FTA RESEARCH

FEDERAL TRANSIT ADMINISTRATION

Rail Capacity Improvement Study for Heavy Rail Transit Operations

OCTOBER 2012

FTA Report No. 0035
Federal Transit Administration

PREPARED BY

William Moore Ede
Paulo Vieira
Duane Otter
Joshua Matthews

Transportation Technology Center, Inc.
A subsidiary of the Association of American Railroads

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SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
^{o}F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^{o}C

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This study offers a combination of considerations and evaluation tools pertaining to relevant means of capacity improvements (technology, operations, route, and vehicle upgrades), both conventional and emerging. Guidance regarding the economics is offered to help balance the mix to minimize cost of achieving the level of capacity improvement required. The report describes principles and concepts related to capacity for heavy rail transit operations. Topics include track and station configuration, rolling stock, train operations, and signal and train control issues. Transportation Technology Center, Inc. (TTCI) identifies promising potential improvements and additions to infrastructure to increase capacity (emphasizing cost-effective technology solutions). Discussion is provided on investment planning to increase transit system capacity by making the various improvements noted. The study also discusses the benefits, effectiveness, and life cycle costs of the various solutions. A sequence for implementation of the various recommended changes is suggested. To illustrate these principles, TTCI evaluated various aspects of the present capacity limitations vs. ridership for two large rail transit systems in the United States to determine to capacity constraints and to identify areas where improved capacity might be needed. One section presents a limited case study of the Washington Metropolitan Area Transit Authority (WMATA) system. A second case study presents an overview of the Bay Area Rapid Transit (BART) system, along with a more in-depth analysis of BART operations and suggestions for capacity improvements. In each case study, analysis of delays shows areas where improvements could be made that would increase system reliability. Reduction in variability and unplanned events can provide not only increased capacity but a better passenger experience. Increased reliability and reduced delays and variability are keys to getting the most capacity out of existing systems. Analysis of train operations and model simulations for congested areas on one system point to the root causes of congestion. Changes and upgrades to train operations and train control systems are then simulated to determine effectiveness of measures to improve system capacity.

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ABSTRACT

This study offers a combination of considerations and evaluation tools pertaining to relevant means of capacity improvements (technology, operations, route, and vehicle upgrades), both conventional and emerging. Guidance regarding the economics is offered to help balance the mix to minimize the cost of achieving the level of capacity improvement required.

The report describes principles and concepts related to capacity for heavy rail transit operations. Topics include track and station configuration, rolling stock, train operations, and signal and train control issues. Transportation Technology Center, Inc. (TTCI) identified promising potential improvements and additions to infrastructure to increase capacity (emphasizing cost-effective technology solutions). Discussion is provided on investment planning to increase transit system capacity by making the various improvements noted. The study also discusses the benefits, effectiveness, and life cycle costs of the various solutions. A sequence for implementation of the various recommended changes is suggested.

To illustrate these principles, TTCI evaluated various aspects of the present capacity limitations versus ridership for two large rail transit systems in the United States to determine capacity constraints and identify areas where improved capacity might be needed. One section presents a case study of the Washington Metropolitan Area Transit Authority (WMATA) system. A second case study presents an overview of the Bay Area Rapid Transit (BART) system and a more in-depth analysis of BART operations and suggestions for capacity improvements.

In each case study, analysis of delays shows areas where improvements could be made that would increase system reliability. Reduction in variability and unplanned events can provide not only increased capacity but also a better passenger experience. Increased reliability and reduced delays and variability are keys to getting the most capacity out of existing systems.

Analysis of train operations and model simulations for congested areas on one system point to the root causes of congestion. Changes and upgrades to train operations and train control systems are then simulated to determine effectiveness of measures to improve system capacity.

EXECUTIVE SUMMARY

The Federal Transit Administration (FTA) notes that over the last decade, rail transit systems have experienced increased ridership that closely matches the increases in gasoline prices. FTA also identified highway congestion and environmental concerns as other factors that have helped to boost ridership. As a result of these and other factors, many major heavy rail transit (HRT) systems have reached or are approaching capacity. FTA has expressed concerns that rail transit systems would not be capable of fully handling the resulting increase in ridership demand.

This study offers a combination of considerations and evaluation tools pertaining to relevant means of capacity improvements (technology, operations, route, and vehicle upgrades), conventional and emerging. Guidance regarding the economics is offered to help balance the mix to minimize the cost of achieving the level of capacity improvement required.

The report describes principles and concepts related to capacity for HRT operations. Topics include track and station configuration, rolling stock, train operations, and signal and train control issues. Transportation Technology Center, Inc. (TTCI) identifies promising potential improvements and additions to infrastructure to increase capacity (emphasizing cost-effective technology solutions). Discussion is provided on investment planning to increase transit system capacity by making the various improvements noted. The study also discusses the benefits, effectiveness, and life cycle costs of the various solutions. A sequence for implementation of the various recommended changes is suggested.

To illustrate these principles, TTCI has evaluated various aspects of the present capacity limitations versus ridership for two large rail transit systems in the United States to determine capacity constraints and to identify areas where improved capacity might be needed. One section presents a case study of the Washington Metropolitan Area Transit Authority (WMATA) system. A second case study presents an overview of the Bay Area Rapid Transit (BART) system and a more in-depth analysis of BART operations and suggestions for capacity improvements.

In each case study, analysis of delays shows areas where improvements could be made that would increase system reliability. Reduction in variability and unplanned events can provide not only increased capacity but also a better passenger experience. Increased reliability and reduced delays and variability are keys to getting the most capacity out of existing systems.

Analysis of train operations and model simulations for congested areas on one system point to the root causes of congestion. Changes and upgrades to train operations and train control systems are then simulated to determine effectiveness of measures to improve system capacity.

The following specific conclusions are noted:

- It should be possible to provide at least a 50 percent increase in the number of trains per hour using a train control system that does not require incremental step-down of speeds, but instead allows trains to be braked to a target stop in one brake application.
- Station dwell time is a significant portion of the headway achievable.
  - Variability of station dwell time is caused by people holding doors, large numbers of passengers boarding and detraining, and equipment failures that cause a car to be taken out of service. When a car is taken out of service, extra walking time is required for passengers to move to an operative car.
- Additional station dwell time due to delays between train stopping and door opening, and also between doors closing and train start, was observed on WMATA, but not on BART.
- Lack of reliability of equipment can cause either significant or frequent delays to trains, which can be minimized by extensive stress testing of components that are likely to fail. Equipment should be accepted only after successful completion of stress testing. Also, defects should be logged and common failures identified so that corrective actions can be taken to make weak components robust. Proactive maintenance, predictive maintenance, and root cause analysis should all be employed to improve equipment reliability.
- Trains ahead of a delayed train can be slowed and paced to minimize further delays to following trains and improve schedule recovery. By slowing trains ahead of a delayed train, those trains will take on additional passengers, helping to reduce dwell times and passenger boarding demand for the delayed train.
- WMATA could achieve a quick increase in headway capacity by modifying or changing the door opening and closing system to achieve performance similar to that of BART (with no detectable delays).

SECTION 1

Introduction

Background

The Federal Transit Administration (FTA) notes that over the last decade rail transit systems have experienced increased ridership that closely matches the increases in gasoline prices. FTA also identified highway congestion and environmental concerns as other factors that have helped to boost ridership. As a result of these factors, many major heavy rail transit (HRT) systems have reached, or are approaching capacity. FTA notes that many HRT systems are behind the curve on infrastructure rehabilitation/replacement and infrastructure projects and that capital investments required to increase capacity typically take years from inception to completion. FTA has expressed concerns that all of these factors may come together in a "perfect storm" driven by events beyond the control of the United States, such as the price of oil, such that rail transit systems would not be capable of fully handling the resulting increase in ridership demand.

Objective

The objectives of this study are to identify the various elements of HRT operating capacity, particularly those elements that limit capacity, and to evaluate alternative means (both conventional and emerging) of achieving capacity improvements (technology, operations, route, and vehicle upgrades). Guidance regarding the economics is offered to help balance the mix to minimize cost of achieving the level of capacity improvement required. New technologies, such as moving block communications-based train control (CBTC), may offer more cost-effective and timely solutions than traditional brute-force plant upgrades for certain scenarios.

To meet this objective, Transportation Technology Center, Inc. (TTCI) has evaluated various aspects of the present capacity limitations versus ridership for two large rail transit systems in the United States to determine capacity constraints and to identify areas where improved capacity may be needed. TTCI identifies potential improvements and additions to infrastructure to increase capacity (emphasizing cost-effective technology solutions). The study also discusses the benefits, effectiveness, and life cycle costs of the various solutions. A sequence for implementation of the various recommended changes is suggested.

Scope

Under this program, TTCI provides a generic study of HRT capacity issues. The study is illustrated by case studies of the current capacity limitations and ridership for two large HRT systems. TTCI identified various infrastructure investments to increase capacity, their level of effectiveness, noted life cycle cost considerations, and how long it would take to put them into place. TTCI conducted the following tasks as identified in the FTA contract:

1. Determine how close the selected systems are to capacity and identify points that are restricting capacity on the basis of operating data.
2. Develop an inventory of potential infrastructure investments that would increase core capacity of rail transit systems, emphasizing cost-effective technology solutions over expensive track additions.
3. Discuss the capacity benefits and relative cost of implementing each investment under applicable scenarios from the selected systems or on a parametric basis.
4. Suggest an implementation sequence and migration path for various investments for the applicable scenarios or on a parametric basis.
5. Summarize and recommend the top infrastructure investments that transit agencies could make that would provide the biggest impact on capacity improvements.

This is a generic report illustrated with sample operations as case studies. The agency for the initial case study was Washington Metropolitan Area Transit Authority (WMATA). Some failure data were gathered, but operational data were not available to TTCI. Beyond the initial observation of operations, the case study on WMATA could not be completed. A second case study was sought. Bay Area Rapid Transit (BART) volunteered data and assistance for this FTA study.

Limitations

This study focuses primarily on train operations (not so much on the ability to move people on and off platforms, station design, pedestrian flow, turnstile and ticketing functions, and security issues). Maximum train length and loading, and minimum time between trains need to be considered in design for these other issues, to accommodate the appropriate passenger flows.

Organization of the Report

Section 2 describes principles and concepts related to capacity for HRT operations. Topics include track and station configuration, rolling stock, train operations, and signal and train control issues. Section 3 discusses investment planning to increase transit system capacity by making improvements in the various issues noted in Section 2. Section 4 presents an overview of the WMATA system. Section 5 presents an overview of the BART system. Section 6 continues with a more in-depth case study of BART operations and suggestions for capacity improvements.

SECTION 2

HRT Capacity Concepts

Basic Capacity Principles for HRT Operations

Typical HRT operations consist of electric multiple unit equipment running on multiple track lines with stations often spaced less than a mile apart, particularly in city center areas. Trains are often closely spaced, with headways (times from one train departure to the next) from one to three minutes during peak hours. High level station platforms and multiple doors per car are used to minimize station dwell time and to facilitate rapid movement of passengers on and off trains.

Although the capacity of an HRT system or route is ultimately characterized by the maximum number of passengers it can deliver or move per hour, it is more useful to analyze it in terms of trains per hour. Station length dictates train length, which limits the number of cars per train. This in turn limits the number of passengers per train.

There are three concepts of capacity that are useful to understand:

- Theoretical capacity; i.e., the maximum number of trains per hour that can be operated unrestricted by a less than clear signal aspect of signal code. It assumes an ideal station dwell time, no delays for equipment or system failures, and no passenger induced delays.
- Nominal capacity; i.e., the number of trains per hour that can be operated unrestricted by a less than clear signal aspect or signal code, assuming typical variability of station dwell times and typical delays to trains for equipment or system failures that do not immobilize a train.
- Close-up capacity; i.e., the number of trains per hour that could be operated past a point (typically a station) operating on restrictive signal aspects or cab codes, a situation that typically occurs following an extended delay when trains are backed up. The number of trains past a given point in a given time may be more than for the theoretical capacity, but travel time for trains operating in this mode will also be extended for as long as the trains are being speed restricted.

This study assumes that during peak periods, a system will be running at nominal capacity in terms of operating full-length trains. Therefore, this report focuses on maximizing the number of trains per hour.

Headway is another useful measure of capacity. Minimum headway represents the shortest time between the head end of two successive trains operating past a given point when the second train does not operate on a restrictive signal aspect or signal code. A 120-second minimum headway is equivalent to a capacity of 30 trains per hour. Because station dwell time is a critical element of headway, stations with large numbers of passengers boarding or detraining can be locations of capacity constraints.

Headway is also used to mean the time between trains in the schedule; for purposes of this report, "schedule headway" will be used for this meaning.

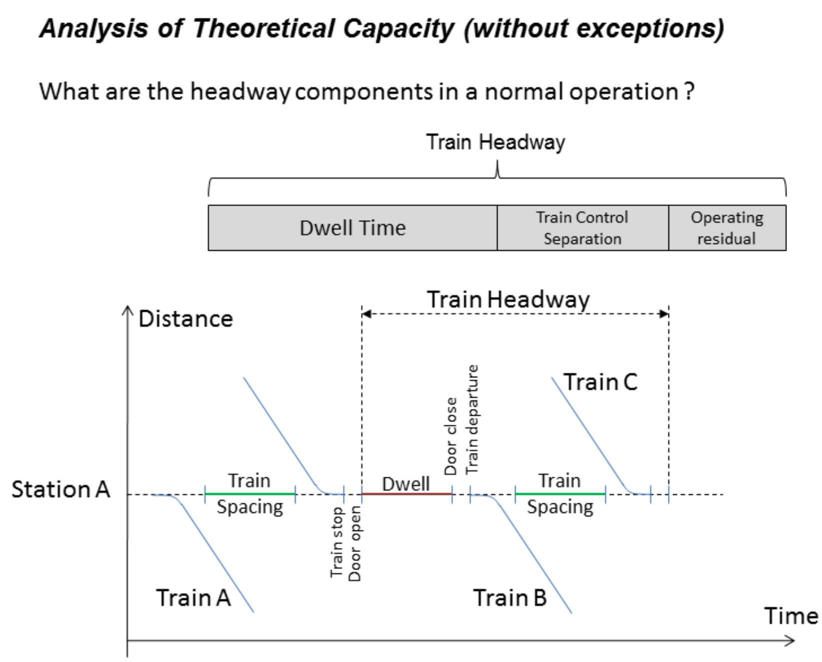
Minimum headway consists of the following:

- Time for a train to traverse its own length
- Station dwell time
- Time separation forced by signal system
- Signal system latency

When headway time is shorter, more trains can be operated. Figure 2-1 depicts the primary components of headway for a typical HRT operation.

Figure 2-1

Time-space diagram illustrating elements of train headway



Ideally, the signal clear-up time behind a train is uniform over the entire route, but speed differences, and particularly variations in station dwell time usually make this impossible to achieve.

Capacity constraints also occur where trains have to operate more slowly or at junctions where trains have to merge. In addition, the interchange points between different lines need to be examined carefully for passenger transfer and interference issues.

For design of new HRT systems, capacity planned for should include projected future demand, because the incremental cost of building additional capacity into a system at the start is typically more economical than adding capacity to an existing system. Several factors need to be considered, some dealing primarily with trip time and others dealing primarily with capacity.

HRT Factors Affecting Trip Time

- **Length of route** – Longer routes will lead to longer trip times, all other factors being equal. For most metropolitan areas, HRT systems operate shorter routes closer to the city center, and commuter rail systems serve outlying areas.
- **Junction and interchange station design, if applicable** – If passengers need to change from one line to another to reach their destination, the connection time is part of the total trip time. In general, the more frequent the service on each line, the lower the average connection time will be for passengers.
- **Distance between stations** – If stations are spaced too far apart, passengers may have to spend considerable time walking to their final destination. On the other hand, if stations are spaced too close, trains will spend much of their time starting and stopping rather than running at top speed. The average train speed will be low. It is common for stations to be spaced closely in dense downtown areas, and stations are more spread out away from the city center.
- **Number of stations** – The number of stations on a route is related to the distance between stations and the length of the route. Each station requires dwell time for boarding and detraining of passengers. Total trip time for trains is increased with the number of stations. However, an insufficient number of stations can mean greater travel distances for passengers, affecting overall passenger trip time.
- **Passenger perception/acceptance of delay** – The way passengers perceive delay can affect their overall trip experience. Regardless of actual trip time, a trip during which a train runs at full speed, but stops for several delays might be perceived as taking longer than one during which a train runs at reduced speeds, but avoids coming to a complete stop for delays.

HRT Factors Affecting Capacity

- **Time between trains** – Running more trains during a given period of time is an obvious way to increase capacity, assuming the equipment is available to do so and it can be done without increasing trip times to unacceptable levels. At some point, however, the signal and train control systems will limit the spacing of trains. For systems already operating near the capacity of their signal and train control systems, an investment in those systems might be needed to further improve capacity.
- **Operating speeds between stations** – The faster that trains can operate between stations, the shorter the trip time for passengers. Operating speed is a function of the equipment performance (acceleration and braking capabilities, top speed) as well as the signal and train control system on the line.
- **Allowance for temporary speed restrictions (frequency and duration)** – Temporary speed restrictions, also known as slow orders, are often necessary during periods of track maintenance. Track structure deterioration necessitates slow orders until repair crews can perform the necessary maintenance. During major tasks such as rail or tie renewals, slow orders may be necessary as well. Allowance should be planned for train operations to recover even when a reasonable number of temporary speed restrictions are in place. Scheduling of maintenance during off-peak hours is common practice to minimize the effects on system capacity during peak periods.
- **Acceleration/deceleration rates for trains** – The faster that trains can accelerate departing a station and brake to a stop approaching a station, the closer that trains can be spaced. For areas with closely spaced stations, the acceleration and deceleration rates of the trains can be a major factor in determining the operating speed between stations.
- **Station dwell times** – Station dwell time is the amount of time a train is stopped in a station for boarding and detraining of passengers. Station dwell times include time required to berth a train at a station and time required to open and close doors. For HRT operations, station dwell times can be a significant component of train headway.
  - Times for door opening/closing – Times required opening and closing doors are part of the station dwell time, as noted above. In particular, any delays between train stopping and door opening to verify proper train berthing, and also between door closing and train departure, negatively affect both capacity and trip time.
  - Time for passenger entry/exit – Time for passengers to board and detrain is often the largest part of station dwell time. There is generally a planned station dwell time in the train schedule, but the actual dwell time is a function of the number of passengers entraining and detraining and may be further affected by passengers holding doors to prevent

them from closing. Additional dwell time may occur when doors are not working on a car, forcing passengers to walk to other cars. For example, during a familiarization trip, TTCI observed an average of 17 seconds of additional dwell time per station during an off-peak time for two cars with inoperative doors.

- Train length and station platform length – Train length and station platform length are important factors in system capacity. Longer trains can carry more passengers, but train length is limited by station platform length.
- Vehicle design and door configurations – Vehicle design and door configurations are important considerations for capacity in several ways. More doors permit more passengers to entrain/detrain simultaneously, at the same time reducing the seating capacity of the train, but not necessarily reducing the total passenger load.
- Electrical power substation rating – Electrical power provided for train operations, if insufficient, can limit the number and/or length of trains that can be operated in an electrical sector.
- Electrical power pickup – Electrical power pickup systems need to be robust and reliable in all weather conditions, and not subject to failure. It is particularly important to ensure good track condition at electrical power boundaries so that power pick-up shoes cannot be knocked off as a result of misalignment between shoe and pick-up rail because of car rocking. Without reliable power, train operations will be erratic at best, and system capacity will deteriorate significantly.
- Train control system – The signal and train control system can limit the throughput of trains for busy systems, particularly in congested areas. Improvements to the train control system can lead to reduced headways, improved recovery capabilities from delays, and significant increases in capacity in some scenarios.
- Equipment reliability – In-service failure of equipment can lead to a variety of service impacts from short delays, ongoing delays resulting from trains continuing to operate albeit at a slower speed, or trains becoming non operative and causing long operational delays, causing other trains to be operated around the failed train. If the failures are frequent, it will impact the ability to plan a schedule. Types of failures are reviewed in the case study sections.
- Ability to single track operations for service recovery – In cases where a disabled train or system failure is blocking a track, it is important to have the ability to operate in single track mode around the obstruction to keep other traffic moving. This typically involves the use of strategically placed crossovers, as well as pocket tracks for short-turning trains. Contingency for service recovery should be designed into an HRT system.

In some cases, these issues interact to affect both trip time and capacity.

Transit time capacity considerations are more applicable when planning new lines than when increasing passenger-carrying capacity where the lines and stations are already in place.

Station Dwell Time Issues

Figure 2-2 shows the how dwell time increases with the number of passengers in a station. As the number of passengers reaches congestion capacity for the platforms, train cars, or train doors, the length of time required to detrain and board passengers increases significantly. Figure 2-3 shows how improvements in passenger flow can handle more passengers for a given station dwell time and prevent delays due to increased passenger loads.

Figure 2-2

Station dwell time increases with number of passengers boarding or detraining

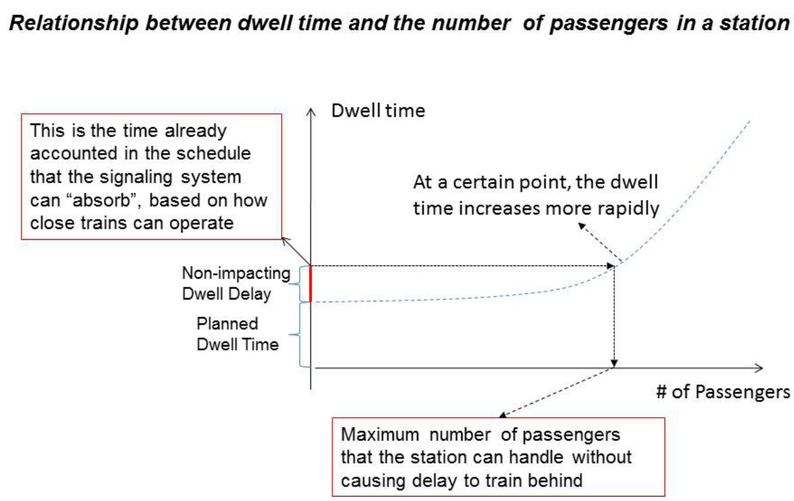
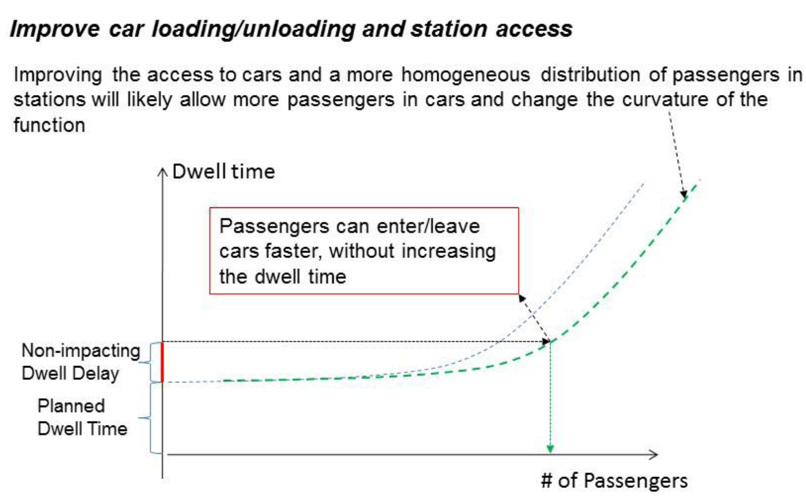


Figure 2-3

Improving passenger flow can improve capacity without increasing station dwell time

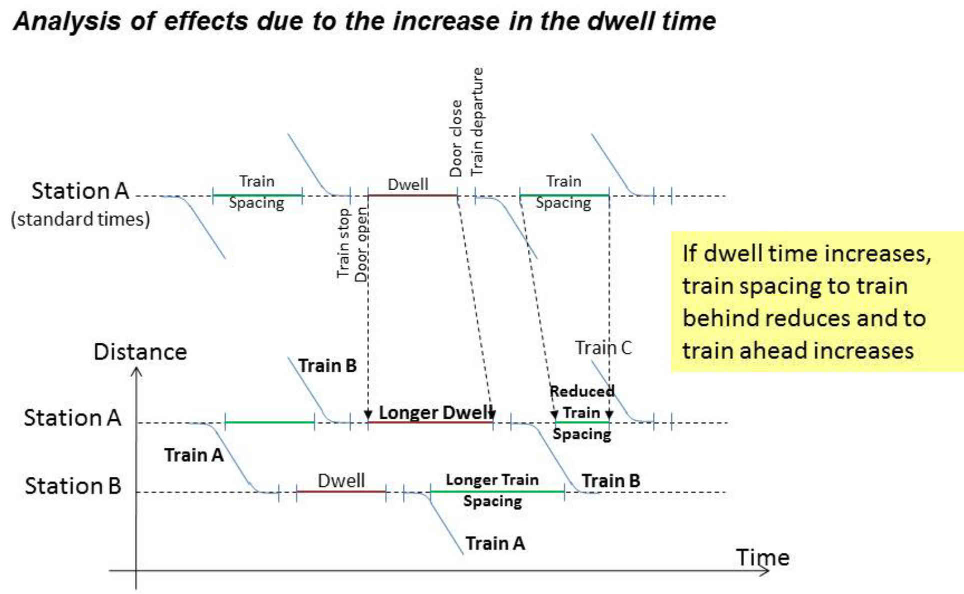


Increases in station dwell time can have a significant impact on train operations, as Figure 2-4 shows. For an isolated incident such as a stuck or held door, the system should be designed so as to be able to absorb the effects with minimal disruption to following trains. Particular attention should be given to dwell times and potential disruptions during morning and evening peak travel times.

There is a secondary impact of a station stop when a delay extends the dwell time longer than scheduled. When a train arrives late at subsequent stations, it will pick up passengers who have arrived after its scheduled departure and who would otherwise have caught the following train. This added passenger load increases the station dwell time and causes the train to fall further behind, increasing the time spacing from the train ahead and decreasing the time to the following.

Figure 2-4

Time-space diagram illustrating effects of station dwell time on train operations



Forms of Signaling and Train Control

Signaling and train control systems provide authorities for access and operating on controlled track. There are two forms of authorities in use: speed authorities and occupancy authorities.

Speed Authorities

Speed authorities are used most often in cab signaling systems and in systems with automatic train operation. Generally, these authorities are provided to the train through cab signal codes delivered through the rails and picked up by the controlling car. However, they can also be delivered by radio signals.

In these systems, the speed at which a train may operate is indicated by a cab signal code rate. A zero code rate is a command to stop. Each block has a cab signal generator, and the code rate generated depends on the status of the block ahead. The commanded speed takes effect at the beginning of the block. Block lengths are designed so that a train loaded to maximum capacity and operating at any of the permitted speeds can apply the brakes and reach the next lower speed within the length of the block. This form of multiple braking to a stop results in a much longer braking distance than for systems that only require a train to apply the brakes once.

In this type of train control, the train has no need to know where it is, and the speed at which it operates is strictly reactive in accordance with the cab signal code it receives. The disadvantage of speed authority systems is that braking always occurs at the start of the block and may result in a train stopping well short of the end of the block. The advantage is that as a preceding train clears a block ahead, the speed signal can be upgraded immediately.

Occupancy Authorities

With occupancy authorities, trains are provided with authority to occupy one or more blocks of track. The end of an authority is a specific point on the track, beyond which the train may not pass without a new authority. This type of train control is found primarily in older systems that are operated manually. The authority generally is conveyed by either wayside or in-cab signal aspect, and some form of supplementary enforcement system will apply the brakes if the train operator fails to respond to a more restrictive signal aspect. There is frequently a slow speed override that will permit a train operator to close up to a signal if the train has been stopped short of the intended stopping point.

Emerging CBTC systems also may use occupancy authorities. If these newer systems are automated or have enforcement overriding manual operations, the on-board system needs to have some form of location determination system to determine where it is and where the enforcement point is, or to determine the distance to the enforcement point.

Junction Issues and Junction Design

Track junctions, where tracks merge or diverge, can also introduce or compound delays, often with rippling effects. Careful consideration should be given to the design of junction track configuration, as well as the location of stations near junctions. Seemingly minor differences can result in significant gain or loss of capacity. Figures 2-5 through 2-9 illustrate some issues to consider regarding both track configuration and station location.

Figure 2-5 illustrates a single-level junction of two lines. Note that the area circled must handle trains moving in both directions, which results in a substantial reduction in capacity as well as delays to trains on both lines.

Figure 2-5

Delays at track junctions can impact both lines

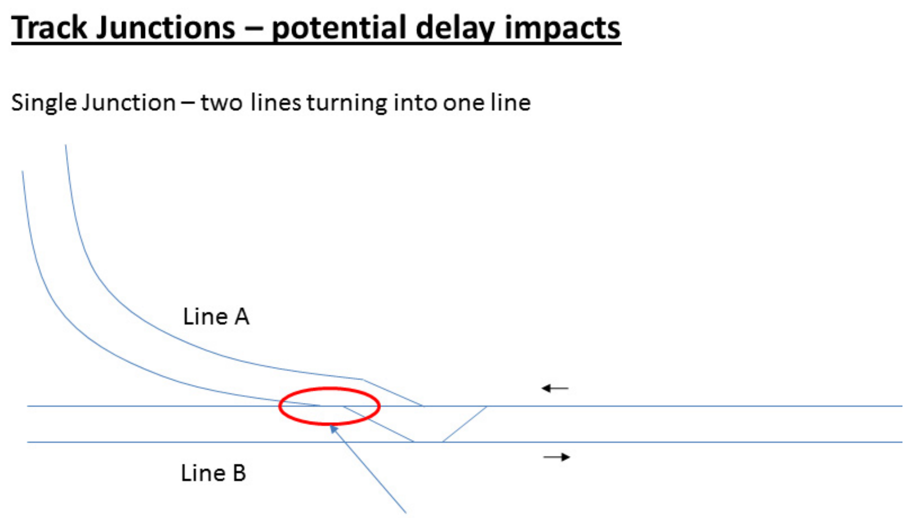


Figure 2-6 illustrates a grade-separated junction of two lines. This configuration is an improvement over the single-level junction in terms of capacity, because there is no longer a segment of track that must handle trains in both directions. This type of junction is more costly to construct, because it requires a bridge or additional tunneling to provide the grade separation, but the incremental cost can be more than offset by the additional capacity gained.

In this design, if merging trains from each line are out of synchronization, the delay incurred occurs in the tunnel, or at least on the line section and not in the station. Furthermore, any delay that occurs to the right of the station propagates to both lines.

Figure 2-6

Station location at track junctions can exacerbate delay impacts – for case with station between tracks

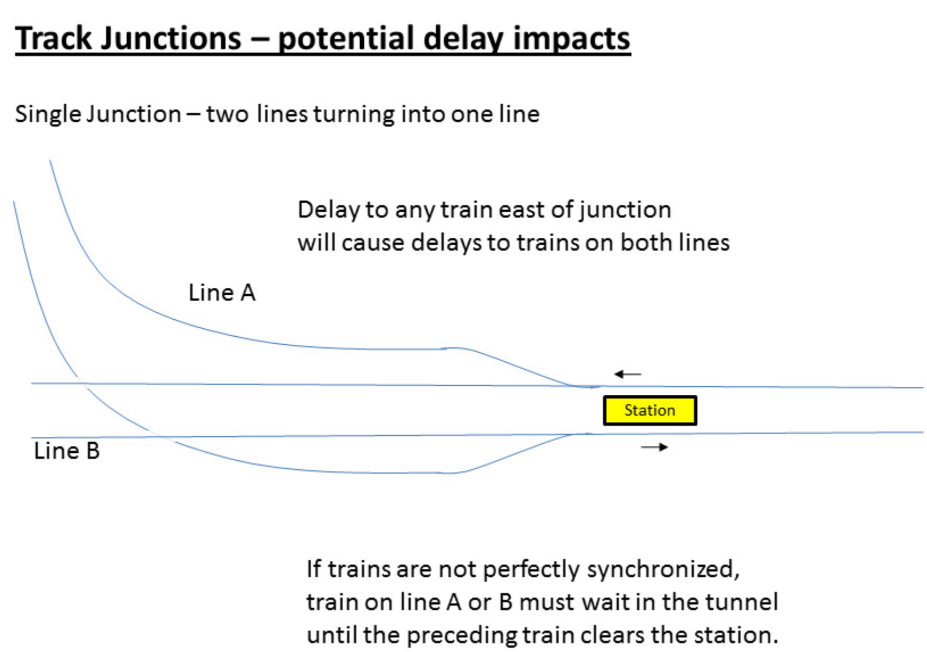


Figure 2-7 shows an alternate configuration for a two-level junction. This configuration uses a two-level station and potentially saves some bridge or tunneling costs. But once again, delays to the right of the station will propagate back to both lines.

Figure 2-7

Station location at track junctions can exacerbate delay impacts – for case with two-level station and tracks

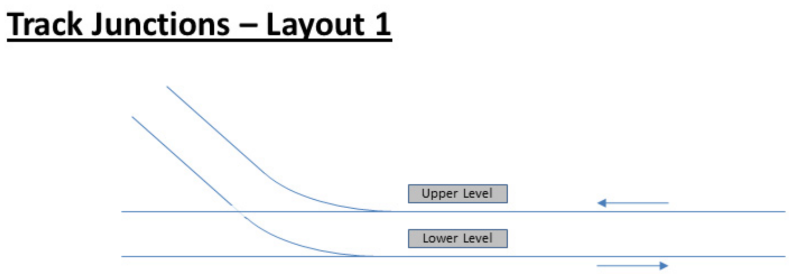


Figure 2-8 shows another alternate configuration for a two-level junction. In this case, the junction for eastbound trains is moved to a location east of the station and the platform is between the tracks of the merging lines. With this configuration, when trains from each line are out of synchronization, the delay can occur in the station, where passengers can detrain, instead of on the line section. This allows overlapping dwell times for trains, reducing the impacts on headways and train operations. Such arrangements also better facilitate recovery from service disruptions.

Figure 2-8

Station location at track junction to reduce delay impacts – two-level station with alternative track arrangement

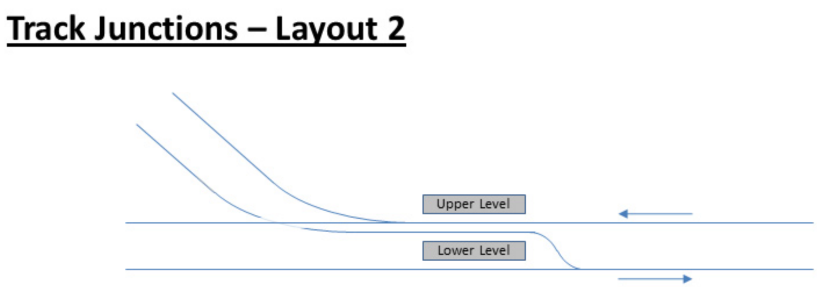
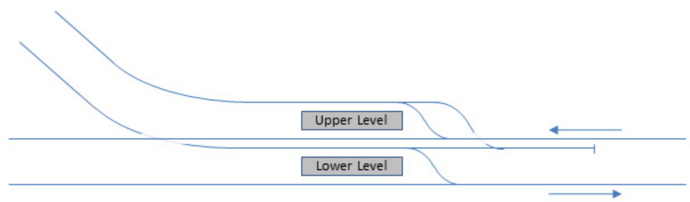


Figure 2-9 shows a variation of the two-level junction above, with the added capability of being able to terminate a train and send it back in the other direction. This configuration requires three additional turnouts, additional track, and additional grade separation structure. Additional right-of-way width might also be required on the upper level. The advantages of this layout are twofold; first, delays that occur to the right of the junction no longer need to propagate to both lines, because trains from Line A can be turned at the junction. Second, if the passenger demand for all or any part of the day does not warrant full service from both lines, Line A trains can be turned at the junction, and passengers needing to continue have only a cross-platform transfer. This junction layout provides for more operational flexibility.

Figure 2-9

Station location at track junction to reduce delay impacts and facilitate change in direction of trains for one line – two-level station with alternative track arrangement

Track Junctions – Layout 3



Interchange Station Issues and Interchange Station Design

Design of stations and track configuration at interchanges also requires careful consideration. Figures 2-10 through 2-12 show interchange station issues and interchange station designs. Station design and track configuration should take into account the flow of major traffic. As much as possible, the need for passengers to transfer from one line to another should be minimized. When passengers are required to transfer, it is preferable to minimize the number of passengers who need to change levels to do so.

The simplest form of interchange station is illustrated in Figure 2-10. In this design, all passengers transferring between lines must change levels. Depending on the volume of passengers transferring from one line to another, congestion in stairways and escalators can result.

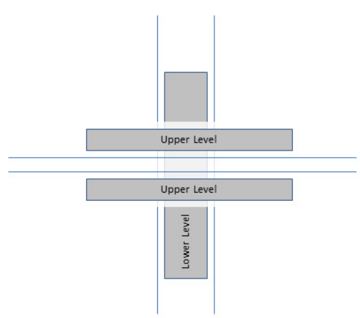
As noted in the figure, when changing from the lower level to the upper level, passengers must choose the correct stairway/escalator to reach the appropriate upper level platform for their intended direction of travel. If they find themselves on the wrong platform, they must go back to the lower level, then up another stairway/escalator to reach the platform on the other side of the tracks. During rush hour, there is a good chance that passengers will not be able to make the first connecting train.

Figure 2-10

Common interchange station design favors through-traffic, resulting in difficulties for transferring passenger movement

Interchange Stations– potential impacts and better handling

Conventional design – one platform level for each line

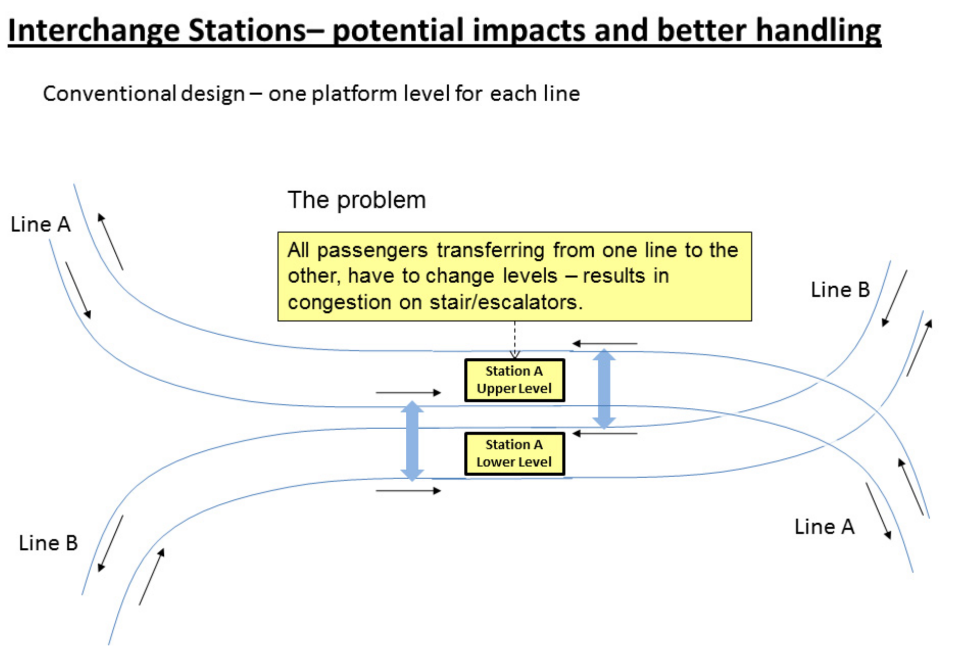


Issues
- ***All*** passengers interchanging between lines must change platform levels
  - Congestion at stairways/escalators
  - High probability of many connecting passenger missing first connecting train (in rush hour)
  - Passenger transferring from lower level to higher must choose correct stairway/escalator (problem for visitors)
- Less costly construction at the outset

Figure 2-11 depicts an alternative configuration for an interchange station. In this layout, each line is on a separate level, with its own platform between the tracks and aligned with each other. All passengers that change lines are still required to change levels, but the opportunity for a passenger to end up on the wrong platform is largely eliminated. The platforms between the tracks offer some flexibility and advantages compared to the configuration shown in Figure 2-10, which has single direction platforms on one level. The configuration in Figure 2-11 will tend to be more costly to construct.

Figure 2-11

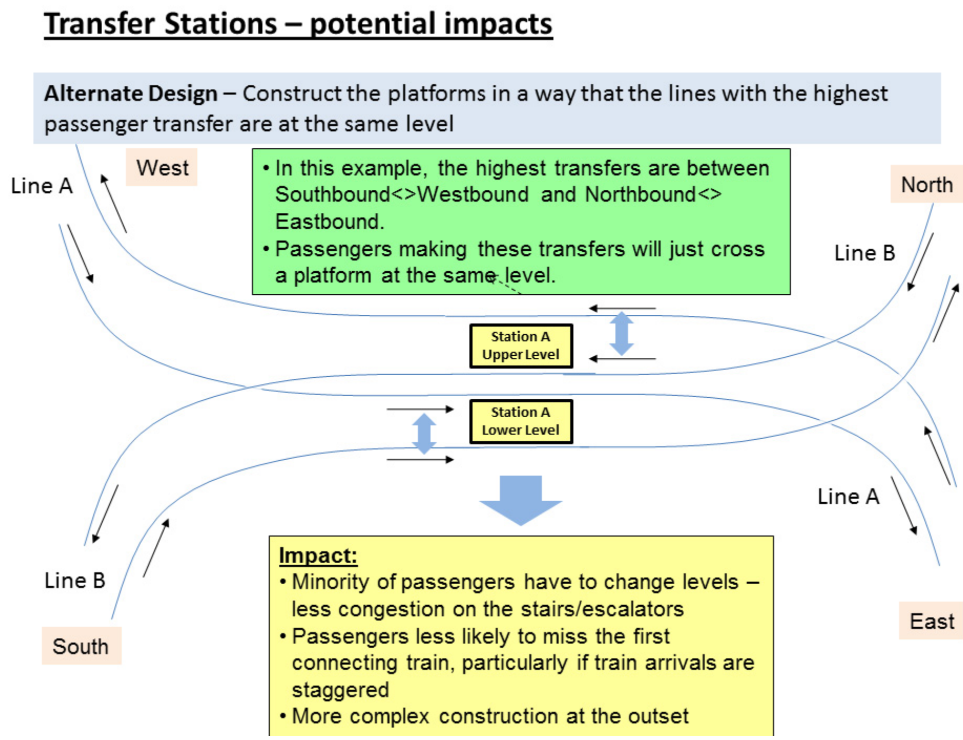
Station design issues to consider at intersecting lines



Another alternative design for interchange stations, as Figure 2-12 shows, permits cross-platform transfer for a segment of transferring passengers, thus easing the crush on stairways and escalators. The objective would be to design the interchange station so that the majority of transferring passengers would be able to transfer across the platform, and only a minority would have to change levels. The particular example illustrated gives preferential treatment to passengers connecting from westbound to southbound trains, and from eastbound to northbound trains. For these transfers, passengers simply cross the platform. Connections from westbound to northbound and from southbound to eastbound will need to use a stairway/escalator to change levels. The station concept could also be configured to favor transfers in the opposite two directional quadrants. This design is more complex to construct and requires careful consideration of grades and curvature.

Figure 2-12

Interchange station design to minimize change of levels for transferring passengers



Other Capacity Design Considerations

A final consideration for capacity is the operational response to critical failures. Key elements to facilitate operations include the following:

- Flexibility in the track configuration (use of crossovers, redundant routes)
- Flexibility in the traffic control system to permit bi-directional operations on any track
- Capabilities and communications available to the operations control center (OCC)

Considerations for Upgrading Capacity for Existing Operations

The same general principles apply to adding capacity to an existing system as apply to designing a new system. Again, the issue of physical capacity versus practical capacity comes into play. For existing systems, one of the most straightforward ways to add capacity is to add more cars to trains. Once train length reaches station platform length, additional trains can be added by reducing the scheduled headway between trains.

For operations planning, two important issues need to be considered:

- **Sustainable capacity during an entire rush hour, from which schedules are developed to account for normal service disruptions**—typically, this would include allowances for 95th percentile dwell times. The goal is to establish headways that will accommodate most of the typical traffic and delays without disrupting schedules.
- **Catch-up capability, which allows the system to recover from disruptions**—this might involve trains running closer together on restrictive signals at some times. Overall trip time will be slower, but impact on schedules of subsequent trains will be minimized.

For systems already operating near these headway capacities, providing additional capacity might require solutions such as reducing 95th percentile station dwell time (by making equipment more reliable or through education or other means to discourage passengers from holding doors open), changing the train control system, or constructing additional infrastructure such as track, additional/extended station platforms, and related infrastructure.

Cost considerations for various options are discussed in the next section.

SECTION
3

Investment Alternatives for Increasing Capacity

Identification and Description of Investment Alternatives

Most of the time, when a transit operation needs to increase its capacity or reduce its operational costs, various capital investment alternatives can be chosen to achieve the desired goals. Investment alternatives may vary, ranging from an increase in the rolling stock fleet to track expansion or improvements in control/signaling systems and stations, among many others. Costs and expected benefits vary considerably among alternatives and usually depend on many characteristics of the operation; the same investment alternative applied the same way in two different agencies may produce better results in one operation than the other.

To support the analysis and decisions on the best alternatives, TTCI developed an inventory of infrastructure and equipment investment alternatives, emphasizing technology solutions, aimed at increasing capacity on transit systems in the most cost-effective manner.

One critical factor that affects capacity in transit/commuter operations is ensuring the average operating speed is kept as high as possible. For transit, this means taking steps to minimize the time spent stopped or operating at slow speed. The inventory of improvements includes the potential equipment and infrastructure investments that support the goal of increasing capacity while maintaining adequate average speed. This inventory should be used as a tool to help an agency estimate costs and deployment efforts, and predict benefits of each investment alternative. The inventory is classified according to the nature of the investment alternative (such as track infrastructure, rolling stock, station) and also on how applicable the investment is under different characteristics of the operation.

Train Operations and Train Control Investments

Train-Related (Operation and Configuration) Investments

Train-related investments include alternatives regarding the operation and configuration of trains, locomotives, cars, and on-board systems. The following is a list of train-related investments to consider for initial system design or for capacity improvement projects.

1. **Increased passenger capacity per train**. Trains with additional vehicles or higher capacity vehicles can carry more passengers. It is important to consider the effects and limitations related to platform lengths, acceleration rates, braking rates, and signal block lengths. With higher passenger capacity per train, fewer trains are required to handle the passenger demand. Other benefits include reduced demand on track availability, stations, and train dispatchers. If new equipment is being purchased, consider vehicles with room for more passengers, as well as improved door configurations to improve passenger flow and reduce station dwell times.
2. **Automated operations**. Automation of train operations can reduce delays due to operator delays, particularly with regards to station berthing, door opening and closing, and station departure. Automated operation is capable of more precise operation than achievable by using human operators. Results will include better adherence to schedules, keeping the network more balanced and, consequently, more manageable when exceptions occur. Automation can also improve operations in terms of signal compliance.
3. **Real-time health monitoring**. Implement systems that monitor the health of components and other systems using on-board and/or wayside systems, issuing alarms and warnings in real-time mode. Prevent train stops and delays resulting from unexpected failures that can be avoided if monitored in real time. Monitor weak components and note elements prone to failure. Take corrective action and schedule maintenance appropriately to improve system reliability. Establish a system to identify recurring failures and institute remedial action.

Train Control/Traffic Management

The Train Control/Traffic Management category contains the investment alternatives regarding the management and control of the operation, including systems/equipment, logistic strategies, and overall train monitoring.

1. **Schedule coordination and integration**. Coordinates the schedule of the operation to maximize track usage and reduce congestion. Improves overall train traffic capacity and efficiency. Analyzes train spacing and terminal congestion.
2. **Optimize signal/block spacing**. Investigate the track signaling configuration to identify sections where the spacing between signal blocks is causing contention or reduction of speed of trailing trains. Include locations of crossovers for single track operations in case of failures, to route trains around a failure incident. Optimal spacing can eliminate contention and/or reduction of speed of trailing trains, consequently increasing average train speed. A special analysis is required in Single Track modes, because train conflicts are more likely to happen and train distribution is more likely to be uneven, though optimal spacing may not necessarily be uniform.

3. **Improved Train Control Technology**. Implement CBTC to improve fixed block operations or to enable the use of moving block operation (train separation defined by brake curvature distance to train ahead). Moving block CBTC can provide more constant headway over a broad range of speeds, quicken recovery from disruptions, streamline communications between train crews and dispatcher, and reduce life cycle costs by minimizing the amount of vital wayside equipment. CBTC implementation generally involves changing from a speed-based authority system to an occupancy-based authority system.
4. **Wayside and on-board systems for real-time monitoring**. Implement systems that allow the remote real-time monitoring of diverse wayside and on-board systems along the network like communication systems (data and voice), and various detectors, including those issuing alarms and warnings in real-time mode. Higher availability of those systems increases overall train traffic performance. Note weak elements and repeated failures, and take corrective action to schedule maintenance and replacement as appropriate. Ultimate goal is improved equipment availability and reliability of operations, with fewer on-line failures and unplanned events.
5. **Improve Operations Control Center (OCC) decision support systems**. Improve or provide systems that help OCC supervisors and dispatchers to make the best "real-time" decisions, taking into account current state of the operation (including planned activities) and the impacts (at least short and medium term) on train movement. Improve overall train traffic capacity and efficiency. The primary capacity benefit is improved operations during unplanned events, including better operations under failure conditions.

Station/Passenger Control

The station/passenger control category contains the investment alternatives regarding the stations, including the handling of passengers.

1. **Platform crowd control**. Implement controls at strategic points in the station that prevent entry to the platform when a train is ready to leave or when doors are to be closed. Reduce additional delays at stations caused by last minute dashers.
2. **Faster passenger loading and unloading**. Design station platform areas and cars to facilitate improved passenger flow and allow faster loading and unloading of passengers. Reduce dwell time at stations and, consequently, reduce overall transit time. Design entry and exit to station platforms at different locations for various stations along a line so as to promote more uniform loading of the train.

Field Infrastructure Investments

The field infrastructure category contains the investment alternatives regarding the track itself and the wayside systems along the track.

1. **Eliminate inefficient track configurations**. Eliminate track configurations that are speed-limiting (track geometry, curvature, or switch configuration) in routes used by trains in regular operation. Reduces overall train transit time and reduces power consumption.
2. **Increase turnout and crossover speeds**. Replace or reconfigure low speed turnouts and crossovers that are used by trains in regular operation. Reduces overall train transit time and reduces power consumption.
3. **Improve operation flexibility**. Implement track structure improvements such as adding alternate tracks at junctions and stations, or adding crossovers to allow for better scheduling, schedule recovery, and flexibility for accommodating failures and unplanned events.
4. **Additional substations**. Improve power availability during peak demand. Reduces the probability of a power shortage during heavy operation.

Benefits of Investment Alternatives

The analysis of the investment alternatives is essentially driven by issues the agency perceives, which are based on current constraints and anticipated demand forecasts such as projected ridership, plant expansion, equipment life, and projected life of other systems and facilities (including track, structures, power distribution, signals, communications, and stations).

As each agency has its own constraints and characteristics, and considering the effects of technology evolution, it is not possible to determine a single rule that can be applied to any agency to determine the best investment alternatives.

In addition, investments usually cannot be evaluated in isolation from other investments, as most times they are interrelated. For example, improving the track infrastructure to support higher speed trains to be able to reduce travel times may not be worthwhile if the distance between stations is so short that trains will barely reach the maximum speed before reducing speed for the next stop. In this case, the power-to-weight ratio of the rolling stock should also be investigated to try to achieve the expected benefits.

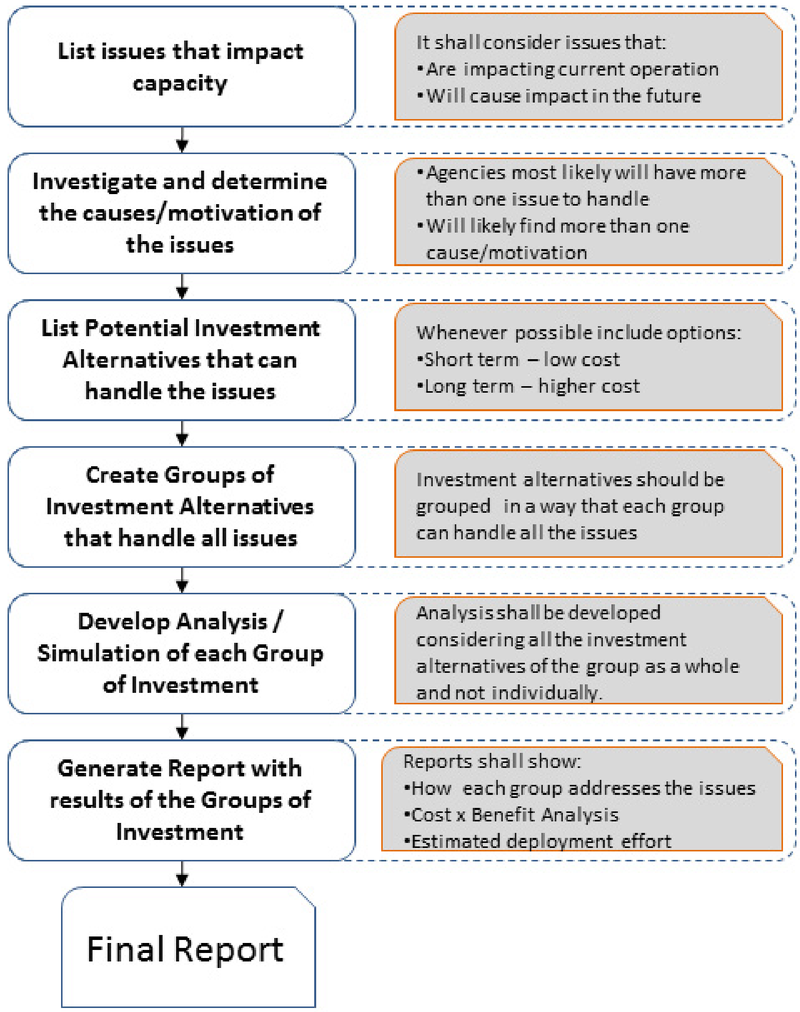
The following methodology provides a sequence of steps to help agencies identify potential investment alternatives and make comparisons among them.

Guideline Methodology

The guideline is based on a methodology composed of a sequence of steps, as Figure 3-1 shows.

Figure 3-1

Guideline methodology for developing investment alternatives for capacity enhancements



List Issues that Impact Capacity

The first step is to create a list with the issues that the agency understands that are impacting the current operation or will impact future operations, such as:

- Current operational problems, like excessive train delays in peak hours, stations and/or trains that are overcrowded
- Current reliability problems, such as excessive train failures or excessive track maintenance problems or slow orders
- Bottleneck areas that limit capacity and prevent expanding the operation

- Projected ridership that will exceed the capacity of the system
- Limited fleet size preventing expansion or ridership increase
- Expansion plans like new stations or new lines
- Equipment and/or systems close to the end of their reliable service lifetime

Investigate and Determine Causes

For each item on the list of capacity impacts, list the cause (or causes, when more than one cause is identified). For example, excessive train delays in current operation, caused by long train dwell times in stations at peak hours. The same type of analysis can be developed for projected scenarios. For example, projected ridership is demanding more trains than the capacity of the system resources. In this case, the cause could be either not enough operational cars to handle passengers or train headways cannot be reduced as the system reaches capacity.

List Potential Investment Alternatives

Associate potential alternatives that can handle each cause listed in the capacity impact list. For example, an insufficient number of operational cars could be handled by adding more cars to the fleet, or a combination of additional cars and improvements in the current fleet (to make more cars available for operation), or partial replacement of the fleet. In many cases, the investment alternative may address more than one issue. For example, buying new cars to increase the availability of the system also addresses a problem of an aging fleet (when cars are reaching the end of their reliable service life).

Create Groups of Investment Alternatives

Group the alternatives in such a way that each group will provide the full amount of the desired additional capacity. Some groups might include only one alternative. Some might require several investments in various aspects of the systems to achieve the desired capacity increase. Some investment alternatives might be included in several groups.

Develop Analysis/Simulation of each Investment Group

Once the alternatives are grouped appropriately, the next step will be the analysis of scenarios that combine selected alternatives. It is not possible to determine a single formula that can be applied to any scenario; however, the analysis should include some of the following developments:

- Theoretical studies of optimal and/or worst-case scenarios
- Simulations of the operation
- Comparative analysis among the scenarios
- Comparison of predicted costs and benefits of various scenarios

Generate Final Report

Generate a report listing alternatives considered, recommended alternatives, and predicted costs and benefits.

Narrow the Potential Investment Alternatives

The analysis of the investments should be "tailored" to the specific issues the agency is handling. Not all the possible investment alternatives need to be investigated, and most times no more than three need to be analyzed in detail, because some alternatives can be dismissed early on the basis of specific highly undesirable characteristics. This section provides a list of questions that will narrow the list of alternatives to be considered for each case.

Subsequent sections describe how to develop the investment alternatives.

Implementation Considerations

Implementation considerations should be discussed including costs and timing of various alternatives. Also, sequence and phasing of implementation need to be considered. For example, lengthening of station platforms would need to be completed before adding cars to trains. Similarly, changes to signal and train control systems will need to be coordinated to maintain existing operational safety and capacity during installation and conversion to a new system.

SECTION
4

Case Study – WMATA Operation

TTCI began working with WMATA at the beginning of this study. Data gathered included delay statistics, which are presented in various figures below. The delay data illustrates typical delay causes for an HRT system.

As subsequent inquiries found that no operational data or signal information was available to TTCI, a detailed case study could not be completed. However, data for failure analysis was available and is presented.

Overview of WMATA Operation and Train Control System

The WMATA Metrorail system currently operates 106 miles of HRT service with 1,118 vehicles, including 86 passenger stations. The system includes five separate lines—Red, Blue, Orange, Yellow, and Green—as Figure 4-1 shows. TTCI staff met with WMATA staff, rode WMATA trains, and observed various aspects of system performance.

Figure 4-1

WMATA Metrorail system map

Capacity Issues Noted in Meetings with WMATA

Equipment reliability is a major performance issue—the current reliability index is 96 percent (minimum acceptable should be 98%, according to the Core Capacity Study). Two key problems were noted:

- Door failures – frequently caused by patrons holding the doors open or getting items stuck in them so they will not close completely on the first try.
- Loss of pick-up shoes, resulting from uneven track causing shoes to line up improperly with the third rail, resulting in overloads in other cars.

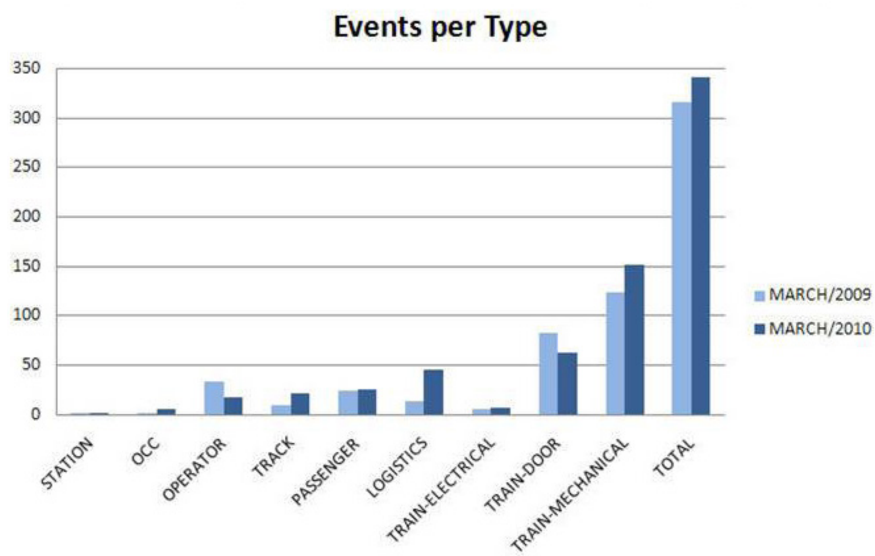
The oldest cars in the fleet (1000 series) are about 30 years old (initial operation between 1974–1978) and need to be replaced by FY2015 (40-year life cycle). This fleet is one of the main contributors to the low reliability index.

- Not enough maintenance facilities and resources were also listed as an issue that contributes to low reliability index.
- There is a concern about maintenance staff retiring and the time it takes to train replacements for maintenance technicians with specialized expertise.

TTCI analyzed data furnished by WMATA related to these issues. A summary of train operation disruption events is shown in Figure 4-2. Note that train mechanical and train door issues are the two most significant causes of disruptions, agreeing with the WMATA assessment. Also note that the total number of disruptions increased from year to year; however, the increase was not uniform for all categories.

Figure 4-2

Causes of disruption events for March 2009 and March 2010 on WMATA



Because there was considerable variation in the causes of disruptions from one year to the next, TTCI further analyzed the events. Figure 4-3 shows the next level of detail. Of particular concern are the event types that increased from year to year: train mechanical, logistics, track, and OCC. The increase in logistics-related events shown for March 2010 is particularly large in comparison to the previous year.

Figure 4-3

Detail for disruption events on WMATA, March 2009 and March 2010

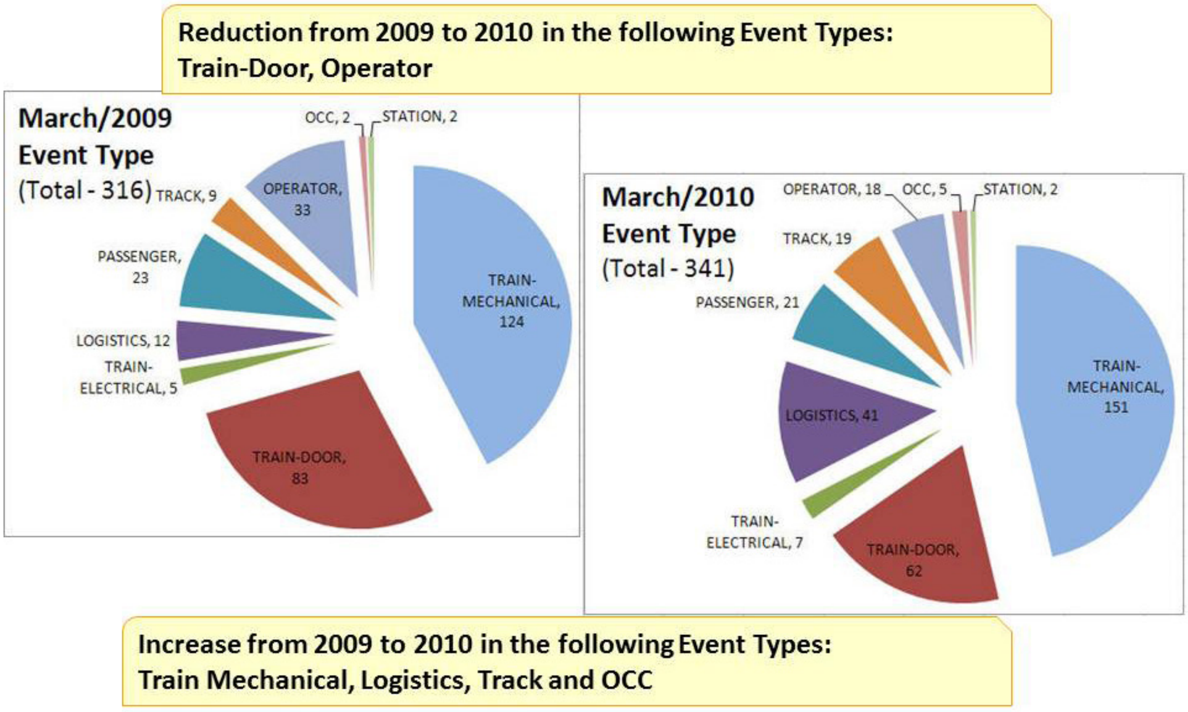
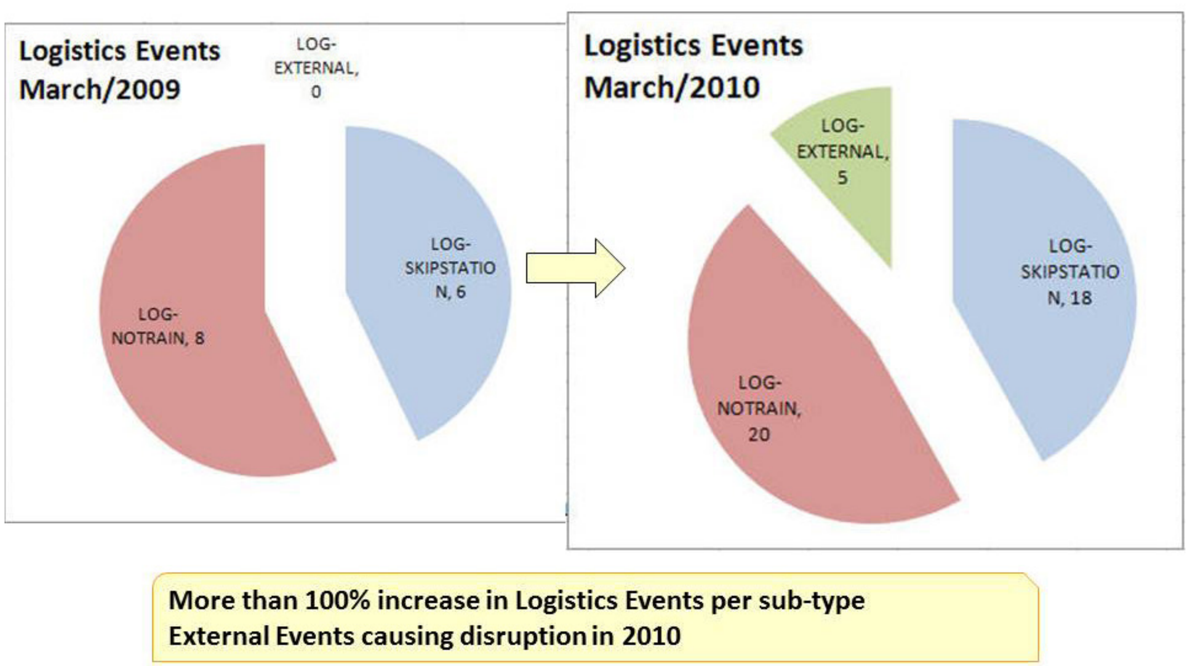


Figure 4-4

Detail for disruption events due to logistics on WMATA, March 2009 and 2010



Station capacity was also noted as a concern. In 2008, a station access and capacity study was completed, but there is no funding to develop the improvements listed.

In 2009, WMATA developed a Capital Needs Inventory that describes projects—most of which are planned to be implemented between 2010 and 2020—that would allow WMATA to support the forecasted passenger traffic.

In 2001, a Core Capacity Study was developed, which has been the main driver of the capacity investments of the agency so far. The study identified that a 135-second headway between trains is a practical limit.

Figure 4-5 shows ridership for March 2009 and March 2010. As expected, ridership on weekends is significantly less than on weekdays. At a first level of analysis, there are no issues apparent that merit further attention.

Figure 4-5

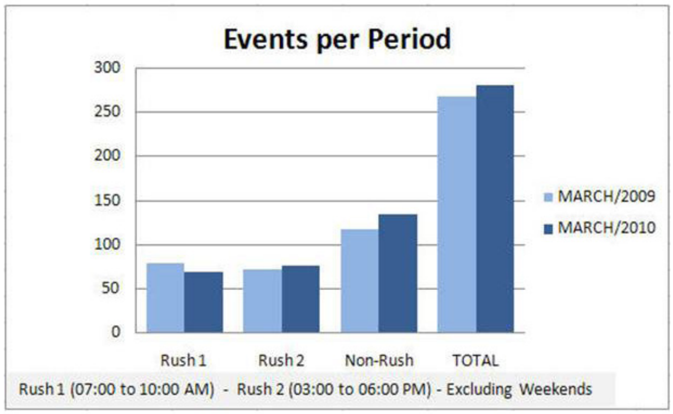
Ridership data by day, March 2009 and March 2010

Overall Ridership increased 1.36% from March/09 to March/10
No specific issue that merits attention at this level of analysis

Figure 4-6 shows a number of disruption events during March 2009 and March 2010 based on time of day, for morning and evening rush hours, as well as non-rush hours. As expected, the sum of the rush-hour events is higher than the number of non-rush-hour events. Additional trains during rush hours, plus additional passengers per train during rush hours are contributing factors.

Figure 4-6

Disruption events on WMATA, March 2009 and March 2010, based on time of day

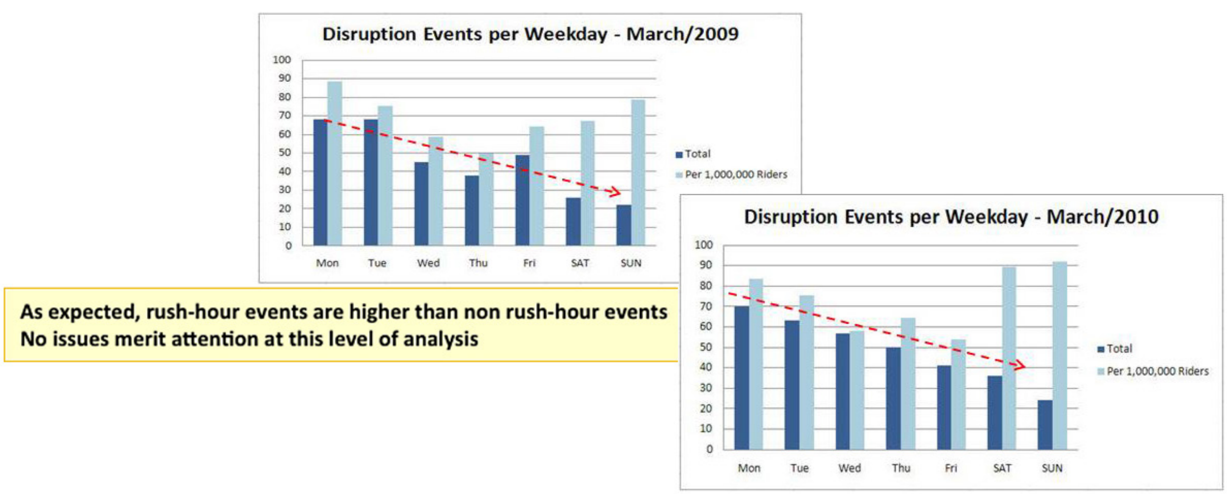


As expected, Rush Hours events are higher than Non-Rush
No issues merit attention at this level of analysis

Figure 4-7 shows the number of disruption events for the same times based on day of the week rather than time of day. Note that the number of disruption events per day decreases through the week for both years. The lower Saturday and Sunday numbers are due, in part, to reduced ridership and reduced train frequencies on weekends.

Figure 4-7

Disruption events on WMATA, March 2009 and March 2010, based on day of week

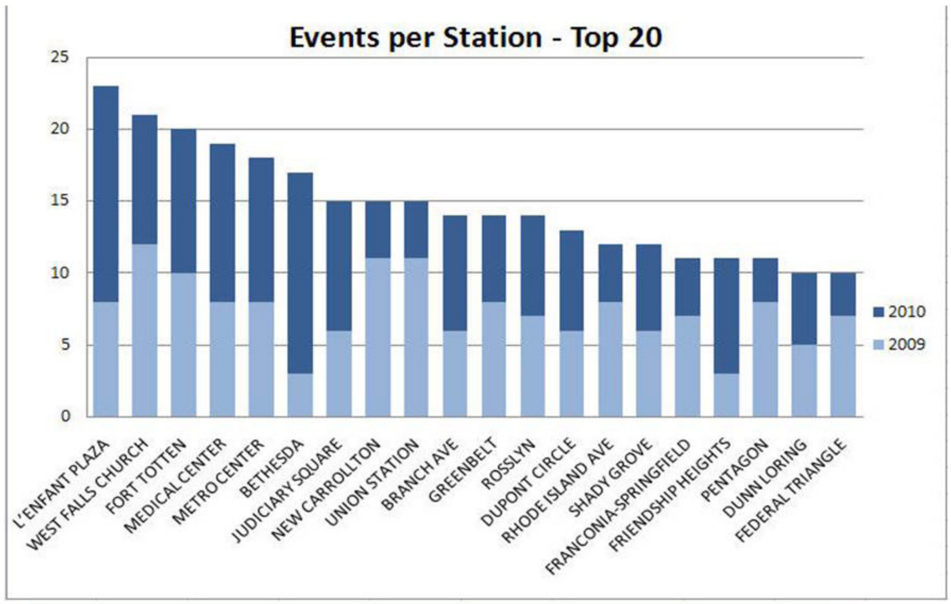


Number of events decrease through the week in both periods
No other specific issue observed from 2009 to 2010 at this level of analysis

Figure 4-8 shows disruption events for the same time periods by stations, for the 20 stations with the largest total number of disruption events. Note considerable variation, some increase, some decrease, from year to year at particular stations. Many of the stations with a high number of disruption events are junction or interchange stations. Others might be stations with a high number of passengers boarding or detraining.

Figure 4-8

Disruption events on WMATA, March 2009 and March 2010, for 20 stations with most total disruptions



Most of the stations are Terminals, Interchanges and Junctions
Need to investigate the types of events and duration per station

Operation

Current operation of the trains is manual. The automatic train operation (ATO) has been turned off since the accident in June 2009. ATO will be turned on again only after problems are identified and fixed. However, automatic train protection (ATP) is maintained under the manual operation.

While the operation of the trains is manual, the opening of doors is automatic after the train is properly berthed and stopped. A local station system performs this function, but it takes a measurable length of time to determine that the train is berthed and to release the train doors.

Observation at Stations

TTCI observed the operation of trains at the most critical stations (as identified by WMATA experts) during rush hours in the morning (07:00 to 09:00 AM), taking notes on train times and operation as well as the flow of passengers. The arrival times (when trains stopped), times that the doors opened and closed, and train departure times (when trains started to move) were recorded.

Gallery Place and Metro Center Stations

It was observed that the elapsed interval between the moment a train closes the door and starts to move is variable, and many times it takes an unexpectedly long time. (Some of this time may have been incurred by the system, but a good portion of the time was the time it took the train operator to move to the controls from observing the door closing.) A similar length of time (and variability) was noted between the time trains stopped and the doors opened. The average time recorded between trains stop and doors open was 9 seconds, and the average time between doors closed and train start was 10 seconds. Table 4-1 shows a summary of the observations.

Table 4-1

Summary of Station Dwell Times Showing Breakout of Open and Close Door Times

Open Doors Delay Time	Close Doors Delay Time	Unloading/ Loading Time	Dwell Time	
0:00:09	0:00:10	0:00:29	0:00:47	Average
0:00:21	0:00:27	0:01:46	0:02:05	Maximum
0:00:05	0:00:05	0:00:10	0:00:28	Minimum

Train headways and train loads were varied during the period. The time between trains varied from 00:25 to 09:45 minutes at Gallery Station (Red Line – Glenmont direction) during the period of observation while the average headway observed was 02:18 minutes.

At least two instances were noted when the train needed to make a second stop before the doors were opened, and several instances of the doors being held open to allow passengers to enter were observed.

Both stations have a huge flow of passengers. Typically, there was no congestion of boarding passengers, except when there was a long headway between trains. Some normal congestion at escalators was also observed when passengers were unloading. Stations were usually clear or almost clear by the time the next train arrived.

As both stations are line interchanges, there were times when a line direction would get crowded or overcrowded even if the headway of trains in this line was regular (or not too far apart), because of the large number of passengers transferring from other lines (coincident with prior train arrivals on other lines).

Pentagon and Court House

Most of the issues observed at Gallery Place and Metro Center stations were also noted at the Pentagon and Court House stations.

No special issues were noted at Pentagon Station – in fact, this station, even with its huge flow, did not seem to be as critical as Gallery and Metro Center.

Court House is the last station before the junction station at Rosslyn. While most of the time trains were able to accommodate all inbound passengers, when there was a long time before a train arrived, passengers were left standing on the platform after the train had left. This occurred even though there was sufficient capacity on the train to take them, albeit on a different car.

In summary, the door open and door close functions take an average of 19 seconds out of an average of 47 seconds total station dwell time (40% of the total). Reduction of these times would permit a significant reduction in scheduled headway.

OCC Visit

The OCC is supported by a conventional dispatching system, with standard dispatching consoles and wall panel displays. There are also some maintenance and support stations in the OCC room.

In normal conditions, train routes are aligned automatically by the field signaling in a fleet mode. In exceptional cases, the Controller needs to switch to manual control (for example, in cases of junction station conflicts or train failures or delays).

Speed restrictions applied in the field have to be manually entered in the dispatching system. There is also no interface between the dispatching system and the on-board systems (ATP, automatic train control [ATC], and ATO).

Areas Selected for Further Examination

TTCI consolidated the information acquired and reviewed the planning documents provided by WMATA. Based on meeting discussions, TTCI identified the following areas for further examination as part of this FTA research project.

Current Signal Control System

A better understanding of the signal control system would allow analysis and investigation of current line limits and identify potential opportunities for improved headways and train performance. It would also help to better understand the elements of operational times, as well as the impacts of delays and opportunities for recovery from delays. The focus of such an analysis would be on the operational efficiency permitted by the signal system, using an analysis of signal block design, interaction of system components, system latencies, and external (non-signal system) influences. An analysis of the track and signal diagrams would enable study of issues arising from historical train movements and delay reports. It would also allow investigation of potential improvements from either signaling adjustments and/or operational strategies when dispatching trains. It would also facilitate evaluation of potential operational benefits of newer technologies being used such as CBTC, as compared to existing systems characteristics and limitations. The study could also compare the difference in capacity available with manual operation versus ATO and potential improvements for each mode.

Potential Improvements to OCC Operations, Particularly to Compensate for Train Delays

If improved information, timeliness of information, or interfacing with the signaling system can help improve the operation, this might be the fastest and least costly way of making changes. In the OCC, the system functions are non-vital and, therefore, may require less development and validation time than making changes to the vital signal system. Identifying potential improvements in the OCC can help better handling of the HRT operation in general, particularly when handling critical areas and exceptions historically observed during the operation. Issues might vary from short to long term actions, including (but not limited to) the following:

- Provide (or improve) automatic monitoring tools like alarm monitoring/train delay/station flow (passenger arrival rate).
- Develop system interfaces to provide more consolidated information to users and to allow systems to perform more automated analysis, particularly as they relate to identification of components subject to repeated or frequent failure.
- Improve human machine interface layout and configuration.
- Develop (or improve) automated and "intelligent" systems to help dispatch trains.
- Review current recovery strategies adopted by Controllers and other support staff at the OCC.
- Improve and implement hot-standby configuration to increase system availability/reliability.

Station Dwell Time and Train Operations

During the first visit to WMATA, TTCI observed some potential issues related to train operation at stations and train headways. These included variability of train arrival times, delays caused by passengers holding doors, berthing at the platform delays, unmarked trains, failed trains, etc. Further discussion has also revealed that these issues are areas of concern for WMATA. These issues that increase station dwell times can have a significant impact on headways, in addition to causing delays to ripple to operations of other trains and stations, as discussed in Section 2.

With regard to the current platform configuration, such a study could provide general guidelines for passenger flow management at core stations. TTCI suggests performing additional site observations at selected stations and train routes as suggested by the results of the analysis of historical HRT operation to ensure that the data is sufficiently complete for the conclusions drawn.

Short-Term vs. Long-Term Capacity Improvements

Although the focus of this study is on short-term operational improvements, some longer-term strategies based on technology advances and newer rail cars coming on line might also be considered. The agencies might also consider studying the feasibility of technology to shorten headways. They could also examine potential ways to verify that the newer technology and equipment meets the reliability requirements specified by WMATA with the end goal of reducing the incidence of service failures. Potential improvements are discussed more fully in the next sections.

SECTION

5

Case Study – BART Operation

Overview of BART Operation and Train Control System

The BART system currently operates 104 miles of HRT service, including 44 passenger stations and 669 revenue passenger vehicles. The system includes five separate train routes—Red, Blue, Orange, Yellow, and Green—as shown in Figure 5-1.

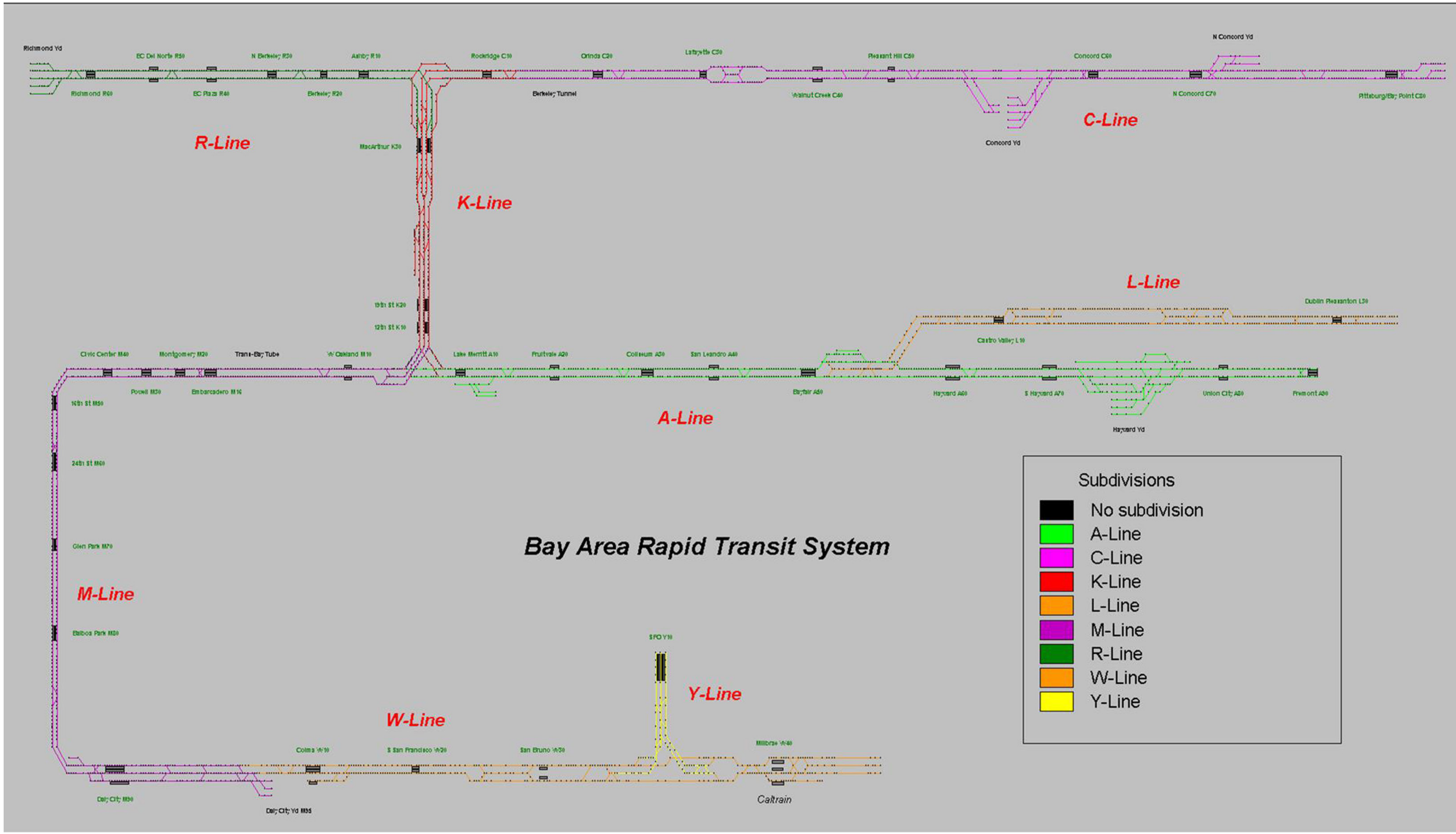
Figure 5-1

BART system map

TTCI engineers met with BART staff, rode BART trains, and observed various aspects of system performance. BART also facilitated sharing of their rail traffic controller (RTC) system operations model with TTCI for modeling as part of this capacity study. The RTC model schematic for the BART system is shown in Figure 5-2. Note that the model schematic depicts the actual track configurations of various line segments over which the various train routes operate. For example, a train operating on the Green Route would traverse the M-Line and the A-Line. The K-Line hosts trains operating the Red, Orange, and Yellow routes. For purposes of further discussions, line segments rather than train routes will typically be referenced.

Figure 5-2

Schematic of BART system from RTC model



The BART system normally functions using ATC, which includes ATO and ATP. In addition, the Sequential Occupancy Release System (SORS) is a non-vital overlay that provides a supplemental level of train protection. Descriptions of portions of BART train control system and train operations follow.

From the BART *Operating Rules and Procedures Manual* (2006):

> **ATC** The system for automatically controlling train movement, enforcing train safety, and directing train operations. ATC includes subsystems forATO, train protection, and line supervision.
>
> **ATO** The subsystem within ATC that performs the functions of speed control, programmed stopping, and door operation.
>
> **ATP** The subsystem within ATC that enforces safe operation, including speed restriction and separation of trains running on the same track and over interlocked routes.
>
> **SORS** A system that provides backup protection to safeguard against loss of occupancy detection by the primary detection system.

From the BART website (www.bart.gov, accessed July 2, 2012):

> **OCC** The OCC functions as the nerve center of BART's 104-mile system, performing supervisory control of train operations and remote control of electrification, ventilation, and emergency response systems. The display boards use computer imaging and video projection to display the entire system, combining information into two: one for track and train positions and the other for maintenance information and electrification. Stations and wayside - Network of control devices and track circuits controlling train speeds, stops, and safe spacing. Backup train protection system - SORS: 52 mini-computers in 26 stations.

More detail about SORS is provided by Kurt Raschke (http://transport.kurtraschke.com/2011/10/signalling-safety-culture, accessed July 2 2012):

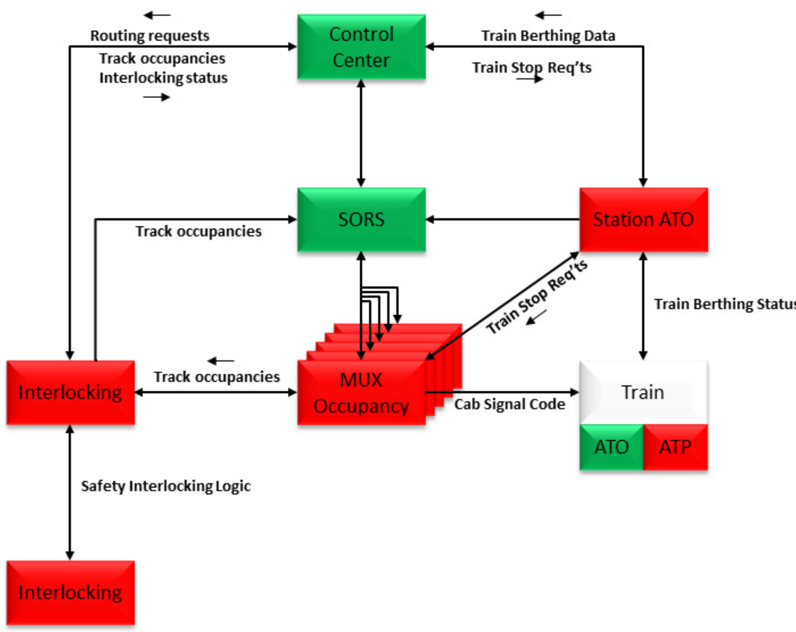
> After CABS came SORS, the Sequential Occupancy and Release System, a more advanced system that will not permit a block to show as "unoccupied" until its track circuit detects an unoccupied condition and the next track circuit in the direction of travel detects an occupied condition. In this manner, if a train travels into a track circuit that fails to detect it, the track circuit behind will not be cleared, and will thus continue to protect the train.

The BART train control system has several discrete operating and step down speeds, including 80, 70, 50, 36, 27, 18, and 6 mph and stop. Automated train operations at these discrete target speeds can restrict capacity in some cases. For example, a curve or turnout with geometry acceptable for operation at 34 mph will be operated at the next lowest speed increment, i.e., 27 mph.

Figure 5-3 illustrates the elements and functions of the BART train control system.

Figure 5-3

Block diagram showing SORS, ATO, ATP, train, and interlockings on BART



Based on discussions with BART, the operation of the railroad is performed with a combination of various control and monitoring systems. Some further characteristics of the train control and related systems are described below:

- Integrated Control System (ICS) is the system that supervises and dispatches the trains in real time. ICS is the name for the ATC system, and it is an in-house development.
- SORS is the non-vital overlay system to ensure that blocks cannot be released prematurely.
- The train control system is based on a fixed block vital interlocking performed in the field. In areas where the traffic is dense or where only slow speed is permitted, the blocks are very short (as short as 70 feet in some cases).
- Trains operate with an ATO system, designed to operate at a maximum speed of 80 mph, but the normal maximum operating speed is set to 70 mph, because of power consumption and maintenance reasons.

- Door opening is automatically triggered by the on-board system based on antennas and sensors that facilitate train stops at stations. Doors are automatically released by the system and can be manually closed after passenger dwell time. The train operator is responsible for closing the doors.
- The field system can still operate trains in case the central system fails. However, if the wayside system fails, speed codes may not be generated and trains will have to be operated manually, according to the OCC instructions.
- Sometimes a train needs to be "reset" due to failures. In such cases, the time to reset the train may take from 2 to 5 minutes, depending on the failure.

OCC Observations

The following observations were noted from a visit to BART's OCC. OCC is supported by the ICS, which provides functionalities for train dispatching and overall system monitoring and alarming. The railroad network is projected on wall panels, with some reduced display of other system components. The OCC operates normally with four train controllers. There are other consoles for monitoring maintenance, communications, and stations. There is also a specific control system for the electric power system, with projected displays and consoles handled by specific operators. There is one OCC Manager per shift, who is responsible for the overall operation. Train conflict resolution and network regulation is done at multiple levels:

- ICS tries to maintain the trains at the targeted running times, regulating the train operation at every arrival at a station.
- In case of conflicts and during manual operation, Train Controllers may make some decisions by themselves and determine the best train operation.
- Decisions that may cause major impacts in the railroad operation are made by the OCC Manager.

All the OCC areas usually are interacting, especially when decisions are being made. In normal conditions, train routes are aligned automatically by the field signaling in a fleet mode (AUTO Mode). In some cases, the dispatching is performed locally at stations (LOCAL Mode), which means that trains will be operated normally, but the dispatching is performed locally and not by ICS. In exceptional cases, the dispatching is performed by the Train Controller (MANUAL Mode), which may cause delays while routes are being requested.

The reliability/availability of ICS has been increased with a recent release of a new version, which is more modular and allows the system to run in dual configuration and with distributed processing.

Additional Information Affecting System Capacity

Additional information pertaining to BART operations, particularly on items that may affect capacity, is noted below:

- The time to recycle from a door held by a passenger is 2 seconds.
- The propulsion and brake services of a car can be cut out and the car can still remain in service, depending on the failure. A train can still operate with some cars cut out in such condition, depending on the number of cars in the train. Depending on the position of the failed car in the train consist, it can take 5–10 minutes to get to the car, cut it out, and return to the cab. If this happens during a peak hour, it causes a major impact in the transit operation. To reduce recycle time, it would be desirable if the train operator could be provided with knowledge of what car has failed.
- During peak service periods, "rush" trains are scheduled to operate between the base headway trains to provide additional capacity.
- It is estimated that additional cars will be required to support increasing ridership in the coming years. Station platforms can accommodate 10-car trains, but few trains are currently operating to that length during the peak rush hours.
- The power supply system will need to be investigated to assess whether it can support an increase in the number of trains.
- BART would like to increase the current peak operation from 24 trains per hour to 30 trains per hour.

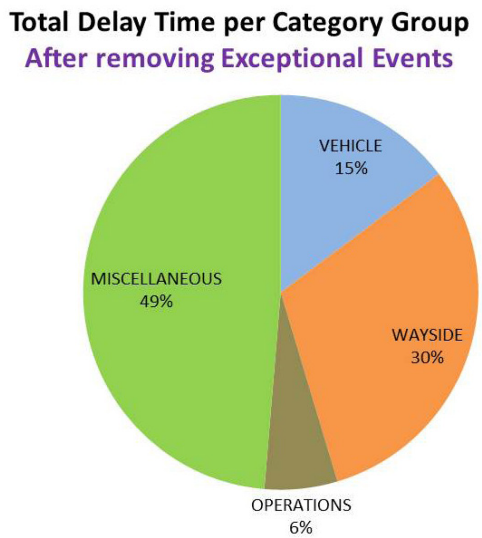
Delays and Service Performance

BART provided delay reports and service performance reports for a six-month period. TTCI performed some preliminary analysis to determine areas where capacity improvements might be achieved. In general, reduction of delays and increase in service reliability will enable increased system capacity.

Figure 5-4 shows delays for the various category groups as tracked by BART's passenger flow model (PFM), which tracks tickets and train performance to determine passenger on-time performance.

Figure 5-4

BART total train delay time due to various sources

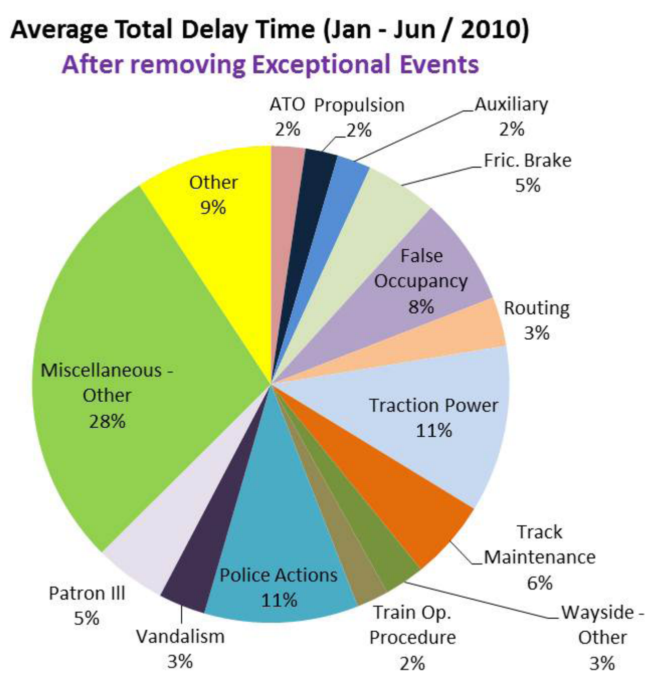


Note that the amount of delay attributed to the miscellaneous category is large. Further clarification is needed to better determine needed system improvements. This data were also sorted by month, but no clear trends over time were evident.

Figure 5-5 shows a breakdown with more detail, including a breakout into individual categories.

Figure 5-5

Detailed breakdown of BART total train delay time due to various sources



The detail provides some better clarification and suggests areas where improvements might be gained. Some of these are somewhat uncontrollable. Further clarification of the "Other" and "Miscellaneous–Other" categories would be useful. Reductions in delays of any sort can improve system reliability and enable increased capacity.

Figure 5-6 shows the average delay time per event. Note that certain causes of delays are responsible for a disproportionate amount of delay time. The category of "Other" is the most obvious example, in comparison to Figure 5-4. In this case, further clarification is needed.

Figure 5-6

Average delay time (minutes) per event due to various sources

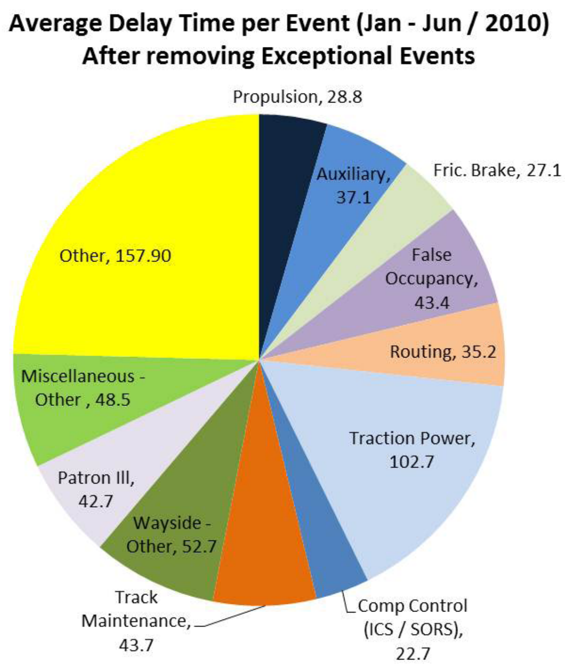


Figure 5-7 shows the monthly average number of trains delayed per event, rather than the total delay time for various category groupings. A detailed breakdown is provided in Figure 5-8. The breakdowns are not much different than those for the delay time as shown in Figure 5-4 and Figure 5-5.

Figure 5-7

Monthly average number of trains delayed due to various sources

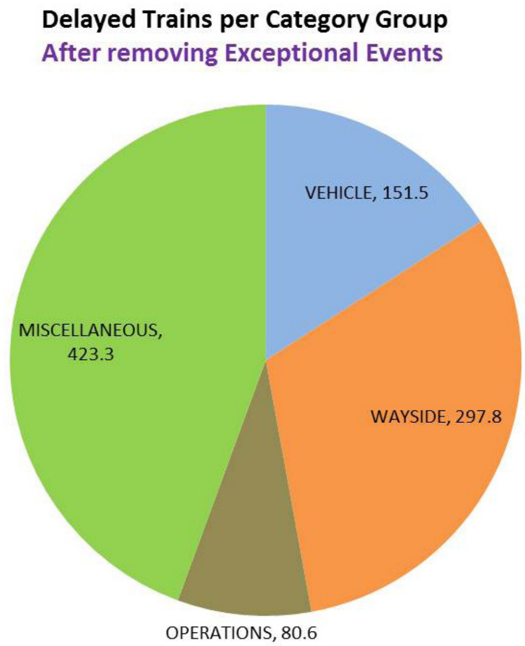
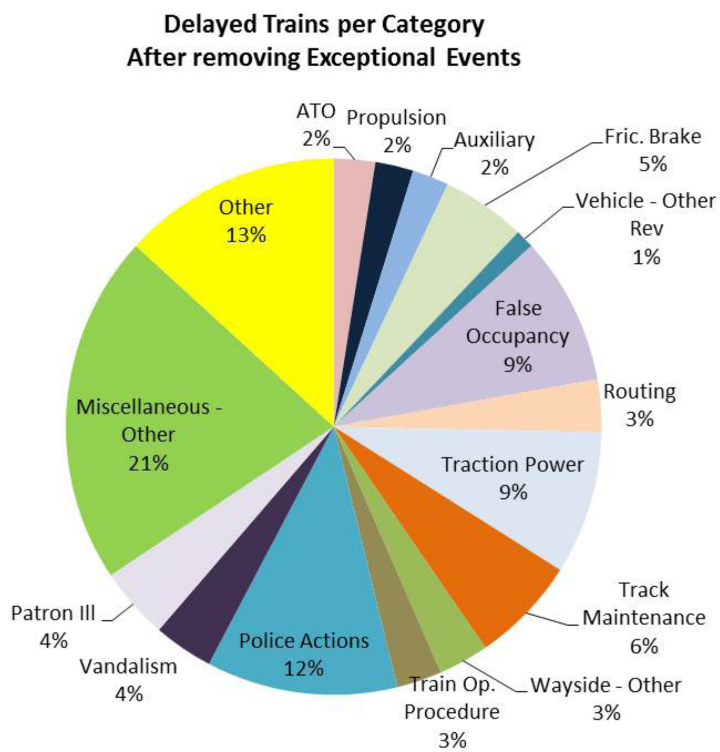


Figure 5-8

Detailed breakdown of monthly average number of trains delayed due to various sources



Tracking of delay causes is an important first step in measuring system performance and determining where improvements and investments can provide the greatest benefits. Reducing delays can provide improved system reliability and enable improved capacity. Removing such variability from the transit system can both enhance system operation and improve the customer experience.

Recommendations might include improving recovery time from "False Occupancy," "Track Maintenance," and "Traction Power" events, by use of monitoring systems and procedures, as well as developing specific operations recovery procedures. Recommendations for reducing the number of delays from "False Occupancy," "Track Maintenance," "Traction Power," and "Friction Brake" events might include revisiting maintenance procedures and investigating the use of new or alternative technologies.

SECTION 6

Case Study — BART Capacity Assessment

Capacity Limitations with Current Infrastructure

Discussions with BART suggested that the most critical areas in terms of needed capacity improvements might be the M-Line in the downtown area, the Oakland Wye, MacArthur Junction, and a SORS system boundary area on the A-Line.

In the downtown area, the M-Line has several closely-spaced stations with high passenger counts, which result in longer station dwell times, particularly during rush periods.

The Oakland Wye is the junction connecting the M-Line, K-Line, and A-Line on the east side of the bay. All five train routes pass through the Oakland Wye. As noted earlier, junctions can often constrain capacity, because of merging traffic issues, particularly with nearby stations. Maximum train speed through this junction is 18 mph, which provides a further operating restriction to be considered.

MacArthur Junction is where the R-Line and the C-Line come together to form the K-Line. As opposed to Oakland Wye, this junction has higher allowable train speeds and more available tracks for intended routes. Also, there is no direct service from the R-Line to the C-Line, greatly reducing the complexity of this junction compared to the Oakland Wye.

On the A-Line, there is a series of three section boundaries in the SORS system between the stations of Fruitvale and Bayfair. BART officials noted that peculiarities in the SORS system in this area seem to cause congestion. In particular, in this area, a local SORS section will not release its last block following a train until the adjacent block in the adjoining SORS section is also released. This has the effect of inserting an extra block length worth of train travel time into the minimum unrestricted headway at these locations.

Capacity Constraints

To quantify the capacity limitations on the M-Line in the downtown central business district, dwell time data were obtained for the stations in that area.

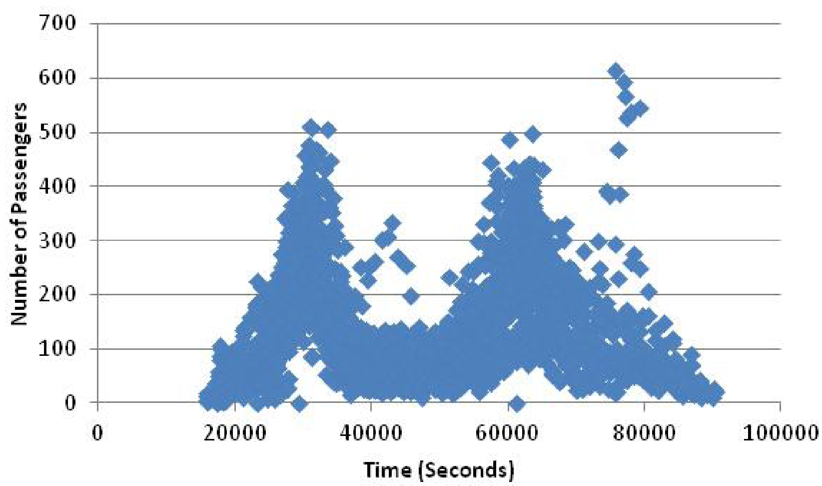
TTCI observed the operation of trains at the Embarcadero station (as suggested by BART experts) during the morning rush hour, taking notes on train times and operation as well as the flow of passengers. Primary passenger flow at this station during morning rush hour is for detraining passengers. Observations included:

- Average train headway was 142 seconds. Maximum headway was 256 seconds.
- The train doors consistently opened without delay as soon as trains stopped.
- The trains consistently departed 3 seconds after doors were closed.
- There was no event of doors being held, nor were there any door failures during the observation period.
- Two trains arrived at reduced speed, causing a little longer time for those trains to pull up to the station stop location.
- One train departed at a reduced speed, taking approximately 45 seconds to clear the station platform.
- Some lines formed at stairways during this period; however, stairs were always cleared by the time the next train arrived. The only exception was when trains from both directions arrived simultaneously at the station.
- The occupancy of the cars was evenly distributed. Trains were neither overcrowded nor under occupied.

Passenger count data for passengers boarding and detraining at the Embarcadero station is plotted in Figure 6-1 against time of day, where zero seconds represents midnight. The morning and evening peak periods are clearly visible. Data includes each train over a four-day period of weekday operations. During the morning and evening peaks, more passengers tend to board or detrain each train as compared to early morning, midday, and night time periods. The morning peak hour is approximately 7:30–8:30 AM.

Figure 6-1

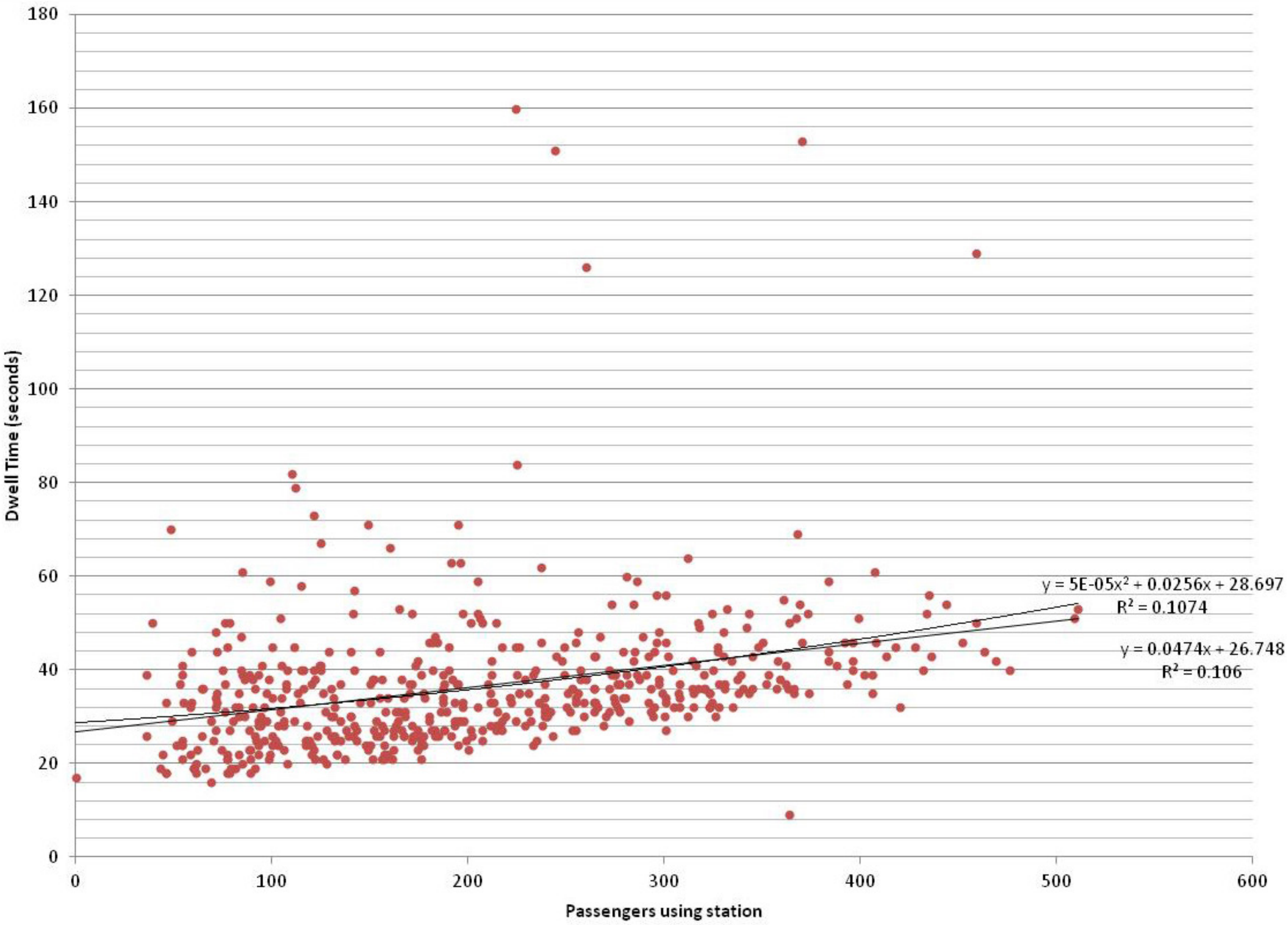
Number of passengers boarding and detraining at BART Embarcadero Station—notice morning and evening peaks



Station dwell time is a function in part of the number of passengers boarding and detraining. Figure 6-2 shows that as passenger count increases, station dwell time increases. These data are from BART's PFM system. Average dwell time values as a function of passenger count can be predicted using trend line equations.

Figure 6-2

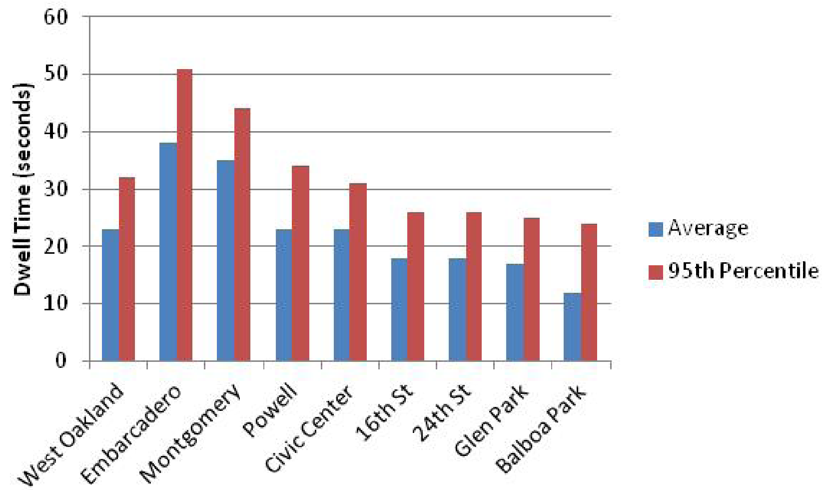
Number of passengers boarding and detraining at BART Embarcadero Station—notice morning and evening peaks



Dwell time data from BART's PFM system were analyzed to determine both the average and the 95th percentile dwell times during rush periods at stations along the M-Line, including those in the central business district. Figure 6-3 shows the results. The Embarcadero station, which has the highest passenger counts, also has the longest station dwell times. The 95th percentile dwell times provide a reasonable upper estimate that the system should be able to accommodate without causing delays. These dwell times are used in the headway analysis presented below.

Figure 6-3

Dwell times at BART Market St. Line stations, outliers excluded



Recommendations for Increasing Capacity

Improvements in the train control system might allow reduced train headways, thus increasing the capacity of this HRT system. For a system of this complexity, a detailed model is necessary to perform the necessary simulations and develop metrics for comparison.

TTCI used the RTC model developed by Berkeley Simulation for BART to analyze the system in four areas of concern: the M-line in the central business district, Oakland Wye, MacArthur Junction, and the A-line south of the Oakland Wye, where the SORS interface causes additional spacing between trains. The objectives of this modeling effort were twofold:

1. Measure achievable headways with the existing train control system (ATC, ATO, ATP, plus SORS).
2. Evaluate potential improvements with alternate signaling and/or train control systems.

Model Used

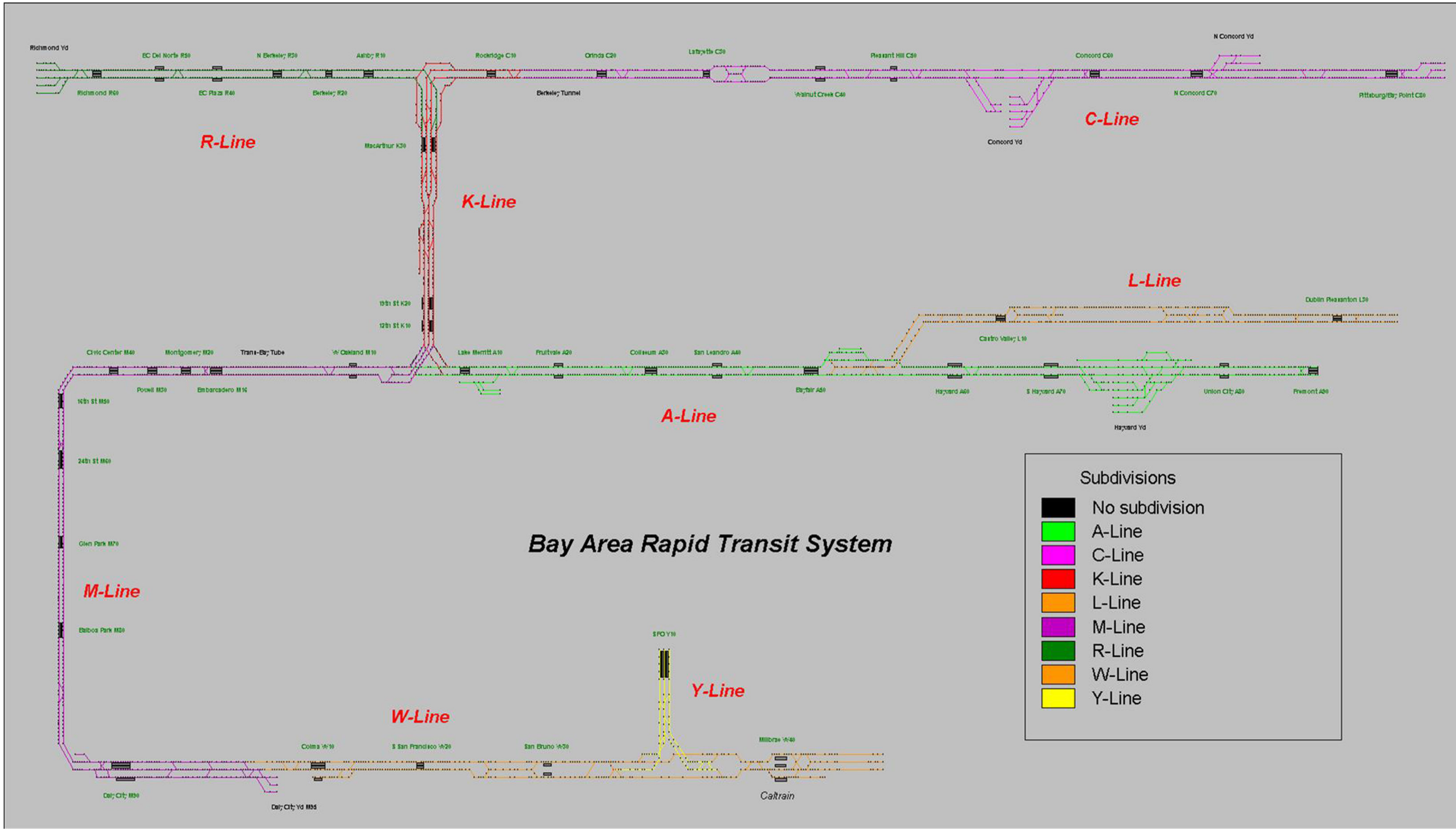
The RTC model of the BART system was created by Berkeley Simulation, the developer of the RTC software package. The model was provided to TTCI by Berkeley Simulation on authority from BART. The RTC model is currently used by BART for train scheduling and planning purposes. The model is a discrete event model and includes the entire BART network, with nearly 200 miles of track, 1,800 individual trains, 8 distinct lines, and 42 stations along with signal blocks, speed limits, signal speeds, and signal sets. The model includes almost everything needed to analyze train operations on the BART system. For purposes of this study, TTCI created specific models derived from this original model to analyze the effects of potential changes in train control/signal systems, train schedules, and track configurations.

In the original model received from BART, there were over 20 different train routes, corresponding to different lines, stations, and schedules. To minimize model run time, only routes that pass through points of interest were chosen for analysis of each particular area of interest. Having individual train sets traversing specific routes created the option of modifying each set individually, thereby allowing multiple aspects of a route or intersection to be analyzed more simply.

Figure 6-4 shows the various sections of the model used for detailed analysis of train headways in the four areas of interest that have been noted to cause train concentration. The K-line is a critical segment that is needed for analysis of both Oakland Wye and MacArthur Junction. In addition, the K-line has several closely-spaced stations and low train speed limits. Southbound trains are limited to the use of one track through the 19th and 12th Street stations. Additionally, the 19th and 12th Street stations are extremely close to one another with a maximum speed limit of 36 mph between them. Because the area around the Oakland Wye is underground, the cost of expanding or reconfiguring the tracks there would be high.

Figure 6-4

Areas of BART system for detailed capacity analysis in RTC model



To analyze the overall effect of changes to individual aspects of the system, modified models were created to manipulate and study each facet in the system. Train headways were changed to force trains to interact at specific points or determine the minimum achievable headway. Station dwell times were changed to determine headways and delays during nominal, average, and heavy volume. Train control and signal options were altered to determine the effects of those changes on headway capacity.

Details of the BART Signal System

In the BART system, cab signaling is used to provide trains a speed-based movement authority that is derived from an occupancy-based fixed-block system. Although a speed limit can be imposed on a train at any point in a particular track block, that speed limit is derived from the location of the preceding train and the track speed limit. The fixed blocks have lengths from 0.01 to 0.16 miles based on the minimum travel time and stopping or slowing distance. Speed increments limit trains to 80, 70, 50, 36, 27, 18, 6, and 0 mph. As a train approaches a preceding train, the train control system (ICS) provides one of these operating speeds based on block lengths and stopping or slowing distance.

When two trains are operating using the ICS and SORS system, there is at least one empty block between them. This is an essential safety feature. For example, if one train is stopped and a following train is approaching, the following train will eventually enter a block where its speed is reduced to 6 mph. Then, if the preceding train remains stopped, the following train will enter a block where it is limited to 0 mph. Because the following train does not begin braking to a stop until it physically enters the 0 mph block, it is imperative to leave an empty block behind each train or the trains could collide.

Considerations Regarding Headway

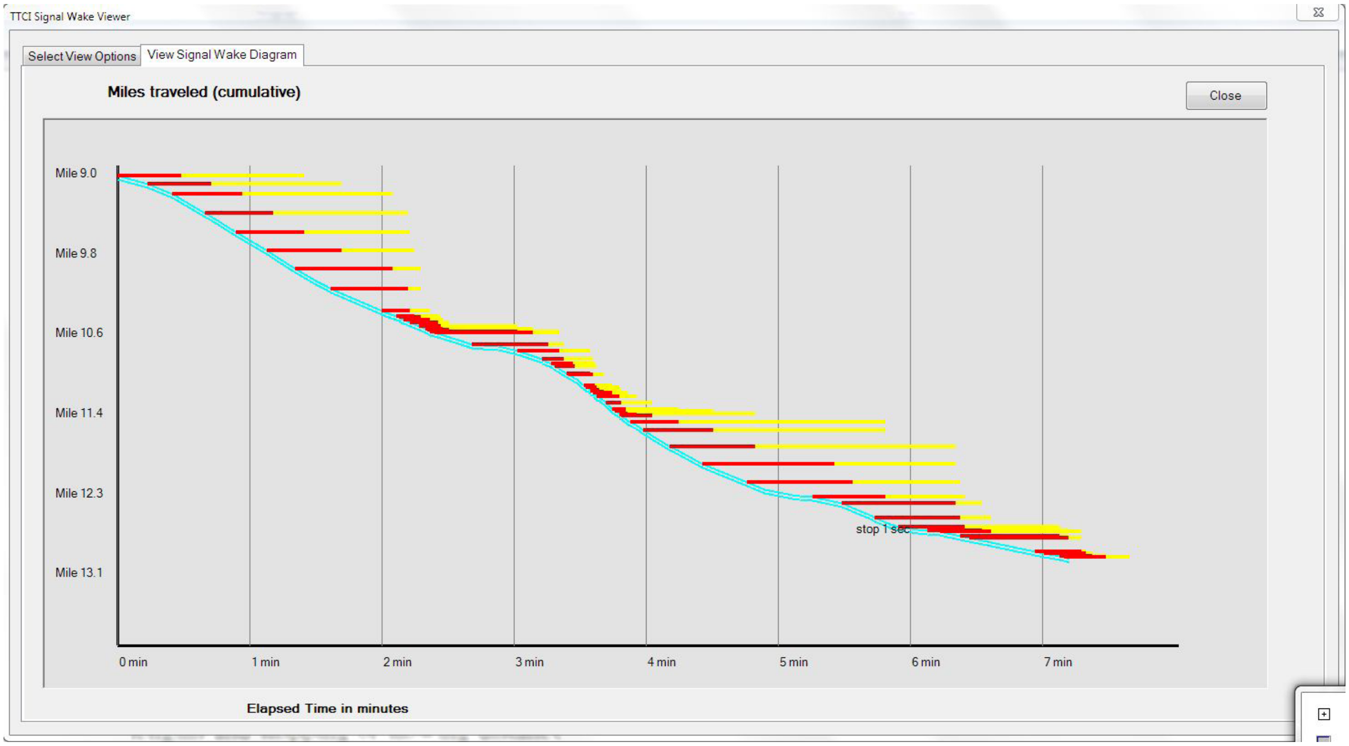
For normal operations and for setting schedules, headway is the closest a train can operate behind another without encountering a restrictive signal.

To determine where delays and congestion occur, time-distance and signal wake diagrams are indispensable. A signal wake diagram is particularly useful for determining headways for trains to operate without encountering any restrictive signals.

Figure 6-5 shows a signal wake diagram. To visually determine the interactions between trains, red represents blocks with a 0 mph speed limit and yellow represents blocks with a speed limit less than the maximum allowable track speed limit and greater than 0 mph. It is easy to see the different speeds, station stops, signal clear-up times, and an overall summary of performance for a train along its route.

Figure 6-5

Signal wake diagram



The time it takes for a signal to go from red to yellow to clear is called the signal clear-up time. The blue-green lines represent the train itself, from the head end to the rear end of train. This figure shows where trailing trains cross into yellow blocks where their speed is reduced by the signal system.

The maximum signal clear-up time governs the minimum unrestricted headway, and the signal wake diagram shows where it occurs. It is often possible for trains to operate more closely, but such operation will result in additional travel time.

In a system where trailing trains do not pass preceding trains, the question of how close trains can run efficiently is important. Although operating trains very closely might allow more trains per hour to stop at a given station, those trains will run slower and have longer travel times and slower average speeds when they are being limited by preceding trains. Such operation might be necessary during recovery periods from an unusual delay, but it is not usually built into a schedule for normal operation.

Potential Means of Increasing Capacity

Four potential capacity improvements were evaluated, including a brief study of a potential speed increase, but the focus is primarily on progressive changes to the train control system. These alternatives were modeled to provide specific measures of potential improvements.

One section of interest where delays occur is on the M-Line between the Civic Center and Embarcadero stations. The speed limit is at or below 36 mph, and there are four stations within 1.5 miles of one another. There is a small section of track between the stations in this section where the speed limit could, theoretically, be increased. Analysis shows that increasing the speed limits between the Embarcadero and Civic Center stations improves headways only by a few seconds. This savings in time may not be economical, because the trains are accelerating and decelerating for most of the trip between stations.

The existing BART ICS system uses a speed-based authority, whereby trains are provided a maximum speed for each segment or block of track. When a train enters a block with a more restrictive speed, it begins slowing to that speed. Such systems are designed with track blocks that are long enough (at minimum) so that trains can slow to the desired speed before reaching the end of the block for each speed increment.

Other systems use an occupancy-based authority, whereby trains are provided or denied permission to enter a particular block of track. In these systems, a means is needed to determine where an authority ends and a train must stop. In manual operations, this is accomplished by fixed signals and the knowledge of the train operator. In automated systems, however, the train must know where it is, using some form of location determination system, it must be given a fixed stopping point, and it must know its braking characteristics. In other words, in contrast to a system with speed authorities in which braking is reactive, in a system with occupancy authorities, trains must be capable of predictive braking.

In practice, there are also systems that use a combination of speed and occupancy based authorities to control trains on various rail systems.

After the initial analysis of the BART system with the existing ICS and SORS, three alternative cases were modeled to determine the extent of headway improvements possible. To implement these alternatives, new off-board and on-board systems are required. They are described in the section on Implementation Phasing that follows.

Case 1 is the current BART system, which is a speed-based authority. (SORS is an occupancy-based overlay system.) Normal maximum train operating speed is 70 mph. Step-down speeds approaching an occupied block include 50, 36, 27, 18, 6, and 0 mph. Wayside units provide the appropriate train operating speed to the train based on input from the ATO, SORS, adjacent wayside units, and interlockers. Track circuits provide occupancy information to the wayside units and the SORS system.

In Case 2, the ICS speed step-down system is replaced with an occupancy-based system using the existing fixed block lengths, but allowing trains to maintain higher speeds until reaching the point at which braking is necessary to stop short of a block limit in a single brake application or, similarly, to reduce speed to a lower speed limit. In this case, one empty block was provided between a train ahead and the stopping point for a following train. Case 2 represents a shift from speed-based authority to occupancy-based authority. It requires some form of CBTC system.

Case 3 is similar to Case 2, except that it no longer maintains an empty block between the train ahead and the stopping point for a following train. As with Case 2, the fixed block lengths used for the simulation are the same ones currently used for the existing ICS. Both Cases 2 and 3 are fixed-block CBTC systems.

Case 4 is a moving block CBTC system (considered an emerging technology at this time) in which there are no fixed track blocks, but authorities are issued to the rear of the previous train, less some predetermined buffer distance. Case 4 provides the closest possible train spacing for following trains.

Comparative Results

For each area of study, trains running through the appropriate sections of the system were studied using multiple train control system configurations (cases described above). In some of the analyses, any particular track section could be responsible for the governing headway on the route. Using RTC, the governing headway was determined by using the maximum signal block clear-up time on a train's route. All the train sets simulated used identical trains, so there were no opportunities for trains to make up lost time. After a delay was encountered by one train, the delay was propagated through to all following trains.

TTCI's signal wake software automatically determines the maximum signal block clear-up time and creates a visual representation of the time, distance, and signaling aspects of three consecutive trains on a route.

Analyzing train control system configurations was done on a route basis. This means trains were simulated over a particular route for each set of signal and train control options. Because RTC is node-based software, the moving block train control system was only simulated over a short section of track (a few miles) to keep the model size manageable. Due to the complexity involved with simulating moving block in the current model, it was only done for the analysis of the M-Line in the central business district (Section 3). All other sections of interest were modeled using train control system Cases 1, 2, and 3 only.

A-Line with SORS Boundary Interfaces (Section 5)

At boundaries between adjacent SORS systems, the SORS boundary blocks are not released for occupancy until the adjacent block in the adjoining system is also released. This results in two empty blocks rather one empty block behind a train when crossing a SORS boundary.

Table 6-1 shows train capacity in trains per hour on the A-Line for both northbound and southbound fleets of trains. Note that the use of occupancy-based train movement authorities in Cases 2 and 3 provide increased capacity compared to the existing speed-based authority system (Case 1). Also note that the use of the current SORS boundary block system restricts the number of trains per hour when used as an overlay on the Case 2 and Case 3 systems. But for the existing system (Case 1), there seems to be no measurable delay caused by the SORS boundary interface operation. Because the moving block train control system (Case 4) does not use fixed blocks, the use of a SORS overlay would not apply. Therefore, it was not analyzed for this section.

Table 6-1

Train Capacity on A-Line with and without SORS Boundary Blocks, No Trains Merging, Assuming 1-Second Station Stops

Boundary Delay Comparison			Scheduled
Case	Trains per Hour	Headway (Time)	Trains per Hour
Case 1a North	29	2:02	12
Case 1b North	30	1:57	12
Case 2 North	61	0:59	12
Case 3 North	61	0:09	12

Case 1a includes delays from boundary nodes. Case 1b and Case 3 do not include delays from boundary nodes. For the model used to generate the data in Table 6-1, trains were run on one route, either northbound or southbound, through Section 5 on the A-Line, with 1-minute initial headways and 1-second station dwell times. For both Cases 2 and 3, there is a significant increase in the trains per hour when the delays at SORS boundaries are eliminated. Note that maximum planned station dwell time needs to be added to the headway shown in the table to develop achievable scheduled headway.

Expanding the simulation, the model was run with trains running simultaneously on multiple routes to include realistic traffic delays. With additional delays, the northbound trains running through Section 5 still have headway capacity governed by the SORS boundaries. Table 6-2 shows the increased capacity in this multiple train and multiple route scenario. Southbound trains running through A-Line Section 5 must also run through the K-Line and the Oakland Wye (Sections 2 and 4), which tend to govern their headways. The results in Table 6-2 are generally similar to those shown in Table 6-1, with the same conclusions.

Table 6-2

Train Capacity on A-Line with and without SORS Boundary Blocks, with Trains Merging Assuming 1-Second Station Stops

Boundary Delay Comparison			Scheduled
Case	*Trains per Hour*	*Headway (Time)*	*Trains per Hour*
Case 1a North	29	2:02	12
Case 1b North	30	1:57	12
Case 2 North	61	0:59	12
Case 3 North	61	0:09	12

M-Line in Downtown CBD Area (Section 3)

The downtown area on the M-Line is a major passenger trip origination and destination area for the BART system, with high passenger counts at many stations, particularly during peak hours. In this area, it was deemed prudent to consider the effects of station dwell times, which can be a major contributor to headway time, as previously discussed. Using data presented above from the BART PFM system, average and 95th-percentile station dwell times were used in the RTC model. Additional station dwell time does not always add directly to the headways of trains, because only one point along a train route governs headway between trains. Unless that point is a station, additional station dwell times would only affect travel time.

Table 6-3 shows the results from the simulations for the various train control system cases, for both average and long station dwell times. In each scenario, the occupancy-based fixed block train control systems offer noted improvement in capacity over the existing speed-based authority train control system. As expected, Case 3, without the additional block protecting behind a train, provided more capacity than Case 2. As expected, the longer station dwell times reduced the line capacity for each train control system. Table 6-3 shows similar results from simulations for northbound traffic using trains on multiple routes rather than a single route.

Table 6-3

Train Capacity on M-Line Downtown with Average and 95th Percentile Station Dwell Times, No Trains Merging

	Scheduled	Average Station Dwell Times		95% Station Dwell Times	
North	*Trains per Hour*	*Final (Trains per Hour)*	*Final (Time)*	*Final (Trains per Hour)*	*Final (Minutes)*
Case 1	22	36	0:01:40	29	0:02:04
Case 2	22	38	0:01:35	33	0:01:49
Case 3	22	45	0:01:20	38	0:01:35
Case 4	22	47	0:01:17	41	0:01:28

Table 6-4 shows data from running one train set north with initial 1-minute headways, from MP8.71-MP6.5 on the M-Line covering stations Embarcadero (M16), Montgomery (M20), Powell (M30), and Civic Center (M40). It is data from a simulation where northbound trains running along the M-Line were merged with northbound trains coming from the A-Line. Southbound is not included, because no merging can occur between two groups of southbound train sets that are restricted after passing through the K-Line. Basically, one train set is always delayed before reaching the M-Line.

Table 6-4

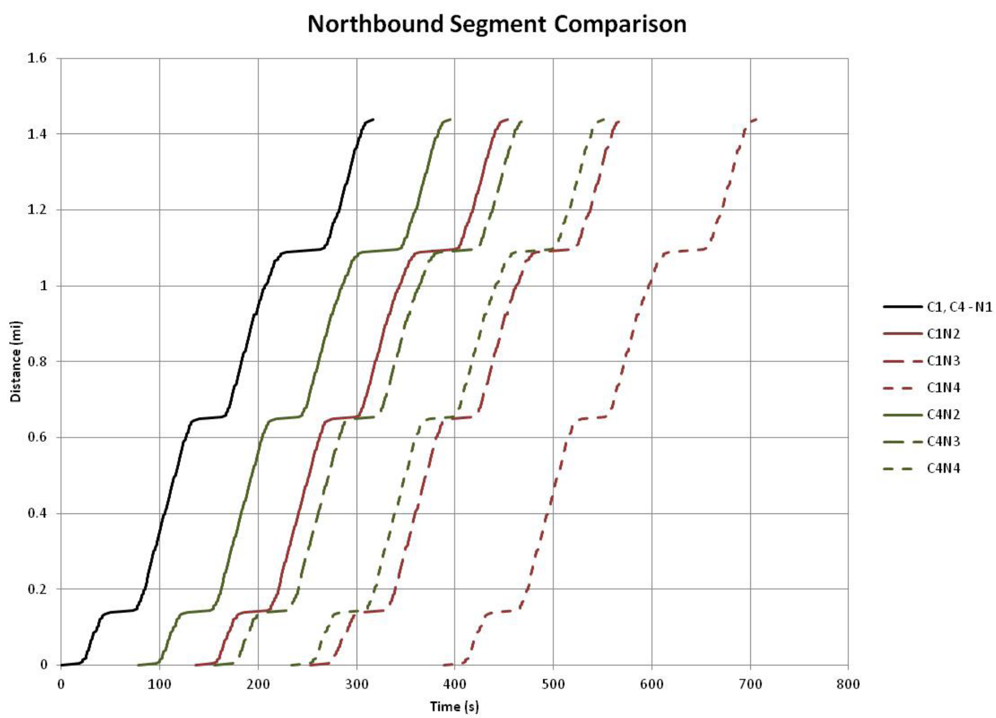
Train Capacity on M-Line Downtown with Average and 95th Percentile Station Dwell Times, with Trains Merging

	Scheduled	M Line, Northbound Merging Comparison			
North	Trains per Hour	No Merge (Trains per Hour)	No Merge (Time)	Merge (Trains per Hour)	No Merge (Time)
Case 1	22	30	1:59	30	1:58
Case 2	22	61	0:59	61	0:59
Case 3	22	61	0:59	61	0:59

Figure 6-6 shows a time-distance diagram comparing the moving block train control system (Case 4) with the existing speed-based authority train system (Case 1, ICS plus SORS). The green lines show that with such a system, four trains can be operated in less time in a moving-block system than it takes for three trains using the existing fixed-block system. The train speeds are the same. They are just able to run at closer spacing, because the moving-block system maximizes headway capacity for following train movements by minimizing extra track space as compared to what is used in fixed-block systems.

Figure 6-6

Time-distance diagram comparison of train following using moving block (green lines) and existing ICS and SORS system (red lines) for M-Line in downtown area



MacArthur Junction, K-Line and Oakland Wye (Sections 1, 2, and 4)

Simulations of MacArthur Junction, the K-Line, and the Oakland Wye areas indicate that MacArthur Junction itself is not a choke point for the system. Rather, headways in that area are governed by congestion on the K-Line. So, no further analysis of MacArthur Junction was performed. The 12th Street and 19th Street stations on the K-Line are so close to each other and to the Oakland Wye that simulations needed to include the entire area, so the results are shown together. The greatest congestion is for southbound traffic on the K-Line, as it is normally concentrated on one track, while northbound traffic has use of the other two tracks. Results from the K-Line (Section 2) simulation are similar to results from the M-Line (Section 3) when station dwell times are studied. Depending on the train control system case, different parts of the Oakland Wye or the K-Line may govern the train headways. Even so, this data is important if a new signaling system is to be implemented. Knowing where to invest in infrastructure and equipment for a specific signal set is as valuable as knowing which signaling set to implement.

Table 6-5 and Table 6-6 present the simulation results for trains on a single route and trains on multiple routes, respectively. Nominal station dwell times are much shorter on the K-Line as compared to the M-Line, so differences between average and 95th percentile dwell times were similarly less. This is reflected in the lower differences in trains per hour figures as compared to those for the M-Line.

Again, the simulation of the occupancy-based fixed-block systems shows that they offer potential headway capacity improvements over the existing system. The two different southbound routes account for trains going towards the A-Line (South 1) and M-Line (South 2). In Table 6-4, a few unexpected results show up when simulating trains on multiple routes. These likely indicate a change in the governing headway location and/or a change in train sequencing through the Oakland Wye. This may be causing apparent benefits to one train control system over another in this complex area under the present simulation. For better results, a series of simulations that include a statistical variation in times could be conducted.

Table 6-5

Train Capacity on K-Line with Average and 95th Percentile Station Dwell Times, All Trains on a Single Route

	Dwell Times		Scheduled
Case	*Average (Trains per Hour)*	*95% Percentile (Trains per Hour)*	*Trains per Hour*
Case 1 South 1	20	20	19
Case 2 South 1	39	39	19
Case 3 South 1	45	40	19
Case 1 South 2	24	17	19
Case 2 South 2	36	34	19
Case 3 South 2	39	36	19

Table 6-6

Train Capacity on K-Line with Average and 95th Percentile Station Dwell Times, Trains on Multiple Routes

	Dwell Times		Scheduled
Case	*Average (Trains per Hour)*	*95% Percentile (Trains per Hour)*	*Trains per Hour*
Case 1 South	19	19	19
Case 2 South	45	34	19
Case 3 South	36	34	19

Implementation Phasing

The simulations show that noticeably improved headway capacity is possible in some of the congestion areas in the BART system. The biggest improvements come from changes in the train control system. A change in maximum train running speed in the downtown area yielded minimal capacity improvement.

The train control system cases examined above represent one logical sequence for implementing train control system changes and progressive operating improvements for the BART system. Other sequences for progressively improving capacity may exist. The following paragraphs suggest a potential implementation of each case.

- *Case 2* – Fixed block with single brake, no step-down braking maintaining one buffer block

  Case 2 envisages conversion from speed-based authorities to occupancy-based authorities in which trains are provided authority limits. This implies additional subsystems for both on-board and off-board trains:

  – *On-board*: Trains require a location determination system to determine where they are and how far they are from an upcoming Stop or slower speed limit. A system using in-track transponders combined with tachometer readings might be best for providing location information to trains in a subway application, because GPS location signals are not available underground. It also implies a need for a database of the track plant and a computational ability to determine where brakes should be applied to bring the train to a stop short of the end of authority. Trains would receive occupancy authorities by digital radio from the off-board system and would provide to the off-board system a location report each time they depart a station.

  – *Off-board*: In this case, all the track-based circuitry currently in place to generate signal codes would remain. In addition, a new office-based control system would be connected with the track-based system fail-safely. It would receive all track indications (block occupancies and the presence or absence of signal codes) from which it would track the movement of trains and generate occupancy authorities based on the current block limits. It would identify trains equipped to receive the authorities by the location reports received from those trains. In addition, the control system could maintain and transmit temporary speed restrictions. These would not need to be limited to one of the speeds permitted by the signal codes.

Case 2 allows operating with both trains that have been upgraded and those that have not. All wayside upgrades and equipment need to be installed before any trains equipped only with the new train control equipment can be operated. Alternatively, two on-board systems are required with provision for switching automatically as required for the territory. But the full benefit of capacity improvements will not be realized until all wayside and on-board equipment has been placed in service.

Modifications of, or additions to, the communication system will be necessary to facilitate communications of train location and target stop location between each train and the office control system.

In Case 2, the office control system would maintain, behind each train, an empty block into which the following train would not be permitted to enter.

- *Case 3* – Fixed-block eliminating buffer-block

  In Case 3, the office control system would no longer maintain an empty block behind each train, but would permit closing up to an occupied block, but would not permit entry to that block (except under emergency operations to rescue a failed train).

  In addition, a new wayside technology would be introduced to detect the location of trains in parallel with the existing track circuits. There is an emerging technology under test that shows potential to determine and report train location to a much finer resolution (within feet) than track circuits. Implementation of this technology would pave the way for Moving Block (Case 4) and eliminates the need for SORS.

- *Case 4* – Moving block

  In moving-block train control, occupancy authorities are provided to the rear of a train ahead. Moving-block is particularly advantageous where trains are moving slowly and are closely spaced. This requires that the location of trains be known with precision. Although trains could report their location frequently to the office control system, the wayside location determination technology suggested for Case 3 would provide this information without the demand for radio bandwidth.

  Implementation of Case 4 includes off-board train control components (fail safe) to perform all interlocking functions in place of the track circuitry.

Junctions and control points that previously were interlockers become fail-safe object controllers (wayside interface units). The off-board train control components communicate with the object controllers and with track circuits (for broken rail detection only). Trains and the off-board train control unit communicate with each other via radio or other means.

A particular advantage of Case 4 is that pacing commands can be provided (any speed, not just fixed increments). This is especially helpful for schedule recovery by slowing trains ahead of a delayed train to take some of the passenger load from the delayed train.

SECTION 7

Conclusions

This study offers a combination of considerations and evaluation tools pertaining to relevant means of capacity improvements (technology, operations, route, and vehicle upgrades), both conventional and emerging. Guidance regarding the economics is offered to help balance the mix to minimize cost of achieving the level of capacity improvement required.

The report describes principles and concepts related to capacity for HRT operations. Topics include track and station configuration, rolling stock, train operations, and signal and train control issues. TTCI identifies promising potential improvements and additions to infrastructure to increase capacity (emphasizing cost-effective technology solutions). Discussion is provided on investment planning to increase transit system capacity by making the various improvements noted. The study also discusses the benefits, effectiveness, and life cycle costs of the various solutions. A sequence for implementation of the various recommended changes is suggested.

The following specific conclusions are noted from this study:

- It should be possible to provide at least a 50 percent increase in number of trains per hour using a train control system that does not require incremental step down of speeds, but instead allows trains to be braked to a target stop in one brake application.
- Station dwell time is a significant portion of the headway achievable.
  - Variability of station dwell time is caused by passengers holding doors, large numbers of passengers boarding and detraining, and equipment failures that cause a car to be taken out of service. When a car is taken out of service, extra walking time is required for passengers to move to an operative car.
  - Additional station dwell time due to delays between train stopping and door opening and also between doors closing and train start was observed on WMATA, but not on BART.
- Lack of reliability of equipment can cause either significant or frequent delays to trains. This can be minimized by extensive stress testing of components that are likely to fail. Equipment should be accepted only after successful completion of stress testing. Also, defects should be logged and common failures identified so that corrective actions can be taken to make weak components robust. Proactive maintenance, predictive maintenance, and root cause analysis should all be employed to improve equipment reliability.

- Trains ahead of a delayed train can be slowed and paced to minimize further delays to following trains and to improve schedule recovery. By slowing trains ahead of a delayed train, those trains will take on additional passengers, helping to reduce dwell times and passenger boarding demand for the delayed train.
- WMATA could achieve a quick increase in headway capacity by modifying or changing the door opening and closing system to achieve performance similar to that of BART (with no detectable delays).

GLOSSARY

ATC	automatic train control
ATO	automatic train operation
ATP	automatic train protection
BART	Bay Area Rapid Transit
CBTC	communications-based train control
FTA	Federal Transit Administration
HRT	heavy rail transit
ICS	integrated control system
OCC	operation control center
PFM	passenger flow model
RTC	rail traffic controller
SORS	sequential occupancy release system
TTCI	Transportation Technology Center, Inc. (the company)
WMATA	Washington Metropolitan Area Transit Authority

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