated lost time per signal cycle by conflicting right turns and pedestrian volumes is shown in Table 3.13.

TABLE 3-18: LOST TIME PER CYCLE DUE TO RIGHT TURN-PEDESTRIAN CONFLICTS

	Time Lost per Cycle at 3 Seconds per Pedestrian			
Typical Values of $R/N_c * P/N_c$	1 Lane	2 Lanes	3 lanes	4 Lanes
4	12	6	4	3
8	**24**	12	8	6
12	**36**	**18**	12	9
16	**48**	**24**	**16**	12
20	**60**	**30**	**20**	15
24	**72***	**36**	**24**	**18**

R = right turns per hour

N_c = number of cycles per hour

P = pedestrians per hour

Source: Levinson, TCRP Report 90, 2003

For a 60 second cycle, time loss should not exceed 25% of the cycle time or 15 seconds. In the table, the boldface values are not acceptable, and turns should be prohibited.

Example: A curbside bus lane operates at an intersection where the green time per cycle is 50 seconds and the cycle time is 90 seconds. The number of pedestrian crossings per hour 200 and the number of right turning cars is 120 per hour. Is there sufficient time to operate a curbside lane with right turning vehicles in the bus lane?

The number of pedestrian crossing per cycle is 5(200/40). The number of right tuning vehicles per cycle is 3 (120/40). The number of conflicts per cycle is 20. If there are 3 pedestrian lanes and the time per pedestrian in one channel is 3 seconds then the time lost due to conflicts is 20 (5 * 4 *3/3). The percentage loss per cycle is 20/90 or 22%. This is less than the 25% threshold, suggesting that the right turn movement volume is compatible with the curbside bus lane.

3.13.1.2 ADJUSTMENT FOR MIXED TRAFFIC IN THE RIGHT LANE

The previous procedure provided guidance as to whether the volume of right turn movements would affect capacity of the bus lane. The actual reduction in capacity can be computed by applying a mixed traffic adjustment factor to the estimated lane capacity.

Mixed Traffic Adjustment Factor $f_m = 1 - f_l\left(\frac{v}{c}\right)$

where,

f_m = mixed traffic adjustment factor (from **Error! Reference source not found.**)

f_l = bus stop location factor (See table below)

v = curb lane volume (veh/h)

c = curb lane capacity (veh/h) (see table below)

The curb lane capacity is a function of the number of conflicting pedestrians and the traffic signal g/c ratio and is shown in **Error! Reference source not found.**

TABLE 3-19: BUS STOP LOCATION CORRECTION FACTOR

Bus Stop Location Factors			
Bus Stop Location	**Type 1**	**Type 2**	**Type 3**
Near side	1	0.9	0
Mid block	0.9	0.7	0
Far side	0.8	0.5	0

Type 1 – Buses have no use of adjacent lane
Type 2 – Buses have partial use of adjacent lane
Type 3 – Buses have full use of adjacent lane (i.e. second lane is a bus lane)

TABLE 3-20: RIGHT TURN CURB LANE VEHICLE CAPACITIES

	g/C Ratio for Bus Lane					
Conflicting Pedestrian Volume (ped/h)	**0.35**	**0.4**	**0.45**	**0.5**	**0.55**	**0.6**
0	510	580	650	730	800	870
100	440	510	580	650	730	800
200	360	440	510	580	650	730
400	220	290	360	440	510	580
600	70	150	220	290	360	440
800	0	0	70	150	220	290
1000	0	0	0	0	70	150

Source: Transit Capacity and Quality of Service Manual

3.14 COMPUTING BUS FACILITY CAPACITY

The bus facility capacity is:

$$B = B_l N_{el} f_m$$

where,

B = Bus facility capacity (bus/h)

B_l = Bus loading area capacity

N_{el} = number of effective loading areas

f_m = mixed traffic adjustment factor

3.15 MEDIAN LANE OPERATION

Median arterial bus lanes are used along wide streets in many cities to avoid the uncertainties and turbulence of curb lane operation. In the design of median bus lanes or busways, the normal practice is to provide an exclusive left turn lane for non-transit vehicles that is independent of the bus lane. These lanes, provided only at signal controlled intersections normally have a protected signal phase. The typical phasing is:

1. Busway plus through traffic on the street parallel to the busway
2. Left turns from the street parallel to the busway
3. Cross street traffic

Buses are not permitted to cross the intersection when left turns or cross traffic have green indications.

3.16 CAPACITY AND QUALITY REDUCTION DUE TO HEADWAY IRREGULARITY

3.16.1 CAPACITY REDUCTION

Most traditional methods of transit capacity analysis with the short bus headways common in developing cities, assume that transit vehicles arrive at a uniform headway and decisions on the appropriate frequency are merely a matter of assuring that the capacity offered is sufficient to carry passengers traveling through the maximum load point constrained by a vehicle loading standard. Over a specified time interval, this will assure that all customers will be carried, although it may not mean that all customers may board the next arriving bus or train.

In actuality, owing to variation in passenger arrival patterns, boarding rates and travel time through signalized intersections there is likely to be some variation in the vehicle interarrival time. This introduces some diminution of actual capacity which may be quantified. If a bus is delayed enroute at the stop just before the maximum load segment, the actual headway interval will exceed the design or published interval. In this case, there will be more customer arrivals than expected. This will result in either loading above the design limit of the vehicle or some customers having to wait until the next arriving vehicle. On the other hand, if the actual time gap is less than the published headway, the vehicle will depart from the station with fewer customers than the vehicle capacity. Since capacity is perishable, once the vehicle departs the critical stop less than fully loaded, the available capacity is lost forever. A possible strategy of holding buses at stations until the actual headway meets the published headway results in fewer vehicles per hour being offered which also diminishes capacity.

The method of quantification of this requires the introduction of a term called effective frequency. This is the equivalent frequency that provides the same capacity as a frequency with a specific variability. The effective frequency is:

$f_e = f/(1 + c_{vh})$ (Eq. 3.10)

Where,

f_e = effective frequency (buses/hr.)

f = scheduled frequency (buses/hr.)

c_{vh} = coefficient of variation of headway (headway standard deviation/mean headway)

The actual capacity of the route is the product of the vehicle capacity and the effective frequency. While this is a good framework, there is limited data available on the factors causing headway irregularity. Evidence indicates that headway variability is low at terminals and increases along the route. The appropriate method of determining actual system capacity is to review headway coefficient of variation at the maximum load segment to determine effective frequency.

Data from the BRT system in Jinan, China which has an exclusive median right of way, suggest that the coefficient of variation in headway on BRT routes is high as shown in **Error! Reference source not found.** below. High frequency routes in Jinan are very susceptible to headway variation since some traffic signal cycle times are on the order of 4 minutes, which exceeds the scheduled headway.

TABLE 3-21: BRT HEADWAY VARIATION - JINAN, CHINA

Line number	1	2	3
Headway (min)	3	3.5	4.5
Headway cv	0.36	0.54	0.42

Source: Huang (2010)

Data from Transmilenio in Bogota, Colombia also reveal a high coefficient of variation of headway on the order of .9 to 1.0. More precisely, this is the cv of buses from multiple routes arriving at a major bus station and using a common berth. The fact that there are several bus routes serving the station adds to the headway variability.

Example: The published frequency of a BRT route is 15 vehicles per hour and the loaded vehicle capacity is 60. What is the effective capacity if the arrival rate of passengers is uniform and if the coefficient of variation of headway is about 0.3?

$f_e = f/(1 + c_{vh})$
$= 15/(1.3)$
$= 11.5$ vehicles per hour * 60 passengers/vehicle = 690 passengers

3.16.2 EXTENDED WAIT TIME DUE TO HEADWAY IRREGULARITY

Note that in addition to capacity reduction, headway variation also deteriorates the quality of the customer experience by increasing the average waiting time for buses (or trains). If headways are constant the average waiting time is h/2 where h is the headway. It can be shown that if there is some variation in the headway denoted by c_{vh}, the coefficient of variation (standard deviation /mean) of headway, the average wait time is:

$w = (h/2)* (1 + c_{vh})$ (Eq. 3.11)

where,

w = average customer wait time

h = average headway

c_{vh} = coefficient of variation of headway (headway standard deviation/mean headway)

There is limited understanding of how the operating environment affects headway variation. The evidence suggests that measures such as traffic signal priority at intersections and management of passenger loading can assist in this effort.[5]

Just as in the case of capacity diminution, the headway variability causes irregular gaps in service and more customers arrive at the stop during longer gaps.

> Example: Compute the average customer wait time at a stop if the headway is 4 minutes with no variance? What is the average wait time if the headway coefficient of variation is 0.3?
>
> Average waiting time with no variance = h/2 = 4/2 = 2 minutes
> Average waiting time with headway coefficient of variation of 0.3 = (h/2)* (1 + cvh)= 2 * (1.3) = 2.6 minutes

3.16.3 TRAVEL TIMES AND FLEET REQUIREMENTS

Proper scheduled running times are essential for proper transit operation. Running times that exceed what is required to maintain schedules result in higher than necessary operating costs. Excessively tight (lower than optimal) running times, on the other hand, result in late arrivals at timepoints. If there is not sufficient schedule recovery time built into driver schedules, inadequate times can also cause delays in terminal departures on subsequent trips, a key factor in late arrivals on successive stops. This requires balancing the requirements for operating efficiency and requirement for sufficient layover time for schedule recovery and operator breaks.

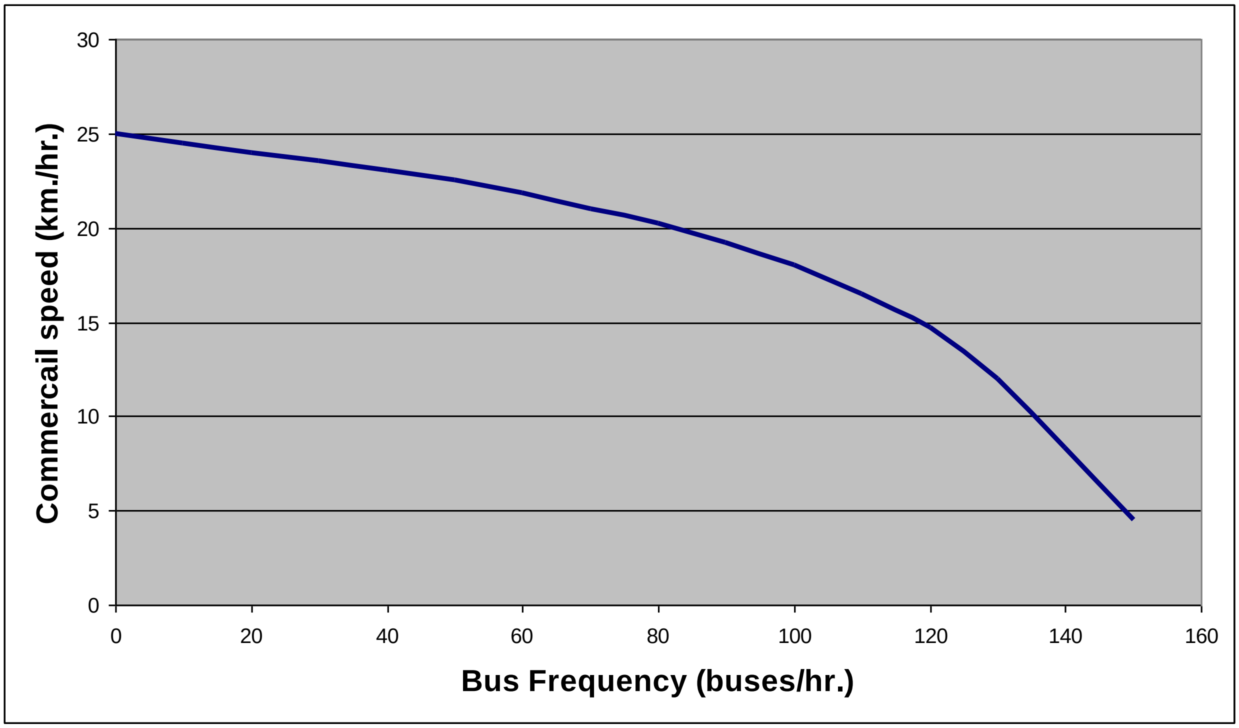
The BRT running time between terminals will depend on both the length of the trip and the speed of travel time. The speed or travel time rate depends on the distance between stops, the time spent at each stop and the number of buses operating during the design period.

Normally, when bus flows are less than about 50-70 percent of the maximum line capacity, there is little reduction in operating speeds. Beyond that point,

[5] For example, on loaded buses the flow rate of customers onto vehicles is very low. Rather than wait until all customers are on board, a policy of loading only until the flow rate falls below some minimum value will probably increase capacity due to reduction of dwell time and dwell time variability, each of which also influence throughput capacity on a route.

however, there is a rapid drop in speeds to about half the free-flowing speed when the ratio is 0.9 or more. An illustrative example for the Avenue Caracas corridor in Bogota is shown in figure 3.3.

FIGURE 3-3: SPEED VS. FREQUENCY



Source: Steer, Davies, Gleave

The actual running time for each individual trip can be prepared based on either observed or archival data. However, preparing schedules in which the scheduled travel times varies very often throughout the day results in irregular headways if the number of vehicles assigned is held constant or irregular fleet assignment patterns if headways are held constant. In actual practice, the number of time intervals must reflect a balance between accuracy in reflecting significant predictable variation among trips and portraying a schedule which is easy to understand by customers and avoids complicated vehicle and staffing patterns.

The optimal half-cycle time, the scheduled time to travel between terminals and time allowance prior to departure of the next trip, balances schedule efficiency, operator layover and schedule recovery. Consider the extreme case in which there is no variability in terminal to terminal time. In such case, a sufficient time would be allowed at the end of the bus trip to allow for operator break. Roughly 10% is allocated to this. On the other hand, for a trip with considerable variability between days, the objective would be to provide sufficient time to assure on-time departure on the next trip from the same terminal. From a simple statistical test, the running time required to assure that the probability that there is sufficient time for 90%, 95% or 99% of trips departing on time can be computed. Specifically, a one-tailed normal test can be used to make this estimate. The best half cycle time would be the larger of (1) the times necessary for driver layover and (2) the time necessary for punctual terminal departure on the subsequent trip. A value of 95% is appropriate. In plain terms, sufficient time should be allowed to assure that the probability that the next trip can depart on time is at least 95%.

Mathematically, the appropriate half cycle time is:

$t_c = \max (t_{m*}(1+r_d)), t_{m*}(1 + (cv * z))$ (Eq. 3.12)

where,

t_c = half cycle time

t_m = mean terminal to terminal time

r_d = driver recovery percent

cv = coefficient of variation of terminal to terminal time

Z = value of unit normal z statistic corresponding to desired probability of on-time departure for the subsequent trip. (**Error! Reference source not found.**)

TABLE 3-22: Z-STATISTIC FOR ONE-TAILED TEST

Desired On-time Probability for next departure	Z -statistic
99%	2.330
95%	1.645
90%	1.280

Example: The average terminal to terminal time in the morning peak hour is 32 minutes, with a standard deviation of 0.1 minutes. Compute the half cycle time required to assure both sufficient driver break time (10%) and schedule recovery if the desired probability of on-time departure for the following trip is 95%. What would the half cycle time be if the coefficient of variation is 0.3 and the desired on time departure was 99%.

t_m = 32 min.
r_d = 10%
cv = 0.1
$z_{95\%}$ = 1.645
$z_{99\%}$ = 2.33
Running time for driver recovery = 1.1 * 32 = 35 minutes
Running time for on-time departure = 32 * (1+(.1 *1.645)) = 37 minutes
The greater of these is 37 minutes
The half cycle time if the desired on-time departure rate for the next trip is 99% is:
32 * (1 + (.1 * 2.33)) =39.5 minutes

3.17 TERMINAL CAPACITY

Some cities in developing countries have major off-street bus terminals. In South America, cities such as Bogota and Curitiba, "integration terminals" are an integral part of the overall system. These terminals have several important advantages. (1) They provide a place for passengers to transfer between bus routes (2) When located near areas of high transit demand, they remove passenger interchanges from street stops and stations (3) They provide sufficient capacity to serve large numbers of passengers both during rush hours and throughout the day. (4). They can serve as stations for express services.Thus they can permit higher roadway vehicles and passenger volumes than with total reliance on busway operation.The berth capacity of a terminal will depend on operating practices – both in terms of berth assignment to routes and stop dwell times. Typical productivity in New York's 200 berth midtown terminal is 4 buses per berth per hour. San Francisco's 40-berth Transbay Terminal serves about 7 buses per berth per hour.

TABLE 3-23: APPROXIMATE CAPACITY OF SINGLE BERTH, WITH QUEUING AREA

1			Failure Rate		
Service Time (sec.)	**Service Time CV***	**Headway CV**	**5%**	**10%**	**25%**
30	40%	40%	48	58	68
	40%	80%	19	33	60
	80%	40%	44	49	58
	80%	80%	17	37	55
40	40%	40%	43	46	54
	40%	80%	23	30	49
	80%	40%	32	41	46
	80%	80%	17	27	40
50	40%	40%	33	35	45
	40%	80%	18	22	41
	80%	40%	25	28	37
	80%	80%	15	19	33
60	40%	40%	25	30	37
	40%	80%	15	20	37
	80%	40%	23	26	33
	80%	80%	13	22	28
75	40%	40%	18	25	29
	40%	80%	13	18	28
	80%	40%	20	22	28

	80%	80%	11	14	21

* CV – coefficient of variation = standard deviation/mean

TABLE 3-24: APPROXIMATE CAPACITY OF SINGLE BERTH, WITH QUEUING AREA

2			Failure Rate		
Service Time (sec.)	**Service Time CV***	**Headway CV**	**5%**	**10%**	**25%**
30	40%	40%	58	64	83
	40%	80%	33	47	66
	80%	40%	45	55	68
	80%	80%	31	38	56
40	40%	40%	44	47	57
	40%	80%	23	35	54
	80%	40%	35	42	52
	80%	80%	24	30	44
50	40%	40%	35	44	50
	40%	80%	20	29	43
	80%	40%	28	30	41
	80%	80%	15	19	37
60	40%	40%	27	33	40
	40%	80%	16	26	37
	80%	40%	25	27	33
	80%	80%	13	22	31
75	40%	40%	25	26	32
	40%	80%	15	18	28
	80%	40%	22	23	28
	80%	80%	11	19	26

* CV – coefficient of variation = standard deviation/mean

TABLE 3-25: APPROXIMATE CAPACITY OF SINGLE BERTH, WITHOUT QUEUING AREA

3			Failure Rate		
Service Time (sec.)	**Service Time CV***	**Headway CV**	**5%**	**10%**	**25%**
30	40%	40%	26	37	51
	40%	80%	10	12	34
	80%	40%	22	34	48
	80%	80%	7	9	32
40	40%	40%	23	32	44
	40%	80%	6	10	23
	80%	40%	18	25	38
	80%	80%	7		26

50	40%	40%	19	26	35
	40%	80%	5	8	18
	80%	40%	16	21	34
	80%	80%	6	10	21
60	40%	40%	16	20	30
	40%	80%	5	7	16
	80%	40%	14	20	26
	80%	80%	6	12	16
75	40%	40%	13	17	25
	40%	80%	5	6	13
	80%	40%	11	15	23
	80%	80%	5		13

* CV – coefficient of variation = standard deviation/mean

TABLE 3-26: APPROXIMATE CAPACITY OF SINGLE BERTH, WITHOUT QUEUING AREA

4			**Failure Rate**		
Service Time (sec.)	**Service Time CV***	**Headway CV**	**5%**	**10%**	**25%**
30	**40%**	**40%**	**29**	**47**	**68**
	40%	**80%**	**10**	**12**	**33**
	80%	**40%**	**27**	**40**	**60**
	80%	**80%**			
40	**40%**	**40%**	**26**	**37**	**53**
	40%	**80%**	**9**	**10**	**30**
	80%	**40%**	**21**	**27**	**50**
	80%	**80%**			
50	**40%**	**40%**	**22**	**30**	**41**
	40%	**80%**	**7**	**9**	**22**
	80%	**40%**	**19**	**25**	**35**
	80%	**80%**			
60	**40%**	**40%**	**18**	**23**	**39**
	40%	**80%**	**6**	**8**	**16**
	80%	**40%**	**14**	**21**	**32**
	80%	**80%**			
75	**40%**	**40%**	**13**	**18**	**29**
	40%	**80%**	**4**	**6**	**13**
	80%	**40%**	**11**	**16**	**24**
	80%	**80%**			

*** CV – coefficient of variation = standard deviation/mean**

TABLE 3-27: APPROXIMATE CAPACITY OF DOUBLE BERTH, WITH QUEUING AREA

5			Failure Rate		
Service Time (sec.)	Service Time CV*	Headway CV	5%	10%	25%
30	40%	40%	67	75	96
	40%	80%	50	68	79
	80%	40%	55	58	76
	80%	80%	46	55	76
40	40%	40%	50	61	76
	40%	80%	43	51	66
	80%	40%	42	48	60
	80%	80%	32	45	59
50	40%	40%	43	48	60
	40%	80%	35	47	58
	80%	40%	32	37	50
	80%	80%	27	35	52
60	40%	40%	37	43	52
	40%	80%	27	40	49
	80%	40%	25	31	43
	80%	80%	23	28	41
75	40%	40%	30	33	39
	40%	80%	22	29	36
	80%	40%	24	28	34
	80%	80%	20	25	35

* CV – coefficient of variation = standard deviation/mean

TABLE 3-28: APPROXIMATE CAPACITY OF DOUBLE BERTH, WITH QUEUING AREA

6			Failure Rate		
Service Time (sec.)	Service Time CV	Headway CV	5%	10%	25%
30	40%	40%	74	90	105
	40%	80%	56	80	94
	80%	40%	56	63	84
	80%	80%	54	64	82
40	40%	40%	55	67	78
	40%	80%	48	62	76
	80%	40%	46	51	61
	80%	80%	39	44	66
50	40%	40%	48	51	68
	40%	80%	36	46	60

	80%	40%	37	41	52
	80%	80%	32	35	50
60	40%	40%	41	45	52
	40%	80%	35	42	54
	80%	40%	25	33	43
	80%	80%	26	32	42
75	40%	40%	30	33	41
	40%	80%	27	31	45
	80%	40%	24	27	34
	80%	80%	20	26	36

*** CV – coefficient of variation = standard deviation/mean**

TABLE 3-29: APPROXIMATE CAPACITY OF DOUBLE BERTH, WITHOUT QUEUING AREA

7			Failure Rate		
Service Time (sec.)	Service Time CV*	Headway CV	5%	10%	25%
30	40%	40%	50	64	85
	40%	80%	28	45	73
	80%	40%	44	55	74
	80%	80%	21	36	65
40	40%	40%	46	50	68
	40%	80%	20	41	62
	80%	40%	32	42	53
	80%	80%	18	30	52
50	40%	40%	35	41	55
	40%	80%	15	29	51
	80%	40%	30	37	47
	80%	80%	16	25	45
60	40%	40%	31	37	49
	40%	80%	15	28	42
	80%	40%	24	27	40
	80%	80%	13	24	32
75	40%	40%	25	30	38
	40%	80%	13	23	36
	80%	40%	20	23	31
	80%	80%	13	19	31

*** CV – coefficient of variation = standard deviation/mean**

TABLE 3-30: APPROXIMATE CAPACITY OF DOUBLE BERTH, WITHOUT QUEUING AREA

8			Failure Rate		
Service Time (sec.)	Service Time CV*	Headway CV	5%	10%	25%
30	40%	40%	64	79	104
	40%	80%	33	49	88
	80%	40%	51	59	82
	80%	80%	28	44	77
40	40%	40%	50	57	81
	40%	80%	23	42	65
	80%	40%	38	48	60
	80%	80%	24	33	55
50	40%	40%	39	50	63
	40%	80%	16	37	56
	80%	40%	32	37	49
	80%	80%	16	25	47
60	40%	40%	31	40	54
	40%	80%	15	31	47
	80%	40%	25	33	42
	80%	80%	13	24	32
75	40%	40%	26	31	42
	40%	80%	13	23	37
	80%	40%	20	26	34
	80%	80%	13	20	31

* CV – coefficient of variation = standard deviation/mean

4 RAIL CAPACITY

4.1 INTRODUCTION

Rail rapid transit systems provide important public transportation service in very large cities in developing countries. Trains operate along rights-of-way that are completely separated from street traffic interference. They carry large numbers of people safely and reliably. Train control signal systems govern train operations and capacities.

This chapter provides guidance for computing the capacities of rail lines and stations. It overviews existing operational experience, identifies the key design and operating factors and sets forth procedures for estimating capacities in terms of trains per track per hour, passengers per track per hour and station platforms and access to them.

4.2 OPERATING EXPERIENCE

Most rail rapid transit systems throughout the world schedule 25 to 30 trains per hour track per hour (2 to 2.5 minute headways). A few systems, however, operate at shorter intervals. They are found in Sao Paulo and Mexico City as well in Hong Kong and Paris. These systems operate single lines without any branching.

Most rail rapid transit systems throughout the world schedule 25 to 30 trains per hour track per hour (2 to 2.5 minute headways). A few systems, however, operate at shorter intervals. They are found in Sao Paulo and Mexico City as well in Hong Kong, Tokyo, Moscow and Paris. These systems operate single lines without any branching.

Some reported peak rush hour passenger volumes are given in **Error! Reference source not found.**. The highest volumes, from 60,000 to over 80,000 passengers per track per hour, are found on lines in Sao Paulo and Hong Kong.

4.3 DESIGN CONSIDERATIONS

Rail transit capacity concepts are similar to those in bus transit in several respects. Essentially, the running way capacity of a system measured in vehicles per hour is constrained by the occupancy of the critical station along a route – the one with the highest combination of mean and standard deviation[6]. While there are no on-street intersections in grade separated rail systems, other operational and design features such as terminals and junctions also limit capacity. Further, with generally larger volumes and either elevated or subterranean operation, level changing devices and platforms have a larger influence on system capacity than they do in bus systems.

TABLE 4-1: HOURLY PASSENGER VOLUME OF RAIL TRANSIT SYSTEMS IN THE DEVELOPING WORLD

Region	City	Peak Volume (pphpd) *
Asia		
	Bangkok	50,000
	Chongqing (monorail)	17,000
	Hong Kong	50,000
	Manila	26,000
Latin America		
	Buenos Aires	20,000
	Mexico City	39,300
	Santiago	36,000
	Sao Paulo	60,000
pphpd - passengers per hour per direction		

Listed below are the various aspects of transit capacity that are subsequently discussed.

1. ***Running way capacity*** including the role of safe separation distance, signal/control systems and turnarounds.

2. ***Platform capacity*** including allowance for circulation, waiting space, number size and location of platform ingress/egress channels

3. ***Facility access elements*** including doorway and corridor widths, turnstiles and other barrier gates

4. ***Fare collection systems*** including staffed fare booths and ticket vending machines

5. ***Level changing systems*** including capacity of elevators, escalators and stairs

[6] Transit analysts generally consider the critical station to be the one with the highest mean dwell time plus two standard deviations of dwell time.

6. ***Vehicle design elements*** including consist lengths and configuration (discrete vehicles or open-vestibule for entire train), interior configuration, doorway number, locations and widths.

4.4 OVERVIEW OF PROCEDURES

Error! Reference source not found. and 4.3 illustrate procedures for assessing the capacity of existing and proposed rail transit lines respectively. These tables also show ways of increasing system capacity.

TABLE 4-2: GENERAL CAPACITY ANALYSIS PROCEDURES - EXISTING RAIL LINE

Data Collection – Critical Stop

1. For each stop determine the mean dwell time and dwell time standard deviation during peak hour. Also determine the peak headway and headway standard deviation. Also determine the number of on-board passengers as each train departs.
2. Identify the critical stop. This is the one with the maximum of the mean dwell time plus two standard deviations.
3. Determine the peak period passenger boarding rate at the critical stop.

Data Collection – Terminal Stop

1. Determine headway, headway variability, dwell time and dwell time variability at terminal stops.

Data Analysis

1. Determine the capacity at the critical station.
2. Determine capacity at the critical terminal stop.

Estimate Future Volumes

1. Passengers

Capacity Expansion Estimate

1. Determine if capacity expansion is necessary over the planning horizon
2. Determine required capacity expansion by year

Assess Capacity Expansion Alternatives for Stops

1. Change service frequency
2. Change vehicle capacity – change consist length
3. Improve reliability (reduce headway variance)
4. Reduce dwell time
5. Reduce dwell time variance

Assess Capacity Alternatives for Terminals

1. Change operating practices – driver takes subsequent train from terminal
2. Reduce dwell time or dwell time variance
3. Add terminal platform(s)

TABLE 4-3: CAPACITY ASSESSMENT PROCEDURE OF PROPOSED RAIL LINE

Initiate a Proposed Service Design

1. Service frequency
2. Train consist length and vehicle configuration
3. Platform sizes
4. Terminal stop configuration
5. Fare collection system
6. Level change system at stations
7. Terminal operating practices

Data Collection – Critical Stop

1. Estimate expected passenger loading per time period at each station.
2. Estimate on-board load after train leaves each station.
3. Estimate expected dwell time and dwell time variance at each station
4. Identify the critical station for planning purposes.

This is the one with the maximum of the mean dwell time plus two standard deviations.

Data Collection – Terminal Stop

1. Determine headway, headway variability, dwell time and dwell time variability at terminal stops.

Data Analysis

1. Determine the vehicle capacity at the critical station. (Section x.x)
2. Determine fare collection capacity at the critical station. (Section x.x)
3. Determine level change capacity at critical station. (Section x.x)
4. Determine platform capacity at critical station (Section x.x)
5. Determine capacity at the critical terminal stop. (Section x.x)

Estimate Future Volumes

1. Passengers

Assess Adequacy of Initial Design

1. Determine if passenger flow at critical station can be maintained. (Section x.x)
2. Fare collection
3. Level change
4. Platform capacity
5. Determine if vehicle flow through critical station can be maintained. (Section x.x)
6. Determine if vehicle flow through terminal stations can be maintained. (Section x.x)

Assess Capacity Expansion Alternatives for Stops

1. Change service frequency

2. Change trainset capacity
3. Improve anticipated reliability (reduce headway variance)
4. Reduce anticipated dwell time
5. Reduce anticipated dwell time variance
6. Change fare collection capacity
7. Change level change capacity
8. Change platform capacity

Assess Capacity Alternatives for Terminals

1. Change operating practices – driver takes subsequent train from terminal
2. Reduce dwell time or dwell time variance
3. Add terminal platform(s)

4.5 LINE CAPACITY

4.5.1 GENERAL GUIDANCE

The capacity of a rail transit line is governed by station capacity or way capacity whichever is smaller. The critical capacity constraints are usually (1) the busiest station in terms of passenger boardings or interchanges (2) terminal stations where trains must reverse direction (or already have heavy boardings and alightings) or (3) junctions.

The passenger capacity depends on (1) rail car size, seating arrangements and door configuration (2) number of cars in the consist (3) allowable standees as set forth in passenger loading standards and (4) the minimum headway (time spacing) between trains. The minimum headway between trains depends on station dwell time and train length; train acceleration and deceleration rates, train control (signaling) systems and track arrangements.

The passenger capacity of a single track can be estimated by the following equation.

$$\frac{\text{Passengers}}{\text{Hour}} = \frac{\text{Trains}}{\text{Hour}} \times \frac{\text{Cars}}{\text{Train}} \times \frac{(\text{Seats} + \text{Standing area}/(\text{area per standee}))}{\text{Car}} \quad \text{(Eq. 4.1)}$$

The precise values for this equation will vary among transit agencies.

4.5.2 RUNNING WAY CAPACITY

The running way capacity in trains per track per hour depends on the passenger dwell time at intersections, the variation in the dwell time (the operating margin), and the safe separations between trains.

4.5.2.1 CRITICAL STATION DWELL TIME

The major limitations on train capacity are usually the dwell time and safe separation time between trains at the critical stop. While this is normally the busiest stop, the distribution of actually observed dwell times has an effect on determining the critical stop. The dwell time depends on the pattern of passenger boardings and discharges and the number of through passengers on the train. Trains with high levels of through passengers take more time to board per passenger than those that are less congested. Dwell time is also influenced by the electrical and mechanical characteristics of the train – including time for the system to recognize that the train is fully stopped prior to door opening, opening and closing time of doors and time for safety checks to assure that all doors are closed prior to train departure from the station. This time is referred to as the *function time*.

Dwell time distributions on existing rail systems can be measured directly and this data can be used in planning new systems. A more detailed approach on determining the dwell time at the critical intersection is discussed below. This treatment discusses passenger boarding and discharge time as well as function time.

A formulation estimating dwell time attributable to Puong (2000) is shown below:

$$SS = 12.22 + 2.27 * B_d + 1.82\, A_d + 6.2 * 10^{-4} * TS_d^3 B_d \qquad (R^2 = 0.89)$$

Where,

SS = dwell time

A_d = alighting passengers *per door*

B_d = boarding passengers *per door*

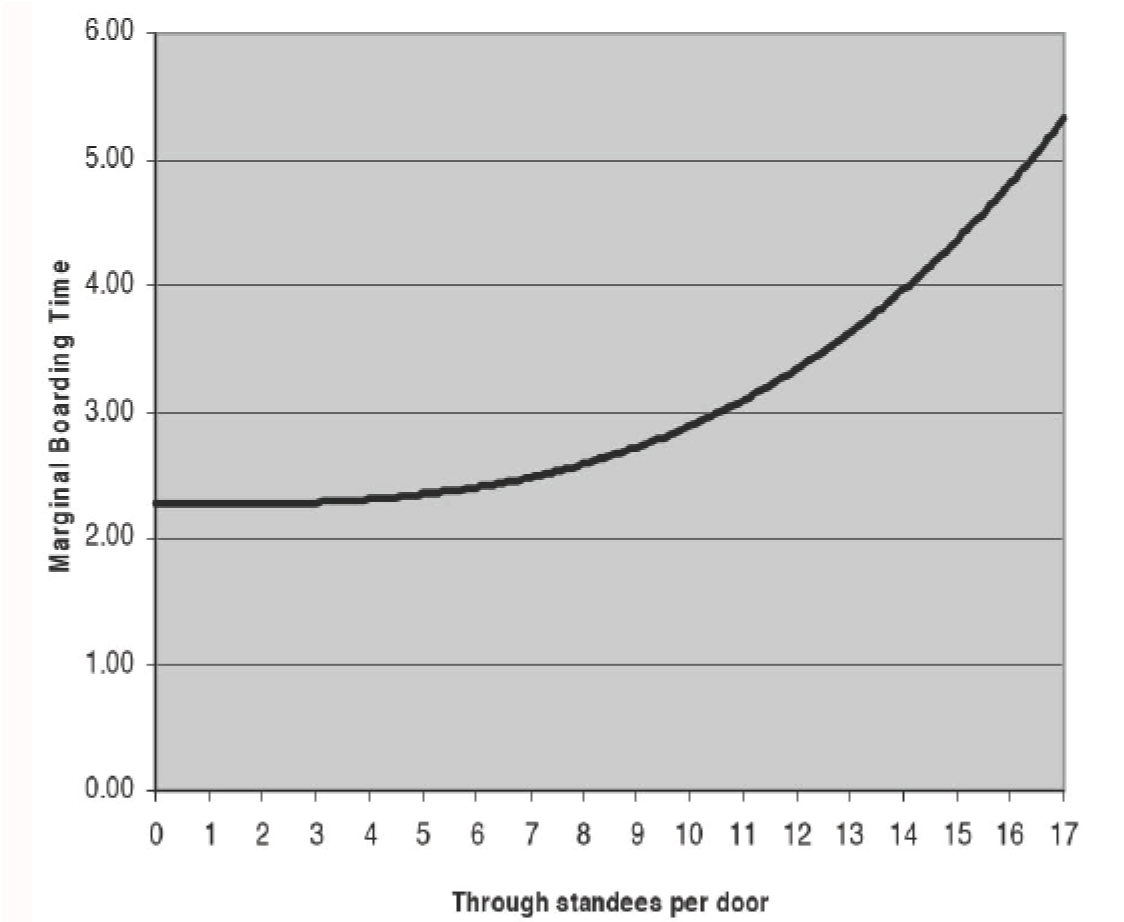
TS_d = through standees *per door*

(i.e. total through standees divided by the number of doors)

This formulation also includes a term ($TS_d^3 B_d$) which accounts for delayed boarding time associated with more crowded vehicles. Source: Puong (2000)

below illustrates the effect of vehicle crowding on boarding flow rates.

FIGURE 4-1: BOARDING TIME AS A FUNCTION OF RAILCAR OCCUPANCY



Source: Puong (2000)

4.5.2.2 OPERATING MARGIN

An operating margin must be introduced in estimating station capacity. This is a buffer time to allow for random variation in dwell time. An operating margin allows for dwell time variability without disrupting scheduled operating.

The operating margin can be set at 25 to 30 seconds or can be based on two standard deviations from the mean observed dwell time. The average dwell times, based on North American experience, range from 30 to 50 seconds and the coefficient of variation ranges from 0.25 to 0.70.

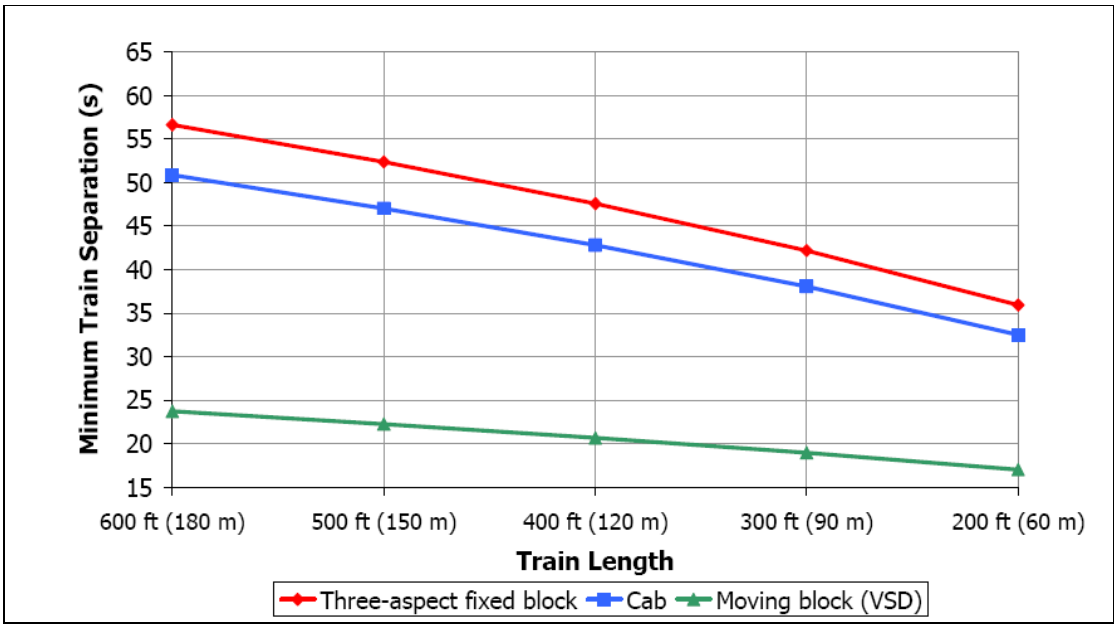
4.5.2.3 MINIMUM SEPARATION INTERVAL

In addition to the dwell time and operating margin, an additional separation time between successive trains is required. This additional separation time is the sum of two related factors.

the time required for a train to travel its own length and clear the station, and, a safe separation time between trains that depends on characteristics of the signal systems, platform length, train length and station.

The safe separation time depends on, among other things, characteristics of the signal system, platform length, train length, and station approach speed. **Error! Reference source not found.** shows safe separation time excluding station dwell time and operating margin as a function of train length, and type of signal system. Note that the separation distance increases with the train length. Further, the figure shows that a three aspect fixed block signal system has the highest safe separation distance, cab signaling is slightly less. The moving block signal system with variable stopping distances has the lowest separation. The Transit Capacity and Quality of Service Manual, part 5, Chapter 7 contains a more detailed treatment of this topic.

FIGURE 4-2: MINIMUM TRAIN SEPARATION



4.5.2.4 MINIMUM HEADWAY RELATIONSHIP

The minimum headway is obtained by summing the various headway components. The basic equation is as follows:

$h = t_d + t_{om} + t_{cs}$ (Eq. 4.2)

Where,

h = minimum headway

t_d = average dwell time at critical station

t_{om} = operating margin

t_{cs} = minimum train control separation

the number of trains per track per hour, the line capacity, is computed as follows:

T = 3600/h (Eq. 4.3)

Where,

T = line capacity (trains/h)

Modern signal systems with 182 meter trains and a critical stop with modest average dwell times (i.e. less than 30-40 seconds) can support between 24 and 30 trains per track per hour.

Modern systems with cab or moving block signals and single routes (no branches or merges) can operate slightly more frequently. Transit managers rarely schedule more than 30 tranis per hour despite the fact that the theoretical capacity is higher.

Example: The critical station in a proposed rapid transit system has been identified and the number of train boardings per hour is expected to be 5,000, and discharges of 2,000. The system will have 6 car trains each 20m long with three doors per car. The design frequency is expected to be about 30 train per hour. The busiest door will have 30% more transactions as the average door and trains are expected to have 10 through passengers per door. Determine if the system can maintain 30 trains per hour.

1. Compute peak flow through busiest doors:
5,000 passengers boarding per hour / 30 trains per hour / 6 cars per train / 3 doors per car = 9.3 passenger boardings per door .
2,000 passengers boarding per hour / 30 trains per hour / 6 cars per train / 3 doors per car = 3,7 passenger discharges per door .

2. Adjust upward for ratio of busiest door to average door:
9.3 * 1.3 = 12 boardings
3.7 * 1.3 = 5 discharges
Using the Puong formulation, the expected dwell time is:
SS = 12.22 + 2.27 * Bd + 1.82 Ad +6.2* 10-4 * TSd3Bd
= 12.22 + 2.27 * 12 +1.82 *5 +6.2 *10 -4 * 103 * 12
= 56 seconds
Operating margin = 25 seconds
Safe separation time = 42 seconds
The total is 123 seconds. It is likely that the 2 minute headway may be maintained.

The running way capacity in trains per track per hour depends on the passenger dwell time at intersections, the likely variation in the dwell time (the operating margin), the time for trains to clear stations and the safe separations between trains.

Example: Compute the train capacity in trains per hour of a rail transit system where the governing dwell time is 45 seconds, the operating margin is 13 seconds and the minimum train control separation is 45 seconds.

Minimum headway: 45 sec + 13sec + 45 sec = 103 sec. This is about 35 trains per hour

4.5.2.5 VARIATION IN LINE CAPACITY

Line capacity is influenced by several variables. These include type of signal control, train consist length and operating speeds. The Transit Capacity and Quality of Service Manual guide indicates the following ranges in train per track per hour.

Fixed block – 30 or less if long dwell times

Cab single controls 30-34

Moving block 35-40

Error! Reference source not found. shows the combined effects of station dwell times, operating margins and signal control times on line capacity.

TABLE 4-4: COMPONENTS OF MINIMUM TRAIN SEPARATION TIME

		Safe Separation Time (sec.)			Maximum Frequency (trains/hr.)		
Average Dwell Time (sec.)	Operating Margin (sec.)	Fixed Block	Cab	Moving Block	Fixed Block	Cab	Moving Block
30	20	24	50	57	49	36	34
30	30	24	50	57	43	33	31
40	20	24	50	57	43	33	31
40	30	24	50	57	38	30	28
50	20	24	50	57	38	30	28
50	30	24	50	57	35	28	26

4.5.2.6 TURNAROUNDS

The basic end-of-line track configuration is illustrated in **Error! Reference source not found.**. An entering train (presumably on the right track) goes to the station platform on the right track unless it is occupied by another train. In such cases, it must crossover to the other platform. The geometry and train performance characteristics will determine a maximum layover duration per train that can be accommodated for each value of scheduled headway. If the layover time exceeds this maximum, then trains will be delayed and the scheduled frequency will not be able to be maintained.

On train systems with short headways and long train length, this may require drop-back crew scheduling in which the driver of the entering train is relieved by a second driver. The first trainman then walks the length of the train and drives the following scheduled train on that platform. This enables some driver layover time, assures on-time departure for scheduled trips and maintains service consistent with the system design.

FIGURE 4-3: TRAIN TURNAROUND SCHEMATIC DIAGRAM

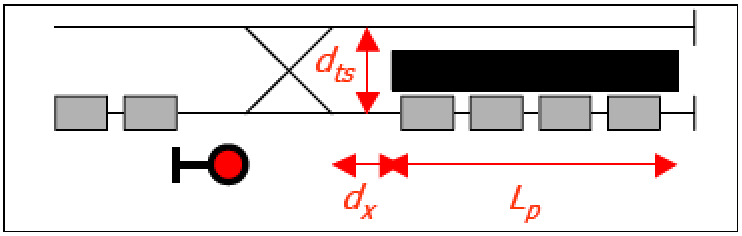


Table 4.6 below illustrates the maximum layover for the simple configuration using common values of geometry and train performance. The last row illustrates the number of seconds that a driver requires to walk the length of the train at a walking speed of 1.9 km/hr.

TABLE 4-5: MAXIMUM TRAIN LAYOVER

Headway		Platform length (m)		
Minutes	**Seconds**	**150**	**200**	**250**
2	120	186	182	179
4	240	423	419	416
5	300	529	525	522
6	360	644	640	637
seconds to walk train length		80	106	134

A common practice in train turnaround design is to extend the track beyond the station (tail tracks) and provide a second crossover there. This allows separate boarding and exit platforms. In such situations, three track terminals are provided with two sets of island platforms. This arrangement allows simultaneous boarding (or alighting) of two trains. Specific designs will depend on service requirements and physical conditions.

In some cases, three tracks are provided at terminal stations. Capacity calculations for such arrangements are more complex.

4.5.2.7 BRANCH OR JUNCTION CAPACITY

Branches and junction are rarely used in modern rail rapid transit design. Analytical relationships are complex and train simulation models may be appropriate. The US Transit Capacity and Quality of Service manual indicates that flat, at grade junctions may support two minute headways but with delays, grade separated relationships can sustain 150 to 180 second intervals between trains.

4.6 LINE PASSENGER CAPACITY

Train consist capacity in terms of people per train depends on (1) train length and width, number of rail cars per train and passenger loading standards. Usually, the capacity is governed by the allowable crowding during the busiest 15 or 20 minutes during the peak hour.

Examples of train capacity are shown in table 4.10. The table shows the maximum train capacity for various rail rapid transit lines throughout the developing world. The capacity is based on the transit agency loading standard for passengers per square meter of standing space plus the number of seats. Standee density ranges from 6 to 8 passengers per square meter. New York City uses a loading standard of 3 square feet per passenger for schedule design purposes. This translates into about .25 square meters per passenger, substantially lower than the comparable density used in developing countries. This suggests that a lower standard might be used in developing countries.

Suggested **schedule** design guidelines for cities in developing countries are as follows:

Standing passengers per square meter	5-6
Total passengers per meter of train length	9-10

As in the case of bus service, the scheduled loading standard should be applied to the peak within the peak. If they are applied across the entire peak hour or peak period, there will be some trains with extraordinarily high loading beyond the standard.

4.6.1 PASSENGER CAPACITY

The previous discussion illustrated computational methods for train capacity in trains per track per hour and the vehicle capacity in persons per train car. The passenger capacity is computed as the product of the train capacity and vehicle capacity adjusted by the peak hour factor:

$$P = TV(PHF) = 3{,}600\ V(PHF)/\ h_{gs} \qquad \text{(Eq. 4.4)}$$

Where,

T = track capacity in trains per hour

V = train capacity

PHF = peak hour factor

Example: A transit system operates 6 car trains which are 20 meters feet long per car. If the peak hour factor is 0.9 and the maximum line capacity is 30 trains per hour what is the passenger capacity of the line.

V = pass/car * cars/train = (20 *10) * 6 = 1200 pass/train
P = V * PHF * trains/hour = 1200 * .9 *30 = 32,400 passengers/hour/track

Vehicle capacity is highly dependent on trainset length and the seating configuration. **Error! Reference source not found.Error! Reference source not found.** below shows the maximum vehicle capacity per trainset for a variety of rail transit lines throughout the developed world. The capacity is based on an assumed loading standard (shown in the table in standing passengers per square meter) and the number of seats.

TABLE 4-6: TRAIN CAPACITY

City	Train length (m)	Cars	Seats	Total Capacity	Loading Standard (p/m^2)
Bangkok	65	3	126	1,139	8
Guanzhou	59	3	142	675	6
Shanghai	140	6	288	1,860	6
Singapore	138	6	300	1,728	6
Shenzen	140	6	288	2,208	6

It is convenient to think about the capacity in the form of seats and standees per meter of length. Planners must trade off seating capacity for standing capacity. Higher seating density such as transverse 2 + 2 seating occupies about 3.5 seats per meter of train length. Longitudinal or peripheral seating occupies about 2.5 seats per meter of length. Using these estimates and various loading conditions, the capacity of various train car lengths can be computed.

A calculation similar to that offered for buses for an approximate capacity of rail cars is as follows:

$$V_c = \frac{(L-1)*(W-0.2)}{S_{sp}} + (1-S_a/S_{sp})N\frac{((L-1)-D_nD_w)}{S_w}$$

where

V_c = Total vehicle capacity (seats plus standees)

L = Vehicle length (m)

W = Vehicle width (m)

D_n = Number of doorways

W_s= Doorway setback (m)

D_w = Doorway width (m)

S_a = Area of single seat (m^2) [0.5 m^2 for transverse,0.4 m^2 for longitudinal]

S_{sp} = Standing space per passenger

N = Vehicle arrangement

[2 for 2 seats/row, 3 for 2 + 1 seats/row, 4 for 2 + 2 seats/row, 5 for 2 + 3 seats/row]

S_w = Seat pitch [0.69 m for transverse, 0.43 m for longitudinal]

Error! Reference source not found. below shows the seating capacity per car of a rail car with transverse seating for varying car lengths and number of doors per side. As in the case for bus capacity, the design number of passengers per unit of area is shown.

TABLE 4-7: TRAIN CAR CAPACITY

Passengers/ sq.m	Rail Car Length (m) and number of doors per side		
	13	20	25
	3	3	4
4	170	202	234
5	227	264	306
6	280	327	378
7	333	389	450
8	387	452	522

There is likely to be some diversity of loading of trains, especially if movement between train cars is prohibited. Similar to the peak hour factor, a loading diversity factor should be introduced to adjust the computed theoretical capacity[7]. The effective train capacity can be computed as:

$V = N * V_c * DF$

[7] There is little published data on this variability. It is reported that the rail transit operator in Santiago de Chile has a system by which individual cars in a train consist are weighed upon departure from busy stations as a means of monitoring passenger load volumes.

where,

V = train capacity

N = number of cars per train

V_c = capacity per car

DF = loading diversity factor

The loading diversity factor is the ratio of the number of customers on the train with the most crowded car to the theoretical capacity of the train.

5 STATION PLATFORM AND ACCESS CAPACITY

The transit station platform and its ancillary access facilities provide an integrated system of pedestrian movement and accommodation. **Error! Reference source not found.**shows how the various elements relate while **Error! Reference source not found.** provides a more detailed description of each element.

FIGURE 5-1" INTERRELATIONSHIP AMONG STATION ELEMENTS

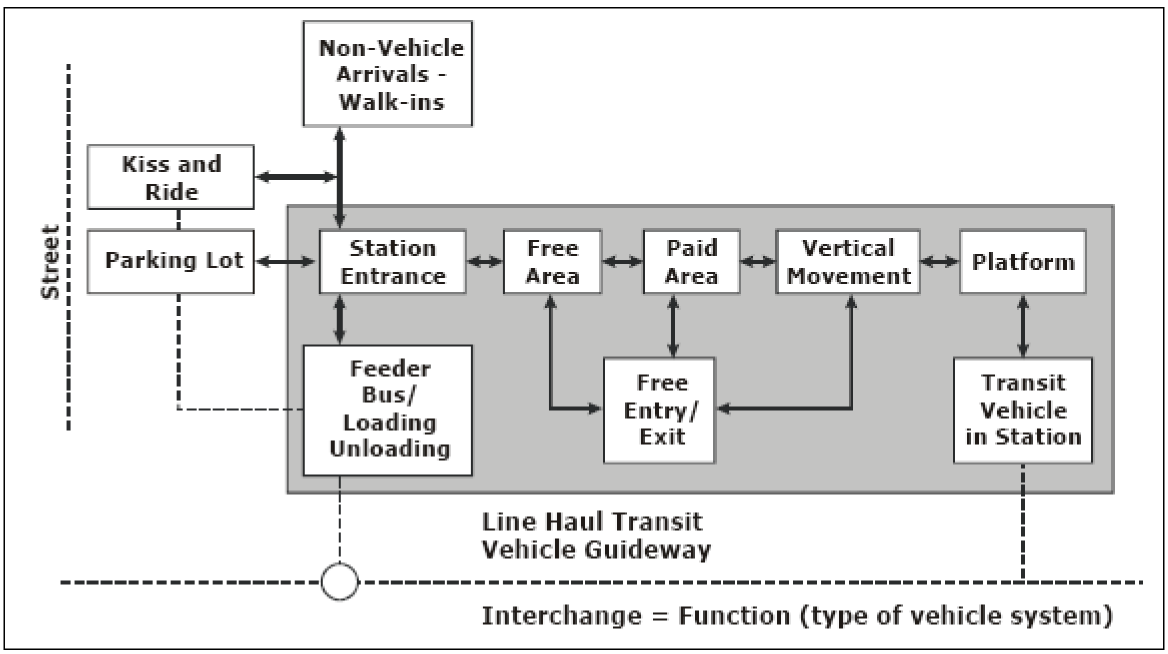


TABLE 5-1: ELEMENTS OF PASSENGER FLOW IN A TRAIN STATION

Train arrival	On or off schedule; train length; number and location of doors
Passengers	Number boarding and alighting; boarding and alighting rates passenger characteristics; mobility device use, baggage or packages carried, bicycles and strollers, etc.
Platform	Length, width and effective area; location of columns and obstructions;

	system coherence; stair and escalator orientation, line of sight, signs maps and other visual information
Pedestrians	Walking distance and time; number arriving and waiting; effective area per pedestrian; levels of service
Stairs	Location; width; rider height and tread; traffic volume and direction; queue size; possibility of escalator breakdown
Escalators	Location; width direction and speed; traffic volume and queue size; Maintainability
Elevators	Location; size and speed; traffic volume and queue size; maintainability alternate provision for disabled passengers when elevator is non-functioning

5.1 PEDESTRIAN FLOW CONCEPTS

An understanding of pedestrian flow through a rail transportation facility should start with some fundamental concepts. Pedestrian capacity can be thought of as either an occupancy level (passengers per unit of area) or a flow (passengers passing a point per unit of space or time.) While in any terminal element, there is a theoretical maximum occupancy or flow rate, actual operations suggest that the practical sustainable level of occupancy or flow is less than the theoretical value. It is this lower level which should be used in design. Design for the maximum level does not allow either a buffer time or space for random unexpected events such as mechanical equipment failure and variation in station dwell time or arrival intervals between successive trains.

The primary relationships among pedestrian speed, density and flow rate were established years ago and are familiar to transit planners and engineers. The governing factors are:

- Pedestrian flow rate – The number of pedestrians who can travel through a point per unit of time.
-
- Pedestrian speed – the average pedestrian walking speed through a facility
-
- Pedestrian density – the average number of pedestrians per unit of space. It is a measure of crowding. The tolerance for varying levels of crowding varies throughout the world.

The relationship between the three is:

v = S x D (Eq. 5.1)

where,

v = pedestrian flow rate (persons/min.)

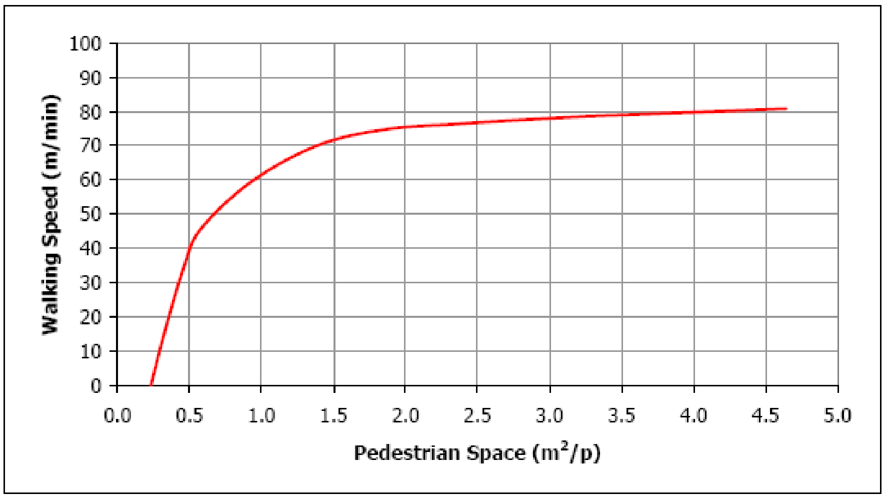
S = pedestrian speed (meters/min.)

D = pedestrian density (persons/meter^2)

The physical relationships are more complicated. At low densities, which might occur during low volume times, the average walking speeds of pedestrians are determined by the free flow speeds of individuals. However, as pedestrian volume increases, facility becomes more congested, the interaction between pedestrians results in reduced average speed. This is because of closer contact between pedestrians and limited ability of people to pass slower walking individuals. It is similar to traffic environments where higher density (cars per mile) is associated with lower speed.

Error! Reference source not found. shows how pedestrian speeds (minutes per meter) increases as pedestrian space (square meters per pedestrian) increases.

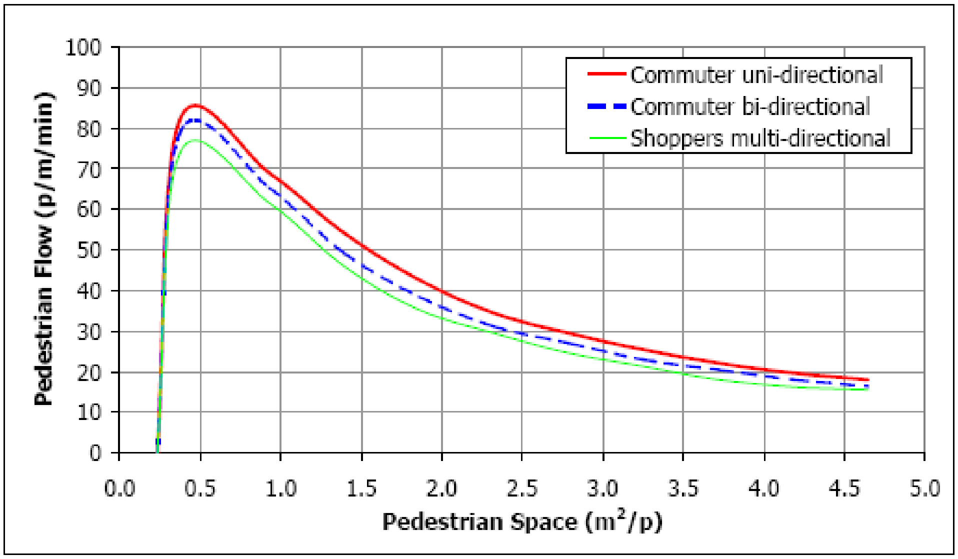
FIGURE 5-2: WALKING SPEED RELATED TO PEDESTRIAN DENSITY



The flow rate, measured in pedestrians per hour is the product of speed and density. Researchers commonly normalize the flow rate per unit width of the facility (corridor, staircase etc.), it is probably more practical to think of flows as flow rates per lane of width with each lane being about 0.75 meters.

Error! Reference source not found. shows how the pedestrians per meter per minute decreases as the square meters of space per pedestrian.

FIGURE 5-3: PEDESTRIAN FLOW RATE RELATED TO PEDESTRIAN DENSITY



An illustration of pedestrian occupancy on station platforms and other queuing areas are shown in **Error! Reference source not found.** gives the ratings of these areas that are used in the United States.

TABLE 5-2 : PEDESTRIAN LEVEL OF SERVICE

LOS	Pedestrian Space (m^2/p)	Avg. Speed, S (m/min)	Flow per Unit Width, v (ped/m/min)	v/c
A	>3.3	79	0-23	0.0-0.3
B	2.3-3.3	76	23-33	0.3-0.4
C	1.4-2.3	73	33-49	0.4-0.6
D	0.9-1.4	69	49-66	0.6-0.8
E	0.5-0.9	46	66-82	0.8-1.0
F	<0.5	<46	Variable	Variable

v/c = volume to capacity ratio

5.2 PLATFORM CAPACITY

The capacity of a rail station platform should be sufficient to avoid overcrowding during normal operations and ensure the safety of passengers during emergency operations. Both conditions require adequate pedestrian access between the platforms and the station entrance.

Station platform dimensions should be adequate to accommodate doors of the longest train operated, with some extra distance in the case of errant stops. They should be wide enough to allow a 0.6 meter edge strip, the entry and maneuvering of wheelchairs and to avoid passenger overcrowding.

Access to and from the station should be sufficient to clear at least one train, preferable two trains, before the second train arrives.

The platform dimensions should be sufficient to minimize passenger crowding. The acceptable degree of overcrowding will vary among systems The following station capacity procedures are keyed to the pedestrian densities (e.g. passenger occupancies) shown in figure xxx.

The first step in determining the required platform capacity is to establish the design quality of service. While US practice is to assign a letter designation (A-F) to various densities of queuing area occupancy, having a design occupancy in persons per square meter will suffice. This level should be adjusted to account for factors such as more persons with large briefcases or handbags.

The design level of customers at any one time should be computed to obtain the net required area for waiting. The platform capacity must include space for passenger circulation and designers should recognize that the effective area is diminished by other factors.

- Passengers avoid platform edges. About 0.5 to 0.6 meters from the edge of platform should be deducted from the queuing space. If platform screens are used, occupancy to the edge of the platform can be assumed.
- There is lower passenger density at the ends of the station platform
- Capacity is diminished by columns on platforms and other items such as street furniture
- Circulation space is required where vertical circulation elements such as stairs and escalators intersect with platforms.

There is some interaction between platform capacity and train headway. The design headway should enable each customer to board the next arriving train at all stations under normal operating conditions recognizing that the ability to board passengers at a station in diminished by the number of through passengers on arriving trains. Under normal conditions, the platform capacity should be sufficient to hold the number of expected passenger arrivals between the scheduled arrival of two successive trains.

The US practice is to design station platforms to be large enough to accommodate the anticipated boardings during the peak 15 minutes under *extreme* operating conditions. The design event for the purpose of platform capacity is to assume that a single train is removed from the service schedule. That is, for a narrow time interval, the effective train headway is twice the published headway. Under these circumstances, there will be a larger than normal number of persons waiting for the train. The design volume of passengers waiting would be the expected arrival rate of passengers per minute during the peak 15-minute interval times the scheduled headway times

2 to account for the train removed from the schedule. Note that emergency egress requirements of arriving trains may require larger platform sizes.

The platform size for waiting passengers is determined by the design number of waiting passengers divided by the design occupancy standard.

5.3 STATION EMERGENCY EVACUATION

Safe evacuation of station platforms in underground transit systems is an important element of their design. Design requirements usually require evacuation of a facility within a certain time limit. This involves an assessment of the design volume and the capacity of the pathway from the platform to a safe location.

In the United States, the National Fire Protection Association (NFPA) develops minimum standards for fire safety. NFPA 130 is the *Standard for Fixed Guideway Transit and Passenger Rail Systems* and is used for designing new stations or renovating existing stations. For the purposes of capacity assessment, essentially, the standard requires that facilities meet two tests:

1. the station platform can be evacuated in four minutes or less
2. every occupant on a platform can evacuate to a safe area within 6 minutes

In order to determine the number of required points of egress, the design station occupant load must be established. The station occupant load is defined as the sum of the entraining (waiting) load on the platform and the calculated train load on the next train at or entering the station. Note that if the station has multiple platforms, a separate calculation of the occupant load and evacuation times must be performed for each one as the guidelines require design for safe evacuation from individual platforms. Methods for computing entraining and on-board train load are discussed later in this section.

After the evacuation load of the station platform is determined, the quantity and location of exits must be determined. NFPA guidelines state that a person should not have to travel more than 91 m or 4 minutes to exit the platform, or be more than 6 minutes from a point of egress. These conditions may, however, be exceeded if certain engineering features (such as emergency ventilation or fire retardant materials) are used. The following table (**Error! Reference source not found.**) details specifications and the flow requirements through various points of egress from the underground station.

TABLE 5-3: EMERGENCY EXIT CAPACITIES AND SPEEDS

	Minimum width	Capacity	Travel Speed
Emergency Exit Type	m	p/m/min	(m/min)
P atforms, Corridors an ramps with slope ≤ 4%	1.73	89	61.0
Stairs, Stopped Escalators up direct on	1.10	63	15.2
Stairs, Stopped Escalators down direction[1]	1 12	72	18.3
Ramps with slope > 4% up direction	1.83	63	15.2
Ramps with slope > 4% down directi n	1.83	70	15.2
Doors and gates	0.91	89	
Fare collection gates[2]	0.51	50 ppm	
Fare collection turnstile[3]	0.46	25 ppm	

ppm = people per minute
p/m/min = persons per meter per minute
mpm = meters per minute

Notes to table:
1. Escalators cannot count for more than 50% of emergency exits
2. Gates cannot exceed 1016 mm in height
3. Turnstiles cannot exceed 914 mm in height

In addition to the main emergency exits, stations are required to have a second emergency means of egress of at least 1.12 m in width. The second exit must also be along a different route than the main exit.

To determine exit capacity of passengers for constricted exits which have a capacity limitation such as doors and stairs, the capacity in persons per meter per minute is multiplied by the width of the exit type. For example:

Doorway Exit Capacity

$$.9\ m \times 89 \frac{p}{m}/min = 80\ ppm$$

For a more conservative approach to determining exit capacity, **effective** exit widths should be used for platforms corridors and ramps. Effective widths take into consideration usable exit widths, and not physical dimensions. For example, a door on side hinges, when opened, may (but not always) limit the exitway from 0.9 m to 0.8 m, and thus reduces the exit capacity to 71 ppm. **Error! Reference source not found.** shows effective widths for different emergency exit types.

TABLE 5-4: EFFECTIVE WIDTH OF EMERGENCY EXIT TYPES

	Minimum width	Effective width
Emergency Exit Type	M	M
Platforms	1.73	1.07 at platform edge 1.22 at walls

Corridors and Ramps ≤4%	1.73	1.22 at walls

Other types of emergency exits, such as doors, do not need effective widths for design purposes, but any unusual features should be kept in mind when calculating capacity on an existing facility.

When designing the flow of persons from the station to a safe distance, it is important to consider the sequence of exit types, and any bottlenecking that may consequently occur during escape. For example, if the path from the platform to the street level consists of a doorway and then a staircase, the total flow will be limited by the staircase. Thus, when calculating the design flow, it does not matter that 81 ppm can pass through the door if the staircase can only service 70 ppm.

Active escalators can be considered emergency exits with some restrictions. If an escalator can operate in both directions, then it is considered an emergency exit. If the escalator can only run in one direction, it is only an emergency exit if running in the exit direction. If it is operating in the wrong direction, the escalator must be capable of manual or automatic stopping to be considered effective in evacuation. Note that a running escalator does not have any additional emergency capacity than a stairway or a stopped escalator. Also, when considering escalators as points of egress, one should design the facility as if the most highly used escalator is out of order for maintenance.

An example of how the evacuation assessment is conducted in contained in an appendix.

5.4 LEVEL CHANGE SYSTEMS

Rail rapid transit stations and some bus rapid transit require a level change for passengers. This can be done before or after fare payment or when exiting from platforms. The methods of changing levels include escalators, stairs and elevators.

5.4.1 STAIRWAYS

Stairway capacity is usually measured in number of passengers per meter of width per minute. However, since persons on stairways (and escalators) normally walk in line, a more practical method of estimating capacity is to assess the flow per lane with each lane being about 0.75 meters wide.

As in the case of pedestrian flows, the flow volume of a staircase depends on average walking speed and the pedestrian density. **Error! Reference source not found.** gives pedestrian flow rates (passengers/min) at low density, free flow operation and at design flow where density is much higher.

TABLE 5-5: STAIRWAY FLOW CAPACITY

Traffic Type	Free Design Flow (.6 P/m²)		Full Design Flow (2.0 P/m²)	
	Speed (m/s)	Flow (p/min)	Speed (m/s)	Flow (p/min)
Young/Middle Aged Men	0.9	27	0.6	60
Young/Middle Aged Women	0.7	21	0.6	60
Elderly people, family groups	0.5	15	0.4	40

Source: Transit Capacity and Quality of Service Manual

5.4.2 ESCALATORS

Escalators can transport passengers for level changes up to 200 feet. In most rail transit systems, they are the primary means of changing level from the ground to the station platform and crossovers. The theoretical and observed capacity are shown the table below. The theoretical capacity assumes that each stair is occupied by a traveler. The more likely case of lower density on escalators results in a nominal observed capacity as illustrated in **Error! Reference source not found.**.

TABLE 5-6: ESCALATOR CAPACITY

Step Width	Speed	Maximum Capacity Theoretical	Nominal Capacity Observed
600 mm	.45 mps	422/5 min 5063/hr	168/5 min 2025/hr
	.50 mps	469/5 min 5626/hr	187/5 min 2250/hr
	.60 mps	562/5 min 6751/hr	225/5 min 2700/hr
800 mm	.45 mps	506/5 min 6075/hr	Same as 600 mm
	.50 mps	562/5 min 6751/hr	Same as 600 mm
	.60 mps	675/5 min 8102/hr	Same as 600 mm
1000 mm	.45 mps	675/5 min 8102/hr	337/5 min 4051/hr
	.50 mps	750/5 min 9002/hr	337/5 min 4051/hr
	.60 mps	900/5 min 10800/hr	450/5 min 5401/hr

Source: Strakosch, 1983.

5.4.3 ELEVATOR CAPACITY

Elevators are necessary to accommodate certain travelers who due to disability, fear or personal preference do not use stairs or escalators. In some deep tunnel transit systems, elevators are the primary means of access to station platforms, with stairs used only for emergency evacuation. In such cases, high capacity, high speed elevators must be deployed.

The throughput capacity of an elevator system is primarily a function of elevator cab size and cycle time. Due to high hoist speeds, the average cycle time does not vary considerably in the normal range of 7 – 10 meters for each level.

Error! Reference source not found. below shows some observed values of elevator cab capacity of a range of commercially available elevators. Note that the observed passenger density in the range of 4-5 passengers per square meter. While densities may be higher in some countries, the capacity of an elevator is also limited by the rated allowable weight.

TABLE 5-7: ELEVATOR CAB CAPACITIES

	Car Inside (mm)			
Capacity (kg)	**Width**	**Depth**	**Area (m^2)**	**Observed loading (passengers)**
1200	2100	1300	2.7	10
1400	2100	1450	3.0	12
1600	2100	1650	3.5	16
1600 (alt.)	2350	1450	3.4	16
1800	2100	1800	3.8	18 or 19
1800 (alt.)	2350	1650	3.9	18 or 19
2000	2350	1800	4.2	20
2250	2350	1950	4.6	22
2700	2350	2150	5.1	25

Source: Strakosch, 1983.

The cycle time of elevators is determined by vertical travel distance and speed, door opening speed and width. Larger elevators have heavier and wider doors resulting in longer door opening times. Further, larger elevators have longer stop dwell time to allow for passenger entries and discharges.

Error! Reference source not found. shows some typical value of throughput capacity. Note that the capacity is not very sensitive to elevator speed since most of the elevator cycle time is used for boarding and discharging passengers.

TABLE 5-8: ELEVATOR THROUGHPUT CAPACITY IN PASSENGERS PER HOUR PER DIRECTION

		Elevator Speed (m/sec)				
Elevator Cab Passenger Capacity	**Floor height (m)**	**0.5**	**1**	**1.5**	**2**	**2.5**
10	4.5	390	410	420	420	430
10	6	380	400	410	420	420
10	9	360	390	400	410	420
15	4.5	430	440	450	450	450

15	6	420	440	440	450	450
15	9	400	430	440	450	450
20	4.5	450	460	470	470	470
20	6	440	460	460	470	470
20	9	430	450	460	460	470
25	4.5	470	470	480	480	480
25	6	460	470	480	480	480
25	9	450	460	470	480	480

Source: Strakosch, 1983.

5.5 FARE COLLECTION CAPACITY[8]

A potential bottleneck in the flow of passengers through a transit station is the sale of fare media. In larger cities, fare media are frequently sold by vendors not affiliated with the transit system. Sales at transit stations (bus or rail) are handled either by staffed agent stations or ticket vending machines.

There are two fundamental approaches to determining the capacity of vending machines or staffed ticket booths. On the one hand, the expected number of transactions during the peak hour divided by the mean service time per machine or service lane provides a rough estimate of the number of machines or service lanes required to meet capacity during the peak hour. On the other hand, the arrival rate of customers and the distribution of service times of TVM's and staffed booths may result in short periods of long delays regardless of the capability of the system to eventually process all customer requests during the peak hour. The analysis of this section will assume a uniform flow rate throughout the busiest hour.

In a simple construct, if TVM transactions take on average 30 seconds, a TVM should be installed for every 120 expected transactions per hour.

5.6 STATION ENTRANCES

The entrance to rail stations (and bus stations) is likely to have a barrier door which constricts entering and exiting passengers from the station. **Error! Reference source not found.** illustrates the range of observations of capacity of a variety of doorway types per lane of travel.

TABLE 5-9: PORTAL CAPACITY

Portal Type	Flow (persons/minute)	Flow (persons/hour)
Gateway	60-110	3600-6600
Clear Opening	60-110	3600-6600
Swing Door	40-60	2400-3600

[8] Some of this material may apply to off-board fare collection at BRT stations.

Swing Door (fastened back)	60-90	3600-5400
Revolving door	25-35	1500-2100

Source: Transit Capacity and Quality of Service Manual

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APPENDIX A - SAMPLE BUS OPERATIONS ANALYSIS PROBLEMS

PROBLEM STATEMENT

A transit agency is expecting a 60% increase in ridership over the next five years. The system is currently carrying 1,800 passengers per hour through the peak load segment with a headway of 2 minutes. Calculate the current capacity and establish options that will increase capacity to account for this increase in ridership

CURRENT OPERATING CONDITIONS

The following are the current operating conditions:

- On-board fare collection
- 1800 passengers through maximum load segment during the peak hour
- Bus length 13m
- Green to cycle time at critical stop (g/C) = 0.6
- Acceptable failure rate= 10%
- 1 Loading area at critical stop
- Peak hour factor = 0.75
- Right turns at critical stop in bus lane – 200 per hour
- 400 conflicting pedestrians per hour
- Critical stop is far side
- Curb Lane Volume = 400 veh/h
- Curb Lane Capacity = 600 veh/h
- Average dwell time = 30 sec.
- Average clearance time = 11 sec.
- Standard deviation of dwell times = 8 sec
- Design standing capacity 4 persons/m^2

ANALYSIS APPROACH

In this analysis, we determine if the offered headway (2 minutes) is sufficient to accommodate the current ridership level at the accepted loading standard. The next step is to determine the capacity of the bus stop at the critical intersection. This will enable an assessment of capacity increasing strategies such as increasing service frequency.

$B = P / (P_{max}\ PHF)$

Where,

P = design peak hour flow

B = number of buses per hour to accommodate the peak flow

P_{max} = maximum capacity of each bus (13 m, 4 m^2/standee)

PHF = peak hour factor

Calculation 1	
P	*1,800*
P_{max}	*11*
PHF	*90*
B	*28*

This assessment suggests that the 30 buses offered per hour is sufficient to accommodate the demand at an acceptable loading level.

Step 1 – Computer current capacity for a single berth stop

1.1 Compute operating margin

$$t_{om} = sZ$$

where,

t_{om} = operating margin (s)
s = standard deviation of dwell times
Z = standard normal variable corresponding to a desired failure rate (See table below).

TABLE 5-10: FAILURE RATE ASSOCIATED WITH Z-STATISTIC

Failure rate	Z
1%	2.33
2.5%	1.96
5%	1.65
7.5%	1.44
10%	1.28
15%	1.04
20%	0.84
25%	0.68
30%	0.53
50%	0

$$t_{om} = 8 * 1.28 = 10.2$$

1.2 Compute bus loading area capacity for one berth

Bus Loading Area Capacity $$B_l = \frac{3{,}600\,(g/C)}{t_c + t_d(g/C) + t_{om}}$$

B_l = loading area bus capacity (bus/h)

3,600 = number of seconds in 1 hour

g/C = green/cycle time ratio

t_c = mean clearance time (s)

t_d = mean dwell time (s)

t_{om} = operating margin (s) (from task 1.1)

Calculation 2	
g/C	*0.6*
t_c	*11*
t_d	*90*
Z	*1.28*
cv	*0.09*
s	*8*
t_{om} = sZ	*10*
B_l(bus/h)	*55*
headway (sec)	*60*

1.3 Adjust for mixed traffic in the right lane

The operating environment includes a right turning lane in the bus lane. This can significantly reduce the flow-through capacity of the bus lane. Fortunately, the bus stop is a far side bus stop which reduces the conflict between right turning vehicles and the through buses. The procedure to determine an adjustment factor to account for mixed traffic is: is to apply the mixed traffic adjustment factor as follows:

Mixed Traffic Adjustment Factor $f_m = 1 - f_l\left(\frac{v}{c}\right)$

where,

f_m = mixed traffic adjustment factor

f_l = bus stop location factor (See table below)

v = curb lane volume (veh/h)

c = curb lane capacity (veh/h) (see table below)

The curb lane capacity is a function of the number of conflicting pedestrians and the traffic signal g/c ratio.

TABLE 5-11: BUS STOP LOCATION CORRECTION FACTOR

Bus Stop Location Factors			
Bus Stop Location	Type 1	Type 2	Type 3
Near side	1	0.9	0
Mid block	0.9	0.7	0
Far side	0.8	0.5	0

TABLE 5-12: RIGHT TURN CURB LANE VEHICLE CAPACITIES

	g/C Ratio for Bus Lane					
Conflicting Pedestrian Volume (ped/h)	0.35	0.4	0.45	0.5	0.55	0.6
0	510	580	650	730	800	870
100	440	510	580	650	730	800
200	360	440	510	580	650	730
400	220	290	360	440	510	580
600	70	150	220	290	360	440
800	0	0	70	150	220	290
1000	0	0	0	0	70	150

Calculation 2	
f_l	*0.8*
v	*200*
c	*580*
$f_m=1-f_l(v/c)$	*0.724*

1.4 Compute Bus Facility Capacity

The bus facility capacity is:

$$B = B_l N_{el} f_m$$

where,

B = Bus Facility Capacity (bus/h)

B_l = Bus Loading Area Capacity

N_{el} = number of effective loading areas (See table below)

f_m = mixed traffic adjustment factor

TABLE 5-13: ON-LINE LOADING AREAS, RANDOM ARRIVALS

Loading Area	Efficiency	Number of Effective Loading Areas (N_{el})
1	100%	1.00
2	75%	1.75
3	70%	2.45
4	20%	2.65
5	10%	2.75

Calculation 3	
B_l	55
N_{el}	1
f_m	0.724
B	40

This suggests that the single berth facility is sufficient to accommodate the design headway of 2 minutes or 30 buses per hour since the capacity is 40 buses per hour.

1.5 Estimate person capacity for a single berth stop

The person capacity is:

$$P = P_{max} B(PHF)$$

where,

P = person capacity (p/h)

P_{max} = maximum schedule load per bus (p/bus) (See table below)

B = Bus facility capacity (bus/h)

PHF = Peak hour factor

TABLE 5-14: BUS VEHICLE CAPACITY

Bus type	single	articulated	bi-articulated
Doorways	2	3	4
Length (m)	13	20	25
Standees/sq. m.			
4	86	136	172
5	97	153	194
6	108	170	217
7	120	188	239
8	131	205	262

Calculation 4	
P_{max}	86
B	40
PHF	0.75
P (pass/hr)	**2580**

The existing maximum person capacity of the berth is 2580 passengers/hour. The current volume is about 1,800. Thus about 70% of the berth capacity is used.

Step 2- Enumerate and Assess Alternatives

If the system peak hour volume is 1,800, a 60% increase in ridership will require a design for at least 2,900 passengers per hour. Four alternatives were reviewed to determine if they were feasible in increasing capacity. These included:

1. introduce larger buses
2. introduce off-board fare collection
3. introduce additional loading areas, and
4. increase the allowable standing density
5. eliminate right turning movements from the bus lane.

The first step is to determine the increased frequency necessary to meet the required demand of 2,900 passengers per hour. With a capacity of 85 passengers per bus, a total of 44 buses per hour are necessary to meet the demand at the current load factor.

$$B = P/\ (P_{max}\ PHF)$$

Calculation 1

P	*2,900*
Pmax	*86*
PHF	*.75*
B	*45*

Note that in task 1.4, the capacity of the single berth stop was determined to be 40. Introducing 45 buses per hour will require either an additional berth or shorter stop dwell times or higher allowable failure rate.

Step 2.1 Assess the introduction of larger (articulated) buses

Using larger buses changes only Calculation 4. The current P_{max}, (maximum load per bus) is 86 at the prescribed loading density. If articulated buses are introduced, P_{max} will be 136. In this assessment, the same frequency of service as is currently operated (30 buses per hour) is assumed.

Calculation 4	
Pmax	*136*
B	*30*
PHF	*0.75*
P (pass/hr)	*3,060*

From this chart, the person capacity with the larger buses will be about 3,000 persons per hour. This increased capacity alone will accommodate the expected ridership increase. In practice, if the increased demand were somewhat less than 50%, the service frequency can be reduced to provide the minimum amount of service to meet the demand at the prescribed loading standard. In this case, the required number of buses per hour will be:

$B = P/(P_{max}\ PHF)$

From the analysis in step 1.4, the number of buses per hour which can be serviced by a single berth stop is approximately 40. The introduction of higher capacity buses will not require a multiple berth stop.

Step 2.2 Assess the introduction of off-board fare collection

Off-board fare collection reduces the amount of time per person during the boarding process and can improve the capacity of the stop by reducing stop dwell time. Further, with off-board fare collection, boarding customers can enter through the rear door, further reducing stop dwell time. More precise data collection at the critical stop will be required to determine if dwell time reduction due to rear door boarding is significant. The assessment will determine the single berth capacity with a reduced dwell.

TABLE 5-15: PASSENGER SERVICE TIME (SEC)

	Observed Range	Suggested Default (s/p)
Boarding		
pre-pay	2.25-2.75	2.5
single ticket	3.4-3.6	3.5
exact change	3.6-4.3	4
swipe card	4.2	4.2
smart card	3.0-3.7	3.5
Alighting		
front door	2.6-3.7	3.3
rear door	1.4-2.7	2.1

$$\frac{4-2.5}{4} = 37.5\%$$

Off-board fare collection (pre-pay) at 2.5 seconds per passenger results in 37.5% faster boarding than on-board (exact change) at 4 seconds per passenger. We can calculate the percent difference in dwell time by comparing the equation below with on-board fare collection and with off-board fare collection.

$$t_d = P_a t_a + P_b t_b + t_{oc}$$

where,

td = average dwell time (s)

P_a = alighting passengers per bus through the busiest door (p)

t_a = alighting passenger service time (s/p)

P_b = boarding passengers per bus through the busiest door (p)

t_b = boarding passenger service time (s/p)

t_{oc} = door opening and closing time (s)

Original boarding time		Reduced boarding time	
P_a	100%	P_a	100%
t_a	100%	t_a	100%
P_b	100%	P_b	100%
t_b	100%	t_b	63%
t_{oc}	100%	t_{oc}	100%
t_d	3	t_d	2.625

By going through the same calculations as previously, but using an average dwell time of 12.5% lower than originally, we determine the capacity of the system using off-board fare collection rather than on-board fare collection.

t_d = 30 * (1-.125) = 26 sec.

The ability to use rear door entry further diminishes the dwell time. A conservative estimate of this reduction is 15%. This results in an estimate of the mean dwell time of 22 seconds. This redetermination of dwell time requires changes to all calculations for the baseline capacity assessment.

Calculation 1		**Calculation 2**		**Calculation 3**		**Calculation 4**	
Bus Loading Area Capacity		*Adjustment Factor*		*Bus Facility Capacity*		*Person Capacity*	
g/C	0.6	f_l	1	B_l	63	P_{max}	86
t_c	11.1	v	200	N_{el}	1	B	45
t_d	22	c	580	f_m	0.724	PHF	0.75
Z	1.28	f_m	0.724	B	45.6		
s	7.9					P	2,900
t_{om}	10						
B_l	63						

By implementing off-board fare collection, the capacity of the single berth, critical stop is increased from 40 to 45. The maximum passenger capacity is 2,900 customers per hour, which is exactly the design requirement. As discussed previously, more detailed data collection at the critical stop would be required to more precisely estimate the dwell time reduction due to rear door entry.

Step 2.3 Assess the introduction of multiple loading areas

Introducing an additional loading area affects calculation 3 for bus facility capacity. This, in turn increases person capacity in calculation 4. By using two loading areas instead of one, the effective number of loading areas is increased to 1.75

Calculation 3		**Calculation 4**	
Bus Facility Capacity		*Person Capacity*	
B_l	55	P_{max}	86
N_{el}	1.75	B	70
f_m	0.724	PHF	0.75
B	70	P	4,500

Based on these calculations, by adding a second loading area, person capacity is increased to about 4,500 passengers per hour. This is in excess of the design requirement of 2,900.

Step 2.4 Eliminate right turn movements from bus lane

The capacity of the critical stop would be significantly improved if right turn movements by autos were not initiated in the bus lane but rather in the second lane. This eliminates the right turn adjustment factor and increases the person capacity of the stop to 3,800, far in excess of the design requirement of 2,900.

Calculation 1		*Calculation 2*		*Calculation 3*		*Calculation 4*	
Bus Loading Area Capacity		*Adjustment Factor*		*Bus Facility Capacity*		*Person Capacity*	
g/C	*0.6*	*fl*	*1*	*Bl*	*63*	*Pmax*	*86*
tc	*11.1*	*V*	*200*	*Nel*	*1*	*B*	*45*
td	*22*	*C*	*580*	*fm*	*.724*	*PHF*	*0.75*
Z	*1.28*	*fm*	*0.724*	*B*	*45*		
s	*7.9*					*P*	*3,800*
tom	*10*						
Bl	*63*						

Step 2.5 Increase the Allowable Standing Density

If the critical bus stop with a single loading berth is constrained to 40 buses per hour, then a calculation can be made of the maximum standing density to accommodate the load.

$P_{max} = P/(B \quad PHF)$

Calculation 1	
P	*2,900*
B	*40*
PHF	*.75*
Pmax	*97*

From the table on bus sizes and densities, this indicates that the peak density on board will be about 5 standing passengers per square meter.

APPENDIX B - SAMPLE RAIL OPERATIONS ANALYSIS PROBLEMS

PROBLEM STATEMENT

A rail transit operating agency is expecting a 40% increase in ridership over the next two years. The system is currently operating at a peak hour headway of 3 minutes. Calculate the current capacity and establish options that will increase capacity to account for this anticipated increase in ridership

CURRENT OPERATING CONDITIONS

The following are the current operating conditions:

- Peak direction, peak hour flow = 16,000 passengers per hour
- Peak Hour Factor = 0.75
- Average dwell time = 30 sec.
- Standard deviation of dwell times = 12 sec
- Train consist – 8 cars
- Train car length – 20 meters, 3 doors per side
- Acceptable loading standard – 6 persons/square meter
- Advanced signal control system with train control separation of 45 seconds

Step 1 – Computer current capacity

1.1 Compute operating margin

The operating margin is:

$t_{om} = 2 * s$ = 24 sec

where,

t_{om} = operating margin (s)
s = standard deviation of dwell times

1.2 Compute train station capacity

The train station capacity is:

$$T_l = \frac{3{,}600}{t_{cs} + t_d + t_{om}}$$

where,

T_l = loading area bus capacity (bus/h)

3,600 = number of seconds in 1 hour

t_{cs} = train control separation time (s)

t_d = mean dwell time (s)

t_{om} = operating margin (s) (from task 1.1)

Calculation 1	
t_{cs}	*60*
t_d	*30*
t_{om}	*24*
T_l (bus/h)	*30*
headway (sec)	*120*

The scheduled train frequency of 20 trains per hour is less than the line capacity of 30 trains per hour.

1.3 Estimate person capacity

The person capacity is:

$$P = P_{max} TC(PHF)$$

where,

P = person capacity (p/h)

P_{max} = maximum schedule load per traincar (see table below)

C = consist length

T = Station capacity (trains/hour)

PHF = Peak hour factor

TABLE 5-16: RAIL VEHICLE CAPACITY

Passengers/ sq.m	Rail Car Length (m) and number of doors per side		
	13	20	25
	3	3	4
4	127	146	172
5	138	157	186
6	148	167	200
7	159	177	214
8	169	188	228

Calculation 2	
P_{max}	167
T	30
C	8
PHF	0.75
P	30,000

The current maximum person capacity is 30,000 passengers per hour. This is the **maximum capacity if the trains were scheduled at the line's maximum capacity of 30** trains per hour.

Step 2- Enumerate and Assess Alternatives

If the system is currently at its maximum capacity, a 40% increase in ridership will require a design for at least 22,400 passengers per hour. Four alternatives were reviewed to determine if they were feasible in increasing capacity. These included:

1. introduce longer traincars
2. introduce longer train consists
3. increase the acceptable load factor
4. reduce the headway.

Step 2.1 Assess the introduction of longer traincars

Using longer traincars (25 meter) at the current loading standard changes only Calculation 2. The existing P_{max}, (maximum load per train car) is 167. If longer (25 m) train cars are introduced, P_{max} will be 200.

Calculation 2	
Pmax	200
T	20
C	8
PHF	0.75
P	24,000

From this chart, the person capacity at the current frequency of 20 trains per hour is 24,000 passengers per hour. This increased capacity will be able to accommodate the expected ridership increase to 22,400 passengers per hour.

Step 2.2 Assess the introduction of longer train consists

Using longer train consists changes only Calculation 2. The consist length can be increased to 10 and the calculation of capacity is shown below.

Calculation 2	
Pmax	*167*
T	*20*
C	*10*
PHF	*0.75*
P	*25,000*

From this chart, the person capacity is increased to 25,000 passengers per hour at the current frequency and loading standard. This increased capacity will be able to accommodate the expected ridership increase to 22,400.

Step 2.3 Assess increasing the acceptable loading standard

If the acceptable loading standard is increased to 8 customers per square meter, the line person capacity is computed as follows.

Calculation 2	
Pmax	*188*
T	*20*
C	*8*
PHF	*0.75*
P	*22,560*

This is just enough capacity to accommodate the target peak load of 22,400 passengers per hour. It should be noted that operating at a higher load standard will likely increase the stop dwell time since the passenger flow rate on and off trains is diminished due to crowding. Given that the computed line capacity is about 20 trains per hour, in the instant case this is not problematic.

Step 2.4 Assess increasing the service frequency

The current scheduled headway necessary to meet the demand is about 180 seconds or 3 minutes (calculated in original calculation 1). This is a frequency of 20 trains per hour. Increasing the frequency by 40% would require scheduling about 28 trains per hour at the current acceptable load factor. From previous calculations, this is determined to be feasible since the flow capacity of the line is 30 trains per hour. The number of trains per hour to meet the requirement is:

$T = P/(P_{max}\ C\ PHF)$

where all terms have been defined previously

Calculation 2	
P	22,400
Pmax	167
C	8
PHF	0.75
T	23

This suggests that scheduling 23 trains per hour will be able to accommodate the passenger demand. This is less than the line capacity of 30 trains per hour.

APPENDIX C - CASE STUDY DATA COLLECTION PROCEDURES

The report ***Capacity Concepts for Urban Transit Systems in Developing Countries*** provides guidance on estimating transit capacity for a variety of high capacity bus and rail transit services. In most cases, a default value is available for use in determining transit system capacity. However, improved assessment of capacity can be obtained by using local data. There are 8 areas where local data would be most useful in improving the accuracy of the results.

TABLE 5-17: LIST OF PROPOSED DATA COLLECTION ACTIVITIES

1. Vehicle capacity (bus)
2. Vehicle capacity (rail)
   Ticket vending machine service time
3. Rail Station headway and dwell time distribution
4. Rail Station passenger service time distribution
5. Bus Station headway dwell time distribution
6. Bus Station passenger service time distribution

These data collection efforts are grouped into two types (1) studies relating to acceptable density on platforms and in vehicles (studies 1-3) and (2) studies relating to the throughput capacity of passengers and vehicles (studies 4-8).

The major difference between US transit capacity analysis and that of developing cities is determination of acceptable crowding conditions. While in the US, densities of about 2-3 persons per square meter are determined to be at the upper limit of acceptable crowding, much greater levels are tolerable throughout the world. The first three data sets will help establish acceptable ranges of static capacity on platforms and on vehicles. Operational data on headway, dwell time and per passenger service (boarding and alighting) times are included in the second group of data sets.

DATA SET #1 – URBAN RAIL PLATFORM CAPACITY

The objective of this data collection effort is to identify the peak capacity based on empirical observation of actual utilization. A relatively few number of observations, if collected at the appropriate station and at the appropriate time can accomplish this task.

Three field measurements are proposed. The first is an estimate of the maximum practical density of platforms in passengers per square meter. This would be complemented by a measure of the effective platform waiting area which is the total platform area deducting for platform edges (about 0.5 meters), structural columns and circulation space near escalators, stairs and elevators. Finally, during peak periods, it would be useful to determine if there is some reduction in density at greater distances from the vertical circulation portals.

Collection method: About four observers at the busiest station platform during the morning and peak busiest hour would be required. This would be done over several days. Just prior to each arriving train (in either direction if on a center island platform), an observation of density would be made at a number of locations along the platform. It is felt that each observer can make two observations per arriving train. Observers would measure density at several points along the platform to determine the average density along the entire platform. Observers would validate the estimate of 0.5 meters from the platform edge as the zone where passenger do not stand for waiting trains.

Alternatively, this data set might be able to be collected by reviewing surveillance video. This would depend on the clarity of the images and the locations of the cameras. A proposed data collection form follows as figure C.1.

The proposed analysis table to be developed from the data collection is shown below.

TABLE 5-18: RAIL PLATFORM DENSITY DATA FORM

Date	____________	Stop	____________
Observer	____________	Location at stop	____________

Train Departure Time	Passenger Density

Train Departure Time	Passenger Density

DATA SET #2 – VEHICLE CAPACITY (BUS)

This data set involves estimating the maximum number of customers which can be safely carried on a bus. Specifically, this effort would determine the effective density of buses in standing persons per square meter of standing space.

Collection method: This study might require two observers on a crowded bus at the maximum load segment of a bus. As in the case of the rail platform capacity, the objective is to determine the **maximum** observed capacity not the **mean** or the distribution. If the location and time of maximum load were determined, relatively few observations will be required to perform this study. A data collection form is shown as Exhibit C-2.

In applying the capacity estimate, users must recognize that the boarding rate to achieve very high loading levels may be sufficiently low as to impede throughput capacity of the system. Data collection for this is treated in separate data collection studies.

TABLE 5-19: BUS ON-BOARD DENSITY DATA FORM

Stop ____________________

Passenger Density

Bus Departure Time	Passenger Density

DATA SET #3 – VEHICLE CAPACITY (RAIL)

This study would be similar to that of the bus capacity discussed previously. On trainsets, it would be useful to differentiate between trains in which customers can easily move from one car to another (open "vestibule" trains) and those in which they cannot. The ability to "disperse" in this way tends to lower loading diversity and thus increases effective capacity, while utilizing the protected space between cars in this type of train (e.g., in Hong Kong, other Chinese cities, Paris Meteor Line,) for standees also increases effective capacity.

Collection method: A data collection effort in which stationary observers on station platforms observe the density of departing trains from the beginning station of the maximum load segment. The data collection would focus on the variation in density along the length of the train. The same staffing plan used for estimating rail platform capacity (one observer for every two cars) would be used for train set capacity. A data collection form is shown as Exhibit C-3.

This study would be similar to that of the bus capacity discussed previously.

DATA SET #4 – TICKET VENDING MACHINE SERVICE TIME

This would be a very simple study to estimate the service time distribution of ticket vending machine transactions.

Collection method: Using a stopwatch an observation would be made of the start time and the end time of a number of TVM transactions. If possible, the method of payment (cash or card) would also be recorded. About 100 observations per transaction type would be sufficient to make an estimate of the mean and distribution of the transaction time. A data collection form is shown as Exhibit C-4.

TABLE 5-20: TVM TRANSACTION TIME DATA FORM

Date	____________	Station	____________
Observer	____________	Start time	____________
		End Time	____________

Transaction Duration	Transaction Type

Transaction Duration	Transaction Type

DATA SET #5 – RAIL STATION DWELL TIME AND HEADWAY DISTRIBUTION

This data collection activity is to estimate the dwell time and headway distribution of a rail transit system. This should be done at the critical stop on a rail system – the one with the highest value of mean dwell time plus two standard deviations.

Collection method: The data collection method is rather straightforward. The dwell time is measured from the time that the vehicle comes to a complete stop until the time that the train starts moving. The arrival time is the time that the arriving train comes to a complete stop. A data collection form is shown as Exhibit C-5.

TABLE 5-21: RAIL HEADWAY AND DWELL TIME DATA FORM

Date	________	Station	________
Observer	________	Direction	________

Time (train stopped)	Time (train departure)	Time (train stopped)	Time (train departure)

DATA SET #6 – PASSENGER SERVICE TIMES AT RAIL STATIONS

Passenger service times are measures of the time it takes to board a passenger under specific circumstances. The determination of passenger service times at rail stations can be labor intensive. The data collection effort will require one observer for each door of a subway car. Generally, only the car determined to be the busiest should be observed.

Collection method: The following are steps that may be used to collect field data on passenger service times. An example of a data collection sheet is shown in Figure C.6.

1. From a position at the rail stop under study, record the identification number and run number for each arriving vehicle.
2. Record the time that the train comes to a complete stop.
3. Record the time that the doors have fully opened.
4. Count and record the number of passengers alighting and the number of passengers boarding at the door.
5. Record the time that the major passengers flows end. (Note: This is somewhat subjective but essential to correlate flows per unit of time. This time for stragglers to board or exit should not be included.)
6. When passenger flows stop, count the number of passengers remaining on board. (Note: If the seating capacity of the transit vehicle is known, the number of passengers on board may be estimated by counting the number of vacant seats or the number of standees.) and record the time.
7. Record the times when the doors have fully closed.
8. Record the time when the vehicle starts to move. (Note: Leave time should exclude waiting where the train must wait for a traffic signal to turn green.
9. Note any special circumstances.

The passenger service time for each transit vehicle arrival is computed by taking the difference between the time that the door opens and the time that the main flow stops. The service time per passenger is computed by dividing the number of passengers boarding (or alighting) by the total service time. A chart showing the flow rate under varying levels of train occupancy after departing from the station is desirable. This can be a staged variable in three levels: all customers seated, standees at a rate of 0-2 passengers per square meter and standees as a rate of greater than 2 passengers per square meter.

TABLE 5-22: PASSENGER SERVICE TIME DATA SHEET

Date______ Time _______ Bus Number________ Bus Type _______

Route _____ Location _____________________________Direction ________

Arrival Time	Doors Open	Main Flow Stops	Doors Closed	Train Leaves	Ons	Offs	Passengers Departing On Board

DATA SET #7 – BUS STATION DWELL TIME DISTRIBUTION

The throughput capacity of a Bus Rapid Transit System, measured in vehicles per hour, is governed by vehicle, traffic and pedestrian and passenger behavior at either the busiest bus stop or the most congested intersection. While it is more likely that passenger activity at the critical stop will govern capacity, it is possible, even with exclusive lanes that the maximum system capacity will be determined by conflicts at intersections. These two cases will be treated separately. The first is dwell time distribution.

Collection method:

A data collection effort at high capacity bus stops is proposed. For each arriving bus the time from when the vehicle comes a complete stop and the time that the vehicle begins movement to leave the stop is recorded. Note: Leave time should exclude waiting where the bus must wait for a traffic signal to turn green. A suggested form is shown as figure C-7.

TABLE 5-23: BUS HEADWAY AND DWELL TIME DATA FORM

Date	____________	Stop	____________
Observer	____________	Direction	____________

Time (bus stopped)	Time (bus departure)	Time (bus stopped)	Time (bus departure)

DATA SET #8 PASSENGER SERVICE TIMES AT BUS STOPS

To determine passenger service times for use in evaluating the differences between systems (such as single- and dual-stream doors, high- and low-floor buses, or alternate fare collection systems), data collection should occur only at high-volume stops. The data collection effort will require one or two persons, depending on the number of passengers.

The following are steps that may be used to collect field data on passenger service times. An example of a data collection sheet is shown in Figure C-6 in the discussion of rail service times.

1. From a position at the transit stop under study, record the identification number and run number for each arriving vehicle.
2. Record the time that the vehicle comes to a complete stop.
3. Record the time that the doors have fully opened.
4. Count and record the number of passengers alighting and the number of passengers boarding.
5. Record the time that the major passengers flows end. (Note: This is somewhat subjective but essential to correlate flows per unit of time. This time for stragglers to board or exit should not be included.)
6. When passenger flows stop, count the number of passengers remaining on board. (Note: If the seating capacity of the transit vehicle is known, the number of passengers on board may be estimated by counting the number of vacant seats or the number of standees.)
7. Record the times when the doors have fully closed.
8. Record the time when the vehicle starts to move. (Note: Leave time should exclude waits at timepoints or at signalized intersections where the vehicle must wait for a traffic signal to turn green.
9. Note any special circumstances. In particular, any wheelchair movement times should be noted.

The passenger service time for each transit vehicle arrival is computed by taking the difference between the time that the door opens and the time that the main slow stops. The service time per passenger is computed by dividing the number of passengers boarding (or alighting) by the total service time.

To determine passenger service times for use in evaluating the differences between systems (such as single- and dual-stream doors, high- and low-floor buses, or alternate fare collection systems), data collection should only at high-volume stops. These stops are typically downtown or at major transfer points. The data collection effort will require one or two persons, depending on the number of passengers.

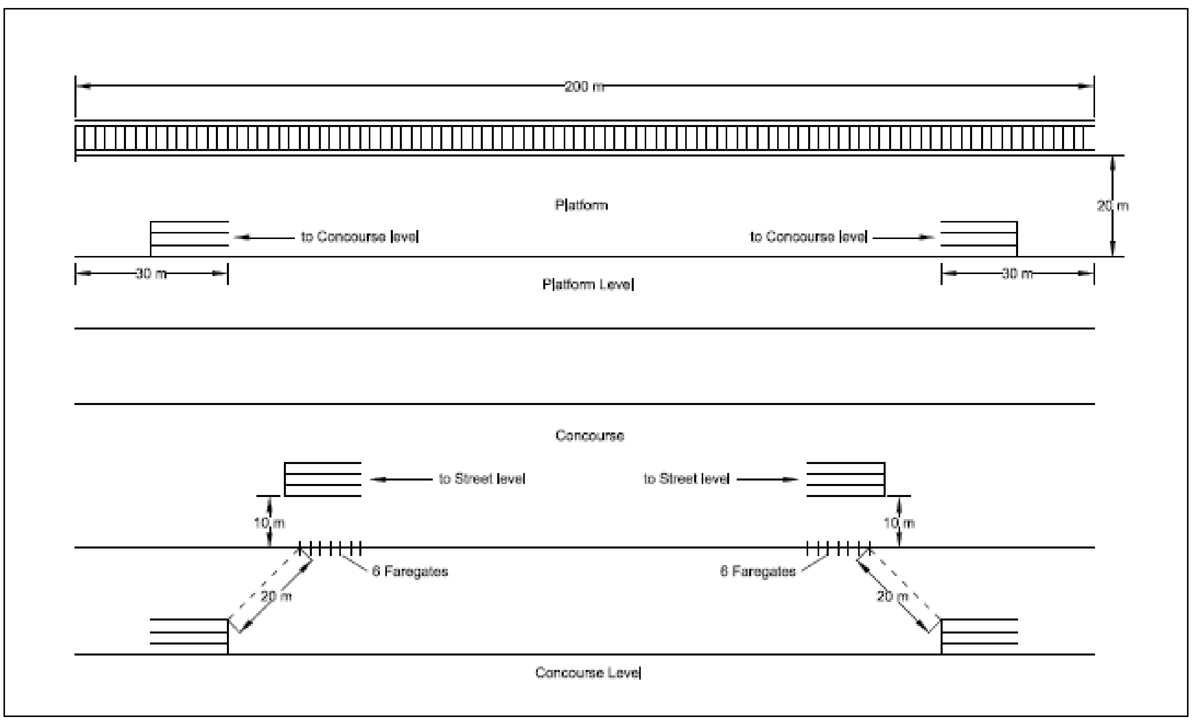
APPENDIX D – RAIL STATION EVACUATION ANALYSIS EXAMPLE

INTRODUCTION

The computation procedure can be used to assess whether or not a particular rapid transit station can meet the two design requirements (platform and station evacuation) of NFPA 130. The assessment procedure involves determining the design evacuation load, computing the platform evacuation time and then computing the evacuation time to a safe location for a passenger at a location farthest from an exit on the platform. The evacuation time is the normal walking time plus any queuing time associated with level change facilities or barriers such as door or fare collection lanes.

The example here is a side platform station with an escalator and staircase at each end of the station. The stairs go to a fare collection concourse and then there is another set of stairs to the outside. Figure D-1 illustrates the system.

FIGURE 5-4: RAIL STATION EXAMPLE



The following are attributes of the system being analyzed:

- Hourly volume of passengers on trains entering the station 5,600.
- Peak hour factor = 0.8
- Published headway = 5 minutes
- Platform length = 200 m
- Train capacity at 6 persons per square meter standing capacity = 193 passengers per car
- Train consist length = 8 cars
- Elevation to fare concourse = 9 m
- Fare gates on fare concourse – 6 lanes at each of two locations
- Distance from top of stairs to fare gates = 20 m.
- Elevation from fare concourse to street = 9 m
- Distance from top of stairs to street = 30 m.
- Customer arrival rate at station = 2400/hour
- Exits = 2 staircases and one escalator – one at each end of the station (2.24 m wide)

Computation of Design Load

The design load consists of two parts (1) the design number of passengers awaiting trains and (2) the design number of passengers on the next arriving train at the station.

Awaiting Passengers

The design number of passengers waiting on the platform is the maximum number of passengers who will be waiting for a train. It is computed as the arrival flow rate per minute adjusted upward by the peak hour factor multiplied by the maximum time between trains. The maximum arrival time between trains is computed as 12 minutes or twice the headway, whichever is larger. The basis for this is that on long headway services (over 6 minutes published headway) the evacuation system is designed for a service where a single train is missing from the schedule. On short headway services (6 minutes or under) the evacuation system is designed so that the maximum time between trains is 12 minutes.

For the design problem:

Arrival rate in 15 minutes = Hourly arrival rate/(60 * peak hour factor) * max(12, 2 * headway)

Awaiting Passenger Design Load = (2400/(60 * .75) *12 = 640

Arriving Passengers

The arriving number of passengers on the next train is computed by determining the hourly flow of passengers on trains arriving at the station during the peak hour, adjusting this result upward by the peak hour factor then dividing by the number of scheduled trains during the hour. This calculation provides the number of customers on the next train during the peak 15 minutes under normal operation. The recommended practice is to increase this number by two to account for a service interruption where a train is eliminated from the headway. The maximum arriving passenger design load is the maximum train capacity.

Arriving Passenger Design Load = (Arriving passengers per hour / (trains per hour * PHF)) *2

Arriving Passenger Design Load = (5,600/(12 * .8)) * 2 = 1,166

Total Design Load

The total design load for platform evacuation is the sum of the design load of awaiting passengers and arriving passengers. This is 640 + 1,166 = 1,806 passengers.

Test 1- Platform Evacuation Assessment

There are 2 staircases and 2 escalators at each end of the platform. The design requirement is to assume that one of the escalators is out of service due to maintenance requirements. Using capacity estimates in **Error! Reference source not found.**, the estimated egress capacity is illustrated in **Error! Reference source not found.** below. This suggests that the evacuation rate from the platform is 454 passengers per minute. It would take just under 4 minutes to evacuate the platform under these conditions. Therefore, the design meets test 1 which requires platform evacuation in 4 minutes or less.

TABLE 5-24 : FLOW RATES OF MEANS OF EGRESS IN SAMPLE PROBLEM

	width (m)	capacity per unit width (Pass/m/min)	Effectiveness	Flow (pass/min)	Effective Flow (pass/min)
Stair 1	3	63	1	189	189
Escalator 1	1.2	63	1	75.6	76
Stair 2	3	63	1	189	189
Escalator 2	1.2	63	0	75.6	0
Total					454

TEST 2 - STATION EVACUATION ASSESSMENT

Walking Time

The station evacuation test requires that all occupants be able to evacuate to a safe location within 6 minutes. The travel time to a safe location is the sum of the travel time without any queuing delays plus to queuing delays caused by restrictions on capacity at stairs and escalators, faregates and doors.

The normal travel time of the person leaving from a point on the platform farthest from the street is computed. **Error! Reference source not found.** below illustrates the computations.

TABLE 5-25: TIME FROM PLATFORM TO EXIT

	Distance (m)	Speed (m/min)	Time (min)
platform to stairs	40	61	0.66
climb stairs	9	15	0.60
stairs to fare gates	20	61	0.33
concourse to stairs	30	61	0.49
stairs to street	9	15	0.60
Total	**108**		**2.68**

The platform to stairs time assumes that an occupant is at the farthest possible distance from a staircase or escalator. The maximum unimpeded time is about 2.7 minutes.

Waiting Time

A separate queuing assessment is made at each location where free flow is restricted. The four restricted spaces are described in the table below.

The first part is computing the waiting time at the platform exit of the last exiting passenger. This is the platform evacuation time (computed at 2.68 minutes) minus the walk time of the last passenger to the platform exit. (This assumes that there will be queue at the platform exit even after walking to the exit from the point farthest from the exit.

$$W_p \text{(waiting time at platform exits)} = W_1 - T_1$$

$$W_p = 4.0 - 0.66 = 2.34 \text{ minutes}$$

The next barrier is the fare exit barrier. The delay time for this barrier is the concourse load divided by the fare barrier exit capacity. The design number of exiting passengers is 1806. The exiting flow capacity of the faregates is 50 passengers per minute. (from table xx). With 8 exit faregates, the time to evacuate all passengers is 1806/(8 * 50) = 4.5 minutes. The delay time

$$W_2\text{(fare barrier flow time)} = \frac{\text{Concourse occupant load}}{\text{Fare barrier exit capacity}}$$

$$W_2 = \frac{1806}{8 * 50} = 4.5 \text{ minutes}$$

The waiting time at the fare barrier gate by the last exiting person is the fare barrier flow time minus the platform clearance time of 2.34 minutes.

$$W_f\text{(waiting time at fare barriers)} = W_2 - W_1$$

$$W_f = 4.5 - 2.34 = 2.16 \text{ minutes}$$

If the flow capacity of the exit faregates were higher than that of the platform exit, then the delay time of the last passenger at the faregate would have been 0.

The next step is to assess the delay time at the stairs from the concourse to the street level. At each of the two exits there is a staircase 3 meters wide. No escalators are used. From the calculation of the exit capacity from the stairs from the platform to the concourse, the maximum flow time at the base of the exit stairway is:

$$W_3\text{(concourse exit flow time)} = \frac{\text{Concourse occupant load}}{\text{Concourse exit capacity}}$$

$$W_3 = \frac{1806}{189 + 189} = 4.7 \text{ minutes}$$

The waiting time at the concourse exit by the last evacuating passenger is

g1 $W_c\text{(waiting time at concourse exits)} = W_3 - max(W_1 \; or \; W_2)$

$$W_c = 4.7 - Max(4.0, 4.5) = .2 \text{ minutes}$$

The total exit time is the sum of the unimpeded walk time plus the sum of the delay time at the three points of restricted flow – the stairs from the platform to the concourse, the faregates and the stairs from the concourse to the street.

$$\text{Total exit time} = T + W_p + W_f + W_c$$

$$\text{Total exit time} = 2.68 + 2.34 + 2.16 + 0.2$$

$$\text{Total exit time} = 7.38 \text{ minutes}$$

This egress system does not meet the NFPA standards. Remedies which could be considered include:

- Adding an emergency staircase from the platform to the street. This would bypass two of the barriers – the faregate and the second staircase.
- Making exit staircases wider
- Increasing the exit capacity through the faregates. This might be done by adding an emergency bypass gate at the faregates. This would increase flow and reduce additional delay time at the faregates.

This discussion is intended to be a preliminary treatment of underground station evacuation requirements. The NFPA requirements should be consulted for more complex treatments such as center island platforms and multiple station access points.

Emergency evacuation provisions are an essential consideration in capacity analysis and station and terminal design. Specific procedures and requirements will vary among countries. Design and performance standards for emergency evacuation in the United States provide a guide in this effort.

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