Junction Capacity and Performance in Rail Transit

by

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Abstract

In this study, steady-state cyclical queueing methods are used to associate utilization rates of junctions to delays, and to determine queueing lengths and estimate delays entering a junction with automatically collected train location data. Capacity is determined for crossings and merge points in urban rail systems, which are characterized by high frequencies and short train lengths. Actual throughput is compared to the theoretical and practical junction capacities to analyze the factors that constrain capacity. A new configuration for the junction is examined based on these factors and suggestions are made where the new configuration has not addressed factors that affect the current capacity.

The Clark Junction at the Chicago Transit Authority is presented as a case study. An analytical study of capacity shows that the junction can handle about 30 trains per hour at each crossing, and 36 trains per hour at the merge point with the current service line frequency ratios. However, during periods of high frequency the crossing of northbound Red Line and northbound Brown Line trains handles about 26 trains per hour, whereas the merge point of southbound Purple Line and Brown Line trains handles only 22 trains per hour. Thus, the junction is not operating at capacity on any of its approaches.

The lower throughput is partly due to the dwell time activity of trains at the neighboring Belmont station. At the current throughput, Belmont station cannot process trains without delays on followers. During the morning peak period the highest congestion is experienced in the southbound tracks and there are on average 13 Brown and Purple Line trains delayed as they approach Belmont station. Queues of as many as three trains form at least once during the peak period on the Brown Line service with the resulting delay being more than 2 minutes. During the evening peak period the highest congestion is experienced in the northbound tracks, resulting in delays on almost a third of the Red Line trains as they approach Belmont station and delays on a fifth of the Brown and Purple Line trains approaching Belmont. On each of the approaches to Belmont, queues

of two or more trains form at least once during the peak period, with resulting delays of more than 2 minutes per occurrence.

Dwell time control can be achieved at Belmont station for the southbound approaching trains by manipulating the arrivals of Red Line trains and Brown (Purple) Line trains at Belmont. Cross-platform transfers at Belmont increase dwell times, but if the arrivals at the station take place simultaneously the increase in dwell times on both trains can be minimized. In the northbound service, the dwell times at Belmont are affected by passenger activity at the station, cross-platform transfers and the routing process at Belmont. When Red Line and Brown Line trains arrive simultaneously at Belmont routing priority for Red Line trains will reduce the dwell times of these trains at Belmont without incurring in higher dwell times for Brown (Purple) Line trains. These recommendations present an opportunity for the agency to reduce travel times on the service lines and obtain better headway regulation at downstream nodes.

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Table of Contents

List of Figures

List of Tables

Chapter 1 Introduction

This document is an effort to determine capacity of junctions and measure their performance in urban rail transit. Capacity is defined as the maximum number of trains that can travel through a segment of track within a specified period of time. At junctions, there are a series of train movements that can take place, some of which may happen simultaneously, others happen sequentially. The scheduled throughput of trains should be somewhat less than capacity levels, to allow an uninterrupted flow of trains. Scheduling at or near capacity levels can dramatically degrade the performance of rail services, generating queues and delays that can increase the run time of trains and deteriorate the quality of service.

Many of the largest urban rail systems of the world operate at or near capacity at critical points in their systems. Ridership has been increasing in many of these systems, demanding increased services. Agencies have been able to meet growing demand by extending existing lines, adding branches to existing lines, and also by building new lines. In each of these cases, the agency purpose is to reach areas that it had not served previously. In areas where service is already provided, agencies attempt to meet growing demand by increasing the frequency of service, or by increasing the number of cars per train. Another alternative that agencies could consider to increase capacity is providing different seating configurations inside the cars, although this alternative may be possible only when ordering new vehicles, since the existing fleet already has a standard seating arrangement. In systems with older infrastructure, capacity may also be increased by enabling the system to operate at higher speeds by rehabilitating the existing right of way.

In each of these alternatives, the agency must consider the financial feasibility of the alternatives. The most common (and cost effective) action that an agency takes is to increase service frequency. The constraints on the service frequency should be examined to determine if the agency can take steps to relax them without compromising safety or the quality of service. Any other action taken by the agency requires a deeper financial commitment which makes them less attractive to the agency.

1.1 Capacity constraining nodes

Systems can reach capacity in various forms. Capacity can be reached on a service line without affecting ridership on other lines. Line capacity itself is a concept widely used, but not always well understood. When studying line capacity, it is critical to identify what element of a line has reached capacity. There are various elements that can govern line capacity and all of these can be referred to as nodes. In each node there is a service process that restricts the amount of throughput possible over any period of time. These nodes are connected by links, which can be thought of as sections of track where there is no interruption in train operation. These different nodes are:

- Stations
- Terminals
- Junctions
- Yards
- Other

The first four elements are common in urban rail systems and each can constrain line capacity. Line capacity is usually determined by the node that experiences the longest service process – thus controlling the maximum throughput that the other nodes can sustain.

1.1.1. Stations

Stations are one of the most important features of any rail transit system. The location of stations shape the service line coverage area. Every station on a line has a different demand pattern; therefore the service processes vary among stations. In addition, stations can have various configurations including:

- Side platforms
- Island platforms
- Side and island platforms

Usually, the position of the train operator is located on the right-hand side of the train, and the operator faces the platform on stations with side platforms. Two examples of stations with side platforms are the MBTA Red Line Downtown Crossing station and the CTA Red Line Chicago station. When the station is an island station and the train berths on the right-hand side of the platform, in a one-person operation the operator has to cross the cabin to open the doors on the left side of the train. Though seemingly insignificant, this action increases the length of the service process at a station by several seconds. Often, island platforms are preferred because it is less expensive to build and maintain one platform and one set of access facilities than for two side platforms. Island platforms are also preferred in places that have more than two tracks, since trains traveling in the same direction can pull into both sides of the platform. Some examples of island platforms are the CTA Blue Line Racine and Red Line Fullerton station (see Figure 1-1). Stations can also have both types of platforms, for example the MBTA Red Line Park Street station. This type of station permits boardings to take place through doors on both sides of the trains, but requires more effort from the train operator, since he/she has to open and close the doors on both sides. This design is used only for stations with very heavy passenger volumes.

Different platform designs have different impacts on capacity. In the case of the MBTA Red Line Park Street station, this station has the highest dwell times of all stations in the Red Line, due in part to the operator having to open and close the doors on both sides of the train. The act of closing doors takes more time than the act of opening them, since the operators has to verify that everyone is inside the train and that the doors can close completely.

Figure 1-1 Station with island platforms: CTA Fullerton station

1.1.2. Terminals

Terminals are also stations, but they differ because trains end their runs only at terminals. The configuration of a terminal has all the components of a station, and also includes rest areas for train operators, and turnout tracks or loop tracks for trains to reverse direction. Service processes at terminals depend on both passenger processing and train processing, and the length of the service process depends on the terminal track configuration. Usually, higher dwell times are required at terminals to allow time for all passengers to exit the trains. If the terminal has a loop track at the end of the station (see Figure 1-2a) then the train can pull out of the station after all the passengers exit the train and turnaround on a loop track that ends at the other side of the station (for inbound service). If the terminal is designed with a double crossover before the platform (see Figure 1-2b) a train can pull into one of the tracks and the platform where all passengers alight the train, and other passengers board the train for the next service run. By providing a double crossover before the platform, another train ending its run can move into the other track and pull into the same platform (if it is an island platform) or another platform (if there is more than one platform at the terminal). This type of configuration is very common among urban transit and commuter rail systems. In this type of terminal, the pullout tracks are commonly located within the alignment, so trains do not pull out of service at an endpoint.

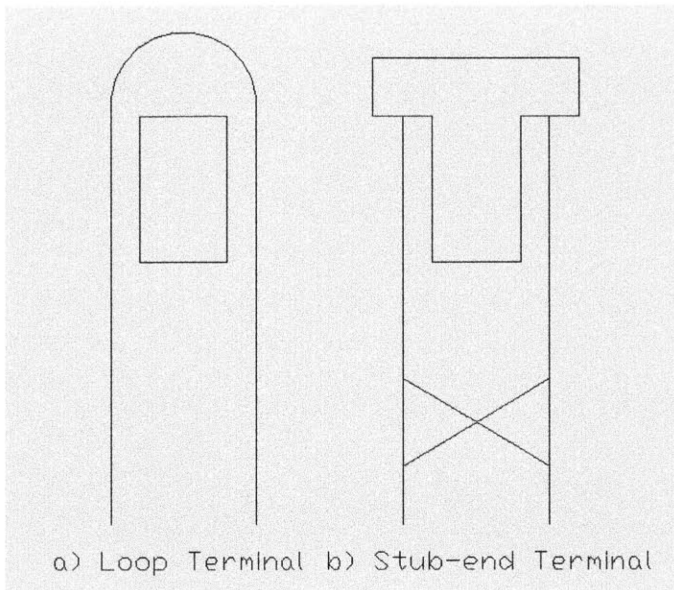


Figure 1-2 Common types of terminals

Since crew layover and train recovery times are built into the terminal processes, the service process for a train is much higher at a terminal than for other nodes. Careful planning of crew layover times and service frequency is required to avoid congestion entering a terminal. For more in-depth analysis of terminals and how to determine their capacity, refer to Lee (2002).

1.1.3 Junctions

Service processes at nodes are not only controlled by passenger or crew related activities. Junctions are also service nodes through which trains are routed to their destinations. Junctions are typical of rail systems that have more than one service line sharing a section of the right of way. The length of the section of shared track is variable; it can be a trunk line that has various stations, or it can be a crossing. Rail junctions can affect capacity because of the need to maintain safe separation of trains on different routes.

Junctions can have several degrees of complexity, depending on the number of interlockings in the system. Grade separation is desirable in junctions with high service frequencies, since it reduces the amount of conflicts and hence delays. Grade separation, however, requires great vertical separation to allow sufficient vertical clearance, and also considerable horizontal separation to permit acceptable gradients. In complex urban rail junctions, these two elements may be very difficult, if not impossible to provide.

Merging services can be processed through a junction relatively easily at low frequencies. If the merging services belong to the same trunk, then the dispatching headways can be adjusted to allow sequenced and regular arrivals into the junction and permit even headways in the trunk. In the simplest case, the branched services will have constant and equal headways, so these are routed alternately through the junction. If the branch headways are not equal, then dispatching of the service line branches is regulated to allow a sequenced arrival at the junction. If the service lines have different and independent headways, then the routing assignment through the junction is more complicated and may not be dealt within a coordinated fashion.

1.1.4 Other

There are other elements in a rail system that can act as capacity constraining nodes. When rail systems are at grade – usually the case in light rail transit systems – the trains interact with roadway traffic. In such cases, these crossings are signalized usually with priority to train traffic, but there may be instances where there is no priority (see Figure 1-3).

Other elements that can act as nodes are sections of the track alignment that can only be operated over at low speeds. Some examples of these are sharp curves, steep grades, track sections with deteriorated rails, or slow zones. Sharp curves may be required in parts of the alignment where there are physical constraints in the way of a smooth geometrical alignment, such as buildings or underground facilities. Sharp curves also pose a concern in two-track sections. Not only are there visual restrictions to the train operator about the line conditions ahead, but also trains moving through the curve simultaneously may collide if the track separation is not sufficient. One example of this is at the CTA Brown Line between Sedgwick and Armitage stations. In this example, train protection is extremely important and separation must be allowed such that trains move alternately through the curved track section.

Figure 1-3 MBTA Green Line crossing with vehicular traffic

1.2 Research Motivation

The motivation for this research comes from a lack of complete understanding of junction performance in urban rail systems. When agencies try to increase capacity in their systems by increasing service frequency, the effects that these create on junctions – and hence other service lines can be hard to anticipate. Increased service frequency leads to increased throughput at junctions. This leads to an increased probability of conflicts generating in the system, which can result in longer service times for the affected trains.

Moreover, it is desired to understand what components of a junction affect its performance. This thesis is an attempt to outline the factors that contribute to junction performance.

There is a lack of adequate tools to determine the source and extent of resulting delays when queues are generated at junctions. Thus, there is a lack of general understanding about how much traffic can be handled by junctions at merging points and crossing points. Train arrivals at the junction are typically subject to some random component which may be attributed to variable demand patterns, weather conditions, train dispatching, and even train operator preferences. Therefore, train arrivals at junctions are somewhat variable. When conflicting trains arrive simultaneously at a junction, the junction appears to be operating under stress conditions, even though the variability in the arrivals is due to the upstream conditions. Only under very tight Automatic Train Control and Automatic Train Supervision can train arrivals effectively adhere to a scheduled sequence.

1.3 Prior Research

There have been various previous studies of rail capacity, many of them dating back to the 1960s. Most of the earlier studies have focused on line capacity as whole, without focusing on the elements that limit capacity.

There are some studies of stations as capacity constraints. Some of these studies have focused on building models for train dwell times at stations, including Lin & Wilson (1991), Song (1997), Wong (1999), and Puong (2000). In another station capacity study, Horsey (2002) looked at unimpeded reoccupation times at a station and run times to understand the effects of slow driving on operations. A few other studies have been done on terminals as capacity constraining nodes. Lee (2002) showed through a simulation model how different operating parameters at the CTA Red Line 95th street terminal affect its throughput and generated delays for the approaching trains.

There is little literature, however, on junction capacity. Federal-sponsored transit research has provided a few studies on transit capacity: one of them being the Rail Transit Capacity report – TCRP 13 which examines line capacity by looking at the elements that affect it. The authors explain how stations, terminals, and junctions can affect line capacity, however, there are many simplifying assumptions made to determine the impact of each. The context of the report is to provide an understanding of the capacity of the transit systems in North America in terms of passenger movement for all types of rail systems – heavy rail, light rail and commuter rail.

Little effort is devoted to the topic of junctions as a capacity constraint. The assessment of capacity at junctions is quite simplistic and makes several assumptions, including that the train approaching the occupied interlocking stops at the signal before the interlocking and accelerates back to full speed after the interlocking has been cleared. This scenario is very unlikely under most forms of train control – especially in cab signaling systems where speed can be regulated several blocks before the train arrives at the home signal. First, the capacity is defined by the time it takes for a train movement to clear the interlocking under flank protection. That is, the capacity is determined by the interlocking conflict that is generated by trains moving in opposite directions. No real effort is spent studying the merging conflict, and the authors assume that junction capacity is constrained only by crossing conflicts.

There is a fair amount of European literature on junction studies, most of which comes from British signal engineers and Dutch rail operators. On the British side, a book on signaling titled *Railway Signaling* provides a description of how railway systems are designed and how capacity is determined. The book, which serves as an introductory manual from the Institute of Railway and Signaling Engineers (IRSE), is edited by railway expert A.S. Nock. The approach is to describe how the signal system should be designed according to the demand requirements, with a heavy focus on intercity railway and mixed train traffic (high-speed, freight, express, etc. on same right of way). This manual is a great resource for signaling design, but in applications to existing systems it provides limited insight.

Some Dutch studies have also focused on intercity railway systems. Rodriguez (2002) takes an optimization approach to how trains can be routed at a junction using a simulator in conjunction with a constraint programming model. In the CP model, the trains are assumed to have a domain of routes available, which is not common of urban transit systems. Urban rail transit lines are characterized by using the same right of way along a route, including route assignments at junctions.

A recent book has been released on railway operations. The book, titled *Railway Operations and Control*, is written by Joern Pachl, a German railroad engineer who provides a comprehensive introduction to railway operations. This effort is one of the few sources of literature where an analytical approach to capacity is applicable to existing infrastructure. Capacity of existing railways systems is presented through the concept of exploitation rate, which he states for a 24 hour period should not exceed 50% if a good quality of traffic is desired. The exploitation rate is defined by the author as the amount of time that a section of tracks is occupied over a period of time. However, this figure is determined from a mixed-traffic intercity railway. For peak period traffic, the exploitation rate should not exceed 80%.

There is also a wealth of research papers on simulation models used to measure line performance and to determine delays. Zhu and Schneider (2001) present a methodology for determining delays through simulation. Primary delays were defined and determined by measuring how much additional time is required for a train movement from one point to another based on the normal run time plus a buffer time. Consequent delays were also defined and determined as the amount of additional run time induced to a train by the previous train that experienced a primary delay. A negative exponential distribution was used to predict the extent of the delays generated by the type of interruption in the service. A mixed-traffic intercity network with a single track and passing tracks was used in the simulation so the delays will be drastically different from those in an urban rail system. The concept of delay propagation, however, is valid and will be used in this thesis.

Delay studies have also been undertaken at the TRAIL school at the University of Delft by Goverde (2001) and Yuan (2001). In Goverde (2001), delays are viewed in the context of recovery times for timetable evaluation as a performance measure. The delay impact of a train is measured as the amount of delay that a train can absorb before affecting the following train. In the same way, the delay sensitivity of a train is defined as the maximum delay that a previous train can absorb before affecting the following train. Using these measures, the author then proceeds to define the circuit recovery time as the sum of these measures for the respective train at a particular node. Yuan (2001) uses a different scope in delay analysis. In his study, statistical distributions are fitted to arrival delays, departure delays, and dwell times at a particular Dutch railway station: The Hague HS. There was a pattern observed between late arrivals and longer dwell times, suggesting that a delayed train experienced further delays and thus reduced the margin between following train. However, there are no relationships sought between the secondary delays and delay propagation, given the findings on dwell times. The applicability to urban rail transit is also not clear because The Hague HS is an intercity service station, so the service frequency does not match that of an urban rail station.

An academic study of urban rail delays was done using Philadelphia's SEPTA Market/Frankford subway section of the line by Casello et al in 1999. In this effort, a simulation of train operations including the transit control center is performed using linear dwell time models and a control logic based on manipulating run times and dwell times in real time to maintain a programmed headway at every station. In this model, delays are defined as the change in headway between two points in a network corresponding to consecutive train progressions. The focus of this study was to determine how delays can be controlled through real time mitigation strategies. The delay mitigation strategies have the same theoretical platform that the MATRA system has programmed at Tren Urbano. In this study, however, it is not clear where the dwell time model comes from. Further, the simulation is not tested with actual subway operations at SEPTA, but rather it is tested in Arena and C++ simulators.

Transit agencies have done studies on junction capacity. At the Chicago Transit Authority, a study was realized in 2000 to look into the effects of different routing schemes in the Loop for Tower 18 and Tower 12 junctions. In this study there are different routing alternatives presented for the different service lines operating through the loop, and also looks at the savings in interlocking setup times for shifting from microprocessor-based to relay-based switches. The performance measures used in this study were number of train conflicts generated at the interlocking section. This study, however, fails to address the effects of the neighboring loop stations and the changes in passenger behavior that would result from different routing schemes.

At London, LUL has developed a web-based tool for internal agency use called HEARTBEAT to view throughput and performance of the rail system from data as recent as the previous day. This tool comes as close to real time analysis as currently available for train throughput, dwell time and run time analysis.

1.4 Scope of Research

This research focuses on urban transit systems which condition sets the stage for a very different type of analysis from the prior junction studies that have focused on optimal routing schemes for intercity/mixed rail traffic.

This study aims at understanding how capacity is estimated for an operating junction, taking into consideration the design elements such as ATP, block lengths and configuration, infrastructural constraints, train lengths and neighboring activity nodes. Special attention is given to the neighboring nodes to the junction, in light of our case study.

The study aims at combining actual data with design characteristics of the system to understand how and whether line capacity is constrained at a junction. The analysis is based strictly on actual operations data and does not rely on simulations or other methods involving on simplistic assumptions. Because the scope of the research is narrowed to urban transit systems, there are no alternative routing schemes presented as normal operation conditions.

This research, however, does not aim at modeling the neighboring elements at junctions, such as stations. Rather, it aims to acknowledge the impacts that these elements have on junction capacity.

1.5 Structure of Thesis

The next chapter provides an overview of the components of a junction in urban rail transit and describes how these components can create critical reductions in performance. This chapter also includes a description an Automatic Train Control system and how it is employed at junctions. The types of conflicts generated at junctions – and the advantages of grade separation versus flat junctions – are covered. The chapter closes with a discussion of how capacity can be determined at junctions in constrained environments.

The various methods and analytic angles for junction performance are presented in Chapter 3. Utilization rates are presented as a method to determine the unconstrained operating limits of the system. A mathematical presentation of delay calculation and queue length estimation with the use of the actual operations data is included. The use of multiple time-space diagrams with a representation of junction occupancy is also presented as a tool to understand simultaneous multiple train movements and how elements that are beyond the control of a junction operator affect routing priorities.

Our case study is introduced in Chapter 4 with the CTA Clark Junction presented with an explanation of how the elements presented in Chapter 2 affect its operation. A description of current system operations is provided which includes tower practices, operation policies and anomalies in the operation. An existing proposal for a new configuration is presented and assessed. Some recommendations are given to modify the proposed new configuration to improve its expected performance.

The application of the analytic methods used to evaluate the constraints in the junction is presented in Chapter 5 for southbound services. The effects of the neighboring elements to the performance of the junction are studied. This chapter also includes the evaluation of the services moving through the junction and recommendations for improved operation policies are made.

Chapter 6 focuses on the northbound performance analysis of the junction. This chapter includes the analysis for the three service lines operating through the junction. Capacity is studied at the conflict point of the northbound train movements and recommendations are presented to improve service.

Finally, Chapter 7 includes a summary of the findings and recommendations to improve performance in the case presented, as well as the techniques used in the analysis. Prospects for future research on urban junctions are discussed.

Chapter 2 Junctions

In this chapter the physical, electrical and design components of a junction will be described. The first section presents the arguments for the study of junctions. The next section presents the components of a junction and briefly explains how each relate to safe operation. Section 2.3 describes the automatic train control technologies that are used in most urban rail systems, with emphasis on junction operation. The components of a junction operate under some degree of automatic train control. The conditions of these elements shape the operating environment of the junction, which is described in section 2.5. Lastly, section 2.6 covers the concepts of capacity for junctions. A summary of the chapter is provided in section 2.7.

2.1 Why study junctions?

Junctions are common in all types of rail transit – urban, intercity and freight. In urban rail systems junctions are built wherever different service lines share the same track infrastructure. As explained in Chapter 1, as traffic volumes increase the junction could become a bottleneck for the lines, creating delays which increase travel time and negatively affect both the quality of service and the cost of operating the service.

Junctions, however, are a favorable element in rail systems because these permit one-seat rides from each branch to trunk destinations and also result in higher frequencies on the higher density trunk portion of the line. Junctions can also provide flexibility to rail operators. Though simple junctions provide the operator with few degrees of freedom, more complex junctions can provide the operator with different routing alternatives that can increase the capacity and flexibility of the system. Such routing capabilities can be observed in very large urban rail systems such as NYCT, London Underground, and also in somewhat smaller urban rail systems such as the CTA.

Junctions can be found at any point of a rail system. While most junctions are usually located at an intermediate portion of an alignment where different service lines meet, these can also be found at terminal points of some service lines. At the CTA there are examples of both instances: Tower 18 Junction is an example of the former, while the Howard Terminal Junction is an example of the latter.

As mentioned in Chapter 1, junctions are unique in comparison to other capacity constraining nodes such as stations and terminals, because the service time at a junction does not vary between trains from the same origin. Unlike junctions, stations can have variable service times that depend on passenger demand by time of day, in-vehicle load, boardings and alightings, all of which are not generating variability in the junction service times. Any variability in service time at the junction could be due to variable train lengths within a service line, but even train lengths are not as variable as the station activity. If the timetables are properly designed, a junction should be able to transfer branch demand to the trunk portion of the alignment without generating interruptions in the service and likewise it should manage traffic from the trunk line to the branches with the same ease.

2.2 Components of a junction

This section describes the principal infrastructure components of a junction. Though some of these elements are present in other track sections, the role these play at a junction may be different and hence have a different impact on the operation.

When a train is routed through a junction, the tracks must be aligned to permit the train to move safely through the junction. These moving tracks are called turnout tracks. When these tracks are aligned to permit a particular train movement between a set of main tracks, there are a series of safety processes that lock the moving tracks such that they can not be displaced while the train is moving through and provide the moving train with an unobstructed path. This is referred to as an interlocking. A junction is formed by a series of interlockings that permit one or multiple train movements to take place simultaneously. When trains are routed through a junction that has more than one interlocking, each interlocking can be set up individually, or these can be set up as a collective unit.

2.2.1 Turnouts, crossings and crossovers

There are several differences between a crossover and a turnout. Turnouts, shown in Figure 2-1a, are present in sections of the alignment to move a train off the main tracks and into a secondary track alignment, such as a branch or a yard. A crossing, shown in Figure 2-1b, is a section where tracks cross without the possibility of trains switching between the tracks. Crossings can be avoided only by providing grade separation.

A crossover is formed by a pair of turnout tracks that connect two tracks, usually placed parallel, and allow trains to move from one track to another. There are three basic types of crossovers: single crossover (Figure 2-1c), universal crossover (Figure 2-1d) and double crossover (Figure 1-2e).

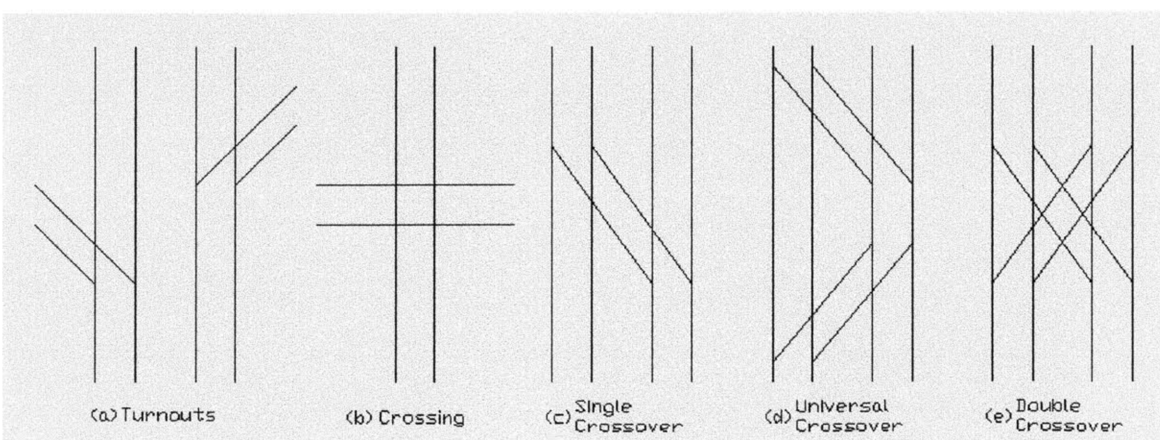


Figure 2-1 Interlocking turnout and crossings

2.2.2 Switches and switch machines

The switches are points in the tracks that displace to provide an entrance, or exit to an interlocking. The switches are also a rail component of an interlocking. Switch machines enable switch movements. There are different technologies in switch machines. The most common technologies are pneumatic switches and electric switch machines. The earliest forms of switch machines were entirely manual and most modern machines still allow manual operation in case of technical failures in the circuit control.

A circuit controller in the switch machine monitors the position of the switches, and receives requests and commands from the interlocking operator. The circuit controller may be operated by relays or microprocessors. In systems designed for high levels of safety, the reaction time might be higher than in other interlocking systems, reflecting the level of complexity of an interlocking. Figure 2-2 shows a switch machine and the switches of an interlocking at Tren Urbano.

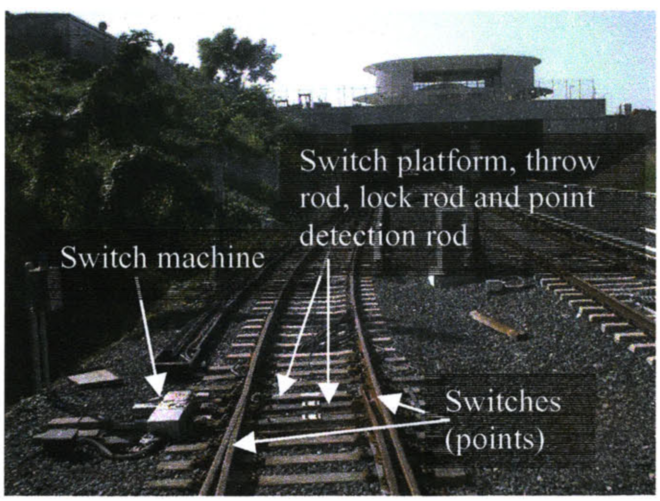


Figure 2-2 Switches and switch machine

2.2.3 Track Circuits

Track circuits serve to delimit sections of track at interlocking areas. The track circuits are closely associated with the Automatic Train Protection system and are used to segment the tracks into imaginary blocks. In essence, track circuits are electrical circuits used to divide the track into segments. There are different types of track circuits, including:

- Audio-Frequency track circuits
- Power-Frequency track circuits
- Binary-Coded AF track circuits
- High-Voltage Impulse track circuits

2.2.3.1 Audio-Frequency Track Circuits

The most common type of track circuit used is the AF track circuit. AF track circuits have transmitters and receivers sending and receiving audio frequencies through the running rails. Figure 2-3 shows a schematic of an AF track circuit with a relay pick-up. There are two types of frequencies sent: track frequencies and train frequencies. The track frequencies are used to identify a particular section of track and detect train occupancy over the circuit, while the train frequencies are coded as cab signal speed commands to the on-board computer in the train. The two distinct frequencies are enabled through the system by splitting them within a code cycle. During one half of the code cycle the transmission is a track frequency, and during the other half the transmission sent is train frequency.

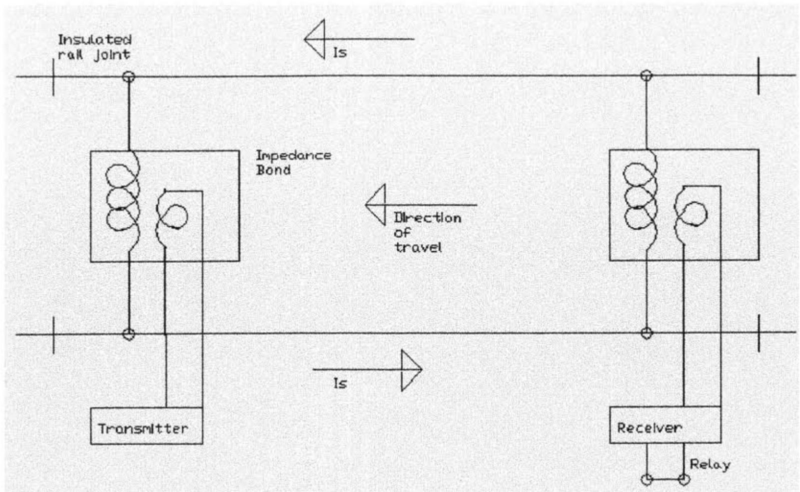


Figure 2-3 Track circuit schematic - vacant circuit

When a train enters a section of track delimited by a track circuit, TC_i, it will interrupt the transmission between the transmitter and the receiver. This interruption will cause a drop in the relay of the track circuit, as Figure 2-4 shows. The relay drop is the indicator of an occupied circuit. When the train leaves the circuit, the transmission will be enabled again and the relay will be picked up, indicating a vacancy in the section of track.

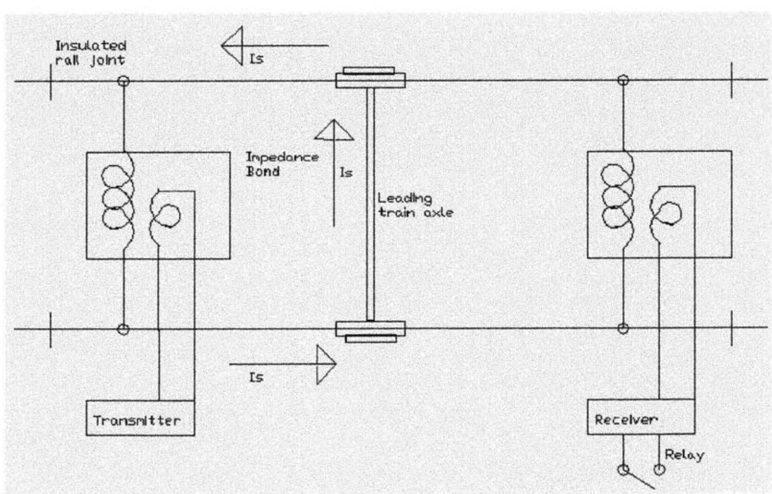


Figure 2-4 Track circuit schematic - occupied circuit

The track circuit operation is essential in providing safe operation by maintaining adequate separation between trains. It is also essential in providing reliable operation by maintaining the flow of trains without creating interruptions in service.

2.2.3.2 Power-Frequency Track Circuits

This type of track circuit is used for interlockings, where AF track circuits cannot be installed due to the segmentation of tracks. Power-frequency track circuits operate on a single running rail. When the train enters the section of interlocking tracks, the power source is transferred to the other rail via the wheel set. The other rail performs as the return rail of the power-frequency track circuit, which is bonded to a ground source. Similar to an audio-frequency track circuit, when the train enters the circuit the wheels shunt the current, causing the relay to drop and indicate an occupancy in the tracks.

These circuits, unlike the AF track circuits, only provide train detection. Train control and speed commands are permitted at interlockings through command transmission loops. The transmission loops are activated when the route is set up and signal clearance is awarded to the approaching train. Transmission is interrupted when the train has cleared the interlocking tracks, if the route has been cancelled, or if any train movement violations are detected.

2.2.3.3 Interference in track circuit

There are two types of failures that may take place in a track circuit which could generate problems in the train protection and reliability of operations. The first type of failure would have a relay drop when there is no train occupying the block. This type of failure is regarded as a nuisance failure, because trains cannot move into the block that indicates a false occupancy. This type of failure can affect the flow of trains and generate minor delays in the system. The second type of failure would have dropped relays that pick up when these should remain dropped. This type of failure is a safety failure and would indicate a false vacancy when the block of track is actually occupied by a train. This type of failure is very serious, as it may cause a collision of trains in the system. In both instances, the failures can be caused by an interference effect in the track circuit transmission.

The failures that have been described are generated by electromagnetic interference. The electromagnetic interference (EMI) that affects a track circuit may come from various sources:

- Magnetic coupling between adjacent track circuits
- Interference generated by the power line (third rail)
- Interference generated by the on-board equipment in a train

Many rail systems in the world experience EMI problems, regardless of the propulsion technology used. In the Chicago Transit Authority, this problem has been detected through the use of the SCADA system. At junctions, this problem can create routing restrictions at the tower, such that the tower person is unable to lock a route in the control panel because the EMI is causing the circuit to register occupancies, or it may prevent trains from advancing in their route even when it has been setup. In such case, the tower person might be forced to override the Automatic Train Protection and route the trains in a restricted mode of operation. A comprehensive look at the EMI problem is found in a book by Nene (1985) titled *Advance Propulsion Systems for Urban Rail Vehicles*.

2.2.4 Signaling

The signaling system is one of the most important components of the train control system, and is vital at interlockings with moderate to high traffic. It complements the track circuit system, which is used to delimit blocks of track. The signals are used as a visual indicator to the train operator whether the train is allowed to enter the block ahead. At interlockings, the signals are used to display the switch setup. Repeater signals can be installed in places with poor visibility such as curves or gradients, to announce to the train operator of downstream conditions.

There are various commands that the operator can receive from a signal depending upon the number of aspects in the signal system which itself varies accordingly to the needs of the railway property. The type of service offered is a key determinant of the aspects requirements; for instance, intercity rail service usually has 4 (or more) aspects, whereas urban rail transit systems have 3 aspects. It is atypical of urban rail transit properties to have more than 3 aspects in the signaling system, because the distances between stations are short and the operating speeds attained are not very high.

The signals at junctions have important functions:

- Protect the section of track ahead, which may be occupied by another train;
- Prevent trains from entering a section of track that may be reserved for another train movement, termed flank protection;
- Display the route that is locked for a train movement – diverging or main line;
- Display whether a Automatic Train Protection Bypass is effected.

There are other functions as well, depending on the type of service and rail system. Figure 2-5 shows the signal aspects used at the Chicago Transit Authority that are present at interlockings for the main movements. The type of movement permitted in the interlocking (normal versus reverse) is displayed as an aspect that is a colored combination. A lunar aspect is present to indicate when there is a restricted mode of operation taking place such as an ATP by-pass. If the interlocking is designed for more than two types of movements, this signal arrangement would not suffice. In such cases the signals are accompanied by flags or by a more complex aspect system.

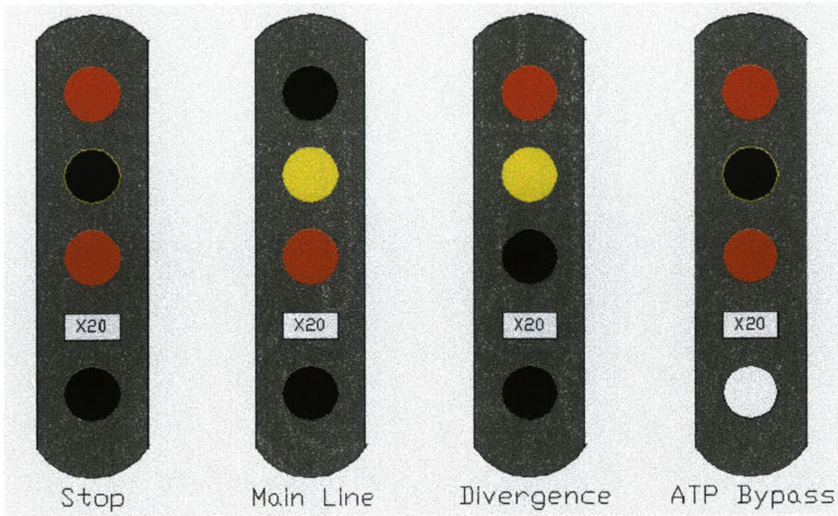


Figure 2-5 Main aspects at CTA interlocking signals

The signal system is usually complemented by equipment at the wayside that provides safety against signal violations. One common safety device at the tracks is the emergency brake tripper. An emergency brake tripper has an arm that serves as a trip mechanism that releases pressure in the air-shaft that holds the emergency brakes of the train, thus bringing the train to a full stop. When the signal is on a stop aspect, the mechanical arm is lifted to prevent trains from violating the signal.

When a train occupies the section of track protected by the signal, the signal will display a stop aspect so no other train can enter the block of track. Train operation can be affected if a track circuit that is protected by a signal is experiencing EMI problems. Specifically trains that could be halted by emergency braking even though the section of track is clear. The signal system may have to be overridden or disabled completely until the problem can be solved, if there are many service interruptions observed that are created by such problem.

2.2.4.1 Overlaps

When the blocks are designed it is customary to provide some allowance in the block length to permit trains that violate the signals to come to an emergency stop before the trains reach the fouling point of an interlocking or a section of track ahead. This extra block length is called the overlap. Overlaps are very important in interlocking blocks to avoid a violating train from colliding with other trains or from reaching switch points and causing damage.

2.2.5 Neighboring elements

There may be elements that are not part of a junction, but are close enough to affect the junction operations. Stations and terminals are classic examples of neighboring elements to junctions since there is a tendency in rail transit planning to locate stations close to junctions, or vice versa. When a station is very close to a junction, the activity at the station may limit the amount of trains that can use the junction. If service is interrupted at the station, the junction will be affected directly. The closer the station is to the junction, the more direct the impact on the throughput it may have.

When neighboring elements are present, it is necessary to understand the impact of these in junction capacity analysis. One of the impacts that will be discussed through this research is the impact on queues that a neighboring element could introduce on the junction.

2.2.6 Routing control

The routing control at the junction determines the level of effort required to operate the junction. Train routing can be achieved locally or remotely. A line controller can set up the routes at the junction if they know which train is approaching the junction and have information on the position of other trains. At complex junctions with no ATR it might be desirable to have a local operator controlling train movements and assigning routes.

In highly automated systems the routing control is automatic – that is, the train requests a route at the junction based on the identification of the train, and an Automatic Train

Routing (ATR) system will assign the route and set up the route without any human intervention. Automated routing schemes demand a lot of information as input to the decision elements. If the system is not capable of collecting the required data, particularly train identification and destination, then automated routing is not possible.

The level of investment for an agency to completely automate a junction operation is quite high and tends not to be a priority. Human operators may well understand the logic behind a junction operation and respond better to failures in the system, so marginal gains from automating the operation may not support the level of investment it would require.

2.3 Automatic Train Control

Virtually all urban rail systems employ some level of Automatic Train Control (ATC). An ATC system is composed of three subsystems:

- Automatic Train Protection (ATP)
- Automatic Train Supervision (ATS)
- Automatic Train Operation (ATO)

These subsystems are present at varying levels of technology in all urban rail systems. Newer systems tend to have advanced forms of ATS and ATO, but the ATP system is present in all urban rail systems and it is based on the fundamentals of block systems.

2.3.1 Automatic Train Protection

The ATP system is based on fixed blocks of track which results from the track alignment being segmented into multiple sections or blocks. No more than one train may occupy a block of track at any time. Trains receive speed commands and proceed based on the occupancy condition of the blocks ahead. This communication is wayside-to-train and is traditionally enabled by the track circuits and the signals. When a train cannot enter a block of track, it will receive a speed command of 0 mph at the adjacent upstream block from the occupied block. If there is a signal at the entrance of the occupied block, it will display a stop aspect. Sufficient separation between trains is assured by designing the block lengths such that a train running at the allowable operating speed can stop before it enters the occupied block.

An advanced form of ATP is based on a moving-block philosophy. In a moving-block operation, the tracks are not segmented into blocks; rather, train-to-train separation is monitored directly. Since there is no purpose in defining blocks of track, there is no need to provide wayside-to-train communication, hence speed and minimum train separation is defined by train-to-train communications. Currently, these technologies are being tested and introduced incrementally in a few systems. Even in a moving block system, however, interlocking movements will still depend on train-to-wayside communications.

At junctions, the ATP is a very important component that is tied to the interlocking movements. The interlocking logic, the track circuits and the signals are all components of the ATP at a junction. When a train is moving through a turnout and a crossing, as shown in Figure 2-6a, the ATP system will ensure that trains cannot enter the section of tracks where the crossing is located, or the section of track where the diverging turnout track is located. If, however, there is a train merging into a section of tracks, as shown in Figure 2-6b, the ATP will only protect the block where the turnout is located and the immediate upstream block.

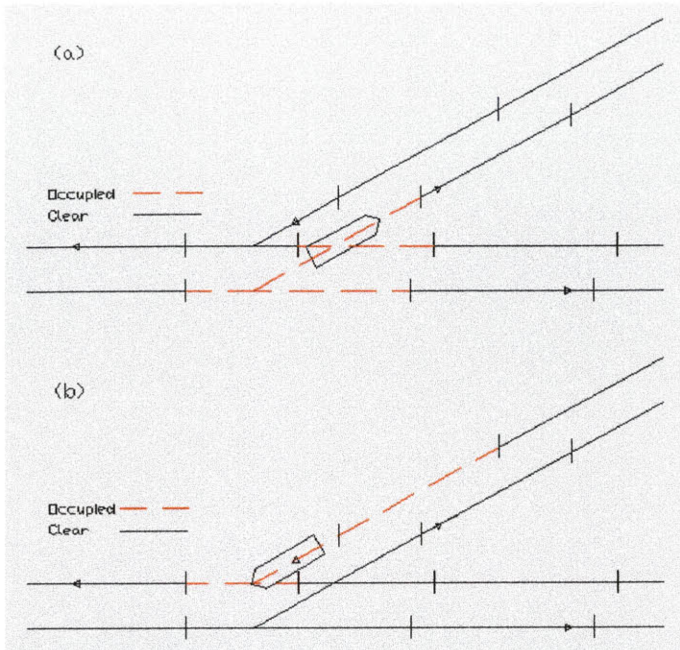


Figure 2-9 Interlocking logic and protected blocks

One of the closest technologies to a moving block system is the Siemens/MATRA system operating at Tren Urbano, the Paris A line of the RER and Mexico City metro lines A and 8. Continuous wayside-to-train communications provide the train with information on the position of the immediate preceding train for speed adjustments to maintain safe separation. Train-to-wayside communications, however, is not continuous, and as such the position of the immediate trains is not updated continuously.

2.3.2 Automatic Train Supervision

Automatic train supervision enables the operations control center to monitor and adjust train routes and train progression depending on the line conditions. Train locations are monitored through the track circuit occupancies, which are displayed as occupied blocks of track at the operations center, where line controllers can view the entire alignment. More advanced ATS systems employ other train detection technologies that can identify train positioning within a block. Line controllers can use the information provided by the ATS to control gaps and regulate headways in the system. Line controllers can also operate switches and interlockings from the operations control center.

A component of ATS is the Automatic Route Setting, also known as Automatic Train Routing (ATR). The ATR is an internal logic mechanism used to assign routes at a junction based on scheduled train movements, service line and arrival discipline. The ATR system can be implemented in rail systems with advanced ATS which can identify the specific service trains approaching the junction and hence determine if they are on schedule. The ATR system sets the route and the ATP locks and protects the section of track from flank movements.

At junctions, ATS can be used to assign priorities in routing schemes, regulate arriving headways, and maintain a desired entry order. ATS can be used to help trains adhere to a schedule at the junction or prioritize trains that are running behind schedule. Without an advanced ATS system, the ATR function is not feasible and the junction is operated manually with the routes set by a junction operator.

2.3.3 Automatic Train Operation

Train operation in most systems is performed by a motorman, also known as a train operator, although speed adjustments, opening and closing of train doors, and announcements can also be performed automatically with an ATO system. The ATO system also has varying levels of technology. Some small systems have very advanced ATO systems and run without an on-board operator. Examples of these are the Chicago O'Hare airport train, and the Dallas-Fort Worth airport train. In Barcelona, Siemens is working on introducing a driverless operation on metro line 9. Most systems throughout the world, however, still have on-board train operators.

2.4 Configuration of junctions

The degree of complexity of a junction varies with the levels of traffic and the types of service lines that operate through it. Junctions can be either grade separated or flat, with grade separated junctions eliminating some train path conflicts, but they do not provide the same degrees of freedom in the operation as a flat junction. The level of complexity of a junction operation depends on a series of factors, including:

- Interlocking setup
- Number of conflicting points
- Number of tracks
- Service headways
- Effects of neighboring elements.

2.4.1 Grade separation versus flat junctions

Grade-separated junctions are common in urban rail transit because of their advantages in high frequency operations. Consider the simple junction shown in Figure 2-7, where grade separation is an option to a flat junction. In dual-track turnout, the lower tracks can have the turnout track crossing with the parallel adjacent tracks, as shown in Figure 2-7a, or the turnout tracks can run over or under the parallel track. The crossing conflict is eliminated in the grade-separated alternative shown in Figure 2-7b, and so the junction can handle more trains, since there is no interaction between crossing services.

2.4.2 Conflicting movements

There are two main types of conflicting movements. The first type of conflict is a merging conflict which is generated by trains from different origins that are traveling to the same destination and merge into a section of shared track (trunk). This type of conflict is unavoidable: no grade separation will eliminate the problem. Merging movements are present in most junctions – only simple crossings do not have this kind of train conflict. The second type of conflict is a crossing conflict generated by trains from different origins traveling to different destinations, but having crossing paths. Such a conflict could be avoided by providing grade separation between the crossing tracks. Although grade separation would almost always resolve this type of conflict, it may not always be achievable because of horizontal or vertical spatial restrictions, budget constraints, or other agency-specific constraints.

Merging conflicts are important because these could constrain the capacity of the branches. Crossing conflicts, in contrast, can constrain the capacity of the junction and may also affect the capacity on both the trunk section and the branches.

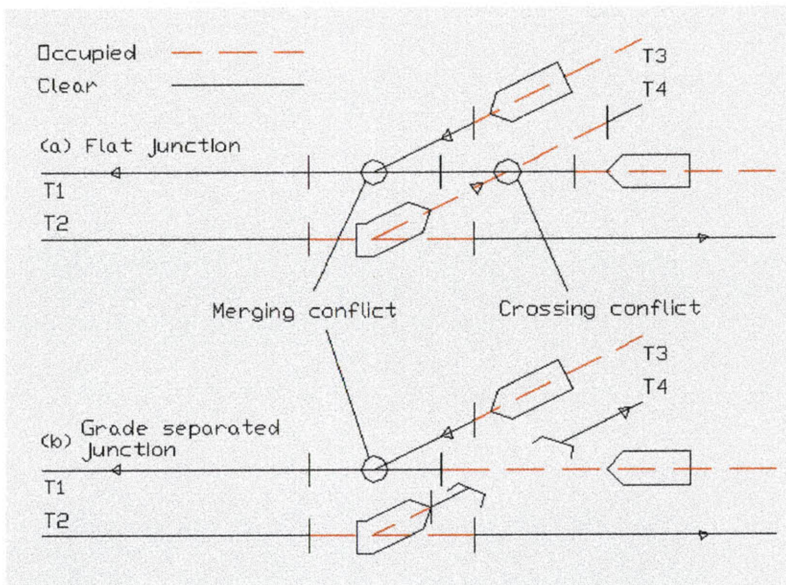


Figure 2-7 Grade separated junction versus flat junction

2.4.3 Degrees of freedom

Interlockings are important because they provide degrees of freedom in a rail operation. This means that in a two-track alignment, a single-track operation is possible if there are crossovers between the tracks. Junctions provide degrees of freedom by making alternative routing schemes available. In urban rail transit, the train routes are usually static so the train follows the same route through the junction, regardless of the alternative routes. The degrees of freedom of a junction are then most important during major interruptions in service or special-event operations.

2.4.4 Interference with neighboring elements

When there are surrounding rail elements that act as nodes, the process becomes service in series. The exit process at the first server will become the arrival process of the next server. Figure 2-8 illustrates an example of servers in series in close proximity.

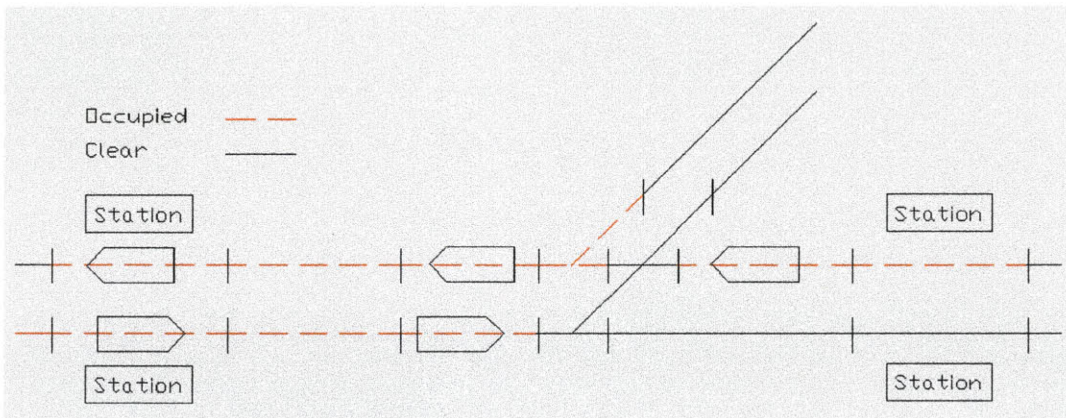


Figure 2-8 Interlocking and neighboring stations

Under steady state conditions, there are two queueing scenarios that can generate underutilization of the junction. In the first scenario, the service time of the second server (station) is longer than the service time of the first server (junction). The second server will then generate a queue that will propagate back and affect the service process of the first server. The queue will develop at the entrance point of the first server. As a result, the process and capacity of the first server (junction) is controlled by the service process of the second server (station).

In the second scenario, the service process of the first server (station) is longer than the service process of the second server (junction). The queueing conditions will be generated by the first server, and the second server will never generate queues. Because the first server is the bottleneck, the second server is underutilized. The throughput at the second server (junction) is controlled by the throughput of the first server (station).

2.5 Operating environment

The utilization of a junction depends on the demand on the service lines that are served by the junction, the number of service lines that use the junction and service management strategies. The three-tiered framework proposed for operational analysis by Rahbee (2001) can be used to understand the operating environment at junctions. This framework is decomposed hierarchically into three components: line characteristics, operating plan, and service management.

2.5.1 System (line) characteristics

A junction is an infrastructure element of a rail system where several lines meet, merge, and diverge. These characteristics do not change over long time spans because changes typically require significant capital investments. At junctions, the location of crossovers, turnouts, switch equipment, signals, track circuits and block design are all line characteristics. The performance characteristics of the trains are also system characteristics which should affect the length of blocks, and the location of signals. Since the track circuits and the signaling system is part of this tier, the ATC system also forms part of it. The configuration of a junction is a system characteristic which should be designed to provide flexibility in the junction operations.

2.5.2 Operating plan

In this tier, the infrastructure and system design characteristics are represented as constraints in the development of a service plan. The capacity of the system is reflected in the operating plan in service frequencies for the lines running through the junction. In this plan the routing procedures are set and each service line is assigned a particular route. Merging conflicts are considered in this plan such that the arriving train sequences are set to minimize the number of conflicts generated.

2.5.3 Service management

In the lower tier of the framework, Rahbee (2001) stressed the dynamics of service management as it applies to day-to-day operations. The system characteristics and operating plan are considered in this tier as constraints on the service management process. In this plan, service priorities are determined based on the characteristics and desired performance of the lines.

Operation policies are also part of the service management and can be considered as an extension of it. These are usually operating guidelines for train operators, but these can also be oriented to assist tower operators in routing practices.

Figure 2-9 shows the interaction between system characteristics and constraints, how these affect junction capacity and performance, and how these fit into the framework proposed by Rahbee. The concept of capacity, as discussed in the next section, is defined as the physical throughput that the junction can handle based on the physical constraints of the system such as blocks, operating speeds and vehicle performance attributes. At the agency level, there are other elements of capacity that are not necessarily related to the operation of the rail system such as budget constraints, labor rules, and human constraints that affect the overall capacity of the agency. These are represented as agency constraints, which are inputs of the service design. The resulting output is a timetable that assigns crew and vehicles to activities and resources. When the timetable is operational, the system is running and the resources are utilized. Real time control is necessary to maintain the quality of service during operations. This control is effected at junctions by tower operators that have an open line of communication with remote line controllers located at the operations control center. The performance of the resulting service design is evaluated and changes in service requirements can take place in the next revision of the service design.

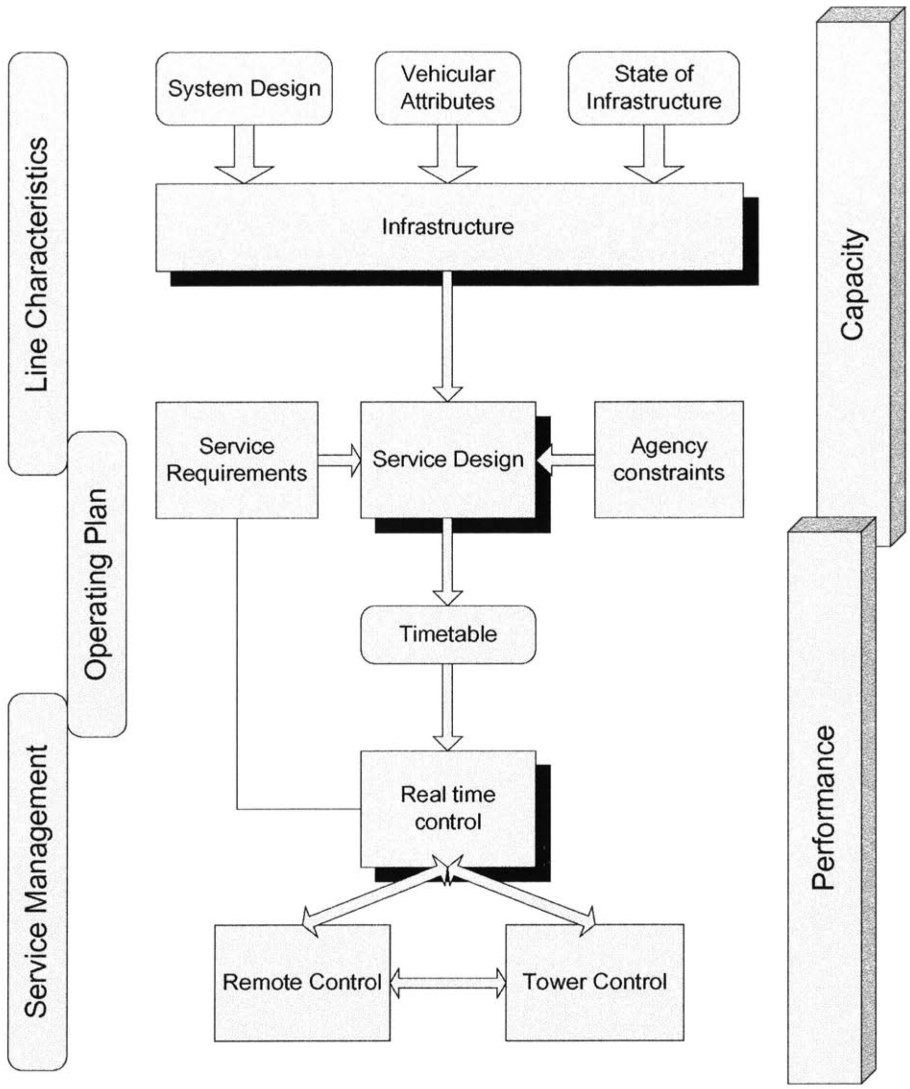


Figure 2-9 Capacity - Performance Diagram

2.6 Capacity

The concept of railway capacity has been researched with strong focus on intercity systems and as mentioned in Chapter 1, there is a general lack of capacity studies for urban transit system junctions. In Pachl's book *Railway Operations and Control*, the author includes a chapter with a comprehensive overview of railway capacity which includes capacity at junctions.

Capacity can be thought of as the maximum number of trains that can use the junction within a specified period of time. In passenger systems, capacity can also be defined as the maximum number of people that can be transported through a node in the specified time period. Ultimately, transit agencies are interested in knowing how many passengers they can carry per unit time.

At junctions, passenger capacity is best explained through train movements and there are important tradeoffs associated with train throughput. For example, longer trains carry more passengers but consume more time at a node. Conversely, shorter trains carry less passengers but more trains can be processed within a time period. A measure of trains per hour is useful as an aggregate movement figure at junctions, and can be easily converted to passengers per hour. This figure, however, might overlook dependencies between service lines such as crossing conflicts, merging conflicts and diverging movements.

2.6.1 Train movement time

In its most basic form, a junction is an activity node in a rail system. There are four events that define the activity at the node: the announcement of the approaching train, the entrance to the node, the exit from the node, and clearance of the node for the next train.

Consider a train moving through a node. The four events that define a train movement through the node are the following:

1. Time when the approaching train *i* is detected, t_0^i
2. Time when train *i* enters the node, t_1^i
3. Time when train *i* exits the node, t_2^i
4. Time when train *i* clears the node area, t_3^i.

These events denote segments of time that vary in magnitude according to service line, train consist, speed, acceleration, etc.

$$t^i_{approach} = t^i_1 - t^i_0$$
$$t^i_{process} = t^i_2 - t^i_1$$
$$t^i_{clearance} = t^i_3 - t^i_2$$

The processing time is a function of the length of the train, the operating speed and the length of the block or blocks of track that the node includes. The acceleration and deceleration rates of the vehicle also affect the processing time and are usually reflected in the block design.

2.6.2 Interlocking movement time

Consider now an interlocking. The approach time to the interlocking can be defined as the time it will take for the train to travel the block before the interlocking. Then the approach time will depend on the length of the block before the interlocking and operating speed of the train.

The service process at the interlocking will begin when the train enters the section of track where the interlocking is located. The service process at the interlocking ends when the rear of the train has completely cleared the section of track of the interlocking. Thus, the process time at the interlocking, also referred to as the interlocking time, will depend on the length of the segment of track where the interlocking is located, the operating speed through the interlocking and the length of the train.

The concept of clearance time at interlockings is somewhat different from other nodes. At interlockings, it is defined as the time it takes for the interlocking to be released to permit other train movements to take place. The release of the interlocking can be a timed event, or can take place automatically after the train has reached a sufficient distance from the interlocking, or it can be triggered by an interlocking operator. At junctions with interlockings in series, route-release can take place partially (at every interlocking), or it can be an entire route release.

Figure 2-10 shows the sequence of the four events for an interlocking movement. In this figure, the route-release event is defined as the time when the rear of the train clears the block adjacent to the interlocking.

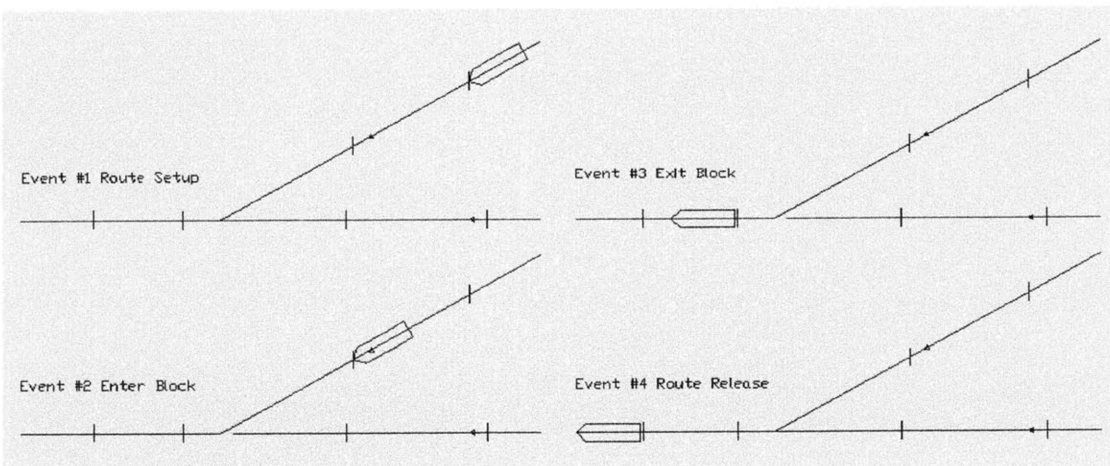


Figure 2-10 Events of a merging movement

The average minimum headway of a system such as the one shown in Figure 2-10 is defined as:

$$CycleTime = \sum_{i}^{I}(t^{i}_{approach} + t^{i}_{\text{int}\,erlocking}) + \sum_{j}^{J}(t^{j}_{approach} + t^{j}_{\text{int}\,erlocking}) + (I+J)*t_{release}$$

$$TrainCapacity = 3600*(I+J)/CycleTime$$

where I is the number of merging trains from one branch in a cycle and J is the number of trains merging from the other branch in the cycle. The approach time and interlocking times are different for both service lines because the trains come from different origin, and the block lengths can be different in each branch and at the interlocking. The route release time is the same for each train, therefore it is treated as a constant that is multiplied by the number of trains in a cycle. The theoretical capacity, measured here as cycles per hour, can be converted to trains per hour by multiplying the number of cycles by the number of trains per cycle. From the capacity equation, the capacity is influenced by the number of trains in the cycle and the mix of trains in the cycle.

In practice, systems do not operate at the theoretical capacity. At the theoretical capacity, the delays generated would be too high for a transit agency to allow if they want to provide a minimum quality of service. Therefore, for each cycle of trains the agency assigns a buffer time to permit a smoother flow of trains and absorb the delays that would be generated at a higher throughput. The buffer time is added to the cycle time to yield the cycle time at a practical capacity. The practical capacity is defined as the capacity at which the agency is willing to tolerate the delays associated with operating a number of trains while providing an acceptable level of service. The buffer time may vary by time of day. During periods of high service frequency, sufficient buffer time should be present such that as much as 70% of the theoretical capacity is permitted in the system. In his book, Pachl suggests that the buffer time should be such that the practical capacity is roughly two-thirds of the theoretical capacity, but can be as high as 80% during peak periods.

2.6.2.1 Multiple track occupancy

For any train movement at an interlocking that involves multiple tracks, the different approach times are considered additional elements of the cycle time for an opposing train route. Therefore, for any train *i* that has an interlocking route crossing the path of train *j*, the cycle time at the crossing is:

$$CycleTime = \sum_{i}^{I}(t^{i}_{approach} + t^{i}_{\text{int}\,erlocking} + t^{i}_{release}) + \sum_{j}^{J}(t^{j}_{approach} + t^{j}_{\text{int}\,erlocking} + t^{j}_{release})$$

At junctions with multiple interlockings, the routes are usually setup from entrance to exit of junction, instead of partially. Therefore the approach time will be considered only for the first interlocking, and the route-release time will be considered only for the last interlocking, but the interlocking time is the sum of all the interlocking times. The equation to determine cycle time would now be,

$$CycleTime = \sum_{i}^{I}(t^{i}_{approach} + \sum_{n}^{N} t^{i}_{\text{interlocking},n} + t^{i}_{release,N}) + \sum_{j}^{J}(t^{j}_{approach} + \sum_{m}^{M} t^{j}_{\text{interlocking},m} + t^{j}_{release,M})$$

where I is the number of trains of one of the service lines in the crossing, J the number of trains per cycle from the other service line at the crossing, N is the number of interlockings in the route set for train *i* and M is the number of interlockings in the route set for train *j*.

The cycle time at the crossing now depends on the number of interlockings in the route set up for each train and the combination of train movements per cycle.

2.7 Summary

We have covered the components of the junction, from the infrastructural level to the design of train control. We have also covered the relevance of having neighboring elements around junctions and shown scenarios in which junction capacity might be underutilized due to neighboring elements.

Lastly, a discussion of capacity at interlockings has shown that the mix of trains within a cycle and the type of conflict at the junction are important determinants of the capacity of the junction.

In the next chapter, we will see how queueing relationships are defined and used for analysis of junction elements.

Chapter 3 Methodology

The methods that will be used to determine capacity in the system are based on steady state cyclical queueing theory. A theoretical understanding of the process times at a junction can be determined through simple kinematics equations. These theoretical processes can be compared with the actual processes to determine if the system is operating as designed.

This chapter presents the techniques used in the operational analysis, which include delay and queue length estimation, junction utilization rates and off-line analysis of tower routing decisions.

For the queueing study, the train arrival process, the service process, and the exit process can be studied using actual train location data. The data can be used to measure and monitor system performance elements such as headways, service times at the junctions, queueing times at junction points and actual junction throughput.

3.1 Queueing Concepts

This section covers the queueing concepts used to identify delays in the system. Queues form at a junction when it cannot process all trains without delays. When this is the case, trains will experience delays in service of variable lengths according to the arrival process and the amount of time required to process a train.

3.1.1 Arrivals

Arrivals are detected by the occupancies registered at the track circuits immediately upstream from the junction. Unless otherwise stated, train arrivals are identified when the train enters the track circuit where the first interlocking signal is located. At junction towers, the trains are detected with sufficient distance to permit the junction operators to decide if the train can be accommodated immediately or if the train will have to stop before entering the interlocking.

Junction arrival times are usually listed in timetables, which can either be followed strictly or used as a guide, with the level of adherence to schedule varying among agencies. In advanced ATC systems, schedule adherence is more plausible because of stronger train monitoring and control techniques. In systems with older generations of ATC and poor schedule adherence, there is little that can be done at junctions to correct the arrival process. A possible solution is to have early trains holding at the entrance of the junction but this is not desired because it leads to increased travel times. The best alternative is then to provide some control at a downstream station where passenger activity can take place.

For simulation purposes, arrival patterns can be modeled using an Erlang distribution. The amount of randomness in the arrival patterns can be adjusted with the scale parameters: a more random system will have a distribution closer to a Poisson distribution, while less variable systems have a much tighter distribution around the programmed headway. In systems with advanced ATC systems, the level of randomness in arrivals can be controlled by strict monitoring and continuous adjustment of upstream operations. With advanced ATC, arrivals at junctions can be programmed according to a timetable, instead of relying on headway adjustments.

3.1.2 Service

The process time at the junction is also known as the service time and is the duration of a train movement through the interlockings that route the train. In the simplest of junctions, there will be only one interlocking movement into the trunk section of the tracks. The service time depends on the length of the blocks of interlocking track and the speed of the train moving through the interlockings. The previous chapter discussed how interlocking movements and route-release times were affected by operating speeds, train consists, length of blocks and number of blocks in the interlocking. The service time is the sum of interlocking movement time and the route-release time.

3.1.3 Utilization Rates

Utilization rates at junctions can be defined by interlocking segments, or as a system of multiple train movements. The utilization rate of an interlocking is measured as the percentage of time that the interlocking is occupied in a cycle of train movements.

The utilization rate of an entire junction can be captured by the utilization rate of the most heavily congested point. The most congested point of a junction may not always be the same at all periods of the day, so the cycle of train movements may also be variable. This cycle is determined by the headway of the service line that generates the highest number of conflicts. At capacity, the utilization rate will achieve as high a value as the train protection design and the block lengths allow, which is close to, but less than 1.0.

3.1.4 Delays

Delays are generated when the arriving trains are not immediately serviced. Delays are an operations problem which disrupt the headway sequence, increase travel time for passengers, and can also propagate to the following trains.

From the junction perspective, delays are indicated by higher-than-expected block occupancies *at the entrance point* of a junction. High movement times through the interlocking itself are not considered delays at the junction. The magnitude of the delays will vary according to the service time of the leading train at the junction and the arrival sequence at the junction.

Junction related delays could be experienced by trains that have not yet arrived at the entrance of the junction. When a delayed train is not at the entrance of the junction, the headway between this train and the train ahead will be the minimum headway for that block of the line. Under these queueing circumstances, the operating margin or reserve resource of the service is lost before the train enters the junction.

3.2 Data sources

The availability of data within an agency to analyze and monitor the performance of rail operations depends on the level of ATC technology available in the system. There is a wide range of data collection sources that vary by level of technology – the most basic form being manual collection. Automated data collection sources are required by agencies to collect the significant data needed to support off-line analysis for service management and planning, and also as a real-time decision support system for operations control. For analysts, the data can be used to validate the models created and as a test data set for simulation.

3.2.1 Method of Collection

The basic form of data collection for train location and tracking and the one used at the CTA, is through the Supervisory Control And Data Acquisition (SCADA) system. Though SCADA systems have traditionally been used to monitor the electrical components of the rail network, such as communications on-line feed, relay houses and track circuit conditions, the system can also be used to record information regarding occupancies at track circuits. It is important that the track circuits connected to the SCADA system provide information at critical points on the line. SCADA can also be used to detect problems such as electromagnetic interference (EMI) at track circuits.

For track circuits, the data that can be collected through the SCADA system is limited to relay drops and pick ups, which are translated into block occupancies and unoccupancies. The relay drops and pick ups can be used to determine times when trains enter and exit track circuits, but do not provide any information on within-block train position.

In advanced data collection systems such as the MATRA system at Tren Urbano, the data collection is far more comprehensive than just relay drops and pick ups from track circuit activity. In the Tren Urbano system, there are various elements that collect data automatically providing exact train position, as well as separation between consecutive trains. The MATRA system is designed as a very strong decision support system for on-line train control that includes simulators and predictors to warn line controllers in real-time when trains are not adhering to a pre-programmed headway or schedule.

3.2.2 Databases

A vital component of automatic data collection is the database in which the data is stored. Databases are vital in systems that require substantial off-line analysis. The database that stores the information coming from the data collection source should be capable of storing immense amounts of data. In the CTA, any day of SCADA data encompasses more than 111,000 records, with more than 670,000 entries in each table. Each day is a table in the database. With data coming from different elements of the SCADA system, it is necessary for the database to be flexible, since the same categories are used for data collected from the communications bungalow, the relay houses, and the power systems.

The design of a database should include relationships between tables to allow changes made in one table to cascade to all related tables without losing data. Therefore, if the ATP configuration is changed by modifying the length of a track circuit, any new track circuits and nomenclature can be easily changed without deleting stored data records.

3.2.3 Data conversion

Once data has been collected in a raw format and stored in a database, transit analysts may retrieve the data and convert it into train movements. Since data is entered into the system as events, the analysts will have access to train times at specific track circuits.

Trains are associated with events and locations, and their trajectories can be tracked by extracting data from successive track circuits. A series of definitions based on manipulation of the SCADA data are included in Appendix A.

Once the trains are tracked over a portion of a line, or the whole line, travel times can be determined for every train run. Occupancies at station track circuits provide a proxy for dwell times for each train and a basis for aggregate dwell time analyses. Headway regulation studies can also be performed once the train tracking has been completed. Other studies that can be performed with the train tracking information include:

- Reoccupancy times at stations, and blocks where trains can queue
- Dwell time progressions through peak periods
- Opening and closing gaps in service
- Terminal dispatching events
- Junction merging and diverging events
- Headway stability at junction entrances (for service branching)

The vast possibilities of line performance studies that can be achieved with the automatic train location and data collection technologies permit analysts to identify aspects of service that can be improved. Equally important, it also allows analysts to understand how much capacity a system provides at various points on the lines.

3.3 Operational Analysis

This section presents the methods used to identify capacity constraints and delay relationships. The first method described is based on the previous studies of utilization rates at nodes and service rates.

3.3.1 Relationships based on utilization rates

Recall from Chapter 2 how the utilization rate is defined for *a section of track* as the amount of time that it is occupied divided by the cycle time. Therefore, the utilization rate is a concept that is associated with a node, or a block and *not a characteristic of a particular train*. However, trains occupy the section of track, so the cycle time can be determined for a set of two (or more) trains.

There have been relationships identified between waiting times for service at a node and the utilization rate of the node (Martland (1997), and Lee (2002)). These studies have shown that waiting time for service at the node increases rapidly when the utilization rate at the node increases above 0.7. This means that at a particular node, the practical capacity of the node should be restricted to about 70% of its theoretical value. In these previous studies, the utilization rates have been treated as aggregate figures for a set of trains during a period of time. In contrast, this study aims at identifying these relationships for individual trains. With the automatically collected track circuit data it is possible to determine the utilization rate of a section of track for each train movement and the waiting time to enter the section of track at an upstream queueing location.

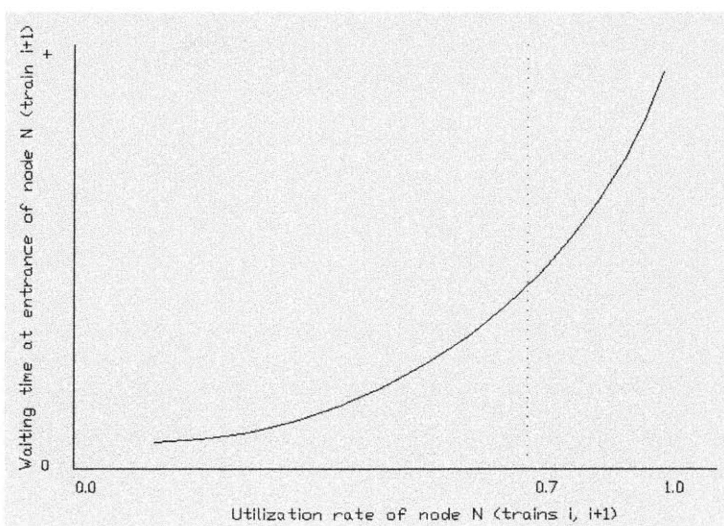


Figure 3-1 Waiting time - utilization rate relationship

Figure 3-1 presents a capacity curve using waiting times at the entrance point of a node and the utilization rate of the node. When the node is not isolated and the waiting times can be affected by other elements, the core relationship is weakened. In such cases, it is useful to determine how the neighboring elements affect this relationship.

The waiting time can be determined at the entrance of the junction by the time that the block remains occupied. If track circuit records are used, the data must be manipulated to have an accurate time of how long the train queued at the entrance block – the waiting time. Offsets are then determined from field observation to represent the time that the train takes to accelerate and clear the block, and also to represent the time from the train entering the block to the moment when it comes to a complete stop. Waiting times are calculated as:

$$t_{waiting} = (OFF_{SCADASTATUS} - ON_{SCADASTATUS}) - \min(OFF_{SCADASTATUS} - ON_{SCADASTATUS})$$

where $OFF_{SCADA\ STATUS}$ is the event recorded when the train clears the block, and $ON_{SCADA\ STATUS}$ is the event recorded when the train enters the block. At times, trains may not stop at the entrance point of the junction, so the waiting time will be at or close to zero.

Recall that the utilization rate and the waiting time are not determined for the same block, so to calculate the utilization rate the track occupancy data required comes from a downstream circuit. If the service time at the node does not show much variability, the utilization rate will be controlled by the reoccupancy time of the node, which is the time that the node remains unoccupied between consecutive trains. There is an inverse relationship between reoccupancy time and utilization rate, as seen in Figure 3-2. During high congestion the reoccupancies will be lower than during less congestion. When the node has high utilization the reoccupancy time will reach a lower bound that is a function of the block separation required for Automatic Train Protection.

When these two relationships are combined the minimum train separation can be determined in the time dimension. This train separation reflects the route-release time for train t and the route setup time for train $t+1$ permitted by the ATP design. Knowing the service time (interlocking time plus route-release time) at the node, the minimum headway can be determined. If the buffer time between train movements is consumed as a result of variability in the system (such as arrival times), the operation will approach the practical capacity and delays will be experienced.

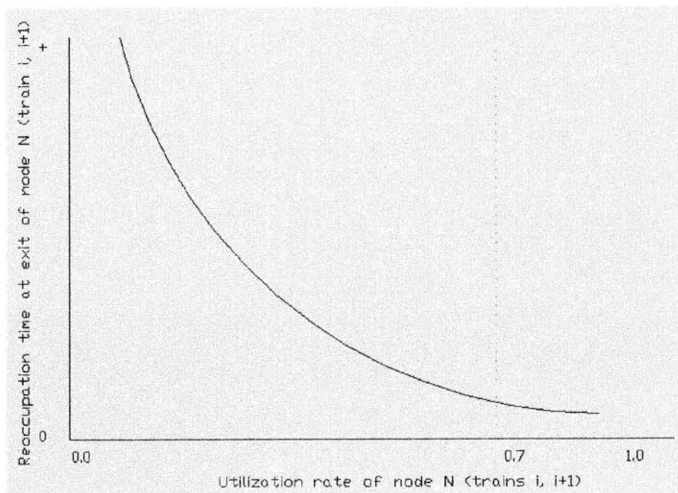


Figure 3-2 Relationship between utilization rate and reoccupancy time at node N

3.3.2 Queue and delay estimation

As mentioned previously, queues are generated when the train has to stop at the entrance point of a node and wait for service. Automatic train detection technology can be used to identify queues and consequently estimate delays.

A queue will form at the entrance of a service node if a train arrives before the leading train has been fully serviced. At interlocking sections, due to the design of the ATP, the train at the queue will have to wait until the train ahead has cleared the interlocking section of tracks and the block ahead – where route release takes place (recall the train progression from Figure 2-11). Since trains queueing at the entrance of the junction can be detected with the track circuit data, delays can be estimated from the track circuit activity. If the track circuit activity at the entrance of the junction is not available, train queueing can be detected by using run-time data for the queued train between an upstream track circuit and a downstream track circuit logging activity.

Queues that develop at the entrance of the junction can propagate to blocks upstream, or to the other track where the conflicting trains approach the junction. For trains queued at the entrance of the junction, the length of time that the train remains queued is defined as the delay associated with the junction service. Delays from longer queues are also associated with the initial queuing process. Delays are estimated by calculating how much additional time a train occupies a circuit at the entrance point of the junction, or the block where the train enters the queue plus the additional delays as the train progresses in the queue. An important assumption is made at this point regarding delay estimation: a delay is considered to be any additional time that a train experiences at the entrance of the junction over the uninterrupted train movement time. There are two important implications for merge conflicts concerning the assumption. First, an uninterrupted train movement should have a route setup time that does not force the train to stop at the entrance of the junction to wait for a signal clearance. Second, the arrival patterns at a junction are variable. Thus, when a train queues at the entrance because there are almost simultaneous train arrivals, the second train will inevitably experience a delay.

Using the relationships explained earlier, a queue at the entrance of an interlocking can be determined by – 1) high occupancy at the entrance block and 2) low reoccupancy time at the interlocking blocks. The reoccupancy time during a queue and the occupancy time at the entrance block can also be determined using kinematic equations and compared with the data to support the empirical findings. Longer queues can be also determined using low reoccupancies and high occupancies as conditions at upstream blocks.

Queues of at least two trains can form in a variety of ways, some of which are presented in Figure 3-3. A two-train queue can form at merge points by two consecutive trains from a same branch, as shown in Figure 3-3a, or these may form when at least one train is on each branch, as shown in Figure 3-3b. At crossings, these may form when trains from conflicting routes arrive at the junction while the crossing is occupied by another train, as shown in Figure 3-3c.

It is important to recognize that a queue of two trains can be identified only when the conditions of a one-train queue have been met for the first train at the queue. The second train will also experience the conditions of a one train queue after the first train is serviced. Delays are estimated in a similar way to the delay estimation for a one-train queue: additional block occupancy, and low reoccupancy times.

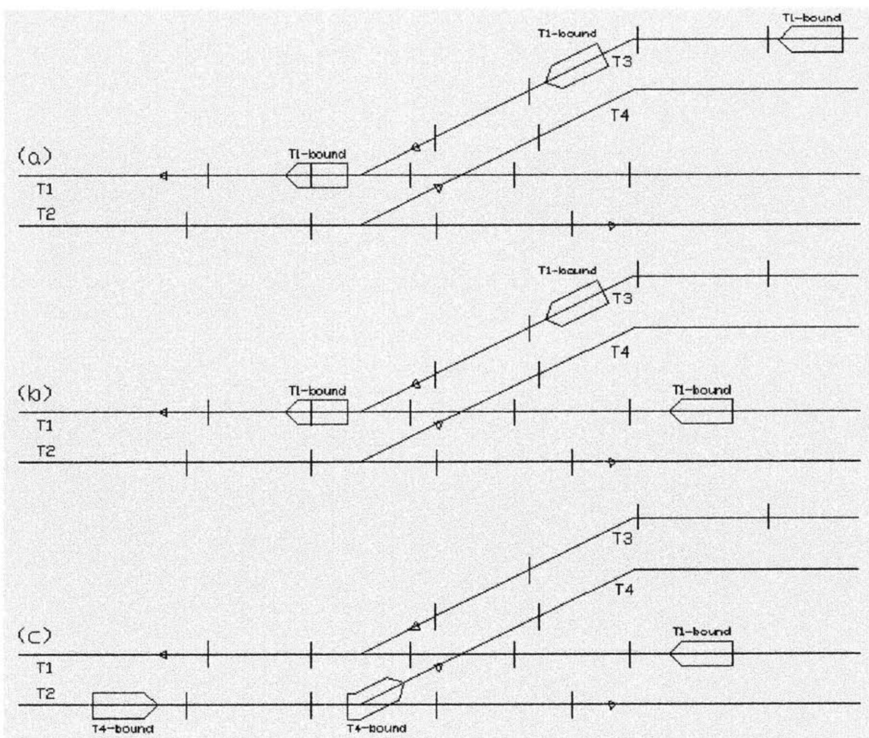


Figure 3-3 Two-train queueing aat merging points and crossings

3.3.3 Replicating tower decisions

The use of automatically collected train tracking data and SCADA data analysis can help represent train movements at an aggregate level for the junction. Since junctions usually consist of various interlockings in which more than one train movement can take place simultaneously, it is important to consider that real time routing decisions are often based on system conditions, instead of schedule adherence which may be harder to determine.

When real time decisions are made by the tower operators it is necessary to understand the underlying impact of these decisions on train delays upstream and on headways downstream from the junction.

Time-space diagrams are useful visual tools for understanding train progression, and these can be used for headway studies and run time performance. A single diagram is sufficient to see train movements in various directions for one- or two-track systems. A classical time-space diagram is shown in Figure 3-4. In this diagram a single direction of traffic flow is depicted for a merge of two service lines, but with the trajectories shown for only one of the upstream branches. From this diagram the train sequence can be readily seen. In the figure the observed routing sequence is A-A-B-A-A-A-B-A-A-B-A. There is no information, though as to what routing priority was used through the junction. From this diagram, we do not know if the routing was *first-come-first-serve*, or if it was a strict scheduled sequence, or if personal discretion was used by the junction operator.

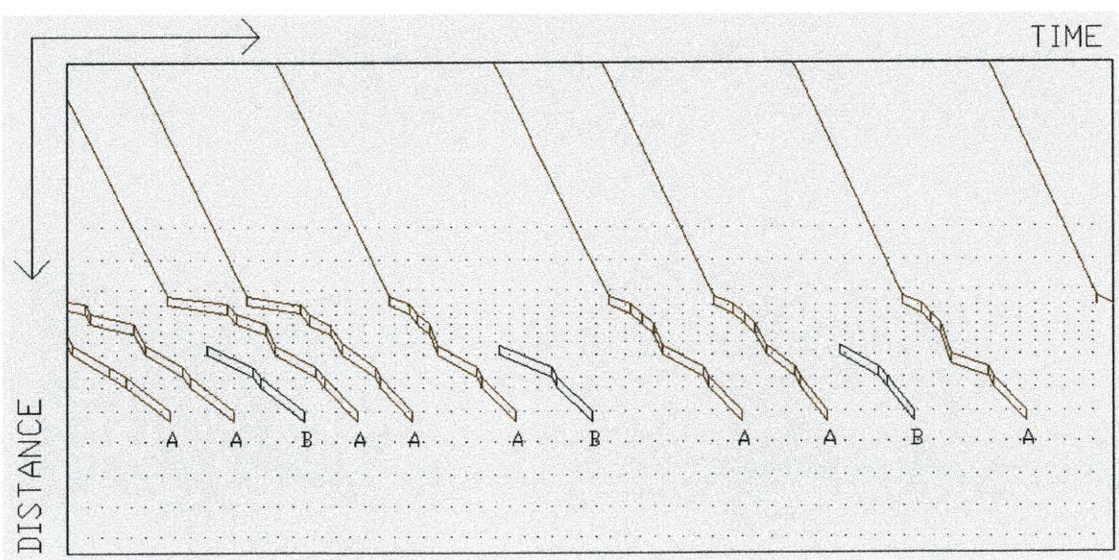


Figure 3-4 Classical time-space diagram

The time-space diagram shown in Figure 3-4 plots time on the horizontal axis and distance on the vertical axis. The vertical separation between the parallel lines that indicate the train progressions is the length of the train. The horizontal separation between the two lines is the time it takes for the train to travel through a point of the tracks, which is also the occupancy at a section of track bounded by two points. This information is particularly useful at stations and at queueing locations, where the train representation will have a more horizontal slope than at other points. Some of these horizontal slopes can be seen in the first set of trains in the diagram.

Another form of time-space representation is to have each activity on a section of track represented through time. This type of diagram is termed a time-block diagram, but can also be referred to as a block occupancy diagram. A crossing or a merge point are sections of track that can be represented in a time-block diagram. This type of diagram can be used to understand the influence of a train movement over a section of track when different service lines meet or cross. Time-block diagrams can show overlaps between train movements at crossings. An overlap happens when a train enters the junction before the previous train has cleared the junction. This is possible when the entrance to the junction for the second train is not at the crossing point, allowing the second train to move into the junction. The second train, however, cannot enter the block where the crossing is located until the other train has cleared and the interlocking as been released.

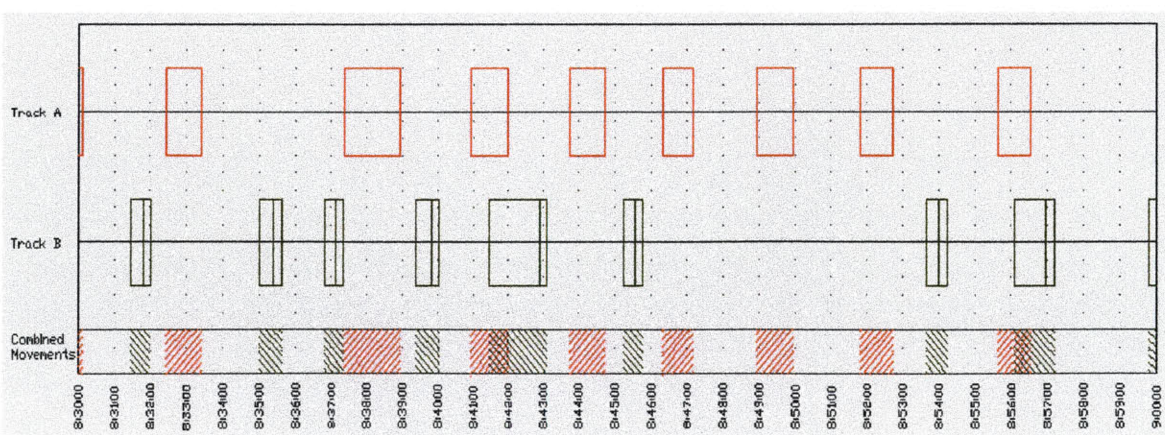


Figure 3-5 Time-block diagram at a crossing

Figure 3-5 presents an example of a time-block diagram for a crossing. Two horizontal lines with vertical offsets represent the crossing section of two tracks, with each line representing one track. At the bottom of the chart, just above the horizontal time axis, the occupancies at the crossings are plotted together to show how much total time is consumed within the observed time period, and to identify overlaps in the route setting process. Occupancies that have several vertical lines, such as those for trains on Track B, include an additional component of time that represents the time required for those trains to clear the interlocking. The additional time component is included when the information from the track circuits does not include the entire process time at the junction.

The time-block occupancy diagram provides limited insight into the tower operations. Since it does not provide information on the arrival process at the junction, approach times are not captured in this diagram.

A more complex form of time-space diagram that combines the diagrams presented thus far would help address the limitations of each. A combined time-space diagram with every branch represented and the junction occupancies shown will enable us to understand the conditions on each branch and to present how much activity is occurring in the junction.

Figure 3-6 presents a multiple movement time-space diagram for a similar configuration to that shown in Figure 3-3. The area where tracks T1 and T2 are depicted shows the movements of trains in two different directions and on different tracks. The shaded horizontal bar located in this part of the diagram represents the interlocking area of the junction. The diverging movement is a crossing, from Figure 3-3c, so there cannot be two crossing service lines at the junction simultaneously. The horizontal time-block diagram located underneath the time-space diagram shows the occupancies at the crossing. If there are two bars over the same time period then there are overlaps in the junction routing. As mentioned before, the tower operator relies on operation policies to decide which service line is granted priority.

The multiple-movement time-space diagram can be a very powerful tool for rail analysis of the complexities of junction operation. All the routing processes can be observed for any period of time, and queues can be identified by looking at the train progressions.

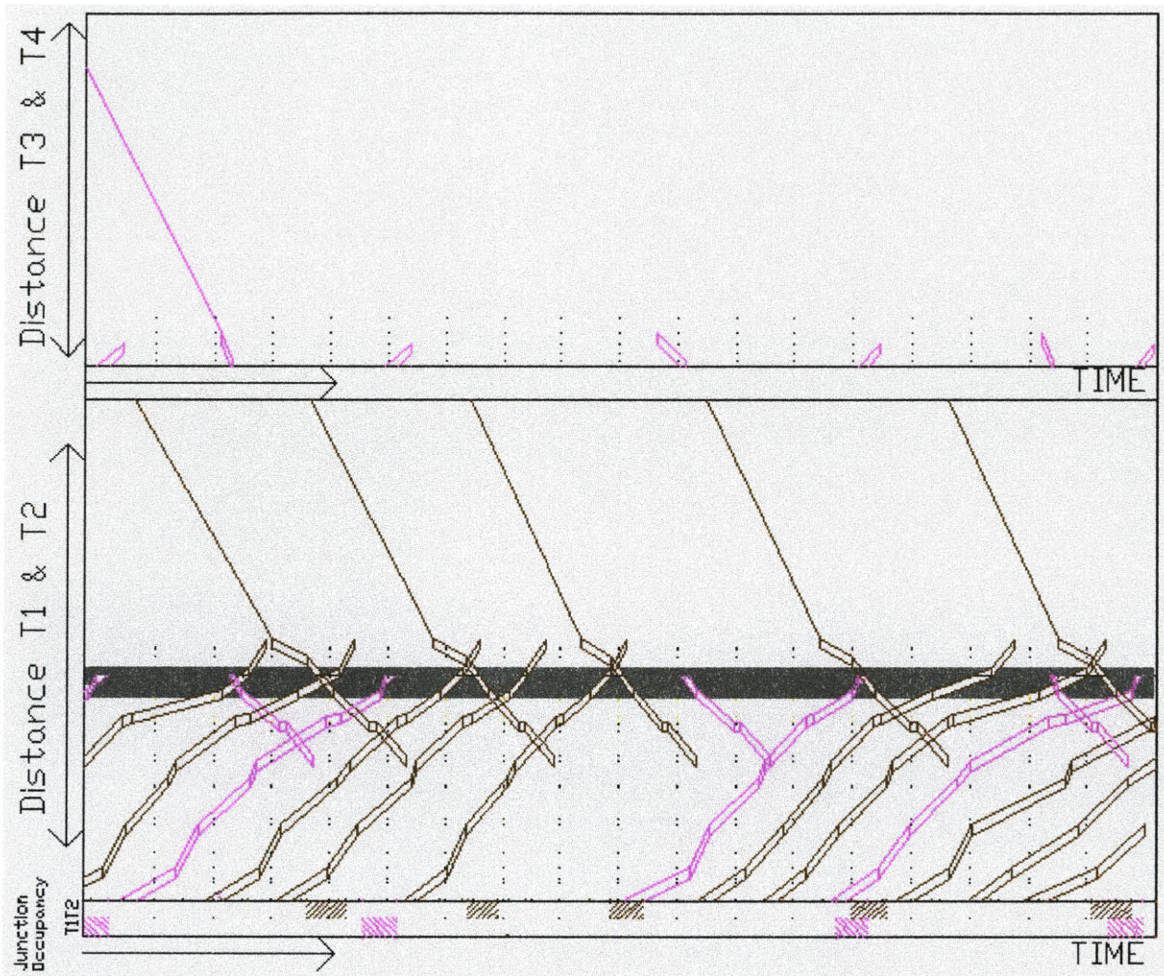


Figure 3-6 Multiple-movement time-space diagram

3.4 Summary

The methodology which has been presented in this chapter will be used to identify queues and determine delays on the Clark Junction at the Chicago Transit Authority which will be introduced as the case study in the next chapter.

The performance analysis will be possible using an existing automatic data collection system (SCADA) that has been traditionally used to monitor the conditions of electrical components of a system. SCADA can collect information on train presence in the block systems because the system collects information on the relay activity – which is a critical component of the track circuitry. The recordings are useful for off-line operations analysis.

Utilization rates at the junction will be used to represent the amount of congestion exhibited at the junction for merge points and crossings. Delays and queues can thus be determined using the utilization rate of the system as a proxy for congestion. High occupancies at the queueing location and low reoccupancies at the service blocks can be used to identify the queues. Delays can be estimated by determining how much additional waiting time trains spend at the blocks where these form the queues compared to the occupancies of uninterrupted train movements. The delay parameters can be determined through the kinematic equations and these can be verified with the automatically collected data.

Multiple-track time-space diagrams have been introduced as a tool to understand decisions taken by the tower operation when the system is experiencing congestion.

Chapter 4 Case Study: CTA Clark Junction

In this chapter the Clark Junction is introduced as the case study of this research. The physical and infrastructural characteristics of the Clark Junction are discussed, along with the routing practices and the operating policies. The chapter closes with an overview of the proposed new configuration for the Clark Junction.

4.1 Site description

The Clark Junction is located in the North Main portion of the CTA rail system, just north of Belmont station for Red Line, Purple Line and Brown Line service. Figure 4-1 shows location of the Clark Junction, which has a 4-track main line (North Main) accommodating the Red and Purple Lines, with two turnout tracks (Ravenswood) accommodating the Brown Line.

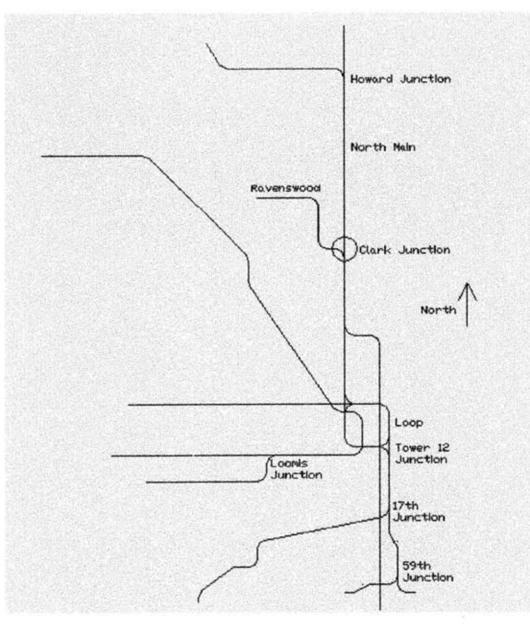


Figure 4-1 Location of Clark Junction in CTA rail network (not to scale)

Clark Junction is one of many flat junctions in the CTA rail system and it is the second busiest (after Howard) processing approximately 872 trains per weekday.

4.1.1 Track and interlocking configuration

The North Main tracks are numbered NM1 to NM4, with NM1 being the outer tracks of the west side of the alignment and NM4 being the outer tracks of the east side of the alignment. The Ravenswood turnout tracks are located on tracks NM1 and NM3. Figure 4-2 shows the location of all the crossovers and the turnouts at the junction, including the location of signals and Belmont station.

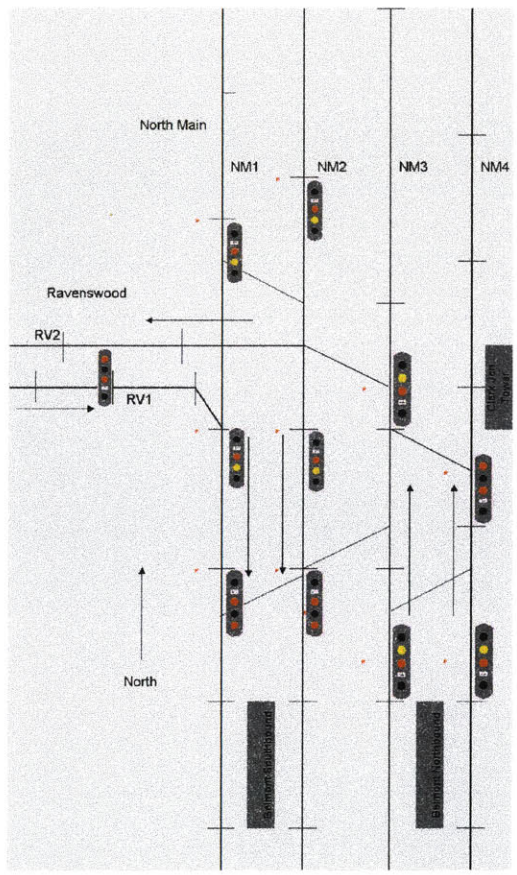


Figure 4-2 Clark Junction interlockings and signal locations (not to scale)

Tracks NM1, NM2 and RV1 are used for southbound service and the northbound service use tracks NM3, NM4 and RV2. Thus, a train branching to the Ravenswood alignment through track RV2 must cross tracks NM1 and NM2. The Ravenswood-bound trains (Brown Line), however, approach the junction from track NM4. The trains move out of track NM4 and into track NM3 and then branches off on the RV2 turnout tracks. This type of movement can be considered a form of crossing, since the train comes from a different origin track and has a different destination track than NM3.

4.1.2 Service lines and routing

As mentioned before, there are three service lines operating through the junction: Brown Line, Red Line and Purple Line. The southbound Brown Line service approaches the junction from the Ravenswood tracks (RV1) and merges into the NM1 tracks. The northbound Brown Line service approaches the junction on track NM4, merges with track NM3 and diverges to track RV2 before exiting the junction.

The southbound Purple Line service operates on track NM1. At the junction it crosses track RV2 and merges with track RV1. The northbound Purple Line service operates on track NM4 and is not subject to merging or crossing traffic.

In the event of special operations, the southbound Purple Line service could approach the junction on track NM2, instead of track NM1, in which case it would branch off and merge into NM1 before exiting the junction. Similarly, in the northbound direction the Purple Line trains could approach the junction from track NM4, then branch off this track and merge into track NM3 before exiting the junction. This routing strategy is implemented to satisfy unusual demand at Addison station, which is 1,500 feet north of the junction and served only by tracks NM2 and NM3, during Cubs baseball night games.

Southbound Red Line service uses track NM2 and northbound Red Line service approaches the junction from track NM3. Train movements on both tracks are affected by northbound Brown Line crossing movements.

4.1.3 Belmont station

Belmont station is located less than 500 feet from the junction and so its operation needs to be considered as part of the junction analysis. Southbound, the station acts as the exit point from the junction, and northbound it acts as the entrance point to it.

The Belmont station platforms are located between track NM1 and NM2, and between NM3 and NM4 (see Figure 4-2). These are island platforms with same direction of traffic on each platform, designed to make it easy for passengers to exit one train at the platform and wait for another service line on the same island platform. When trains are berthed at the platform simultaneously, passengers can transfer from one service to the other without experiencing any waiting time at the platform. This type of transfer activity is referred to as a *cross-platform transfer*. Since the Brown and Purple Line service runs on the same tracks, whereas the Red Line service runs on separate tracks, cross-platform transfers may take place between Red Line service and either Brown Line or Purple Line service. Transfers can also take place between Purple Line and Brown Line, though these cannot take place simultaneously and are thus not considered cross-platform transfers.

Studies by Puong (2002) on heavy rail transit and Lin & Wilson (1991) on light rail transit have shown that train dwell times are affected by the number of passengers alighting and boarding, as well as by the passenger loads in the vehicles and on the platform. At Belmont station, these variables will have some influence on the dwell times. If the cross-platform transfer activity during simultaneous train berthings is taken into consideration, then the dwell times could be much higher than dwell times in which there is no cross-platform transfer activity taking place because there will be much higher congestion on the platform due to the amount of passenger activity on the platform.

The possibility of cross-platform transfers is high during peak periods of service. The morning peak period of service is defined from 7:00 AM to 9:00 AM, where as the evening peak period if defined from 4:00 PM to 6:00 PM. Table 4-1 presents a summary of headways on the service lines during morning and evening peak period. The lower headways occur during the middle of the peak period and the higher headways at the beginning and end of the peak periods.

	Southbound Brown Line	Southbound Purple Line	Southbound Red Line	Northbound Brown Line	Northbound Purple Line	Northbound Red Line
AM peak	3-5 min	8-10 min	3-5 min	3-7 min	10-15 min	4-5 min
PM peak	3-6.5 min	6-10 min	4.5-5 min	3-7 min	6-10 min	3-4.5 min

Table 4-1 Peak period service headways at Belmont

The combined headways of Brown and Purple Line yield a lower headway for tracks NM1 and NM4. At such high frequencies, it is expected that some trains will arrive at Belmont station simultaneously. It is therefore expected that some trains will have high dwell times at Belmont station due to the cross-platform transfers.

4.2 Tower Control

Route assignment and interlocking control at Clark Junction is a relay-based operation with a push-button control panel. A tower operator sets the routes for the approaching trains, which are displayed on the control panel and confirmed visually or through radio communication.

The route setting process takes between 3 to 6 seconds to lock and provide signal clearance, as determined through field observations. As mentioned in Chapter 2, routes can be formed by a series of interlockings. Routes that cross more than one interlocking can be set up individually for each interlocking or these can be set up as an entire unit. Routes that are set partially are referred to as *partial line-ups*. A route set from the approach point to the exit point of the junction is termed a *full line-up*.

Since the routes are set up by a tower operator, the elapsed time from the moment that an approaching train is identified to the moment when the tower operator sets the route for the approaching train will be subject to the conditions at the junction and the reaction time of the tower operator. Since these could be variable, the approach time for a train movement will also be variable.

4.2.1 Decision support

As mentioned the tower operator is notified of an approaching train through the control panel. The trains approaching the junction are detected as they near the circuit where the home signal is located, giving the tower operator less than a minute to set the route without delaying the train. If the route cannot be setup within this time frame, the approaching train will have to stop at the home signal. This train will then queue until the route is cleared of any conflicting train movement and the route is setup.

During periods of high congestion the queue can propagate to following trains. On the Ravenswood tracks, this propagation goes undetected by the tower operation because it is not shown in the control panel and the buildings and other structures around the junction obstruct the view of upstream conditions on these tracks. Similarly, in the northbound direction the extent of the queue goes undetected by the tower operator because the control panel display is limited to the Wellington track circuits, which are adjacent to the Belmont track circuits. For southbound movements, however, there is a partial view of the upstream section of the alignment that permits the tower operator to see the conditions at least as far as Sheridan.

4.2.2 Operation policies

There are a series of tower operation policies currently available to help the tower operator make routing decisions in the system in the absence of a good decision support system. The operation policies are mainly aimed at providing a logical and robust routing sequence. The routing sequence is based on a series of conditions, including:

- Order of arrival at the junction,

- Upstream track congestion,
- Downstream conditions, and
- Service time at the junction.

At Clark Junction, there are also operation policies aimed at improving the dwell process at Belmont station. Similar to the junction routing prioritization logic, the dwell time control policies are based on:

- Arrival headway at the station,
- Upstream track congestion,
- Service time at the station,
- Possibility of transfers between service lines, and
- Congestion at the junction

There are a series of factors that could constrain the deployment of effective routing strategies. The operating policies aim at providing the tower operator with a logical routing sequence given the information provided by the control panel. However, the lack of sufficient supporting information on the control panel is the reason why operating policies are needed. Thus, the effectiveness of the routing strategies on system performance is also uncertain.

In addition, operating policies should be kept simple enough to apply that the tower operator can make decisions without delay. This means that the number of operating policies should be limited and the decision rules need to be clear. The conditions to be met to select the best prioritization should be less than a handful.

4.2.2.1 Current policies

Operation policies are effective during period of high service frequencies which are from 7:00 to 8:45 AM and from 4:00 to 5:30 PM. The current operation policies at Clark Junction are aimed at three different aspects of the system:

1. Routing priorities

2. Queueing positions
3. Dwell time control at Belmont station

For southbound Brown Line and Purple Line train movements there are simple tower operation policies for prioritization through the merge point:

a) a first-come-first-serve routing discipline for these two service lines based on the arrival of the approaching trains at their respective home signals.
b) when trains arrive simultaneously, priority is assigned to the southbound Purple Line service.

The current policy for southbound Brown Line queueing is to advance the trains into the junction as far as the signal system will permit if the queueing is occurring from Belmont station process, instead of holding at the merge between Brown Line and Purple Line trains. Brown Line trains can move into the junction since they do not affect other service lines other than the Purple Line. Purple Line trains, however, do not have currently this operation policy, as will be explained in section 4.3.3 on block design.

Another policy applies to train dwell times at Belmont station. To reduce dwell times, train operators are encouraged not to hold at the station for Red Line trains that have not arrived before the normal boarding process has been completed. This operating rule is intended to free up Belmont station so that trains can move through the merging point with less delay. High dwell times at Belmont station can reduce the throughput at the merge point because Belmont station is the exit point of the junction for southbound movements.

There are also some other policies for the northbound service that aim to control the dwell time at Belmont station. Specifically, northbound Brown Line trains should not dwell at the Belmont station for more than 60 seconds during the evening peak period. There are no policies for Red Line or Purple Line service.

Though not an operation policy, routing practices for the northbound services have been oriented to prioritize northbound Brown Line trains.

A routing practice is to advance the northbound Brown Line trains to track circuit A13T when there is a follower at Wellington and the complete route through the junction cannot be assigned to the Brown Line train. This permits the Brown Line follower to move into Belmont station under a restricted mode of operation while the Brown Line train is queueing at track circuit A13T. At the CTA this is allowed as an exception to the normal operations which allow a minimum separation of trains of at least one block, and is referred to as Rule R6.4.

In this study, different operation policies are sought to reduce queueing and delays in trains approaching Belmont and the junction.

4.3 State of Infrastructure

The current state of infrastructure at the Clark Junction is less than optimal. There is an array of infrastructure and design problems that substantially limits the capacity of the system.

4.3.1 Track conditions

The junction is designed to have train operating speeds of 35 mph, however the aging structure and the rail conditions limit the speeds to a maximum of 15 mph. This represents more than a 50% reduction in the operating speeds that increase travel times through the interlockings. The increase in movement time at the interlocking, as expected, leads to a reduction in both the theoretical and practical capacity of the junction. To put this into perspective, the theoretical capacity of the RV2 turnout switch at the design speeds is 75 tph and the practical would be roughly 50 tph. The theoretical capacity at the current operating speeds is 45 tph with a practical capacity of about 30 tph. This represents a 40% reduction in the capacity of the turnout switch.

4.3.2 Signaling system

Recall from Chapter 2 how the track circuit and the signal system were tied together into the ATP/ATS system. There are various blocks at the junction that are experiencing EMI problems, as has been identified by tower operators and is apparent in the SCADA database. The false occupancies indicated in the track circuits – even those where the route has been locked – generates unnecessary delays in the system and some of the significant delays that occur at Clark Junction are the result of these problems. Blocks that are protected by signals are critical hosts of EMI and the signaling system responds by preventing the entrance of trains to the block of track containing the problem circuit. The emergency brake tripper is activated every time that the circuit indicates occupancy and trains that have a clear route and approach the track circuit showing a false occupancy will trip on the emergency arm and will make an emergency stop.

This problem has been observed at various track circuits, which are identified by shaded ovals in Figure 4-3. These are track circuits N1-237 (Belmont station) and N3-246, which is immediately downstream of the exit point from the junction for northbound Red Line trains. At track NM1, the false occupancies at track circuit N1-237 will cause the signal before track circuit 15T to indicate a red aspect, activating the emergency brake tripper. At track NM3, the false occupancies at N3-246 will give the trains a cab signal speed of 0 mph at 3T, preventing the train from clearing the junction and thus blocking the crossing. This will prevent northbound Brown Line trains from moving through the junction.

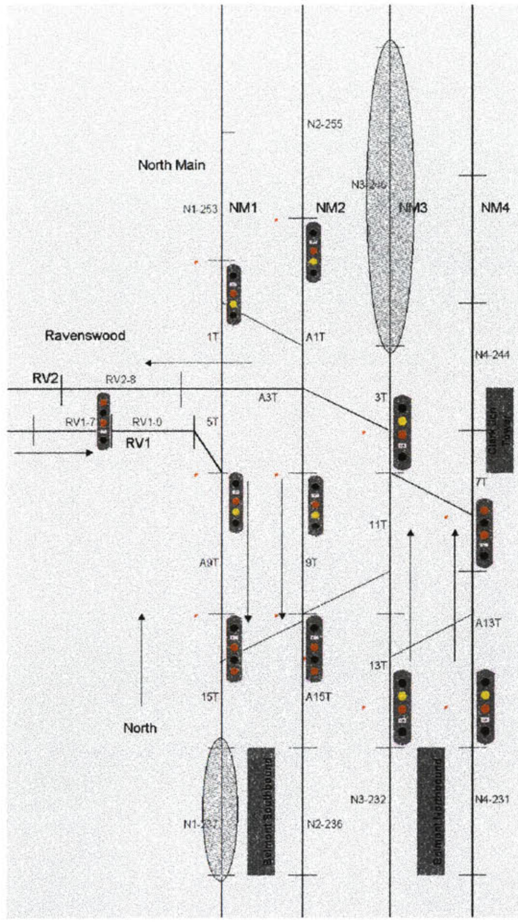


Figure 4-3 Clark Junction track circuits with EMI problem

4.3.3 Block design

Currently, Brown Line and Purple Line services run 6-car trains while Red Line service runs 8-car trains. In the current block design, Belmont station acts as the exit point of the junction for the southbound service and the entry point for the northbound service. A closer examination of the block lengths, train lengths, and the functions of each signal at each approach, however, leads to the conclusion that Belmont station is not necessarily the exit point of the junction southbound, or the entry point for the northbound Purple Line and Brown Line service.

All CTA trains have car lengths of 48 feet. Therefore, a 4-car train is 192 feet long, a 6-car train is 288 feet long and an 8-car train is 384 feet long. Table 4-2 provides the lengths of each block for each track.

Track NM1/RV1		Track NM2		Track NM3		Track NM4/RV2	
Circuit Name	Length (ft)	Circuit Name	Length (ft)	Circuit Name	Length (ft)	Circuit Name	Length (ft)
N1-237	651	N2-236	477	N3-232	497	N4-231	462
15T	377	A15T	440	13T	463	A13T	474
A9T	274	9T	267	11T	232	7T	345
5T	133	A1T	709	3T	328	N4-244	589
1T	496	N2-255	655	N3-246	700	A3T	290
N1-253	719					RV2-8	538
RV1-0	307						
RV1-7	243						

Table 4-2 Clark Junction track circuit lengths

An example of a train movement for which Belmont station is not necessarily treated as the entrance of the junction is the northbound Brown Line service. A 6-car Brown Line train is 288 feet long while the circuit before the first interlocking (A13T) is 474 feet long. Therefore, it is possible for a northbound Brown Line train to enter track circuit A13T and queue in this block for service at the junction, instead of lining up for service at Belmont.

Southbound Red Line service is an example where Belmont station is not necessarily the exit point from the junction. Red Line service runs with 8-car and 4-car trains. When Red Line service runs on 8-car trains, the trains can move into the junction as far as track circuit 9T when there is a leader at Belmont station. However, since track circuit 9T is not sufficiently long (267 feet) to accommodate an entire 8-car train (388 feet), the rear of the train will be occupying track circuit A1T while queued for service at Belmont. This would block the crossing with the RV2 turnout track, preventing northbound Brown Line trains from moving through the junction. Therefore, southbound Red Line trains are held at track circuit N2-255. In contrast, a 4-car Red Line train (192 feet) could advance as far as track circuit 9T without blocking the crossing when a leader is at Belmont. Therefore, the Belmont station is not the exit point from the junction when Red Line service operates 4-car trains.

As mentioned, one of the current operating policies is that southbound Brown Line service can advance as far as track circuit A9T when there is a leader at Belmont station. This track circuit, however, cannot accommodate the entire train so the rear of it will be at track circuit 5T occupying the turnout track. If the practice of moving into queueing position at track circuit A9T is copied by Purple Line trains, then the rear of the train will block the crossing of the RV2 turnout track. Therefore this operation policy is not applied to southbound Purple Line trains. Some tower operators might decide to move the Purple Lines as close to Belmont as they do with Brown Line trains so these go into Rule R6.4 and permit the Purple Line trains to move into the A9T track circuit and enter halfway into track circuit 15T so that the rear of the train enters track circuit A9T. For both the Brown Line and the Purple Line trains, the queueing problem is the result of an outdated block design. Clearly, the junction could operate appropriately if the services were operated with 4-car trains.

4.4 Capacity of Clark Junction

This section estimates the capacity at Clark Junction under the current operating speeds. First, the capacity of the merge point between the turnout track RV1 and the main track NM1 is estimated. Based on the capacity of this merge point and the number of approaching trains from the NM1 track, the capacity of the crossing of turnout track RV2 and track NM1 will be determined. Then the capacity of the remaining crossing will be estimated.

4.4.1 Merge point: RV1 & NM1

The Brown Line and Purple Line services operate with 6-car trains. The southbound Brown Line service approaches from the Ravenswood tracks and the southbound Purple Line train approaches the junction from the North Main tracks. Their approach times and interlocking movement times are different, but their route-release times are the same because both services have the same train consists.

The approach time for southbound Brown Line trains is defined as the time it takes for the train to travel through the entrance point of the junction (track circuit RV1-7) at 15 mph. Since the circuit is 243 feet long, it takes 11 seconds for the train to enter the junction from the moment it enters track circuit RV1-7. The interlocking time is defined as the time the train consumes from the moment it enters track circuit RV1-0 to the time that the rear of the train exits track circuit 5T. The interlocking distance includes a train length because it measures the time from the front of the train entering the first interlocking block to the time for the rear of the train exiting the last block of the interlocking. The interlocking includes blocks RV1-0 and 5T, therefore the interlocking length is approximately 728 feet. At a speed of 15 mph the interlocking time is 33 seconds. The route-release time is defined by the time it takes for the rear of the train to exit the last block of the merge point, which is A9T, from the time that the rear of the train exited 5T. The block is 274 feet long and for an operating speed of 15 mph it takes 13 seconds to release the route once the train has cleared the interlocking. The total movement time is the sum of the approach time (11 seconds), the interlocking time (33 seconds) and the route-release time (13 seconds), which is 57 seconds.

Similarly, for southbound Purple Line service the approach time is measured as the time it takes for the train to enter the interlocking from the time it enters N1-253. The interlocking time is defined by the interlocking blocks which are 1T and 5T. The route release is in the same block as Brown Line service, track circuit A9T. As mentioned previously in section 4.3.1, the maximum permissible speeds are 15 mph.

Table 4-3 shows the train movement time through the interlocking based on the current 15 mph operating speeds.

Train movement time	SB Brown Line	SB Purple Line
Approach time	11 secs	33 secs
Interlocking time	33 secs	42 secs
Route-release time	13 secs	13 secs
Total time	57 secs	88 secs

Table 4-3 Movement time for SB Brown Line and SB Purple Line at Clark Junction

Recall from Chapter 2 that the cycle time is determined by the combination of trains at a node and the movement time of each through the node. At the merge point for tracks NM1 and RV1, the cycle time is determined by the ratio of Brown Line trains to Purple Line trains. For a one-to-one ratio, the cycle time will be based on the movement time of a Brown Line train and the movement time of a Purple Line train. The cycle time will be the sum of the total movement time for each service: 145 seconds. Since the capacity of this point is determined by the number of cycles that can be completed in an hour: 24 cycles can be completed in a one-to-one train progression. Thus, 24 Brown Line trains and 24 Purple Line trains can be processed for a total of 48 trains per hour. The amount of buffer time required for a smooth operation is such that the practical capacity is roughly two-thirds of the theoretical capacity. Therefore, about 16 cycles can be programmed through the junction. The 16 cycles take roughly 39 minutes out of every hour to complete. This leaves about 80 seconds of buffer time for every cycle. The buffer time can be distributed evenly between train movements, or it could be assigned in proportion to the amount of movement time for each train.

Train Combinations per Cycle	1 SB Brown Line : 1 SB Purple Line	2 SB Brown Line : 1 SB Purple Line	1 SB Brown Line : 2 SB Purple Line	3 SB Brown Line : 2 SB Purple Line
Cycle Time (secs)	145	202	233	347
Trains per cycle	2	3	3	5
Theoretical Capacity (tph)	49	51	46	51
Practical Capacity (tph)	33	34	30	34

Table 4-4 Capacity of merge point with different train combinations

Table 4-4 shows an array of ratios and their respective capacities. Under the current operating plan, there are two southbound Brown Line trains scheduled for every southbound Purple Line train. Therefore, if the merge point is an isolated node, the capacity would be 34 trains: 23 Brown Line trains and 11 Purple Line trains. This would represent a headway of roughly 2 minutes and 45 seconds for Brown Line service and 5 minutes and 30 seconds for Purple Line service.

4.4.2 Crossing point: RV2 & NM2

At this crossing the southbound Red Line service crosses the northbound Brown Line service. The approach time for Red Line service begins when the train enters track circuit N2-255, which is 655 feet long. At the permissible speed of 15 mph the approach time will be 30 seconds. The interlocking time begins when the train enters the interlockings at track circuit A1T and terminates when the rear of the train exits this circuit. The length of this circuit is 709 feet and the length of a Red Line train is 384 feet, therefore the interlocking time lasts 50 seconds. The route-release time will be the time it takes for the rear of the train to exit track circuit 9T, which is 267 feet long. Therefore the route-release time is 12 seconds.

Train movement time	NB Brown Line	SB Red Line
Approach time	15 secs	30 secs
Interlocking time	45 secs	50 secs
Route-release time	14 secs	12 secs
Total time	74 secs	92 secs

Table 4-5 Movement times for northbound Brown Line and southbound Red Line at Clark Junction

Table 4-5 shows the movement time components for these two services and Table 4-6 shows the capacity at the crossing point based on different train combinations.

Train Combinations per Cycle	1 NB Brown Line : 1 SB Red Line	2 NB Brown Line : 1 SB Red Line	1 NB Brown Line : 2 SB Red Line	3 NB Brown Line : 2 SB Red Line
Cycle Time (secs)	166	240	258	406
Trains per cycle	2	3	3	5
Theoretical Capacity (tph)	44	45	41	44
Practical Capacity (tph)	30	30	28	30

Table 4-6 Capacity at crossing of NM2 and RV2 for different train combinations

The combination of trains at this crossing will affect the combination of trains on the crossing between northbound Red Line trains and northbound Brown Line trains, as discussed in the next section

4.4.3 Branching RV2 & NM3

The other critical point in the junction is the switch of turnout track RV2 and the main track NM3. Northbound Brown Line trains approach the junction on tracks NM4, branch from these tracks to tracks NM3, and branch from these tracks to track RV2. This action is classified as a crossing for northbound Brown Line service with the northbound Red

Line service, which runs on track NM3. Table 4-7 shows the train movement times for these two service lines.

Train movement time	NB Red Line	NB Brown Line
Approach time	15	15
Interlocking time	52	45
Route-release time	15	14
Total time	82	74

Table 4-7 Movement times for NB Red Line and NB Brown Line at the Clark Junction

The approach time for northbound Red Line service is defined in the same way as the approach time for the northbound Brown Line service. The interlocking time for the Red Line trains is the elapsed time from the train entering track circuit 13T to the time that the rear of the train enters 3T. Similar to the northbound Brown Line trains, the Red Line trains enter the interlocking accelerating to the permissible speed. The interlocking time is estimated to be 52 seconds. The route-release time is measured as the elapsed time from the rear of the train exiting the interlocking at circuit track 11T to the time when the rear of the train clears track circuit 3T, which is 15 seconds.

The capacity of this crossing for different train combinations is shown in Table 4-8. The cycle time for a one-to-one train combination is 156 seconds. Thus 23 cycles can take place in an hour for a theoretical capacity of 46 trains per hour. The practical capacity will be roughly 31 trains per hour. Currently the operating plan has a similar number of train movements on the Red Line and Brown Line services in the northbound direction during peak periods. At 31 trains per hour with a one-to-one ratio the minimum headway for the service lines would be 4 minutes.

Train Combinations per Cycle	1 NB Brown Line : 1 NB Red Line	2 NB Brown Line : 1 NB Red Line	1 NB Brown Line : 2 NB Red Line	3 NB Brown Line : 2 NB Red Line
Cycle Time (secs)	156	230	258	406
Trains per cycle	2	3	3	5
Theoretical Capacity (tph)	46	46	45	46
Practical Capacity (tph)	31	31	30	31

Table 4-8 Capacity at crossing of NB Red Line and NB Brown Line with different train combinations

For all the crossings with northbound Brown Line service the capacity of each will be determined by the one most utilized. During the evening peak period the most heavily utilized crossing is the one for northbound Red Line service and northbound Brown Line service. During the morning peak period, the most heavily utilized crossing is between southbound Red Line service and northbound Brown Line service.

The combination of trains at one crossing affects the combination at the other crossings because each of the crossings is used by the northbound Brown Line trains. Since the movement time of southbound Red Line trains is only 10 seconds longer than the movement time of a northbound Red Line train, the maximum number of northbound Red Line trains for a particular ratio of northbound Brown Line to northbound Red Line trains will be same as the maximum number of permitted southbound Red Line trains. Therefore, if there are 15 northbound Brown Line trains and 15 northbound Red Line trains programmed through the crossing of tracks NM3 and RV2, then there can be as many as 15 southbound Red Line trains programmed at the crossing between tracks NM2 and RV2 for the same period of time. Therefore, the junction can process as many as 45 trains (Red Line and northbound Brown Line). If we consider that the ratio of northbound Brown Line to northbound Purple Line trains is 2-to-1 at tracks NM4, then there will be 7 additional trains on the northbound direction. This means that 52 trains can be processed at the junction including northbound Purple and Brown Line trains and all Red Line trains.

At this point the effect of the Belmont station on junction capacity has not been introduced. The effects of the Belmont station on the throughput of trains at the junction will be studied in the next chapter.

4.5 New Configuration

This research coincides with a capital investment project that the Chicago Transit Authority is making to rehabilitate and reconfigure the Clark Junction. At the current time, the new configuration is close to 100% design, however there is still a window of opportunity to provide input on the new configuration design, which the agency can consider in approving the final design. The 95% design of the new configuration is shown in Figure 4-4.

The rehabilitation project will renew the current infrastructure including the existing steel structures, the ties and rails, the circuitry, the signals and the stations. The new infrastructure will allow operating speeds through the junction of 25 mph and 35 mph, compared with the actual 15 mph operating speeds. Most notably, the new configuration retains the main tracks and turnouts from the existing configuration, while the rest of the interlockings are replaced with a symmetrical configuration of 3 double crossovers.

4.5.1 Tracks and crossovers

Based on the new double crossovers, there are the same number of points on tracks NM1 and NM4, and one additional point in both tracks NM2 and NM3. The additional points on the inner tracks permit additional routing flexibility, such that a train approaching the junction from the Ravenswood tracks could be routed to track NM3. There is a symmetrical set of interlockings south of Belmont, permitting additional flexibility in the operation.

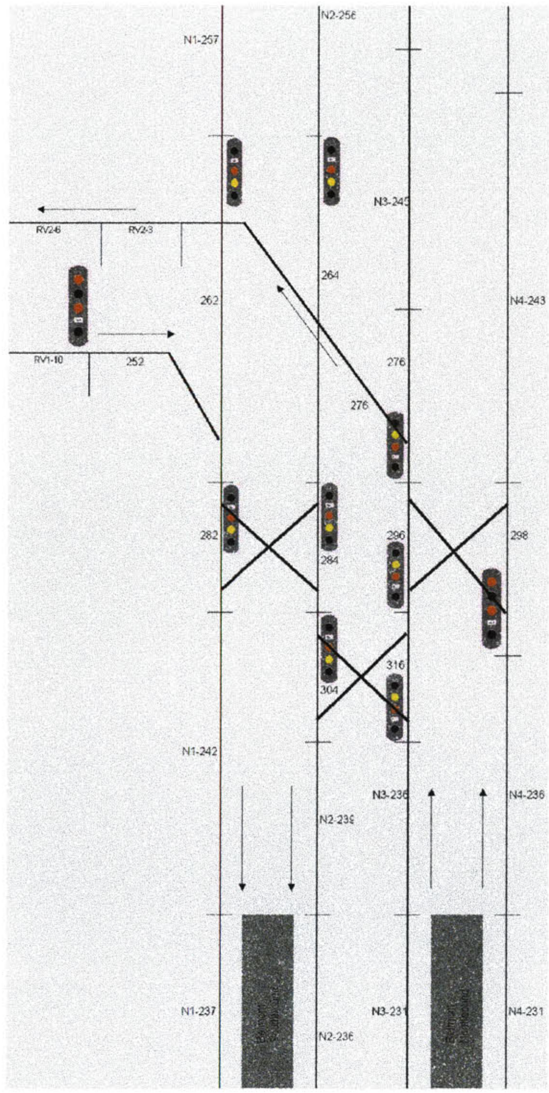


Figure 4-4 Proposed new Clark Junction configuration, 95% design (not to scale)

The turnout tracks remain in the same location, permitting the same operating flexibility that the junction currently exhibits when routing diverging trains. Under this design, trains approaching from the Ravenswood tracks can be routed onto tracks NM1, NM2 or NM3. Trains approaching southbound on track NM2 could be routed into either track NM1 or NM3, unlike the current design that permits a route to NM1 but not to NM3.

In the proposed design, track NM3 has all routing options available; thus, northbound trains can be routed into any of the other tracks, including both Ravenswood turnout tracks.

4.5.2 Signal and block design

The added routing flexibility does not change the distance between the junction and Belmont station. In this configuration the Belmont station continues to act as the northbound entry point to the junction on track NM3, and also acts as the exit from the junction for tracks NM1 and NM2.

Even though the distance separating Belmont station from the Clark Junction is not sufficient to treat them as entirely independent nodes, the train movements at the junction and at Belmont station can be designed to minimize their interdependence.

Considering southbound movements on track NM1, under the current routing scheme, the merging point is the source of conflict between southbound Purple and Brown Line service. The southbound Purple Line service also has a crossing point with the turnout track RV2. Having two conflict points, a Purple Line train progression could be segmented into the junction movement and the Belmont station approach. The junction movement would be defined as the train progression through the conflict points, and the Belmont approach defined as the train progression between the merging point exit and the entrance to the Belmont station. According to the proposed design, the home signal for the Belmont station is signal 282, which also controls the interlocking connecting blocks 282 and 284. This design has the entrance of the junction also acting as the entrance to Belmont station. This could be improved by providing a home signal at Belmont station within 250 feet of the start of the Belmont station block. At a train operating speed of 25 mph the block would be long enough for a train to brake safely in emergency mode if it violates the signal. This would effectively separate the train movement in the junction from the Belmont station approach because an 8-car train could stage its approach to Belmont station in the junction while a diverging train movement to the Ravenswood track RV2 could occur simultaneously.

Considering now the southbound train movements on track NM2, under the proposed new configuration, train movements will take place following the same discipline as currently, but at higher speeds. Under the current configuration the home signal for the junction acts informally as the home signal for the Belmont station, because trains are not allowed to stage for Belmont station at its formal home signal. The block lengths are not long enough to allow an 8-car train to stage before the Belmont station without blocking the turnout track RV2. This issue is not resolved in the new design. However, the displacement of the double crossover between tracks NM2 and NM3 can provide a feasible solution to this problem without compromising the flexibility of the routing alternatives. If the double crossover is located immediately north of the Belmont station blocks, then there would be 463 feet available for an 8-car train to stage for service at Belmont station without blocking the crossing with turnout track RV2. Figure 4-5 shows the alterations which would permit independent operation of the junction and the Belmont station approach without a significant redesign.

Under the new configuration the possibility of having a partial line-up for northbound service on track NM3 can be explored, especially with the proposed changes to the new configuration. This alternative is possible because blocks 316 and N3-236 are sufficiently long to permit an 8-car train to stage after the entire train has exited Belmont station.

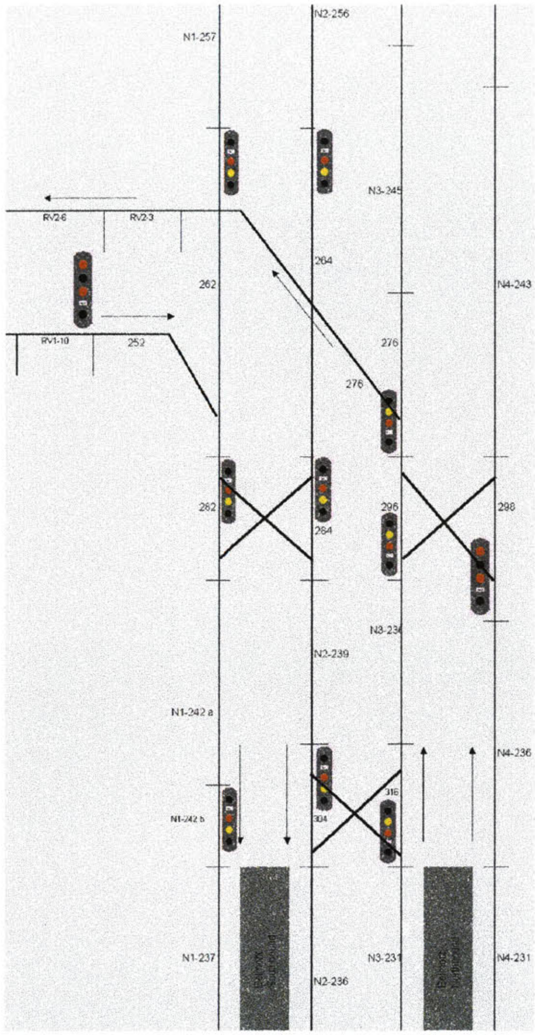


Figure 4-5 Proposed changes to new configuration

4.6 Summary

This chapter introduced the Clark Junction as the case for the junction performance and capacity analysis, which will be presented in Chapters 5 and 6. The problems associated with the infrastructure have been identified and some alternatives have been presented to solve these issues within the current configuration. The capacity of the junction has been determined for the crossings and merging points and has been found to be close to 30 trains per hour at the crossings and 34 trains per hour at the merge point. The new configuration was also presented under the 95% design. Several problems were identified where the new configuration does not solve some of the routing concerns experienced with the current configuration. Some suggestions were presented to allow the core train movement processes at the junction to be separated from the train approaches and processes at Belmont.

Chapter 5 Southbound Performance

This chapter discusses the results found from the analysis of southbound operations at the Clark Junction, starting with congestion analysis. The track circuit occupancy data collected in the SCADA database will be used to determine queue length and estimate delays. An example of queue lengths and delays for a congested AM peak period is presented. Multiple-movement time-space diagrams are used to illustrate the train progressions in the example and to identify cases where the cross-platform transfers take place at Belmont. Findings are presented on the delays that take place at the junction during the AM peak period. Capacity is determined for the merging point between southbound Brown Line and Purple Line service. Recommendations are developed for routing practices at Clark Junction to control arrivals at Belmont station.

Southbound service has the heaviest traffic during the morning peak period, with the majority of the riders heading to the loop as their destination, or making transfers downtown to other rail or bus lines. The merge point between Brown Line service and Purple Line service is thus a focal point of the congestion analysis, and the train and passenger activity at Belmont station will be shown to constrain the merge point capacity. Figure 5-1 shows the track circuits in the vicinity of the Clark Junction and Belmont station.

5.1 Congestion analysis

Congestion at the merge point can develop when the arrivals from tracks NM1 and RV1 are not effectively sequenced. The first arriving train will move through the junction and into Belmont station while the second train will have to wait for the first train to enter Belmont station before proceeding. Since Belmont station is a high activity node, the tower operator has two alternatives for the second train arriving at the junction:

1) the train can be held at the entrance of the junction, or

2) the train can move into the junction as far as the automatic train protection will permit (to track circuit A9T).

If the tower operator decides on the first alternative, then Belmont station will act as the exit point for the junction, so the second train's waiting time at the entrance of the junction will include the first train's dwell time at Belmont station. The movement time through the junction then includes track circuit 15T, which is immediately north of Belmont station. If the tower operator selects the second alternative, then the movement time of the second train through the junction will be influenced by the dwell time of the first train at Belmont station. The additional train movement time at the junction when trains hold at the entrance of it is greater than the additional train movement time from trains that move as far into the junction as possible, because the trains that move into the junction have minimum waiting times which outweighs the additional movement time of trains holding at the entrance. Regardless of the tower operator's decision though, the dwell time process at Belmont station will always affect the merge point capacity.

The decision of the tower operator also affects the formation of queues and the ability to detect these from the available data. When the tower operator decides on the second alternative, the congestion at the junction will be reflected through the queueing formation just upstream of Belmont station.

Any queueing takes place mainly at the Ravenswood branch because there is an operation policy that gives southbound Purple Line routing priority at the merge point when there are simultaneous arrivals at the junction of southbound Brown Line and Purple Line trains. Further, the high frequency of service on the Brown Line, with 3-minute headways, in comparison to the 7.5-minute headway on the Purple Line creates much greater likelihood of queues propagating on the Ravenswood branch than queues on the North Main tracks. Finally, the visual restrictions at the Clark Junction tower to the Ravenswood branch and the lack of complete information on the control panel do not allow the tower operator to know the queue length for Brown Line trains.

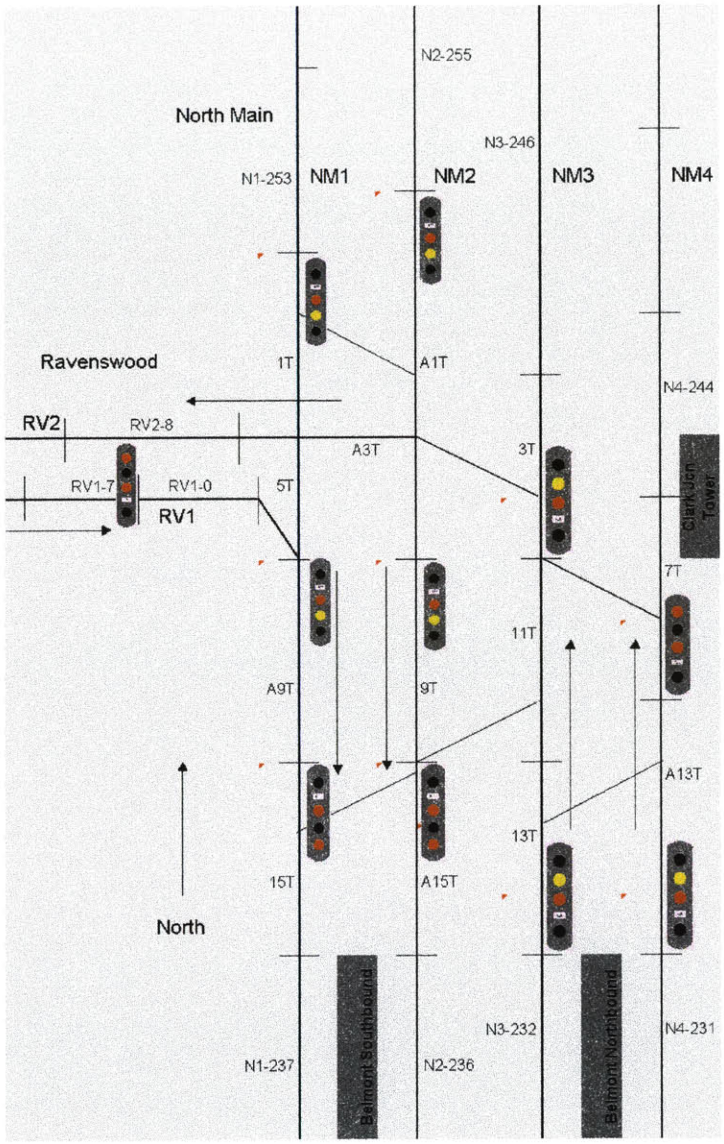


Figure 5-1 Clark Junction track circuits (not to scale)

The congestion relationships introduced in Chapter 3 are now estimated through manipulation of the track circuit occupancy data based on:

1. Movement time for train *i* between track circuits RV1-7 (entrance of junction for Brown Line) and N1-237 (Belmont station).
2. Reoccupancy time at N1-237 between trains *i*, and *i+1*.
3. Occupancy time of train *i* at circuit RV1-7.
4. Utilization rate of train *i* at circuit RV1-7.
5. Reoccupancy time at RV1-7 between train *i* and train *i+1*.

6. Run time between track circuit RV1-77 at Addison station (not shown in Figure 5-1) and RV1-7 for train *i+1*.

A strong relationship is identified between queueing at track circuit A9T and the levels of train activity at Belmont station. Specifically, when trains queue at track circuit A9T, the reoccupancy time at Belmont track circuit N1-237 is very short, and as a result the utilization rate at track circuit N1-237 approaches 0.9. As a result of the queuing at A9T, the movement time for trains between the entrance of Clark Junction (track circuit RV1-7) and Belmont station (track circuit N1-237) increases. Figure 5-2 shows the relationship between movement times through the interlocking and the utilization rate at Belmont from July 15, 2002 to August 16, 2002 between 6:30 AM and 9:00 AM.

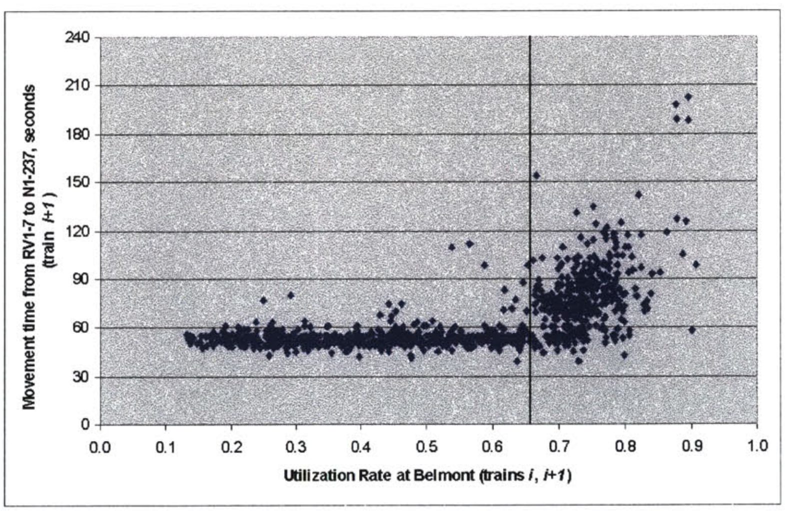


Figure 5-2 Movement time from the entrance of the junction to Belmont versus utilization rate at Belmont July 15, 2002 to August 16, 2002 7:00 to 9:00 hrs

Not surprisingly, Figure 5-2 shows a dramatic increase in movement times when the utilization rate at Belmont station is above 0.66. This finding is consistent with prior rail capacity studies by Martland (1997, 2003), where he found that delays in most rail queueing system increase rapidly as the utilization of the system exceeds 0.7.

The relationship between reoccupancy time at the exit of the junction and the utilization rate at this point was found to be strong as expected. Figure 5-3 shows the reoccupancy times between consecutive trains at the Belmont circuit as a function of the levels of traffic. The minimum reoccupancy at the Belmont circuit is determined from Figure 5-3, as just under 30 seconds. This minimum reoccupancy time is the train protection threshold by having a one-block minimum separation between consecutive trains. The resulting range (25-60 seconds) at high utilization reflects variable reaction times of train operators and the tower operator in the final leg of the junction clearance.

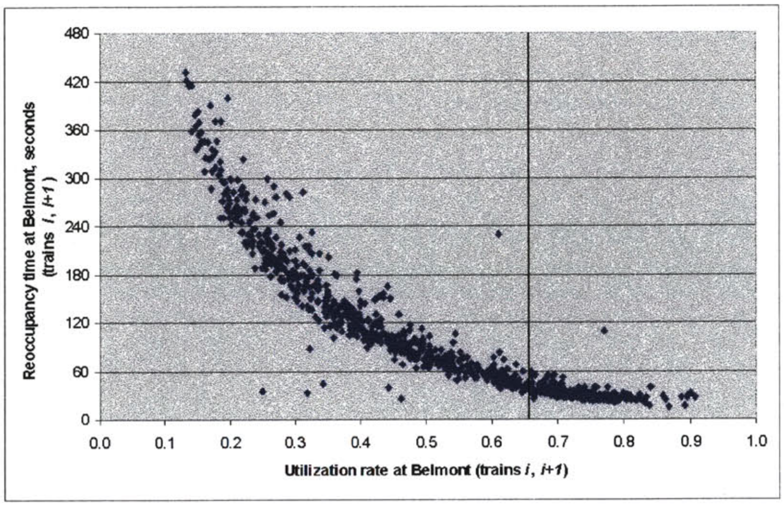


Figure 5-3 Reoccupancy time versus utilization rate at N1-237 July 15, 2002 to August 16, 2002 7:00 to 9:00 hrs

5.2 Queueing and delay estimation

As expected from the background research, the congestion at the junction – which is reflected in congestion approaching Belmont station – begins to generate delays and queues when the congestion levels approach 70% of the theoretical maximum.

Assuming that all Brown Line trains form a queue for service at Belmont at track circuit A9T, queue lengths of at least one train can be detected when the following conditions are met:

1) high movement times for a train between track circuits RV1-7 and N1-237, and

2) low reoccupancy time at track circuit N1-237 that is determined by the arrival of the queued train.

A high movement time between track circuits RV1-7 and N1-237 indicates that the train has queued somewhere between these circuits, which under the current operation policy is at track circuit A9T. Based on the reoccupancy time plot in Figure 5-3, the delay parameters establish an upper bound for reoccupancy time at Belmont of 60 seconds.

The movement time delay parameter is set at 35 seconds based on the mode of the movement time distribution between RV1-7 and N1-237, shown in Figure 5-4. The parameter for the reoccupancy time at Belmont is determined such that the trains have had to queue at A9T. The final condition that must be met for the one-train queue is that the queued train must be at circuit A9T while the leading train is at the Belmont station. This condition can be checked using the SCADA data. A train will have entered the junction while there is a train occupying the Belmont track circuit.

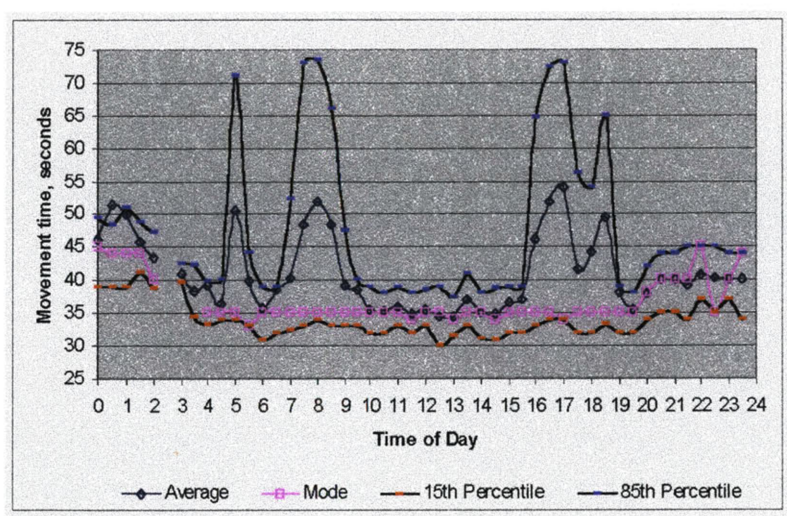


Figure 5-4 Movement time between RV1-7 and N1-237 July 15, 2002 to August 16, 2002

Two-train queues where a Brown Line train is the second train in the queue can happen in two ways:

- Brown Line train queued at A9T followed by a Brown Line train queued at RV1-7, or

- Purple Line train queued at A9T followed by a Brown Line train queued at RV1-7.

When determining queues of at least two trains where a Brown Line train is the second train in the queue, the main condition to be satisfied is a high occupancy at track circuit RV1-7. Figure 5-5 shows the distribution of occupancies at track circuit RV1-7 used to determine the delay parameters. An uninterrupted movement through the circuit usually takes about 55 seconds to complete. In the analysis, any occupancy above 60 seconds will be used as an indication that a train has queued at track circuit RV1-7. In addition, the second train has to be queued while the first train is at A9T and the leading train is at the Belmont station. These queueing conditions have to be met along with the conditions for a one-train queue.

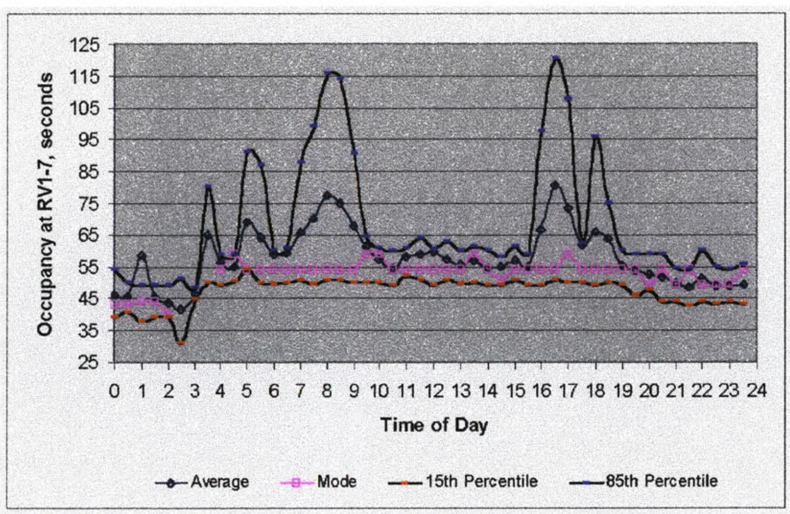


Figure 5-5 Occupancy distribution at track circuit RV1-7 July 15, 2002 to August 16, 2002

There are two ways in which a three-train queue forms and a Brown Line train is last in the queue:

- Trains are queued at track circuits A9T, RV1-7, and an upstream circuit from RV1-7. The sequence can be either Brown – Brown – Brown, or it can be Purple – Brown – Brown.

- Having trains queued at track circuits A9T, RV1-7, and N1-253. The sequence of trains would be Brown – Purple - Brown.

The delays stemming from the arrangement in the second bullet point can be determined with the conditions that satisfy queues of at least two trains, as presented thus far. Hence, it is of interest to identify instances of the first arrangement, where a queue forms upstream from track circuit RV1-7.

The conditions that will be met when train $i+3$ is queued at a point upstream from RV1-7 are:

1) low reoccupancy time at track circuit RV1-7 generated by trains $i+3$ and $i+2$,
2) high run time between the Addison station track circuit RV1-77 and track circuit RV1-7 for train $i+3$,
3) train $i+2$ being at RV1-7 while train $i+1$ is at A9T and train i is at Belmont station, and
4) the conditions for a two train queue being satisfied for train $i+2$ and $i+3$.

To satisfy condition #2 it is required to consider the delay parameter as dynamic because the dwell time activity and run time at intermediate stations are a function of demand patterns which vary over time. The delay parameter for the run time between track circuits RV1-77 and RV1-7 is determined by the distribution of run times shown in Figure 5-6. An uninterrupted run time of about 180 seconds is the lower bound on run times throughout most of the day. During AM peak period service however, the run time is inherently higher due to increased dwell times at intermediate stations. From 7:00 to 7:30 it is 185 seconds, from 7:30 to 8:00 is 190 seconds, from 8:00 to 8:30 it is about 195 seconds, and from 8:30 to 9:00 it is 185 seconds.

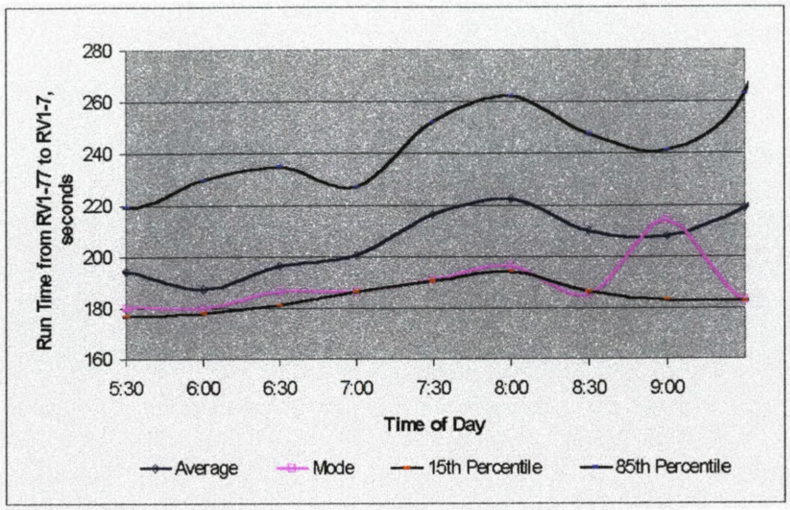


Figure 5-6 Run time distribution between RV1-77 and RV1-7 July 15, 2002 to August 16, 2002

When longer queues form on the Ravenswood tracks, the last train in the queue will be held at Southport station, since there is queueing room for only two trains between Southport and the junction. In this case, the occupancy at Southport station will be higher than normal. However, the SCADA data set that is studied does not include track circuit activity for Southport station and so it is not possible to determine longer queue lengths.

These queueing and delay estimates are based on the treatment of Belmont station as the exit point of the junction. Therefore if the tower operator decides to hold the trains at the entrance of the junction, instead of within the junction, the queueing conditions and delay parameters will be different from the ones presented. For instance, reoccupancy times at Belmont will have a lower bound higher than 35 seconds and will generally be higher, as shown in Figure 5-7. Occupancy times and reoccupancy times at the entrance of the junction will have the same parameters as the current delay parameters for queues of two or more trains.

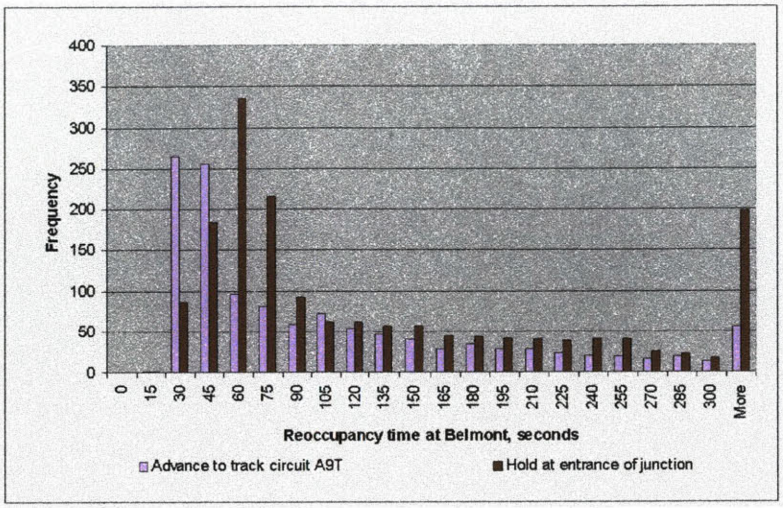


Figure 5-7 Reoccupancy time histograms for queueing policies at Belmont

The following tables present an example of a queue in formation. The trains listed in Table 5-1 are numbered consistently with Figure 5-8. There are three tables, one for each track circuit. The first table presents circuit and train related events at the Addison circuit (RV1-77), at an upstream point from the junction on the Ravenswood tracks. The second table shows the information derived from the events that are recorded at the entrance of the junction on the Ravenswood branch (track circuit RV1-7). The third table shows circuit related information for the Belmont station (track circuit N1-237). In the third table, the last column *Queue Length*, shows the lengths of queues when the trains arrive for service approaching Belmont station. The next to last column, total delay, shows the amount of time that each train spent in the queue **as a result of the activity at Belmont**.

The example in Table 5-1 is for the 8:00 AM to 9:00 AM peak period on a single day. During this time there are 16 Brown Line trains served at the junction, 13 of which experience queueing delays.

Table 5-1 Brown Line delays July 17, 2002 8:00 to 9:00 AM

RV1-77 Addison

Train	Reoccupancy (s)	ON	OFF	Occupancy (s)	Headway (min)	Utilization Rate	Running Time (s)	Delay to RV1-7 (s)
1	133	7:59:22	8:00:02	40	3.0	0.2	183	0
2	191	8:03:13	8:06:44	211	3.8	0.8	**220**	25
3	64	8:07:48	8:08:35	47	4.6	0.4	**238**	43
4	64	8:09:39	8:10:19	40	1.8	0.3	**348**	153
5	92	8:11:51	8:12:38	47	2.2	0.4	**301**	106
6	75	8:13:53	8:14:39	46	2.0	0.1	**297**	102
7	269	8:19:08	8:19:55	47	5.3	0.3	**247**	52
8	123	8:21:58	8:22:40	42	2.8	0.1	**233**	38
9	255	8:26:55	8:27:47	52	4.9	0.5	**240**	45
10	52	8:28:39	8:29:26	47	1.7	0.4	**408**	213
11	85	8:30:51	8:31:32	41	2.2	0.1	**386**	201
12	318	8:36:50	8:37:36	46	6.0	0.3	**209**	24
13	99	8:39:15	8:40:01	46	2.4	0.2	**191**	6
14	182	8:43:03	8:43:45	42	3.8	0.2	**255**	70
15	229	8:47:34	8:48:13	39	4.5	0.1	182	0
16	343	8:53:56	8:54:41	45	6.4	0.1	185	0

RV1-7 Clark Junction Entry Point

Train	Reoccupancy (s)	ON	OFF	Occupancy (s)	Delay at RV1-7 (s)	Headway (min)	Utilization Rate	Running Time (s)	Δ Reoccupancy	Delay at RV1-7 (s)
1	93	8:03:05	8:05:56	**171**	111	2.5	0.4	**77**	-40	42
2	268	8:10:24	8:11:57	**93**	33	7.3	0.7	**57**	77	22
3	**36**	8:12:33	8:15:44	**191**	131	2.1	0.9	33	-28	0
4	**23**	8:16:07	8:17:15	**68**	8	3.6	0.7	**55**	-41	20
5	**24**	8:17:39	8:19:17	**98**	38	1.5	0.8	34	-68	0
6	**19**	8:19:36	8:20:41	**65**	5	1.9	0.2	**61**	-56	26
7	201	8:24:02	8:26:14	**132**	72	4.4	0.9	**35**	-68	0
8	**19**	8:26:33	8:30:21	**228**	168	2.5	0.7	**77**	-104	42
9	86	8:31:47	8:35:47	**240**	180	5.2	0.9	**93**	-169	58
10	**27**	8:36:14	8:37:02	48	0	4.4	0.5	**141**	-25	106
11	**56**	8:37:58	8:39:55	**117**	57	1.7	0.6	**75**	-29	40
12	70	8:41:05	8:42:01	56	0	3.1	0.4	**62**	-248	27
13	71	8:43:12	8:47:17	**245**	185	2.1	0.9	**56**	-28	21
14	**43**	8:48:00	8:49:16	**76**	16	4.8	0.4	**53**	-139	18
15	119	8:51:15	8:52:10	55	0	3.2	0.1	**37**	-110	2
16	336	8:57:46	8:58:39	53	0	6.5	0.1	33	-7	0

N1-237 Belmont

Train	Reoccupancy (s)	ON	OFF	Occupancy (s)	Headway (min)	Utilization Rate	Δ Reoccupancy	Total Delay (s)	Queue Length
1	63	8:07:13	8:08:31	78	1.7	0.3	-30	153	2
PL	**29**	8:11:18	8:12:28	70	4.1	**0.7**			1
2	**26**	8:12:54	8:14:28	94	1.6	0.5	-242	55	1
3	109	8:16:17	8:17:44	87	3.4	**0.8**	73	131	1
4	**26**	8:18:10	8:19:17	67	1.9	0.7	3	28	1
5	**34**	8:19:51	8:21:07	76	1.7	0.7	10	38	1
6	**35**	8:21:42	8:22:59	77	1.9	0.3	16	26	1
7	230	8:26:49	8:28:18	89	5.1	0.6	29		
PL	**29**	8:29:15	8:31:09	114	2.4	**0.8**			1
8	**29**	8:31:38	8:34:29	171	2.4	**0.9**	10	210	2
PL	**29**	8:34:57	8:36:49	112	3.3	**0.8**			1
9	**31**	8:37:20	8:38:55	95	2.4	**0.8**	-55	238	2
10	**28**	8:39:23	8:40:42	79	2.0	**0.7**	1	319	3
11	**28**	8:41:10	8:42:34	84	1.8	**0.7**	-28	298	3
12	**29**	8:43:03	8:45:27	144	1.9	**0.7**	-41	27	1
PL	**29**	8:46:28	8:47:38	70	3.4	0.7			1
13	**35**	8:48:13	8:49:30	77	1.8	0.7	-36	206	2
14	**39**	8:50:09	8:51:19	70	1.9	0.4	-4	104	3
15	88	8:52:47	8:54:12	85	2.6	0.3	-31		
PL	**29**	8:57:11	8:58:28	77	4.4	0.6			
16	**44**	8:59:12	9:00:35	83	2.0	0.3	-292		

Consider train 13. This train entered as the second train in the queue and is delayed 206 seconds. This train arrives at the entrance to Clark Junction without exhibiting conditions of a queued train. While this train is at track circuit RV1-7 there is a train at Belmont. The indicators of high occupancy at RV1-7 (245 seconds) due to prioritization of the Purple Line train, and occupying RV1-7 while there was a train at Belmont will indicate to us that the train was either first or second at the queue. The high run time from RV1-7 to N1-237 (56 seconds), coupled with the low reoccupancy time at Belmont (35 seconds) indicates that the train advanced in the queue to a position at track circuit A9T.

There are also trains queueing at the entrance of the junction that could form the queue at track circuit A9T. Careful study of the data reveals that train 3 queued at the entrance of Clark Junction, indicated by the occupancy at track circuit RV1-7 while train 2 is at Belmont. Even though the reoccupancy time at Belmont is not under the 60 seconds upper threshold, the train exhibits the queueing conditions. From the data it is not possible to determine the reason why the train was not advanced to track circuit A9T. In this case, the delay cannot be attributed to the processing of train 2 at Belmont station. This case cannot be detected with the method proposed because it violates one of the assumptions made which was based on normal operation policies.

It can be seen from this example that the delays generated in the system are generally the result of the activity at Belmont station. Though most of the queues are forming at the entrance of the Belmont station, there are a few forming at the entrance of the junction. The queue propagation reaches the entrance of the junction for queues of more than one train. When a Purple Line train is routed between consecutive Brown Line trains, the Brown Line train will have to start the queue at the entrance of the junction if the Purple Line train has not entered Belmont station.

5.3 Visualization

Table 5-1 presents in tabular form how delays were determined and synthesized, and Figure 5-8 shows a basic time-space diagram as it applies to the same day.

Much information can be derived from the time-space diagram in Figure 5-8, including occupancies, reoccupancies, delays, and run time, which are all identified in the figure. The delays can be determined from careful observation of the slopes and train positions at a given time. For example, in Figure 5-8 Brown Line train 9 is seen to be the second train of a two-train queue. Brown Line train 8 is at Belmont station when train 9 arrives at the junction, but a Purple Line train is given priority. The resulting queueing delay of train 9 is calculated as 278 seconds, as shown in Table 5-1. Most of this delay is incurred while waiting at the entrance of the junction. The extent of this delay generates further delays upstream, such that train 10 has to queue before the junction entrance, as does train 11. Each of these two trains enters the queue as the third train in the queue.

Once the delays have been identified, it is of interest to know what alternatives, if any, were available to the tower operator, and whether the tower operator made the best possible decision. In addition, it is not known from Figure 5-8 or Table 5-1 whether cross-platform transfers affected the dwell time of train 8 at Belmont station, or if the Purple Line trains were also held at the entrance of the junction.

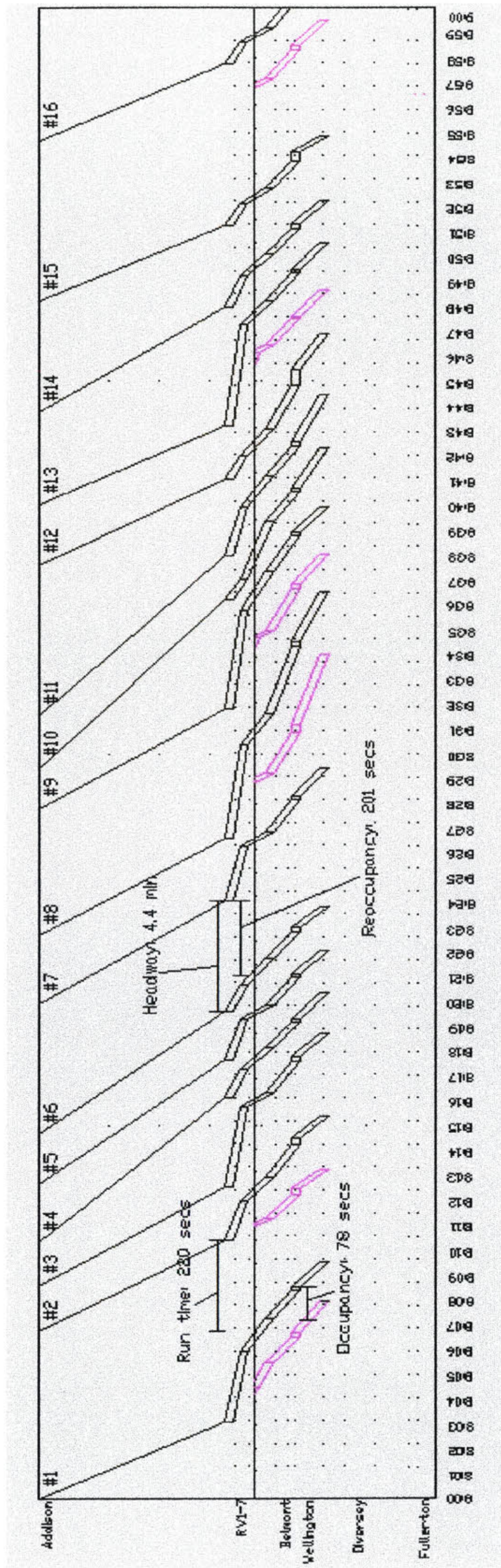


Figure 5-8 Time space diagram for Table 5-1 July 17, 2002 8:00 to 9:00 AM

To help understand these interactions, Figure 5-9 shows a multiple-movement time-space diagram for the same morning peak period. This diagram shows all the trains that were berthed at the Belmont station simultaneously with southbound Red Line trains. The bottom row of the chart shows a block occupancy diagram with the train occupancies at the Belmont track circuits of tracks NM1 and NM2. When there are simultaneous occupancies at Belmont for tracks NM1 and NM2 then cross-platform transfers take place. The Brown Line trains that had cross-platform transfers with the Red Line trains were 2, 3, 4, 6, 8, 10, 12, 13, 15 and 16. Three of the five Purple Line trains routed between the Brown Line trains also had cross-platform transfers.

A closer look into what happened to the progressions of trains 7 through 11 reveals that the long queues and propagation of delays are due to a series of decisions where a combination of short Purple Line headways coupled with high dwell times at Belmont station that are produced by paired arrivals at the station with Red Line trains, generate queues on the Ravenswood tracks.

There are various conclusions that can be drawn from this example. First, the queue length conditions provide a useful way to understand queuing and cumulative delays for a train movement or a series of train movements. Second, the queueing process starts downstream of the merge point and propagates back to the merge point and often, beyond it. Third, as expected the length of the queue determines the extent of total queueing delay for a train.

This example reveals an average delay of 51 seconds for trains that enter as the first trains in the queue, an average delay of 202 seconds for trains that enter as the second train in the queue, and about 240 seconds on average for trains that enter as the third train in the queue.

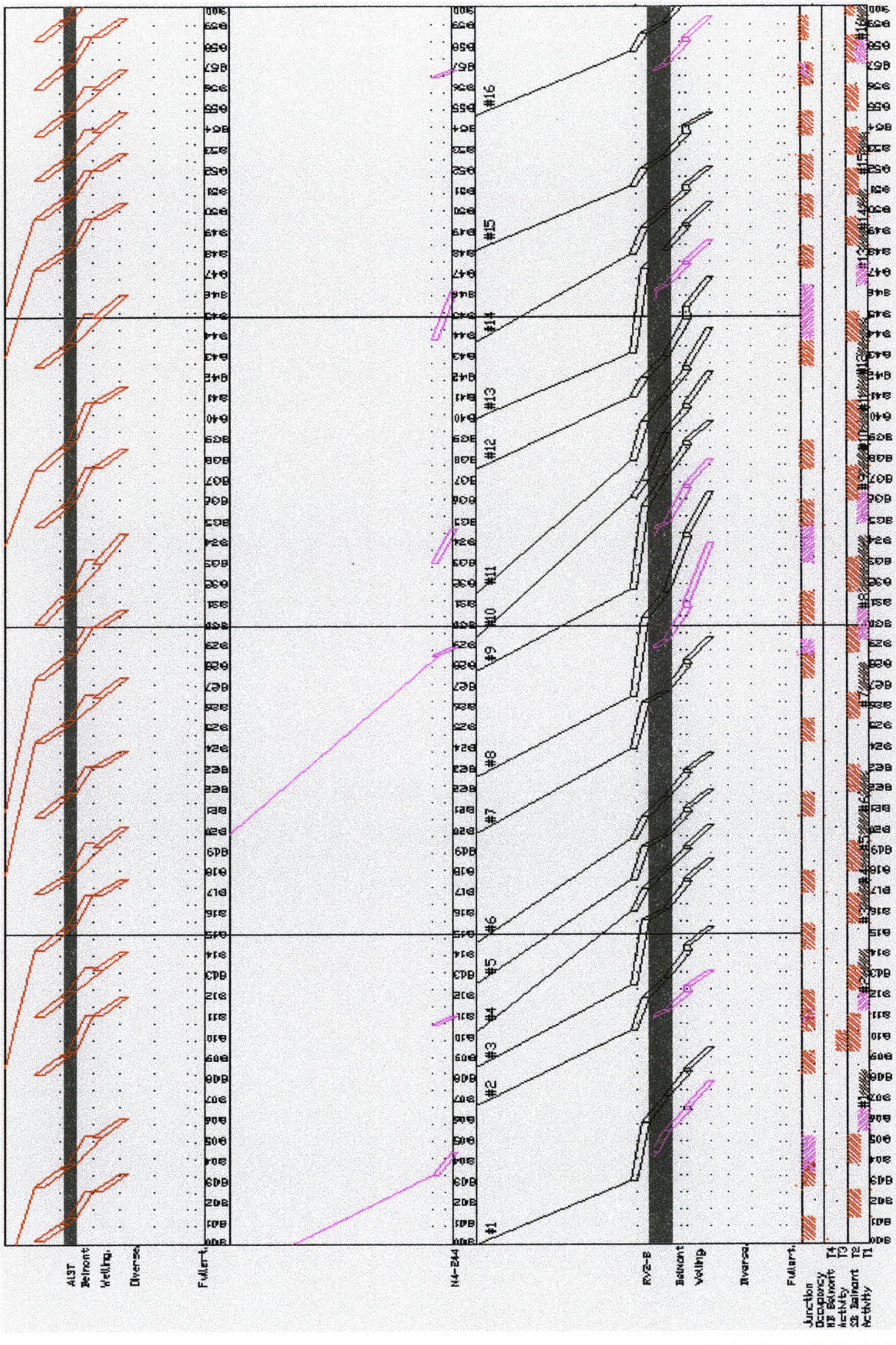


Figure 5-9 Multiple-movement time-space diagram for Table 5-1 July 17, 2002 8:00 to 9:00 AM

5.4 Delays

Summary of delays, queue lengths, and average delays in the AM peak period is shown in Table 5-2 for weekdays between July 15, 2002 and August 16, 2002. Between 7:00 AM and 9:00 AM, an average of 43 trains run in the system (22 per hour), 7 of which are delayed roughly half a minute, 5 are delayed for about 84 seconds and there is 1 incidence of a train forming a three-train queue and experiencing an average of 2 minutes of delay. Further, there are on average 6 Purple Line trains queueing at circuit A9T.

As seen from the table, the average delay for Brown Line service during the morning peak period when all train movements are accounted for is about 12.5 minutes. These 12.5 minutes are lost productivity on the Brown Line service resulting from operating at the current levels and having the service at Belmont station generating queues.

Queue Length	Incidence	Total Delay (minutes)	Average Daily Incidence	Average Daily Delay (minutes)	Average Delay per train (seconds)
			All trains		
No queue	**607**	---	**24**	---	---
			Brown Line		
1-train queue	**186**	**90**	**7**	**3.4**	**29**
2-train queue	**113**	**158**	**5**	**7**	**84**
3-train queue	**36**	**76**	**1**	**2.1**	**127**
			Purple Line		
1-train queue	**149**	---	**6**	---	---

Table 5-2 Summary of queueing incidence form July 15, 2002 to August 16, 2002 7:00 to 9:00 AM

In this analysis, queues of more than three trains were not determined because of the lack of proper data to determine queueing relationships for a fourth Brown Line train in a queue. It unlikely, though, that these queueing lengths happen at least once for every AM peak period, considering that queues of three trains happen only once per AM peak period.

5.5 Capacity

In this section we review capacity for the southbound merge of Brown and Purple Line service, in section 4.4.1, to estimate how close to the practical capacity are the current operations, and how the current delays in the Brown Line service, determined in the previous section, indicate proximity to the practical capacity.

Movement time (seconds)	SB Brown Line	SB Purple Line
$t_{approach}$	11	33
$t_{interlocking}$	33	42
$t_{release}$	13	13
Total Time	57	88

Table 5-3 Train movement times at merge point

Table 5-3 shows the train movement time components. Assuming a two-to-one ratio of Brown Line trains to Purple Line trains, which is close to what the actual headways suggest, the cycle time for the three-train movements would be (57 + 57 + 88 =) 202 seconds. This leads to a theoretical capacity of 17.8 hourly cycles with a practical capacity of about 12 cycles. Thus, about 24 Brown Line trains per hour and 12 Purple Line trains per hour can be routed for a practical capacity of 36 trains.

This practical capacity (36 tph) is far greater than the actual throughput (22 tph) which is clear evidence that **the capacity at the merge point is not binding**. The delays experienced in the system, however, lead to the conclusion that the operations at Belmont station are near capacity.

5.6 Recommendations

The following recommendations are based on dwell time control at Belmont station that might be achieved by modifying tower operation policies. It has been shown that the dwell time activity at Belmont station affects the duration of the movement times at the junction, and as a result of queueing propagation it can restrict the throughput at the junction. At best, it would be useful to examine the cross-platform transfers at Belmont station and suggest operation policies to manipulate the arrivals at Belmont station so as to reduce dwell times on the southbound Brown Line and Purple Line service.

Cross-platform transfers can lead to high dwell times at Belmont station. Most of the Brown Line and Purple Line trains, though, do not experience cross-platform transfers with Red Line trains. Figure 5-10 shows the probability density functions of trains that do and do not experience cross-platform transfers. Clearly, trains that do not experience transfers have dwell times between 20 and 50 seconds, whereas trains with cross-platform transfers may have dwell times as high as 80 seconds.

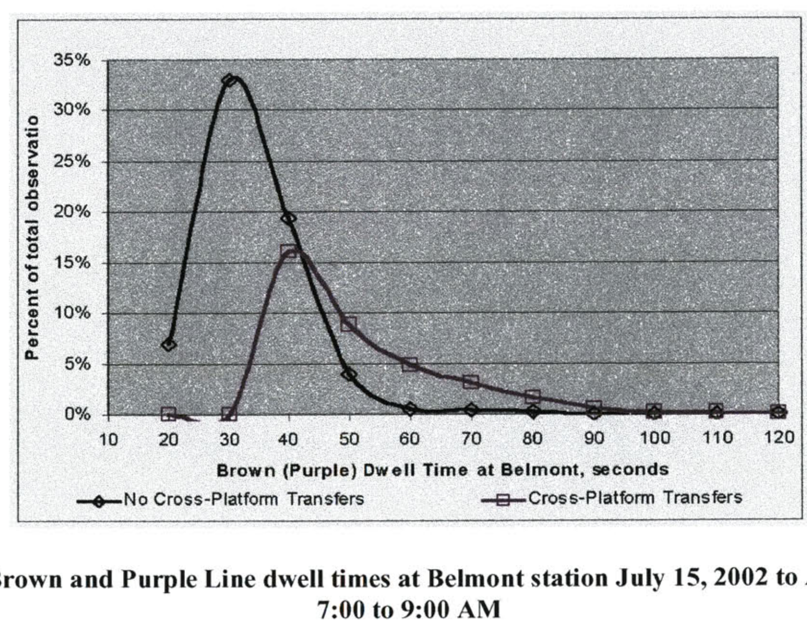


Figure 5-10 Brown and Purple Line dwell times at Belmont station July 15, 2002 to August 16, 2002 7:00 to 9:00 AM

Dwell times are most strongly affected when there are significant offsets between the arrival times of Brown (and Purple) Line trains and Red Line trains. In Figure 5-11, the highest dwell times are generated when the Brown (Purple) Line trains arrive more than 15 seconds before the Red Line trains. The other two series have similar characteristics, though the series where Red Line trains arrive at Belmont station almost simultaneously with Brown (Purple) Line trains is more frequent.

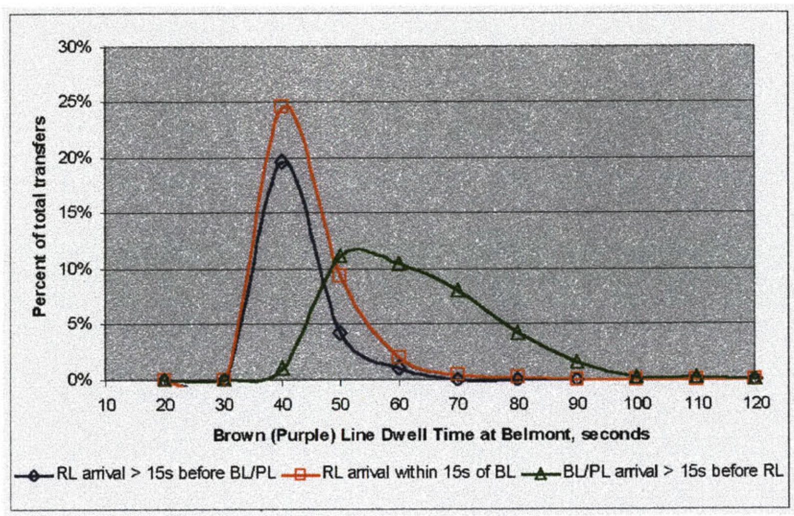


Figure 5-11 Brown and Purple Line dwell time probability density functions by arrival patterns at Belmont July 15, 2002 to August 16, 2002 7:00 to 9:00 AM

In practice, tower operators should aim to manage the routing process at the junction so as to allow Red Line trains to arrive at Belmont station simultaneously with Brown (Purple) Line trains. Figure 5-12 (based on Figure 5-10) presents a hypothetical distribution of dwell times based on the assumption that all cross-platform transfers can be controlled such that trains arrive simultaneously at the station.

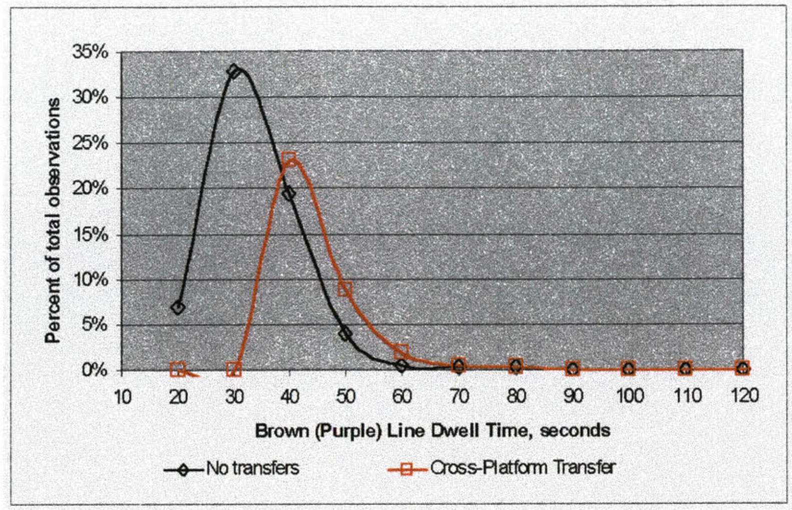


Figure 5-12 Brown and Purple Line dwell time probability density functions with proposed cross-platform control: simultaneous arrivals between Red Line and Brown and Purple Line

With this type of cross-platform transfer control, 82% of all trains would have dwell times under 40 seconds, compared to the 75% of trains that currently have dwell times under 40 seconds. This would mean having one or two additional trains with dwell times less than 40 seconds during the peak period.

The effects of this operating strategy can also benefit Red Line trains. Cross-platform transfers also generate longer dwell times for Red Line trains, compared to those trains that do not have transfers, as Figure 5-13 shows.

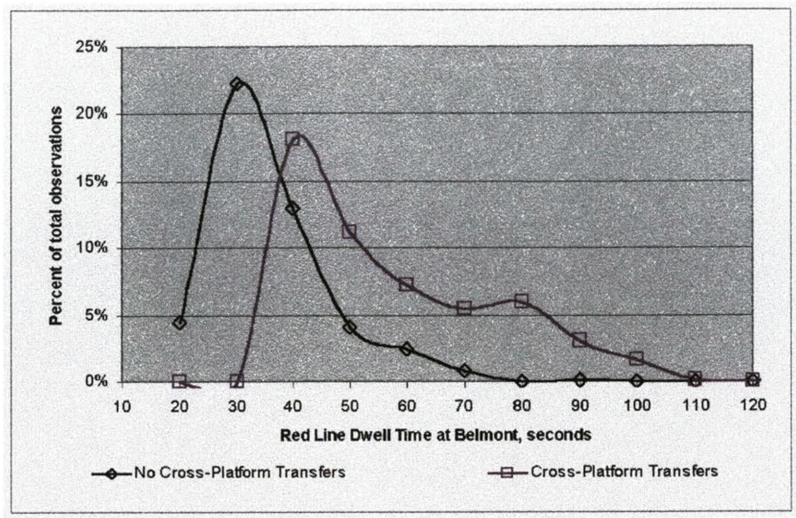


Figure 5-13 Red Line dwell time probability density functions by transfer conditions July 15, 2002 to August 16, 2002 7:00 to 9:00 hrs

Like the Brown and Purple Line trains, the Red Line trains experience the highest dwell times when they arrive at Belmont station more than 15 seconds before the other train arrives on the opposite side of the platform. Figure 5-14 shows the probability density functions of Red Line dwell times based on three different arrival patterns at Belmont station when cross-platform transfers take place.

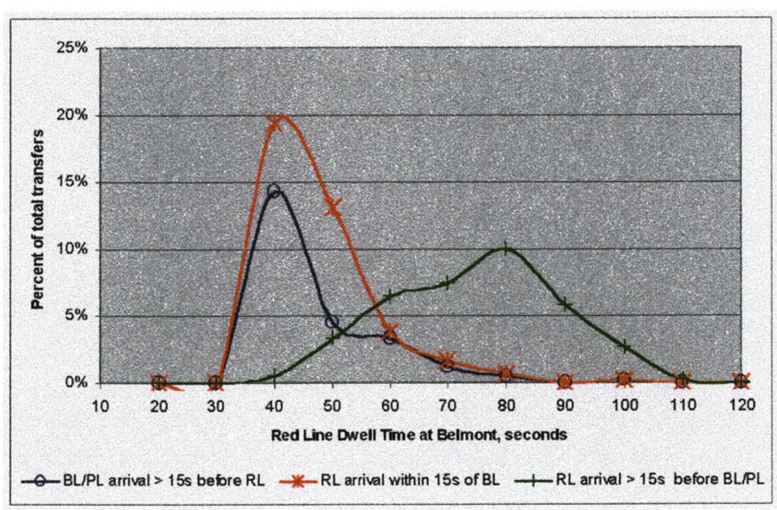


Figure 5-14 Red Line dwell time probability density functions by type of cross-platform transfer July 15, 2002 to August 16, 2002 7:00 to 9:00 hrs

The operation policy of facilitating simultaneous arrivals between Brown (Purple) Line trains and Red Line trains also benefits the Red Line trains, as the dwell time cumulative density functions in Figure 5-15 show, comparing the actual dwell time distribution of all Red Line trains at Belmont with the hypothetical improvement. The dwell time cumulative density function for the proposed change shows a remarkable improvement with 95% of all Red Line trains having dwell times under 60 seconds, compared with the 82% at present.

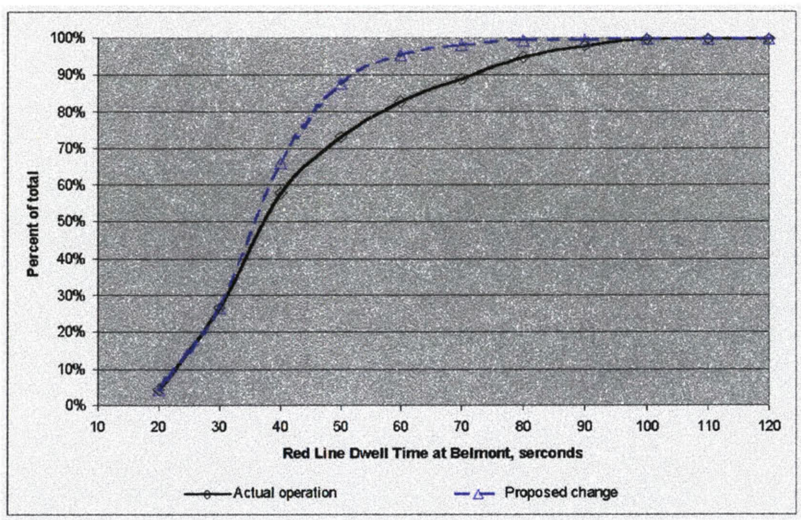


Figure 5-15 Red Line cumulative distribution function by operating plan

This operation policy could be implemented in the new configuration if the proposed changes to the design are made. The simultaneous arrival of trains is possible when these are queueing at the same distance from the station. Therefore, if the southbound Brown and Purple Line service has a home signal for Belmont immediately north of the station, then Red Line trains should also have a home signal to Belmont as close as possible.

5.7 Summary

In this Chapter we have shown how the queueing concepts are applied to our case study during the morning peak period, where southbound service has critical levels of congestion.

Queueing and delay estimation methods have revealed that queueing in the southbound direction is mainly generated by the dwell time activity at Belmont station. Queueing delays in the southbound direction at Belmont immediately propagate to the junction and beyond, and constrain the amount of trains that the junction can process.

Time-space diagrams were used to understand delay propagation at Belmont station, and identify when trains queue at track circuit A9T and RV1-7. Multiple-movement time-space diagrams have were used to understand the operating environment at the junction and to understand how cross-platform transfers at Belmont station induce high dwell times, increasing the waiting times of queued trains and reducing the throughput of trains at the merge point.

The practical capacity at the merging point for the southbound Brown and Purple Lines is close to 36 trains per hour: 24 Brown Line trains and 12 Purple Line trains. This is much higher than the actual 22 trains per hour where an average total delay of 12 minutes is experienced during the AM peak period. The actual throughput is close to 60% of the practical capacity of the merge point.

Some recommendations for operational improvements are based on dwell time control at Belmont station that can be achieved by manipulating the arrival times at Belmont to control cross-platform transfer at the Belmont station by allowing Red Line trains to enter Belmont station simultaneously with Brown (Purple) Line trains or before these trains.

The results and recommendations presented in this chapter represent the southbound analysis. In Chapter 6 the results of the analysis and recommendations for northbound service will be presented.

Chapter 6 Northbound Performance

The performance of the junction in the northbound direction is most critical during the evening peak period and is affected by the interaction between the Red Line and the Brown Line services. The interaction takes place at Belmont station and at the junction, where the Brown Line crosses the Red Line tracks to branch off to Ravenswood. Since Belmont station acts as the entry point of Clark Junction for northbound services, queues generated by the junction activity will develop at Belmont and will propagate south.

This chapter presents the findings from queue and delay estimation for the Red Line trains and for the Brown and Purple Line trains and presents recommendations for improving operations for the northbound services based on operation policies that can be introduced at Clark Junction.

6.1 Red Line service

The Red Line service uses Belmont station as the entrance to the junction. The dwell time of Red Line trains at Belmont station depends on the tower assigned priorities between Red Line and northbound Brown Line trains. The interlocking movement time is not affected by downstream conditions, although the Addison station is located only about 1,500 feet north of the junction.

6.1.1 Congestion analysis

As discussed in Chapter 2, for two nodes in series, if the activity at the second node has a higher service time than the activity of the first node, then the queues generated at the second node will propagate to the first node (as happens in the southbound direction, the first node being the merge point and the second Belmont station). Under these conditions the utilization rate of the exit point can be used as a proxy for congestion at the junction.

If, however, the service time of the first node is higher than the service time of the second node, then the congestion will appear at the first node, but not at the second node. We are interested in finding whether the Belmont station exhibits congestion that is not present at the junction, or if the congestion at the junction propagates to Belmont station.

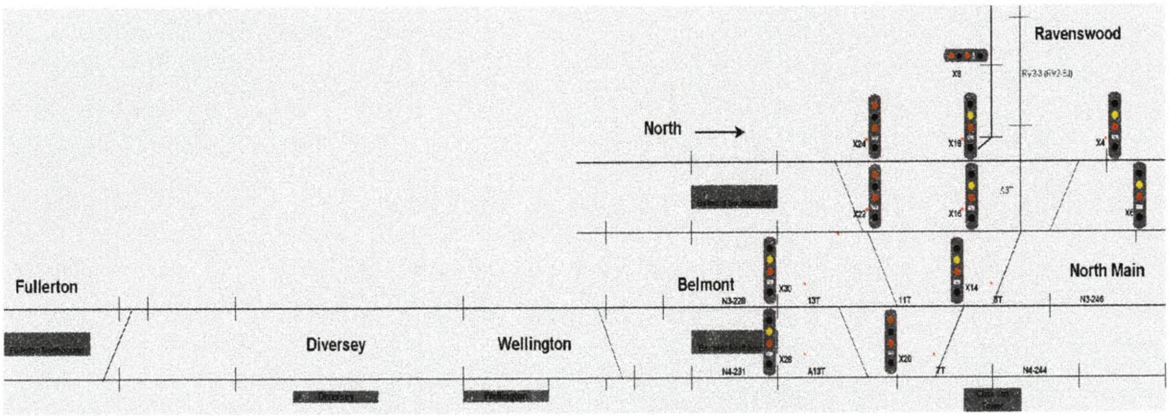


Figure 6-1 Clark Junction (not to scale)

Figure 6-1 shows a schematic of Clark Junction and the northbound approach tracks. Since Red Line trains run on tracks NM3, there are no stations between Fullerton and Belmont. If queueing at Belmont propagates upstream, the trains will queue at the Wellington circuit and longer queues will propagate to Diversey and further south.

As mentioned in Chapter 4, Belmont station is the entrance to the junction for northbound Red Line trains. The dwell times of Red Line trains at Belmont station are influenced by passenger activity, cross-platform transfers, and the routing decisions at Clark Junction. When Brown Line trains are prioritized at the junction, Red Line trains will experience high dwell times at Belmont while they wait for the Brown Line train to clear the interlocking. Figure 6-2 shows the dwell time probability density functions and cumulative density function for Red Line trains at Belmont during the PM peak period. When dwell times at Belmont are high, followers could arrive at Wellington and form a queue until the Belmont station is clear. Notice that about 15% of Red Line trains have dwell times above 2 minutes and a third have dwell times above 70 seconds.

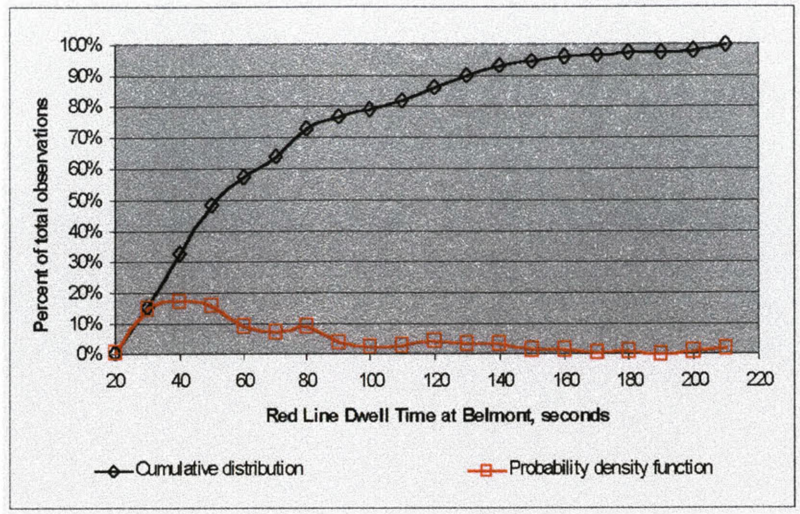


Figure 6-2 Red Line dwell time density functions at Belmont July 15, 2002 to August 16, 2002 16:30 to 18:30 hrs

When Red Line trains queue south of Belmont the relationship between the waiting time at the immediate upstream block (Wellington) and the utilization rate at Belmont follows the classical pattern: higher congestion leads to increased waiting times. The increased occupancies at Wellington are the result of high utilization rates at Belmont, as shown in Figure 6-3.

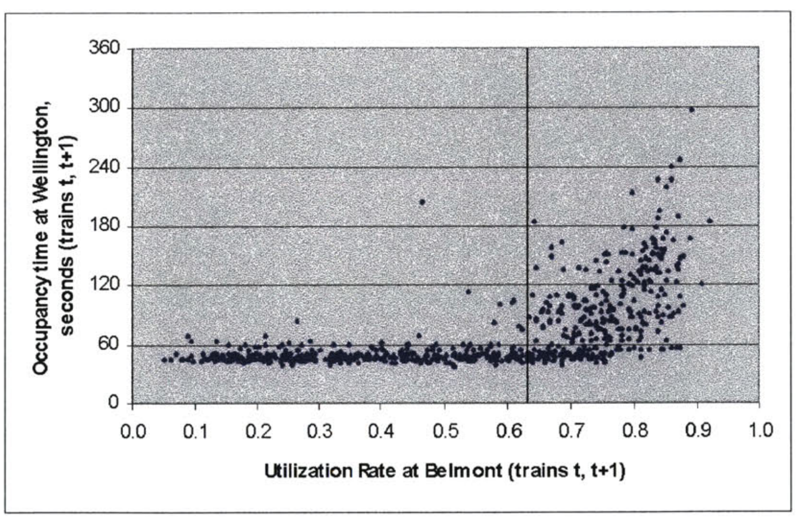
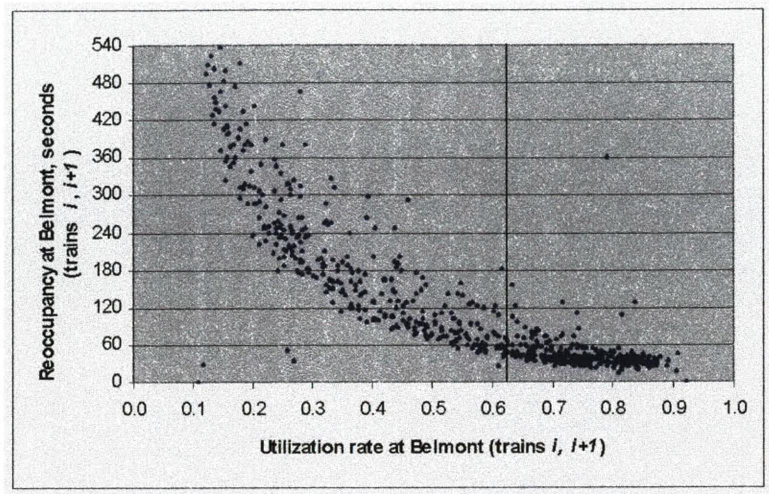


Figure 6-3 Red Line occupancy at Wellington versus utilization rates at Belmont: July 15, 2002 to August 16, 2002 16:30 to 18:30 hrs



.Figure 6-4 Red Line reoccupancy time at Belmont versus utilization rate at Belmont July 15, 2002 to August 16, 2002 16:30 to 18:30 hrs

Similarly, the inverse relationship between reoccupancy time and the utilization rate is evident in Figure 6-4 for Belmont. It can be observed from these two figures that the waiting times increased when the utilization rate at Belmont is above 0.6 and reoccupancy times at Belmont where the utilization rate is above 0.6 has a minimum of about 30 seconds and an upper bound of close to 60 seconds. These relationships will be used to identify queueing trains at Wellington by looking at the occupancies at Wellington and the reoccupancies at Belmont that result from the movement of the train exiting Belmont and the queued train moving into Belmont.

The relationships observed in Figures 6-3 and 6-4 between waiting time and utilization rate, and reoccupancy time and utilization rate are also identified for queueing at Diversey and will be used to identify queues of at least 2 trains. The figures showing the queueing curves can be found in Appendix B for Wellington and Diversey.

6.1.2 Queueing and delay estimation

The Red Line queueing analysis is presented in this section. As mentioned previously, queues in the northbound Red Line service are defined by increased occupancies at the Wellington block and are formed when the leading Red Line train experiences a high dwell time at Belmont station.

To identify a queue of at least one train where the queued train is $i+1$, the following conditions must be met:

1) Low reoccupancy time at Belmont reflected by the movements of trains i and $i+1$,
2) High occupancy of train $i+1$ at Wellington.

Low reoccupancy times at Belmont are indicative that there are trains at Wellington waiting for service at Belmont station, whereas the high occupancies indicate delays. In Figure 6-5, the 15th percentile of the occupancy distribution identifies the occupancy of trains at Wellington when there is no train at Belmont, which is 45 seconds. Because of variability in the train operations and other exogenous conditions the occupancy can be as high as 60 seconds when there is no train at Belmont station. Therefore, any occupancies above 60 seconds will be considered delays.

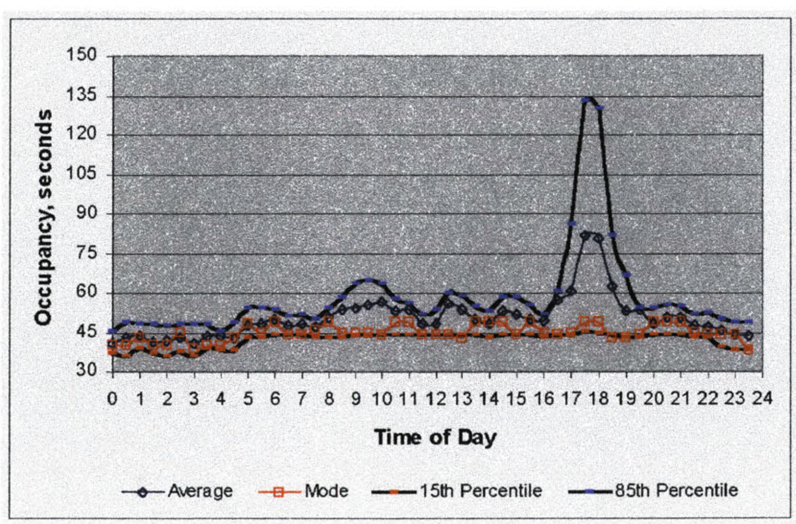


Figure 6-5 Occupancy distribution at Wellington by time of day July 15, 2002 to August 16, 2002

A queue of at least two trains exists when train $i+2$ is queued at Diversey. For a two-train queue, the conditions that must be met are:

1) High occupancy at Diversey for train $i+2$,
2) Low reoccupancy time at Wellington reflected by the movements of trains $i+1$ and $i+2$,
3) Conditions of a one-train queue satisfied for trains $i+1$, and $i+2$.

Occupancies at Diversey generally last between 38 and 50 seconds when there are no queues, as determined by the 15th and 85th percentile distributions shown in Figure 6-6. During most of the day there are no queues, with the exception of the AM peak period where delays are minimal, and the PM peak period which shows that occupancies can be as high as 90 seconds. Throughout most of the day, most of the occupancies range between 38 and 50 seconds. Occupancies above 50 seconds are considered to be due to queueing.

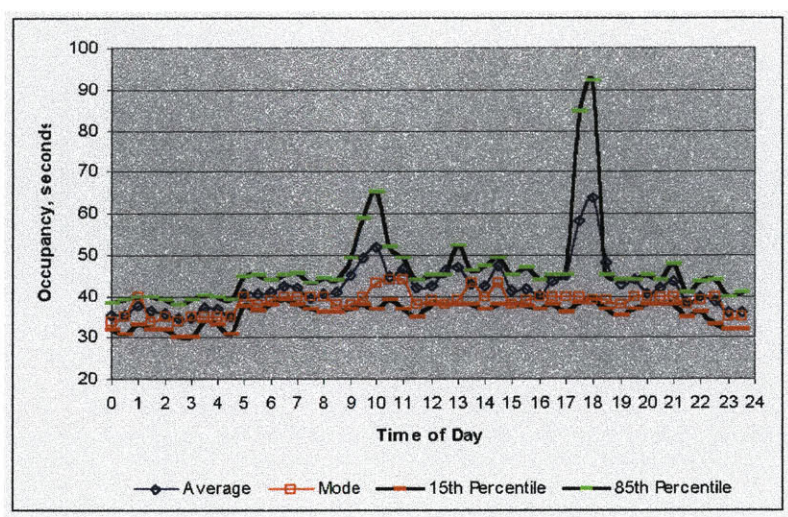


Figure 6-6 Occupancy distribution at Diversey by time of day July 15, 2002 to August 16, 2002

Though rare, a three-train queue may form at either Fullerton or between Fullerton and Diversey. The conditions needed to identify a queue of at least three trains are:

1) Low reoccupancy time at Diversey (if train $i+3$ is not held at Fullerton) or an opening gap for N3-180 and N3-201 that corresponds to trains $i+1$, $i+2$ (if train $i+2$ is held at Fullerton),
2) High occupancy at Fullerton for train $i+3$ (if train $i+3$ is held at Fullerton),
3) Conditions of a two-train queue are satisfied for train $i+3$ and $i+2$.

The delay parameters for the queueing estimation are determined similarly to those of the southbound Brown and Purple Line service. The figures that show the upper bound for reoccupancy times under queueing conditions are included in Appendix B.

An example of Red Line northbound queueing is presented in tabular form in Table 6-1, and graphically as a time-space diagram in Figure 6-7. There is a sequence of 16 Red Line trains routed through the junction between 17:30 and 18:30 – the period of highest traffic during the evening peak. Nine of the sixteen trains are delayed before entering the Belmont station, two of which enter as second trains of a two-train queue. Trains that enter as the first train in the queue experience an average delay of 82 seconds, whereas the two trains that enter as second trains in the queue experience an average delay of 232 seconds.

Run times in the Fullerton table are defined as the time between the train clearing Fullerton and entering the Diversey track circuit. The run times in the Clark Junction are defined as the time between the train exiting Fullerton and exiting track circuit 13T.

Fullerton

Train	Reoccupancy (s)	On	Off	Occupancy (s)	Headway (min)	Utilization Rate	Run Time (s)
1	255	17:28:12	17:29:26	74	5.3	0.6	29
2	**59**	17:30:25	17:32:18	**113**	2.2	0.7	25
3	**41**	17:32:59	17:34:56	**117**	2.6	0.8	26
4	**26**	17:35:22	17:36:34	72	2.4	0.6	18
5	**41**	17:37:15	17:38:19	64	1.9	0.4	36
6	112	17:40:11	17:41:16	65	2.9	0.2	**45**
7	226	17:45:02	17:46:37	**95**	4.9	0.3	25
8	213	17:50:10	17:51:24	74	5.1	0.4	28
9	92	17:52:56	17:54:15	79	2.8	0.5	28
10	95	17:55:50	17:57:46	**116**	2.9	0.7	28
11	**50**	17:58:36	17:59:37	61	2.8	0.3	28
12	151	18:02:08	18:03:03	55	3.5	0.4	24
13	84	18:04:27	18:05:42	75	2.3	0.1	21
14	555	18:14:57	18:16:16	79	10.5	0.3	23
15	199	18:19:35	18:20:49	74	4.6	0.6	30
16	**59**	18:21:48	18:22:42	54	2.2	0.1	24

Diversey

Train	Reoccupancy (s)	On	Off	Occupancy (s)	Headway (min)	Utilization Rate	Delay (s)
1	289	17:29:55	17:30:34	39	5.5	0.2	0
2	129	17:32:43	17:33:27	44	2.8	0.3	0
3	115	17:35:22	17:36:01	39	2.7	0.4	0
4	**51**	17:36:52	17:37:33	41	1.5	0.3	0
5	82	17:38:55	17:39:35	40	2.0	0.2	0
6	146	17:42:01	17:46:18	**257**	3.1	**0.9**	197
7	**44**	17:47:02	17:47:52	50	5.0	0.2	0
8	240	17:51:52	17:52:30	38	4.8	0.2	0
9	133	17:54:43	17:57:37	**174**	2.9	**0.8**	114
10	**37**	17:58:14	17:58:50	36	3.5	0.3	0
11	75	18:00:05	18:02:45	**160**	1.9	**0.8**	100
12	**42**	18:03:27	18:04:06	39	3.4	0.3	0
13	117	18:06:03	18:06:58	55	2.6	0.1	0
14	581	18:16:39	18:17:17	38	10.6	0.1	0
15	242	18:21:19	18:22:03	44	4.7	0.4	0
16	**63**	18:23:06	18:23:50	44	1.8	0.1	0

Wellington

Train	Reoccupancy (s)	On	Off	Occupancy (s)	Headway (min)	Utilization Rate	Delay (s)
1	278	17:30:24	17:31:18	54	5.5	0.3	0
2	118	17:33:16	17:34:04	48	2.9	0.3	0
3	107	17:35:51	17:36:38	47	2.6	0.5	0
4	**46**	17:37:24	17:38:45	**81**	1.5	0.7	21
5	**37**	17:39:22	17:44:19	**297**	2.0	**0.9**	237
6	**48**	17:45:07	17:46:56	**109**	5.8	**0.7**	49
7	**40**	17:47:36	17:49:19	**103**	2.5	0.4	43
8	181	17:52:20	17:54:48	**148**	4.7	**0.9**	88
9	**22**	17:55:10	17:58:13	**183**	2.8	**0.9**	0
10	**27**	17:58:40	18:00:19	**99**	3.5	**0.8**	39
11	**19**	18:00:38	18:03:36	**178**	2.0	**0.9**	118
12	**20**	18:03:56	18:06:30	**154**	3.3	**0.9**	94
13	**16**	18:06:46	18:08:36	**110**	2.8	0.2	50
14	515	18:17:11	18:17:56	45	10.4	0.2	0
15	237	18:21:53	18:22:37	44	4.7	0.4	0
16	**64**	18:23:41	18:24:30	49	1.8	0.1	0

Belmont

Train	Reoccupancy (s)	On	Off	Occupancy (s)	Headway (min)	Utilization Rate	Total Delay (s)
1	233	17:31:03	17:32:38	95	5.4	0.6	0
2	76	17:33:54	17:35:47	113	2.8	**0.7**	0
3	**40**	17:36:27	17:38:04	97	2.5	**0.8**	0
4	**32**	17:38:36	17:43:26	290	2.1	**0.9**	21
5	**35**	17:44:01	17:45:57	116	5.4	0.7	237
6	**50**	17:46:47	17:48:14	87	2.8	0.6	246
7	**55**	17:49:09	17:53:53	284	2.4	**0.9**	43
8	**39**	17:54:32	17:56:47	135	5.4	0.6	88
9	75	17:58:02	17:59:32	90	3.5	**0.8**	0
10	**28**	18:00:00	18:02:49	169	2.0	**0.8**	39
11	**33**	18:03:22	18:05:47	145	3.4	**0.8**	218
12	**33**	18:06:20	18:07:57	97	3.0	**0.7**	94
13	**34**	18:08:31	18:10:24	113	2.2	0.2	50
14	442	18:17:46	18:19:15	89	9.3	0.3	0
15	197	18:22:32	18:23:50	78	4.8	**0.7**	0
16	**30**	18:24:20	18:27:36	196	1.8	0.3	0

Clark Junction

Train	Reoccupancy (s)	On	Off	Occupancy (s)	Headway (min)	Total Run Time (s)	Queue length
1	280	17:32:17	17:32:59	42	5.5	238	
2	147	17:35:26	17:36:10	44	3.2	257	
3	100	17:37:50	17:38:31	41	2.4	240	
4	279	17:43:10	17:43:55	45	5.3	466	1
5	107	17:45:42	17:46:22	40	2.5	508	1
6	94	17:47:56	17:48:41	45	2.2	470	2
7	293	17:53:34	17:54:20	46	5.6	488	1
8	131	17:56:31	17:57:16	45	2.9	377	1
9	116	17:59:12	17:59:56	43	2.7	365	
10	155	18:02:30	18:03:17	47	3.3	356	1
11	129	18:05:26	18:06:14	48	2.9	422	2
12	90	18:07:44	18:08:21	37	2.3	343	1
13	107	18:10:08	18:10:48	40	2.4	331	1
14	492	18:19:00	18:19:44	44	8.9	233	
15	227	18:23:31	18:24:15	44	4.5	231	
16	181	18:27:16	18:28:09	53	3.8	352	

Table 6-1 Northbound Red Line example August 1, 2002 17:30 to 18:30

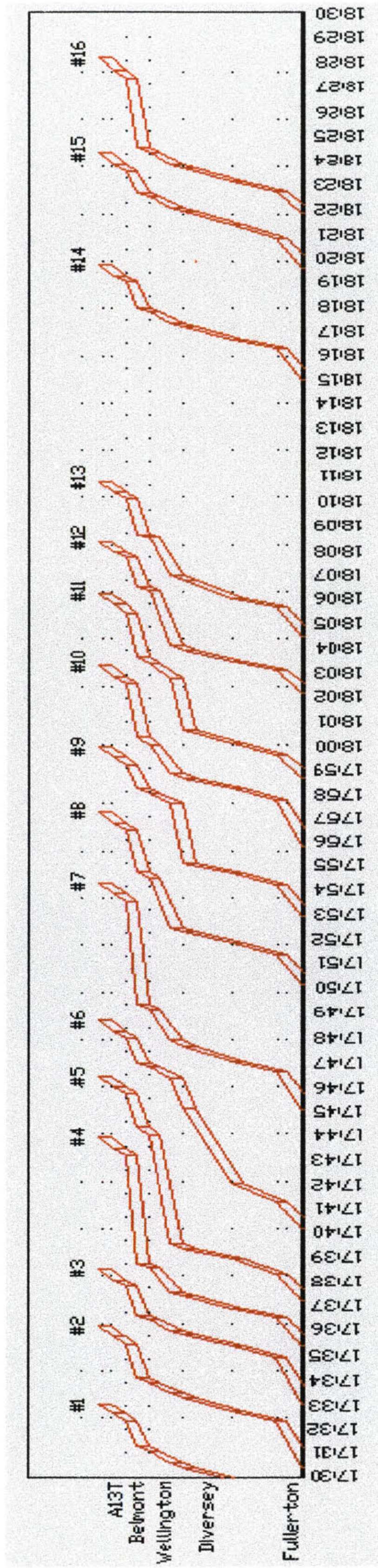


Figure 6-7 Time-diagram for Table 6-1

The queueing process is clearly evident from the time-space diagram of Figure 6-7. In this figure, it can be seen that train 4 is the first train to experience a delay at Wellington. This train then experiences an unusually long dwell time at Belmont. The repercussions of the dwell time at Belmont are delays for train 5, which queues at Wellington for a long period (about 4 additional minutes), and for train 6 at Diversey. The 5-minute headway between trains 6 and 7 is sufficient to prevent train 7 from experiencing delays caused by train 4 at Belmont. Train 7, however also experiences a long dwell time at Belmont – triggering another cycle of queues and delay propagation.

6.1.3 Visualization and tower decisions

At this point we can speculate that the trains that experienced long dwell times at Belmont station causing followers to queue were held at Belmont to allow northbound Brown Line trains to move through the junction. A multiple movement time-space diagram helps visualize the entire junction operation to see if the high dwell times at Belmont station were, in fact, due to the Brown Line prioritization, or high transfer activity, or if there were other factors at work that are not captured through the existing automatic data collection, such as a mechanical failure on the train at Belmont or a medical emergency.

The multiple movement time-space diagram shown in Figure 6-8 shows the train movements in tracks 3 and 4. There are two time-block diagrams incorporated which are for the occupancy at the crossing between northbound Red Line trains and northbound Brown Line trains, and for the occupancies at Belmont for tracks NM3 and NM4. Since Belmont station and the junction are adjacent, train occupancies will be shown on the Belmont station block occupancy diagram and immediately after these appear in the junction block occupancy diagram. The long dwell times of Red Line trains at Belmont can be examined more carefully to determine whether these were due to northbound Brown Line movements at the junction. The Red Line trains are numbered in the time-space diagram and the block occupancy diagram for the Belmont station track circuits.

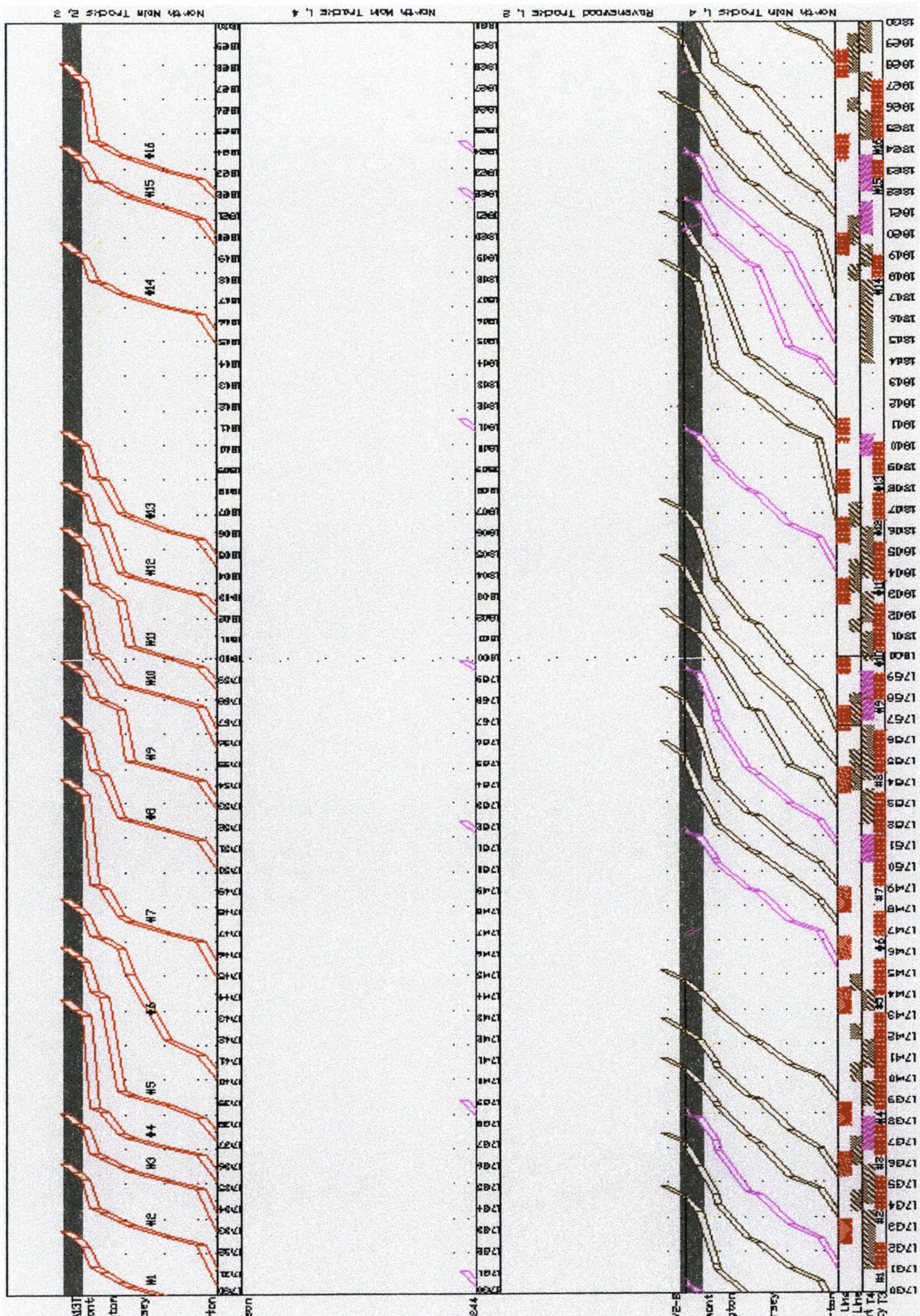


Figure 6-8 Multiple-movement time-space diagram for Table 6-1 August 1, 2002 17:30 to 18:30

In the block occupancy diagram for Belmont station in Figure 6-8, we can see that Red Line train 4 had a long dwell time at Belmont station and had cross-platform transfer with two northbound Brown Line trains on track NM4. We know that these are Brown Line trains because they also appear in the block occupancy diagram for the junction immediately after these trains clear Belmont station. The second of these two Brown Line trains arrives at Belmont before the first train exits the junction and is prioritized at the junction over train 4. Looking at the time-space diagram for the northbound Brown and Purple Line trains, there appears to be some congestion on tracks NM4, but not sufficient to justify the decision to process the second Brown Line train through the junction before train 4 because the follower to the second Brown Line train was not at Wellington, nor showing indications of queueing when the Brown Line train was routed.

The other Red Line train that had a very long dwell time was train 7. From the block occupancy diagram for Belmont station it is determined that this train was also held at Belmont station and had cross-platform transfers with two northbound trains, the first of which was a Purple Line train and the second a Brown Line train. We know that the first train was a Purple Line train because this train does not appear in the block occupancy diagram of the junction after the train clears Belmont station. At this point, train 7 should have been processed at the junction but it was held at the station, allowing cross-platform transfers with the following Brown Line train.

For this example the multiple-movement time space diagram has shown the interactions taking place at the Clark Junction between routing prioritization, holding at the Belmont station and cross-platform transfers. Some conclusions can be drawn with respect to the queueing process, the dwell times, and the findings from the diagrams and the delays. First, the queueing process is generated by the service process at Belmont. Second, the service process at Belmont can be influenced by the tower practices of holding at the station for cross-platform transfers and prioritization of the northbound Brown Line trains at the junction. The longest dwell times were experienced by trains that held for cross-platform transfers with more than one train. Third, the use of block occupancy diagrams can complement the time-space diagrams to give a much better understanding of the line conditions that can be synthesized into delay and queueing statistics.

6.1.4 Delays

In this example there were 16 Red Line trains served in the 60 minutes of the heaviest traffic. As mentioned in the summary of delays for the example of Table 6-1, the trains that experienced queueing approaching Belmont had on average delays of 82 seconds when these formed one-train queues, whereas those that formed a two-train queues had an average delay of 232 seconds. In comparison with the peak periods throughout the 25-weekday period of July 15, 2002 to August 16, 2002, the peak period of August 1, 2002 could be classified as a "bad day" of service.

A summary of delays experienced during the weekday evening peak period from July 15, 2002 to August 16, 2002 is shown in Table 6-2. During the 25-weekday period there were only three observations where queues of three trains developed. The low number of observations does not provide intuitive results on average run time and average delay because there is high variability in these 3 observations.

Queue Length	Incidence	Average Incidence Per Peak Period	Average Run Time Per Train	Average Delay Per Train
No queue	473	19	223 seconds	---
1-train queue	142	8	302 seconds	79 seconds
2-train queue	23	1	353 seconds	130 seconds
3-train queue	3	0	316 seconds	93 seconds

Table 6-2 Summary of delays for Red Line: July 15, 2002 to August 16, 2002 16:30 to 18:30 hrs

It is also worth noting that on average there are 28 trains serviced at the junction between 4:30 pm and 6:30 pm. There are, however, 31 trains scheduled through the junction, which suggests that there are more trains scheduled than operating through the junction in this period.

6.2 Brown and Purple Line service

The northbound Brown Line service enters the junction when it exits Belmont station and the tower operator normally uses Belmont station as the entry point to the junction, although the block immediately ahead of Belmont station could also be used as the entry point. Northbound Purple Line service is not subject to conflicting train movements as it enters the junction, although northbound Brown Line trains that are queueing at signal X20 may block the progress of Purple Line trains.

6.2.1 Congestion analysis

The queueing behavior of Purple and Brown Line trains is similar to the queueing process of the northbound Red Line trains, but there are some differences. Unlike the northbound Red Line service, Belmont station could be treated as an independent node from the junction for northbound Brown Line trains when these have partial line-ups. Track circuit A13T will be the entry point to the junction when partial line-ups are assigned to Brown Line trains.

The process time at Belmont station influences the arrival of Brown and Purple Line trains at the junction, therefore in this analysis the station utilization will be used to assess the congestion near the junction. The nature of congestion at the Belmont station and its relationship to the interlocking movement time of Brown Line trains is shown in Figure 6-9. There are two well-defined clusters of observations. The first is a vertical concentration observed for train movement times of 20 to 30 seconds, indicating the actual uninterrupted interlocking movement time for the Brown Line trains regardless of the amount of traffic on the NM4 tracks. The second cluster is a horizontal concentration of observations when the reoccupancy at Belmont is less than 60 seconds. This cluster indicates the variability of the interlocking movement time due to a partial route assignment of Brown Line trains when the northbound Brown and Purple Line trains are on close headways. The tower operator can set a partial line-up to signal X20 for the leading Brown Line train so the follower can move into Belmont.

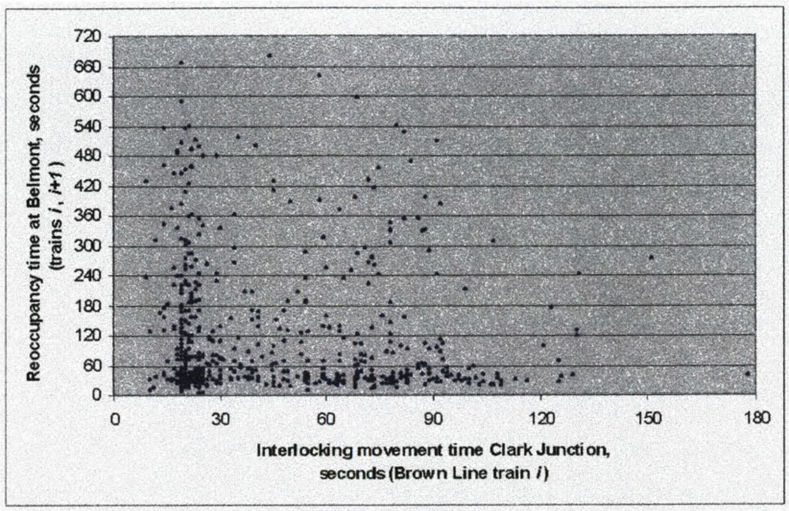


Figure 6-9 Reoccupancy time at Belmont versus the movement time of the leading Brown Line train July 15, 2002 to August 16, 2002 16:30 to 18:30 hrs

The scatter of remaining observations is evidence of variability in junction operation. That is, some Brown Line trains may be given a partial line-up even if there is no immediate follower.

The utilization rate of the junction cannot be used for queueing analysis because there is a divergence of Brown Line trains from the main tracks and the Purple Line movement through the junction is not constrained by crossings or merging with other service lines. Partial line-ups for northbound Brown Line trains can be considered queues at the interlocking, but this action can be weighed against the alternative of holding the train at Belmont, as will be discussed in section 6.4 on recommendations for dwell time control through operation policies. Since this action is a substitute for a higher dwell time at Belmont station, the congestion will be studied in the context of Belmont station.

The queues that develop south of Belmont can be identified using the utilization rate of Belmont as a proxy for congestion. A high occupancy at Belmont station is indicative of high passenger activity (including transfers) and/or tower control. The latter is most important because the tower operator has direct control over the exit process at Belmont and can thus influence the length of the dwell times at the station.

Figure 6-10 presents the probability density function and the cumulative distribution function of Brown and Purple Line dwell time at Belmont station expressed as percentages of total observations. In comparison with the Red Line dwell time distributions (see Figure 6-2), the dwell times at Belmont for the Brown and Purple Line are much shorter. About 80% of all evening peak dwell times are under 60 seconds, compared to less than 60% for Red Line trains.

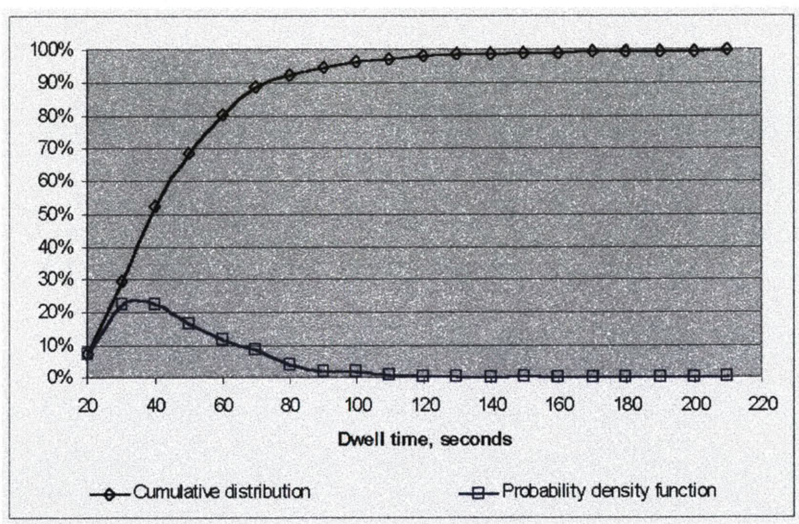


Figure 6-10 Brown (Purple) Line dwell time distributions at Belmont: July 15, 2002 to August 16, 2002 16:30 to 18:30 hrs

In spite of the generally low dwell times at Belmont, queues can and do still form. High occupancies at Wellington happen when the utilization rate at Belmont is above 0.6, as shown in Figure 6-11. The high occupancies at Wellington are considered to be occupancies above 90 seconds. The inverse relationship between the reoccupancy time and the utilization rate at Belmont shown in Figure 6-12 indicates that reoccupancy times under 60 seconds are directly associated with the higher occupancies at Wellington.

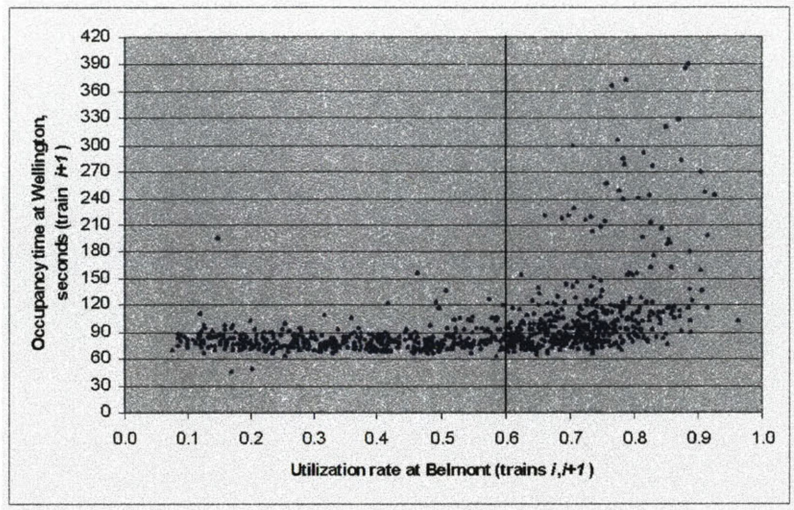


Figure 6-11 Brown(Purple) Line occupancy time at Wellington versus utilization rate at Belmont July 15, 2002 to August 16, 2002

There are significant implications to Figure 6-11: Wellington station is served by Brown Line and Purple Line trains – but the higher occupancies happen only when higher levels of congestion are exhibited at Belmont station. The dwell time at Wellington station in the PM peak period has very low variability, so any delays experienced at the Wellington block are directly associated with the activity at Belmont.

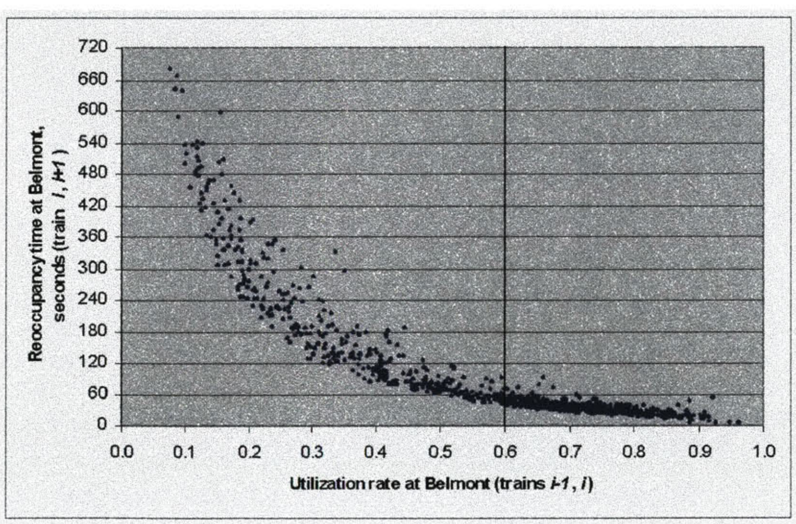


Figure 6-12 Brown (Purple) Line reoccupancy time versus utilization rate at Belmont July 15, 2002 to August 16, 2002 16:30 to 18:30 hrs

In Figure 6-12, notice that the low reoccupancy times at Belmont are due in part to the restricted operation of trains into Belmont when the leader is at track circuit A13T.

6.2.2 Queueing and delay estimation

Decisions by the tower operator are a critical element of queueing for northbound service. During the PM peak period operation, very low headways on both the northbound Red Line and Brown Line services can create numerous conflicts between the two lines. Decisions at the tower are made on priority for the Brown Line and Red Line trains; but the high frequencies of both service lines make crossing conflicts inevitable. Tower operators usually assign routing priorities between northbound Red Line and Brown Line trains based on the arrival times at Belmont. Some tower operators will process the first arriving train at Belmont while other tower operators will prioritize the Brown Line trains at all times.

When Brown Line trains form a queue between Belmont and the interlocking, at block A13T, the queues can be identified by observing their movement through the junction. The trains that exhibit this queueing behavior will meet the following condition:

- High run time Belmont and the exit block of the junction (track circuit RV2-8).

When queues form at Belmont due to the queueing of Brown Line train *i* at signal X20, the following conditions are also satisfied:

- High occupancy at Belmont by northbound train $i+1$.

An extended dwell time for train *i* at Belmont may cause the follower, train $i+1$, to queue at Wellington. Queues forming south of Belmont can be determined in a similar way to the northbound Red Line queueing case. However, the delay parameters for the northbound Brown and Purple Line queueing are different. In addition, the queueing parameters are dynamic for Wellington, Diversey and Belmont, varying by time of day to account for passenger activity at the stations. Figure 6-13 shows how the occupancy at Wellington varies by time of day. A simplifying assumption is made at this point: dwell time activity varies little between consecutive trains during a segment of time, say 30 minutes, although it may be considered variable by time period. This assumption is made in the absence of accurate passenger activity data.

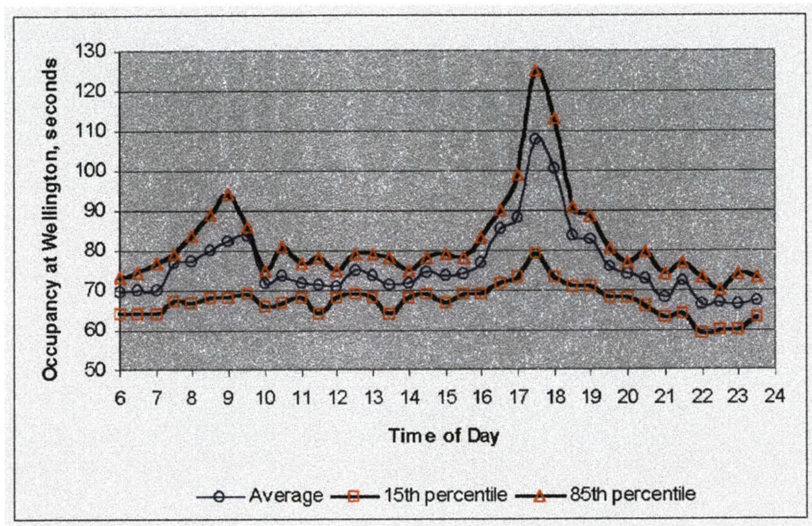


Figure 6-13 Occupancy distributions at Wellington by time of day July 15, 2002 to August 16, 2002

General information is available on the occupancies of the trains at the circuits. The trends indicate that the average occupancy times increase at Belmont, Wellington, Fullerton and Diversey stations during peak periods (see Appendix B for the occupancy distributions at Diversey and Fullerton by time of day). Delays in the system translate into higher occupancies at the track circuits, contributing to increased averages and variances. It is necessary to consider several conditions that determine accurately when queueing is taking place in the system.

For a one-train queue with Belmont the service point, train $i+1$ will queue at Wellington. The following conditions indicate a queue of at least one train:

- High occupancy at Wellington for train $i+1$,
- Low reoccupancy at Belmont generated by the departure of train i and the arrival of train $i+1$.

As mentioned previously, high occupancies at Wellington have a lower bound of 90 seconds, whereas the low reoccupancy times at Belmont have an upper bound of 60 seconds.

A two-train queue exists when the last train in the queue, train *i+1*, has not moved out of the Wellington circuit, so train *i+2* will have to queue at Diversey. In addition to trains occupying the Wellington and Diversey blocks while a leader is at Belmont, the following conditions indicate queues of at least two trains in the system:

- High occupancy at Diversey for train *i+2*,
- Low reoccupancy at Wellington generated by the departure of train *i+1* and the arrival of train *i+2*,
- Conditions of a one-train queue satisfied for train *i+1*.

Figure 6-14 shows the queuing relationship for trains at Diversey based on the congestion at Wellington. A high occupancy at Diversey will have a lower bound at 90 seconds. Trains at Diversey could experience delays when the utilization rate of Wellington is above 0.75. From the figure it can be seen that even at utilization rates close to 1, trains at Diversey may not necessarily experience delays.

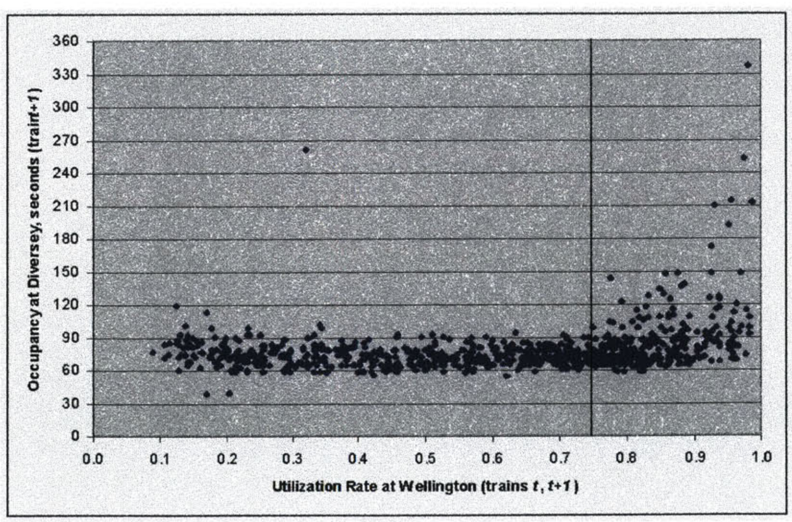


Figure 6-14 Occupancy at Diversey versus utilization rate at Wellington July 15, 2002 to August 16, 2002 16:30 to 18:30 hrs

Since dwell times at Belmont are not generally high (see the probability density function in Figure 6-10) and partial lineups are assigned to the trains at Belmont when there is a follower at Wellington, it is unlikely for a northbound Brown Line train to cause queues to propagate beyond Wellington. Figure 6-15 shows that only 12% of the trains at Diversey exhibit the high occupancies that indicate delays due to queueing.

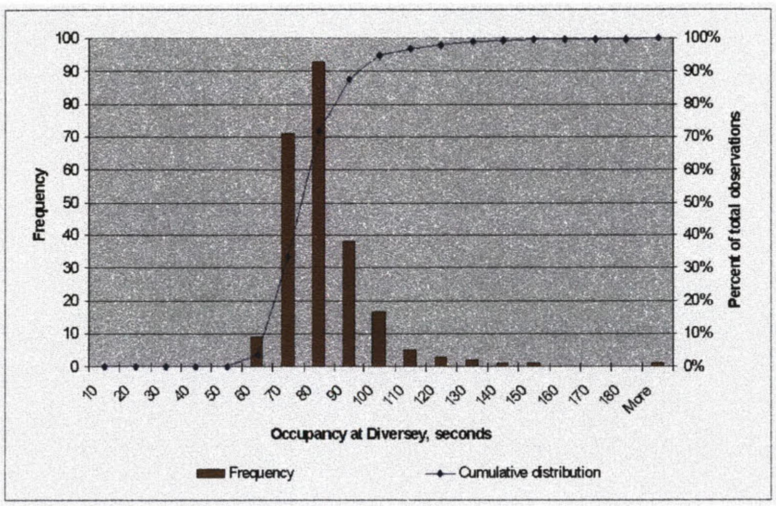


Figure 6-15 Histogram of occupancy times at Diversey: July 15, 2002 to August 16, 2002 16:30 to 18:30 hrs

In the event of a queue of more than two trains forming, the last train in the queue may form the queue at Fullerton or between Fullerton and Diversey. If the last train forms the queue between Fullerton and Diversey, the defining conditions would be:

- High movement time between Fullerton and Diversey for train $i+3$,
- Low reoccupancy time at Diversey generated by the departure of train $i+2$ and the arrival of $i+3$, and
- Conditions of a two-train queue satisfied for train $i+2$ and $i+3$ as it advances in the queue.

Figure 6-16 shows the run time distribution of Brown and Purple Line trains between Fullerton and Diversey. The run times in non-queueing conditions vary between 30 and 40 seconds. Therefore, the lower bound for run times including delays will be 40 seconds.

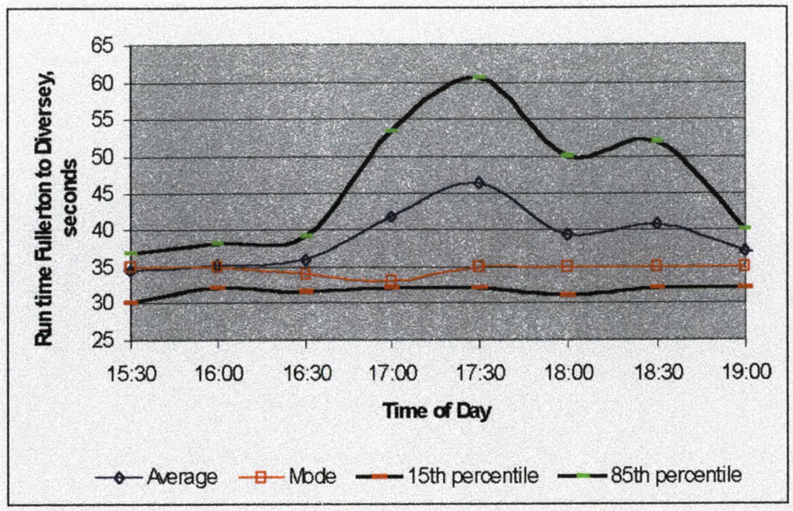


Figure 6-16 Run time distribution between Fullerton and Diversey by time of day July 15, 2002 to August 16, 2002

As an example, the northbound Brown and Purple Line trains of the evening peak period on which the Red Line example in Table 6-1 is based on, are shown in Table 6-3. In this example there are 22 trains: 15 Brown Line and 7 Purple Line trains. Of the 22 trains, 10 of them experience some level of queueing between Fullerton and Clark Junction, 7 of which form the queues at Wellington and the other 3 form the queue at Diversey. There were 15 Brown Line trains, of which 7 were given a partial line-up to track circuit A13T as determined by looking at the high run time of Brown Line trains (in bold) on the *Run Time* column of the Clark Junction table. This column shows the run time from Belmont to the exit of the junction for each service line. The queueing delay at X20 is shown in the adjacent column *X20 Queueing Delay*. The last column of this table *Total Run Time* shows the train run time from entering Diversey to exiting the junction

Diversey

Train	Reoccupancy (s)	ON	OFF	Occupancy (s)	Headway (min)	Utilization Rate	Delay (s)
1	60	17:25:41	17:27:06	85	2.4	0.5	0
2	81	17:28:27	17:29:45	78	2.8	0.5	0
3	83	17:31:08	17:32:18	70	2.7	0.6	0
4	52	17:33:10	17:34:37	87	2.0	0.6	0
5	50	17:35:27	17:37:01	**94**	2.3	**0.7**	4
6	**36**	17:37:37	17:39:08	**91**	2.2	0.5	1
7	95	17:40:43	17:41:52	69	3.1	0.2	0
8	340	17:47:32	17:48:56	84	6.8	0.7	0
9	**42**	17:49:38	17:50:42	64	2.1	**0.7**	0
10	**27**	17:51:09	17:52:30	81	1.5	0.7	0
11	**36**	17:53:06	17:54:27	81	2.0	**0.8**	0
12	**26**	17:54:53	17:57:27	**154**	1.8	**0.9**	64
13	**24**	17:57:51	17:59:14	83	3.0	**0.7**	0
14	**28**	17:59:42	18:01:36	**114**	1.9	0.3	24
15	279	18:06:15	18:07:44	89	6.6	0.3	0
16	194	18:10:58	18:12:17	79	4.7	0.7	0
17	**35**	18:12:52	18:14:03	71	1.9	0.7	0
18	**37**	18:14:40	18:18:26	**226**	1.8	**0.9**	136
19	**39**	18:19:05	18:20:20	75	4.4	0.7	0
20	**34**	18:20:54	18:22:18	84	1.8	**0.7**	0
21	**34**	18:22:52	18:24:40	**108**	2.0	**0.8**	18
22	**27**	18:25:07	18:26:54	**107**	2.3	0.4	17

Wellington

Train	Reoccupancy (s)	ON	OFF	Occupancy (s)	Headway (min)	Utilization Rate	Delay (s)
1	60	17:27:10	17:28:55	**105**	2.3	0.6	0
2	59	17:29:54	17:31:18	84	2.7	0.5	0
3	74	17:32:32	17:34:37	**125**	2.6	**0.9**	35
4	**9**	17:34:46	17:37:09	**143**	2.2	**0.9**	53
5	**15**	17:37:24	17:38:59	**95**	2.6	**0.8**	5
6	**18**	17:39:17	17:40:52	**95**	1.9	0.6	5
7	73	17:42:05	17:43:26	81	2.8	0.2	0
8	339	17:49:05	17:50:28	83	7.0	**0.8**	0
9	**27**	17:50:55	17:52:20	85	1.8	**0.8**	0
10	**18**	17:52:38	17:54:20	**102**	1.7	**0.8**	12
11	**28**	17:54:48	17:57:27	**159**	2.2	**0.9**	69
12							0
13	**9**	17:57:36	18:01:40	**244**	2.8	**1.0**	154
14	**5**	18:01:45	18:03:45	**120**	4.1	0.3	30
15	252	18:07:57	18:09:30	**93**	6.2	0.3	0
16	176	18:12:26	18:13:52	86	4.5	**0.8**	0
17	**27**	18:14:19	18:18:26	**247**	1.9	**0.9**	157
18	**15**	18:18:41	18:22:18	**217**	4.4	**0.9**	127
19							0
20	**14**	18:22:32	18:24:25	**113**	3.8	**0.8**	23
21	**25**	18:24:50	18:26:43	**113**	2.3	**0.9**	23
22	**18**	18:27:01	18:28:30	89	2.2	0.4	0

Belmont

Train	Reoccupancy (s)	ON	OFF	Occupancy (s)	Headway (min)	Utilization Rate	Total Delay (s)	Queue Length
1	70	17:28:41	17:30:04	83	2.8	0.6	0	
2	**59**	17:31:03	17:33:49	166	2.4	**0.9**	0	
3	**20**	17:34:09	17:35:56	107	3.1	**0.7**	35	1
4	**47**	17:36:43	17:38:14	91	2.6	**0.7**	53	1
5	**31**	17:38:45	17:39:57	72	2.0	**0.7**	0	
6	**37**	17:40:34	17:41:56	82	1.8	0.5	0	
7	80	17:43:16	17:44:12	56	2.7	0.1	0	
8	363	17:50:15	17:51:32	77	7.0	**0.7**	0	
9	**33**	17:52:05	17:53:44	99	1.8	**0.8**	0	
10	**25**	17:54:09	17:56:42	153	2.1	**0.9**	12	1
11	**16**	17:56:58	17:59:18	140	2.8	**0.8**	69	1
12	**38**	17:59:56	18:01:11	75	3.0	**0.9**	218	2
13	**6**	18:01:17	18:03:03	106	1.4	**0.8**	154	1
14	**33**	18:03:36	18:06:08	152	2.3	0.4	54	2
15	188	18:09:16	18:10:29	73	5.7	0.3	0	
16	193	18:13:42	18:17:46	244	4.4	**0.9**	0	
17	**24**	18:18:10	18:19:25	75	4.5	**0.7**	157	1
18	**34**	18:19:59	18:21:28	89	1.8	**0.7**	263	2
19	**34**	18:22:02	18:23:41	99	2.0	**0.8**	0	
20	**28**	18:24:09	18:25:47	98	2.1	**0.7**	28	1
21	**46**	18:26:33	18:27:36	63	2.4	**0.7**	41	2
22	**29**	18:28:05	18:30:03	118	1.5	0.5	0	

Clark Junction

Train	Line	ON	OFF	Headway (min)	Utilization Rate	Run Time (s)	X20 Q'ing Delay	Total Run Time
1	***Purple***	17:30:19	17:31:02	16.6	0.1	15		232
2	Brown	17:34:32	17:35:00	6.1	0.2	**43**	3	306
3	Brown	17:37:05	17:37:32	2.5	0.1	**69**	29	300
4	***Purple***	17:38:22	17:39:07	8.1	0.1	8		261
5	Brown	17:40:34	17:41:05	3.5	0.3	37		221
6	Brown	17:42:24	17:42:56	1.8	0.2	28		219
7	Brown	17:44:46	17:45:14	2.4	0.0	34		189
8	***Purple***	17:51:42	17:52:16	13.3	0.1	10		191
9	Brown	17:55:24	17:56:02	10.6	0.2	**100**	60	307
10	Brown	17:58:02	17:58:36	2.6	0.2	**80**	40	358
11	***Purple***	17:59:27	17:59:55	7.7	0.0	9		307
12	Brown	18:01:35	18:02:12	3.6	0.2	24		
13	Brown	18:04:21	18:04:53	2.8	0.2	**78**	38	437
14	Brown	18:07:02	18:07:31	2.7	0.0	**54**		346
15	***Purple***	18:10:43	18:11:18	11.3	0.1	14		201
16	Brown	18:18:16	18:18:45	11.2	0.2	30		379
17	Brown	18:20:34	18:21:03	2.3	0.1	**69**	29	404
18	***Purple***	18:21:38	18:22:12	10.9	0.3	10		211
19	***Purple***	18:23:50	18:24:25	2.2	0.0	9		
20	Brown	18:26:08	18:26:43	5.6	0.2	21		251
21	Brown	18:29:12	18:29:45	3.1	0.4	**96**	56	295
22	Brown	18:30:27	18:30:54	1.2	0.2	24		233

Table 6-3 Brown/Purple Line queueing and delays: August 1, 2002 5:30 PM to 6:30 PM

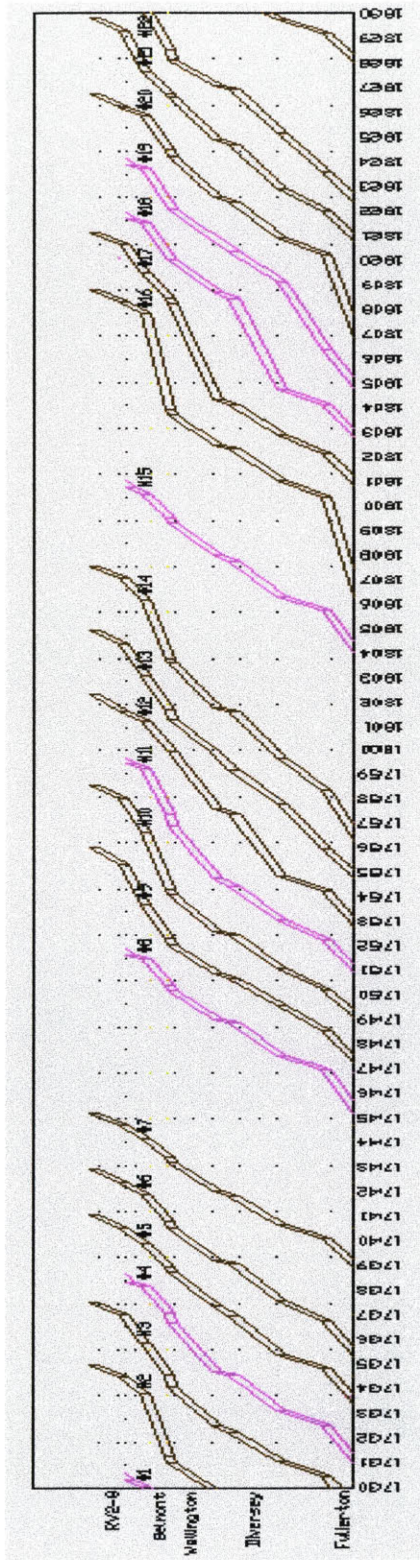


Figure 6-17 Time space diagram for Table 6-3

The time-space diagram in Figure 6-17 shows the trains bunched in three sets for this period. Thus, it is expected that some trains will experience delays.

A summary of the delays in this example is provided in Table 6-4. The average dwell times are not very different among trains with different queue lengths. The difference in average run time between various queueing lengths is in the order of 35 seconds, but the delays are about 70 seconds for trains entering in a one-train queue and 140 seconds for trains entering as the second train in the queue.

Queue Length	Incidence	Average Delay per train in queue (seconds)	Average Dwell Time at Belmont (seconds)	Average Run Time Diversey to Clark Junction (seconds)
No queueing	11	0	66	341
1-train queue	7	73	70	408
2-train queue	4	144	55	443
Queued at X20	7	36	---	---

Table 6-4 Summary of train activity in Table 6-3

6.2.3 Visualization and tower decisions

From studying the time-space plot of Figure 6-17, it seems that the tower operator managed to maintain dwell time control at Belmont for all trains with the exception of trains 2 and 16. The variable run times of Brown Line trains from Belmont to the exit of the junction are indicative of tower operation control over the route assignment at the junction. From these figures it is not known if these high run times were due to:

- tower decisions to move trains out of Belmont to allow followers to move into the station and stage them for service at the home signal of the interlocking (signal X20), or
- tower decisions to advance the trains to the home signal and hold them there while other conflicting trains move through the junction, or
- a combination of both.

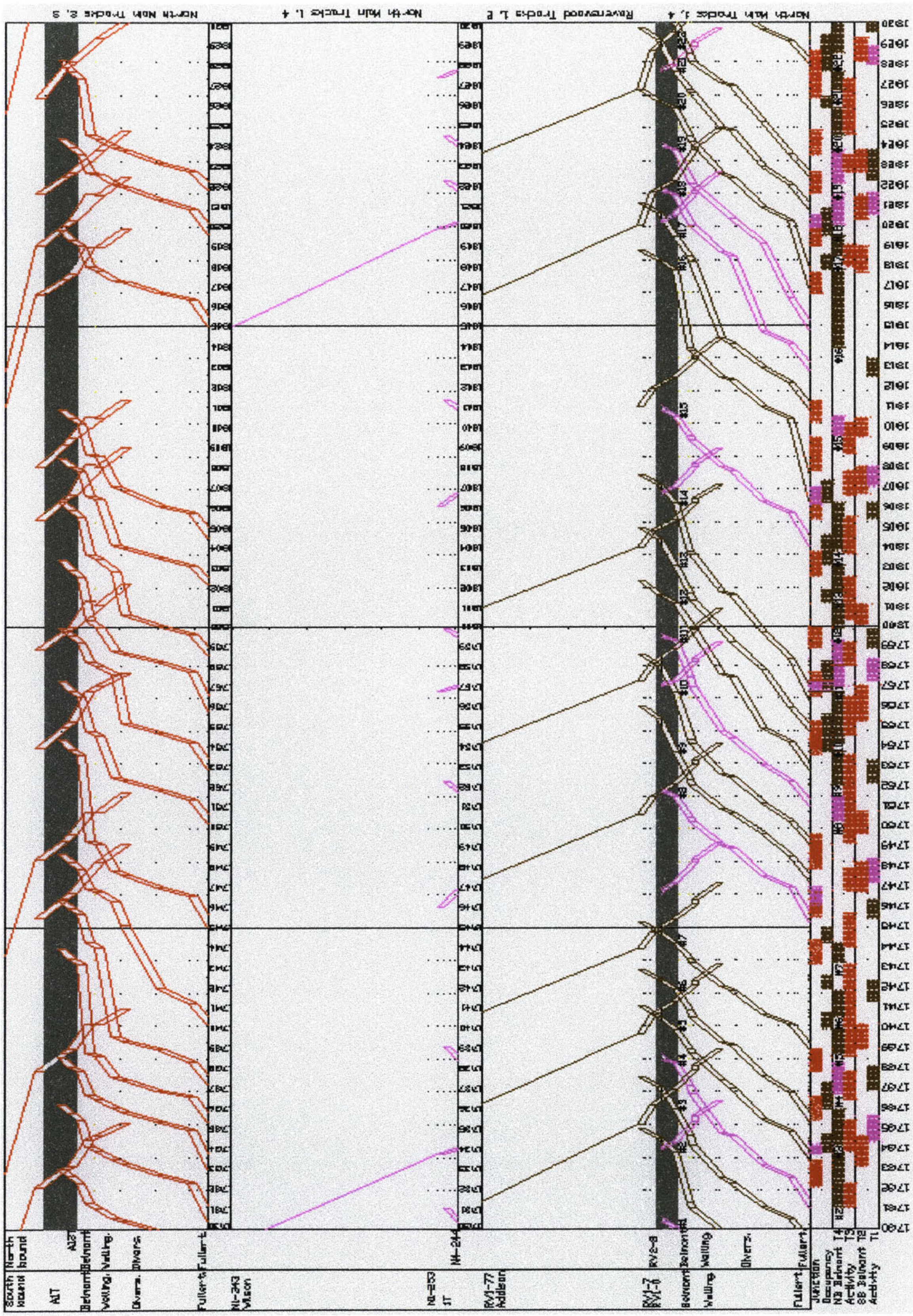


Figure 6-18 Multiple-movement time-space diagram for Table 6-3

Figure 6-18 shows the same multiple-movement time-space diagram as presented in Figure 6-8 with emphasis on the northbound Brown and Purple Line movements. It can be seen from this figure that Brown Line train 2, which triggered the delays of trains 3 and 4, was at Belmont for slightly less than 3 minutes because the northbound Red Line train 1 was assigned a route before the Brown Line train. The excess occupancy at Belmont that generated delays in followers could have been reduced by a partial route assignment to the entrance of the junction, as was done for trains 3, 9, 10, 13, 17 and 21.

Brown Line train 16, also has a very long dwell time at Belmont. From the time-space diagram, it appears that part of this dwell time is attributed to a holding decision at Belmont by the tower operator while a southbound Red Line train was processed at the junction. Such a decision increases the delays for trains 17 and 18.

Some conclusions can be drawn from this example. First, northbound Brown and Purple Line trains arrive in bunches, so dwell time control at Belmont station is critical to avoid queue formation. Second, long dwell times at Belmont should be avoided by partial route assignment of Brown Line trains and cross-platform transfer control for both Brown and Purple Line trains. It is likely that the tower operator was unaware of the bunching situation because the control panel does not display upstream line conditions.

6.2.4 Delays

During evening peak periods, from 4:30pm to 6:30pm, there were an average of 37 trains observed, compared to the 39 trains scheduled. Roughly two out of every three trains are Brown Line trains, which means that there are 25 Brown Line trains and 12 Purple Line trains during every peak period: 12 Brown Line trains and 6 Purple Line trains per hour. A tabular summary of queueing incidence and delays at Belmont is presented in Table 6-5. On average there are 6 trains entering as the first train of a queue, 1 train enters as the second train of a queue and less than 1 train as the third train. The average run times are not very different between trains that are not queued, and trains forming a queue of one or two train lengths. On average, the delays of a queued train are not very different from trains in a two-train queue.

Queue length	Total incidents	Incidents per peak period	Average run time per train Fullerton to Belmont	Average delay per train	Average run time per train Fullerton to Junction
No queue	603	30	312 s	---	373 s
1-train queue	147	6	354 s	64 s	420 s
2-train queue	28	1	411 s	104 s	484 s
3-train queue	8	0	387 s	83 s	465 s

Table 6-5 Summary of northbound Brown and Purple Line delays: July 15, 2002 to August 16, 2002

The additional run time for trains between Belmont and the exit of the junction is between 60 and 80 second. Just like the northbound Red Line delays, the average run times for trains that enter as third trains of the queue is suspect due to the low number of observations. Queues of more than two trains occurred on average once every three days

6.3 Capacity

The capacity of the junction at the crossing point between northbound Red Line trains and northbound Brown Line trains can be determined by considering the junction as a node isolated from the Belmont station. Purple Line capacity is not of interest at this point because it does not have a crossing conflict with other trains at the junction. Capacity on the northbound Brown Line crossing with the northbound Red Line and the southbound service lines has been discussed in Chapter 4 in section 4.4.

During the PM peak period the northbound Red Line and the Brown Line are the highest frequency services through the junction. Red Line trains take about 82 seconds to complete their movement through the junction. This is the total movement time, which as defined in Chapter 2, is the sum of the approach time, the interlocking time and the route-release time. For northbound Brown Line trains, the total movement time through the junction is 74 seconds.

The cycle time for a combination of 1 Red Line train and 1 Brown Line train is calculated at 156 seconds. Therefore the theoretical capacity of the crossing point with a 1:1 routing sequence between Red Line and Brown Line trains will be 23 cycles, which are 46 trains per hour.

82 seconds/Red Line + 74 seconds/Brown Line = 156 seconds per cycle

3600 seconds/hour / 156 seconds/cycle = 23 cycles/hour

Allowing for a 50% buffer in the cycle time, the practical cycle time will be 232 seconds for a capacity of 15 cycles. The 15 cycles indicate that there are a total of 30 trains routed through the crossing point at the junction: 15 Red Line and 15 Brown Line trains. For a two-hour peak period there can be 30 Brown Line trains and 30 Red Line trains routed through the junction.

Currently, there is an average throughput of 28 Red Line trains during the peak period and an average of 25 Brown Line trains. Even with a generous buffer time of approximately 40 seconds per train movement through the junction, there are not as many trains processed as the junction can handle. It is apparent that the crossing point is not a bottleneck for the junction.

6.4 Recommendations

The examples of northbound Red Line queueing and northbound Brown and Purple Line queueing have shown that there are operational improvements that can be achieved from creating or modifying existing operation policies. It has been shown that dwell time activity at Belmont and delays at the station are related in part to the routing practices at the junction.

The following set of recommendations are presented as alternatives to examine for the northbound services at Clark Junction and Belmont station which should be tested individually, although these could be tested simultaneously.

There are two objectives behind the following recommendations:

- Reduce process time at Belmont station
- Increase the effective utilization of the junction

The first recommendations are aimed at reducing the process time at Belmont, which is the delay generator for the northbound movements during the evening peak period. Currently, there are no operation policies to control dwell times at Belmont for northbound services. There is only one routing policy that enforces prioritization of northbound Brown Line trains at the junction when these have been assigned a partial line-up at the junction and there is a follower queueing at Wellington.

Some tower operators apply a first-come-first-served junction discipline dictated by the arrival patterns at the Belmont station between Brown Line trains and Red Line trains, while others assign priority at the junction to Brown Line trains, regardless of arrival sequence at Belmont station.

To understand the effects of the routing practices on Red Line performance, Figure 6-19 shows dwell times in the case of cross-platform transfers based on arrival patterns.

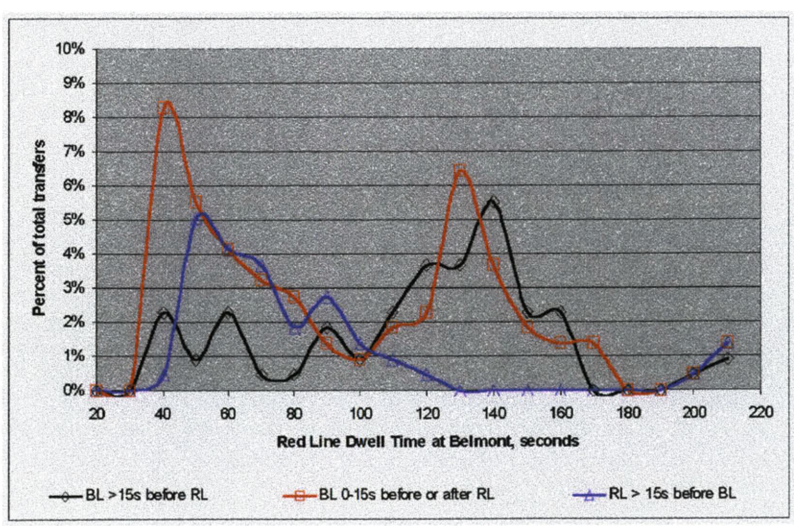


Figure 6-19 Red Line dwell time probability density functions by by arrival at Belmont - exclusively with Brown Line cross-platform transfers

Cross-platform transfers induce higher dwell times at Belmont (see Appendix C for supporting data). Transfers take place frequently – for 40% of Red Line trains and 43% of Brown (Purple) Line trains. Hence it is not reasonable, or indeed desirable, to attempt to eliminate them, but rather the aim is to reduce the number of Red Line trains with dwell times over 90 seconds, particularly those trains which arrive at Belmont at about the same time as Brown Line trains. As will be discussed shortly, Brown Line dwell times do not have as high values as Red Line trains, and these can be controlled through the partial line-up process.

When Red Line trains arrive before Brown Line trains, they generally have lower dwell times, most in the range of 30 to 90 seconds. These trains make up 25% of all Red Line trains interacting with Brown Line trains. In Figure 6-19, this explains the first peak in the probability density function for the series of Red Line trains that arrive within 15 seconds of the Brown Line trains: in these cases the Red Line train is being given priority.

On the other hand, when northbound Brown Line trains arrive at the Belmont station before the Red Line trains, the Red Line trains experience higher dwell times because the Brown Line tends to be given priority at the junction. About 22% of all observed Red Line trains arrive at Belmont after a northbound Brown Line train, and these trains often have dwell times between 100 seconds and 170 seconds. These lower priorities explain the second peak in the probability density function for the series of Red Line trains that arrive within 15 seconds of the Brown Line trains.

On the Brown (Purple) Line service, the effects are not as negative when there are cross-platform transfers as in the case of the Red Line trains. Figure 6-20 shows the probability density functions for similar series of Brown (Purple) Line trains where they arrive at the Belmont station with Red Line trains but with different arrival time offsets.

The dwell time control at Belmont for the Brown and Purple Lines is easily achieved because the trains can be moved out of Belmont station with at least a partial lineup to the entrance of the junction.

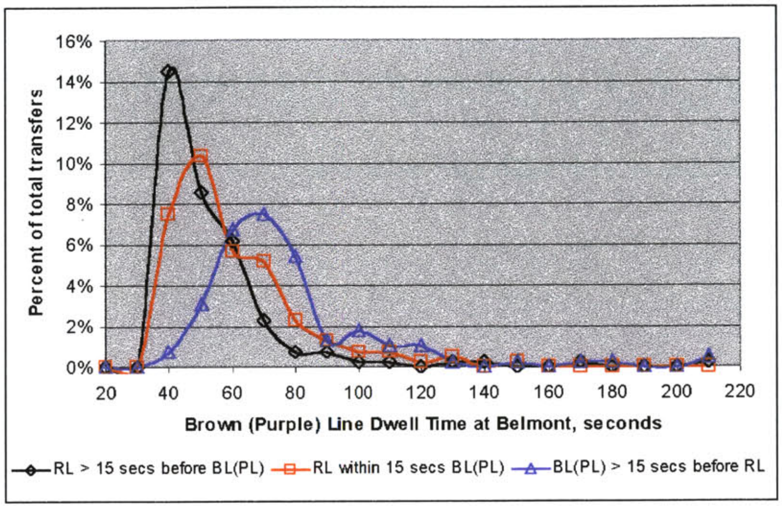


Figure 6-20 Brown (Purple) Line dwell time probability density functions by arrival at Belmont - cross-platform transfers

The proposed operational improvement to control dwell times for Red Line trains at Belmont can be achieved by giving Red Line trains routing priority over Brown Line trains when these arrive at Belmont close together.

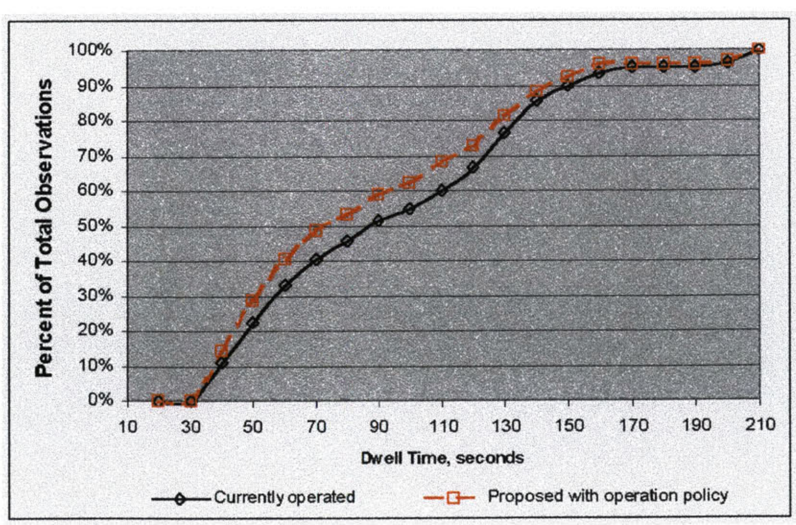


Figure 6-21 Comparison of actual operations with no routing control versus proposed Red Line routing control - exclusively with Brown Line cross-platform transfers

Figure 6-21 shows how the proposed change would hypothetically reduce Red Line dwell times in comparison with actual operations. The figure shows the cumulative distribution function of dwell times for all exclusive Red Line cross-platform transfers with Brown Line trains. With the proposed change, 50% of all Red Line trains having cross-platform transfers with Brown Line trains have dwell times under 70 seconds, as opposed to the current operation where 40% are under 70 seconds.

When Red Line trains are given routing priority over the Brown Line trains, the tower operator has two options for the Brown Line trains: 1) hold the trains at Belmont while Red Line trains move through the junction, or 2) assign a partial line-up to the train at Belmont up to signal X20. It has been found that there are reductions in run times for the northbound Brown Line trains when these are given a partial line-up, as Figure 6-22 shows.

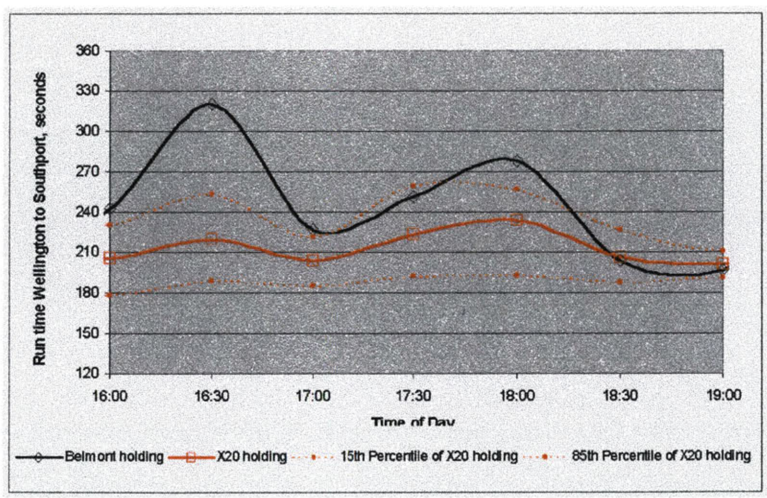


Figure 6-22 Routing alternatives for Brown Line trains without routing prioritization at junction

The recommended strategy for Red Line prioritization through the junction over Brown Line trains can be implemented without negatively affecting Brown Line service. When Brown Line trains are not prioritized, they can be given a partial route to signal X20 when there is a follower at Wellington. When there is no train at Wellington, Brown Line trains can be held at the Belmont station until the Red Line service clears the junction. This should result in significant improvements in Red Line service, in particular headway regularity downstream as trains head to Howard.

The second recommendation seeks to improve the effective utilization of the junction by having more trains using the junction at the same time whenever there are no crossing movements taking place by northbound Brown Line trains. Ideally, the routing prioritization of the northbound Red Line trains should be complementary with routing of southbound Red Line trains, since these have about the same movement time and about the same headway. Thus, the crossings could be used at any time either by northbound Brown Line trains or the combination of Red Line trains. This would lead to a higher effective utilization of the junction because more trains can use the junction over a given period of time. Even though this scheme optimizes the utilization of the resources of the junction, it is more complicated to carry out because it depends on the arrivals of southbound Red Line trains to the junction, and the dwell times of the northbound Red and Brown Line trains.

In summary, for the Red Line prioritization on the first recommendation a set of decision rules would include:

- If Red Line trains arrive at Belmont in tandem with Brown Line trains (within 15 seconds of each other) or Red Line trains arriving more than 15 seconds before the Brown Line train at Belmont, then
  - Assign a full junction route to the northbound Red Line trains and,
  - Assign a partial line-up to Brown Line trains when there is a Brown (Purple) Line follower at Wellington, or if the Red Line train has a follower at the Wellington block in tracks NM3.
- Do not hold Brown Line trains at Belmont for more than one cross-platform transfer.

A set of decision rules for the routing policies to achieve higher effective utilization at the junction on simultaneous Red Line trains moving through the junction would include:

- When northbound Red Line trains have cross-platform transfers with northbound Brown Line trains at the junction, the northbound Brown Line trains will be given priority when,
    - No other crossing movements are programmed at the junction, otherwise
    - Allow the northbound Red Line trains to move through the junction while the southbound Red Line or southbound Purple Line trains are moving through the junction.

As mentioned at the beginning of the sections, these recommendations are presented as separate alternatives for experimentation which can be tested individually or may be tried together.

6.5 Summary

The queueing delays for Red Line service are mainly related to the effects of cross-platform transfers and affect roughly one in every three trains during the PM peak period. Trains in the queues experience delays of more than 60 seconds. Routing practices at the junction, specifically between northbound Brown Line and Red Line trains, can affect dwell times on Red Line trains.

Northbound Brown and Purple Line queueing delays are generated by the activity at Belmont station and could be reduced by facilitating short dwell times when there are followers at Wellington. Queues affect roughly one of every 5 trains, inducing delays of more than 60 seconds. For Brown Line service, the duration of dwell times at the Belmont station can be influenced by decisions of the tower operator to hold the trains at the station while other trains are moving through the junction.

Time-space diagrams have been used to visualize delay propagation at the Belmont station. Multiple-movement time-space diagrams have been used to understand the operating environment at the junction and to identify cross-platform transfers at Belmont station that cause long dwell times and generate queues.

At the crossing point of Red Line and Brown Line service, a practical capacity of 30 trains can be achieved with a one-to-one mix of trains, however, the actual throughput is about 26 trains per hour, suggesting that the junction is not a bottleneck for these service lines. Belmont station acts as a junction entry point for Red Line trains and dwell times are quite high for this service.

Operational improvements can be achieved though dwell time control at Belmont that can be achieved through routing priorities between Red Line and Brown Line trains, partial route line-ups for Brown Line trains during periods of high congestion, and permitting not more than one cross-platform transfer for every train.

Chapter 7 Conclusions

In this chapter, we review the lessons learned from previous chapters. A discussion of the recommendations for Clark Junction follows. Areas of further research are explained in section 7.3. Finally, section 7.4 provides a closing statement to this work.

7.1 Summary

Junctions are studied because they are common among urban rail transit systems and can have significant impacts in line performance. Most of the studies on junction capacity have focused on the intercity railway problems, which may have multiple routing schemes, unlike urban transit systems, which are characterized by static routing patterns.

Junctions are composed of a series of interlockings that are used by trains traveling between different origins and different destinations. Signals are present at junctions to control the entry of trains to the interlockings and are used to guide the train to its destination path. Audio-Frequency and Power-Frequency track circuits form the electrical component of the junctions which enable Automatic Train Control, Automatic Train Protection and Automatic Train Supervision. The design of the Automatic Train Protection system is a critical determinant of the total movement time of trains at junctions. Capacity is determined as the number of cycles in which two conflicting train routes, or a combination of conflicting train routes can be run through the junction. Each cycle is the sum of movement times for each train sequenced within a cycle. Studies have shown that the practical capacity, based on the additional buffer time that is required per cycle to allow a junction to operate properly, is roughly between two-thirds and 70% of the theoretical capacity.

A methodology has been presented to measure the performance of a junction by determining delays and queues. Utilization rates at nodes, defined as the occupancy of a train at the node divided by the cycle time of the process at the node, can be used to identify increases in waiting time to enter the nodes, and the reoccupancy times are inversely related to utilization rates. Queueing and delay propagation can be identified visually through the use of time-space diagrams. Merging and diverging movements can be visualized in time-space diagrams if the branches are presented separately. At junctions, it may be necessary to represent a particular section of track, for which a time-block (block occupancy) diagram is a helpful visual tool. These diagrams can be combined to form a multiple-movement time space diagram, which represents train progressions from different origins and destinations traveling through a shared section of track, such as a crossing.

The Chicago Transit Authority Clark Junction is presented as a case study for application of the methods presented. Clark Junction is a flat junction with four trunk tracks and two turnout tracks branching to Ravenswood, connecting with the outer southbound tracks and the inner northbound tracks. There are three service lines operating through the junction – Red Line, Brown Line, and Purple Line - with six different train movements routed during morning and afternoon peak period operations. Located immediately south of the junction, Belmont station are two island platforms that each services the Red Line on one end of the platform and the Brown and Purple Lines on the other end of the platform. These stations are overlapping with the junction entry and exit points. The route assignment is a relay-based manual operation from a tower overlooking the junction. Operation policies for the Clark Junction are created and used as standards by tower operators to assign routing priorities and dwell time control at Belmont station. A new configuration at the junction would allow faster operating speeds through the junction, but would not eliminate some of the core problems of the junction – the influence of dwell times at Belmont station on the throughput of crossings and merge point.

It has been found that the merging point of southbound Brown Line and Purple Line service produces queues and delays for approaching Brown Line trains. However, at this merging point, the service process is controlled mainly by the dwell time activity of southbound Brown and Purple Line trains at Belmont station. The dwell time activity at

Belmont has been found to be longer than the processing time of trains through the junction, particularly when Brown or Purple Line trains are berthed at the station simultaneously with southbound Red Line trains. The practical capacity at the merge point of southbound Brown Line and southbound Purple Line service is about 36 trains per hour, based on the 2-to-1 ratio of Brown Line to Purple Line service frequencies. The actual throughput is about 22 trains per hour, suggesting that the merge point is underutilized and is not a capacity constraint for Brown or Purple Line service.

For the northbound services, the primary conflict occurs at the crossing between Red Line and Brown Line trains. There is a practical capacity of 30 trains per hour at this crossing point, but the actual throughput during the PM peak period is about 26 trains per hour. Hence, the crossing is not a capacity constraint for Red Line and Brown Line services. Belmont station acts as the entry point of the junction for northbound Red Line and informally for northbound Brown Line trains. The dwell times at Belmont are quite high for Red Line service, particularly when there are cross-platform transfers and when Brown Line trains are prioritized at the junction. These conditions cause queueing and delays for about one of every three trains. Queues also affect Brown and Purple Line services for approximately one out of five trains.

7.2 Recommendations

The proposed new configuration includes some operational modifications that will reduce travel times for trains and also provide a moderate increase in throughput at the junction. The new configuration would permit southbound approaches to Belmont station from track NM1 to queue at the entrance of the junction. However, this configuration would leave the routing process as is, without providing a queueing location after the merge point for trains waiting for service at Belmont. This problem can be partially solved by subdividing block sections between the interlockings and Belmont station to allow a closer approach of trains to the station that will permit the tower operator to release their routes and assign routes to other trains.

On the southbound tracks NM2, the Red Line trains also have to queue at the entrance of the junction for service at Belmont station. A modification of the junction configuration where the double crossover connecting tracks NM2 and NM3 is placed at the block immediately north of Belmont station, would allow the home signal to this interlocking to be used as the home signal of Belmont station, while separating the crossing conflict between northbound Brown Line trains and southbound Red Line trains from the station activity. With southbound Red Line and Brown (Purple) Line trains queueing for service to Belmont at the same distance from the station, these can arrive simultaneously to the junction, thus presenting remarkable improvements in the dwell times at Belmont.

Operation policies are suggested for the northbound Red Line and northbound Brown Line service to modify routing preferences and control dwell times of Red Line trains at Belmont station. The current practice of assigning Brown Line trains a path through the junction before the northbound Red Line trains when these arrive simultaneously at the Belmont station generates high dwell times for Red Line trains that can exceed 120 seconds. A routing prioritization of Red Line trains would reduce dwell times of these trains at Belmont without generating delays in Brown and Purple Line service. This will lead to a reduction in dwell time at Belmont, which is the delay generator. A higher utilization of the junction can be achieved by routing southbound Red Line trains in tandem with the northbound Red Line trains. Northbound Brown Line trains will not experience higher dwell times at Belmont because these can be assigned a partial lineup to signal X20. In the event of followers to the northbound Brown Line train, they can move into Belmont station which would be a violation of the Automatic Train Protection, but it can be carried out in a restricted mode of operation, as is commonly practiced now.

7.3 Further Research

There are a some areas where further research can help understand further the effects of stations on performance of junctions and also line performance.

The phenomenon of cross-platform transfers where trains berth simultaneously at both sides of platforms is understood from a block occupancy and arrival perspective. A dwell time model to predict dwell times at the station would require a lot of information, such as boardings, alightings, number of boarding passengers that have transferred, load on the trains, and passenger load on the platform. At the platform level, there is not sufficiently detailed information available on how many passengers do cross-platform transfers per train, or per car. The CTA is currently developing a load profile model which can provide detailed information on train loads at many points of the alignments. This development could help understand how much congestion is inside the trains, and with an automatic passenger counter technology, coupled with the SCADA data, a dwell time model for the Belmont station could be more feasible to develop.

At the Chicago Transit Authority, there are other junctions with some of the same complexities of the Clark Junction. Tower 18 junction, located at the northwest corner of the loop, is a crossing point for four different service lines. There are stations adjacent to the junction at 3 of the 4 approaches of the junction. Similarly, tower 12 has the same traffic that Tower 18 has, but the routing of trains takes place differently and the junction has three approaches. The Howard junction is a complex set of interlockings with a station that acts as a terminal for the Red Line, the Yellow Line and the Purple Line. For Purple Line service, the Howard station acts as station during AM and PM peak periods, when these trains are expressed to Belmont station.

7.4 Closure

Junctions have been studied in this thesis to understand one of the components of rail capacity. Although these may not be present in every urban rail system, it is important to understand that junctions can become capacity constraints for service branches. Even though urban rail agencies tend to build junctions nearby stations, it has been shown that this practice can become a constraint for transit agencies seeking to increase capacity in their systems. It has been shown that systems operating over practical capacity levels are bound to experience increases in run time, which effectively reduce the efficiency of the resources and decreases the quality of service.

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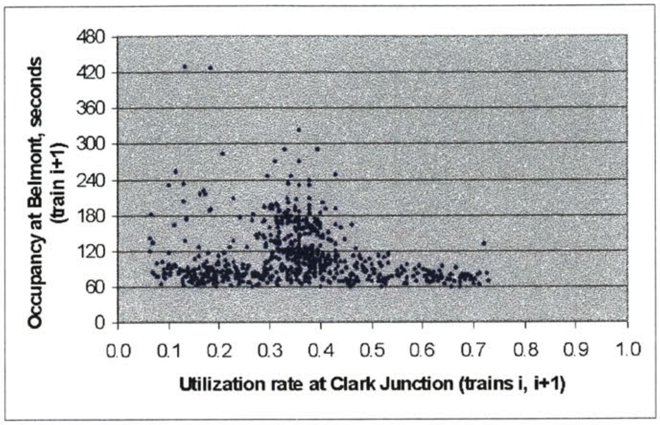
Appendix A

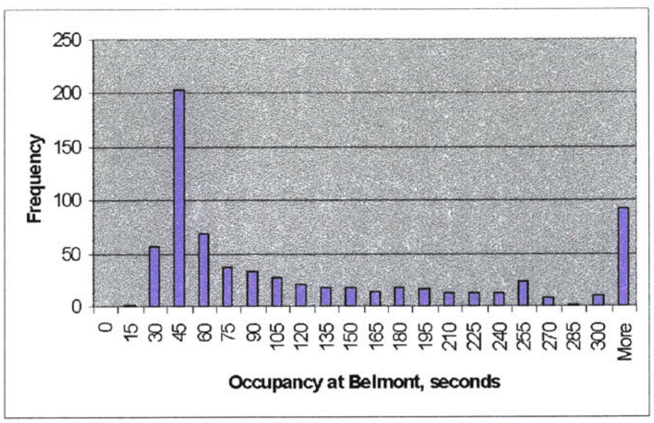
Terminology for SCADA

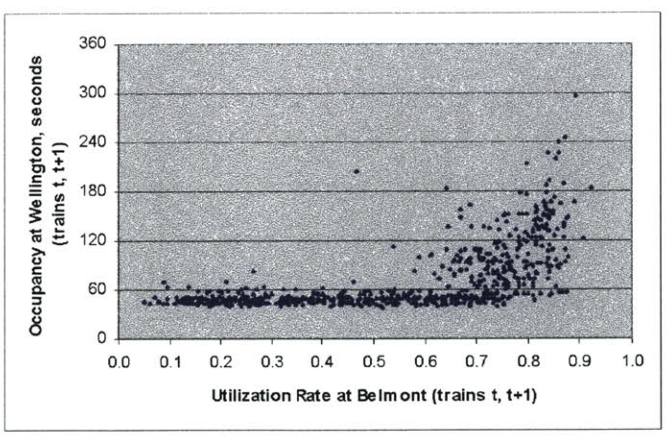
1. $ON_{SCADASTATUS}$: Event in every track circuit where a relay drop is caused by an interruption in the transmission of current through the running rails. This event is usually caused by a train entering the track circuit, but may also be caused by EMI.
2. $OFF_{SCADASTATUS}$: Event in every track circuit where a relay pick-up is caused by the current flow in a track circuit. This event always happens after a relay drop.
3. Occupancy: A property of track circuits, it is the elapsed time at a track circuit from the SCADA ON event to the SCADA OFF event caused by a train i moving through the block of the track circuit.
4. Reoccupancy: A property of track circuits, it is the elapsed time at a track circuit from SCADA OFF event for train i to the next SCADA ON event for train $i+1$.
5. Headway: A property of track circuits, it is the elapsed time at a track circuit from the event SCADA ON caused by the movement of train i through the track circuit to the next SCADA ON caused by the movement of train $i+1$ through the track circuit.
6. Utilization Rate: A property of track circuits, it is the rate of the occupancy of train i to the headway at the track circuit between trains i and $i+1$.
7. Run Time: A property of trains, it is defined as the elapsed time between two track circuits TC_t and TC_{t+1} for train i. Depending on the information desired, it can be defined by SCADA ON for each circuit, or SCADA OFF for each circuit, or it can be defined from SCADA OFF at TC_t to SCADA OFF at TC_{t+1}.
8. Δ Reoccupancy: A train-track circuit property, it is defined as the difference in reoccupancy between track circuit TC_t and track circuit TC_{t-1} for two consecutive trains i and $i+1$. A positive value will indicate an opening gap in service. Conversely, a negative value indicates a closing gap in service.

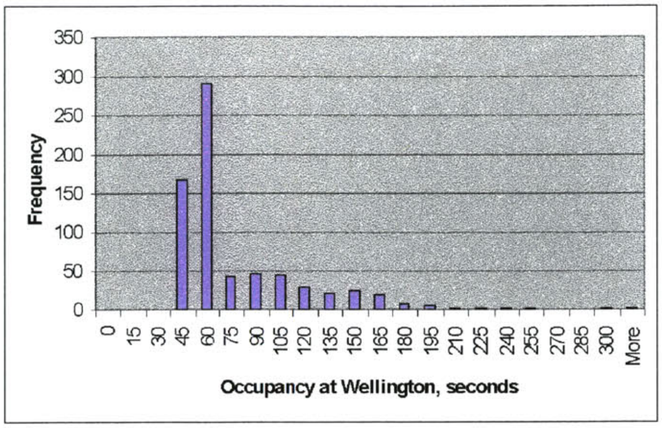
Appendix B

B.1 Queueing relationships on track NM3





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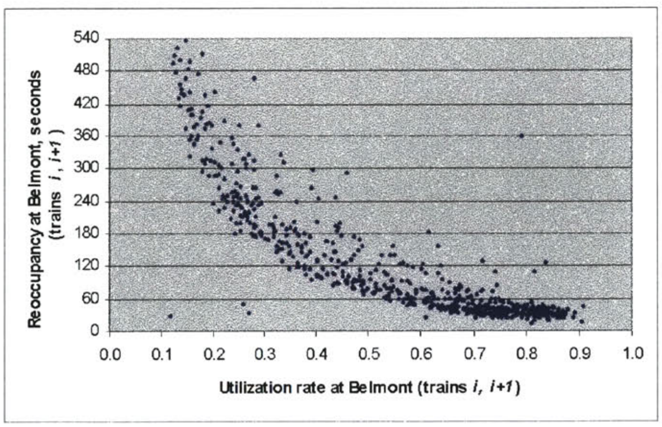
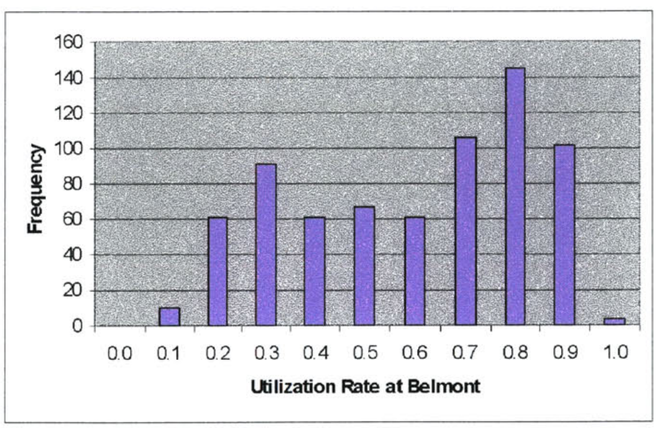
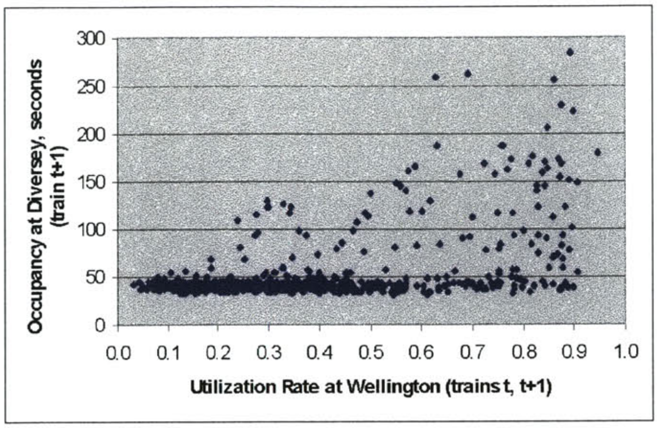
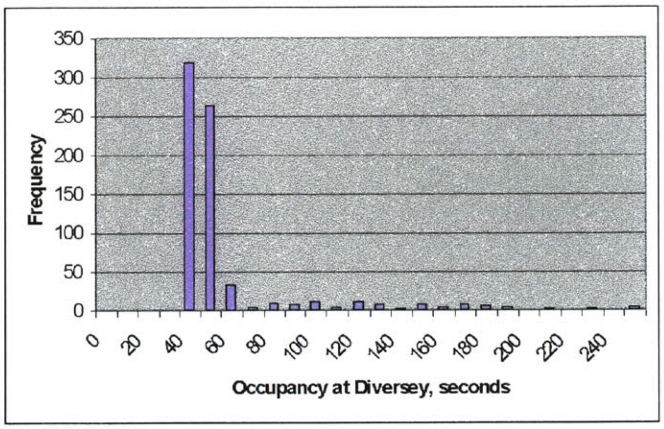
300
250
200
150
100
50
0
Frequency
0
15
30
45
60
75
90
105
120
135
150
165
180
195
210
225
240
255
270
285
300
More
Occupancy at Wellington, seconds


540
480
420
360
300
240
180
120
60
0
Reoccupancy at Belmont, seconds (trains i, i+1)
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
Utilization rate at Belmont (trains i, i+1)

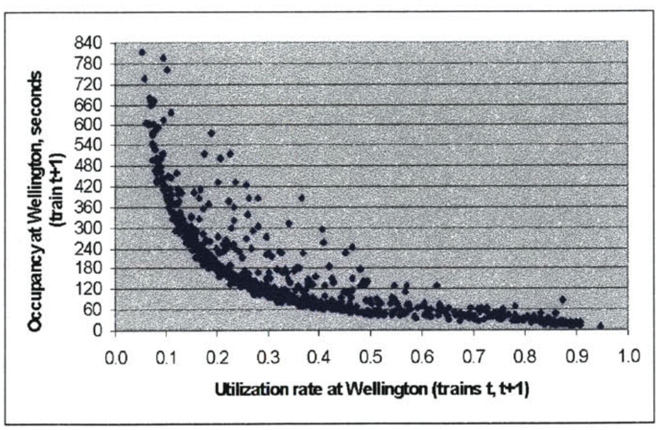

160
140
120
100
80
60
40
20
0
Frequency
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
Utilization Rate at Belmont



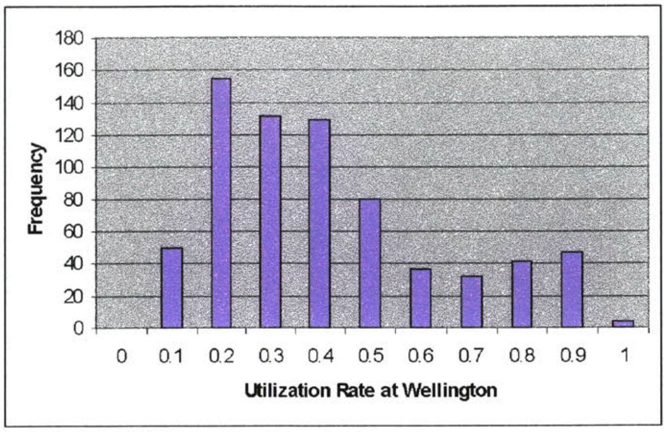
300
250
200
150
100
50
0
Occupancy at Diversey, seconds (train t+1)
0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0
Utilization Rate at Wellington (trains t, t+1)

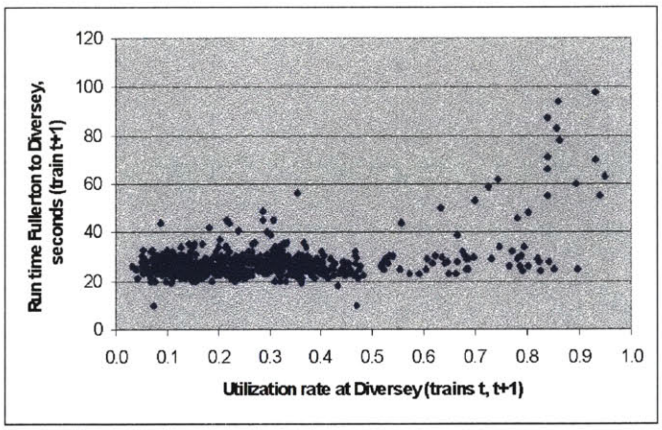


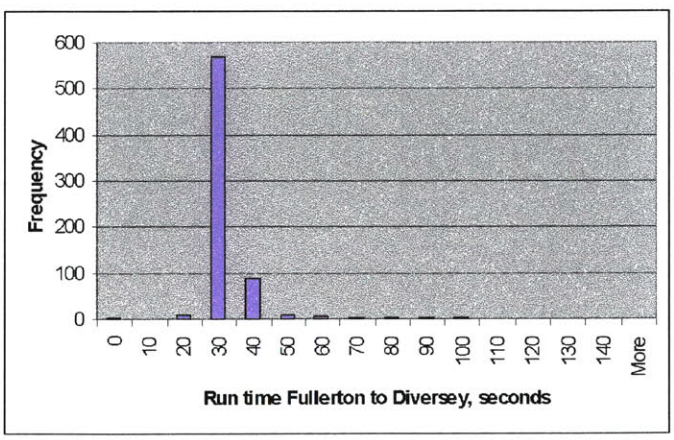
350
300
250
200
150
100
50
0
Frequency
0 20 40 60 80 100 120 140 160 180 200 220 240
Occupancy at Diversey, seconds

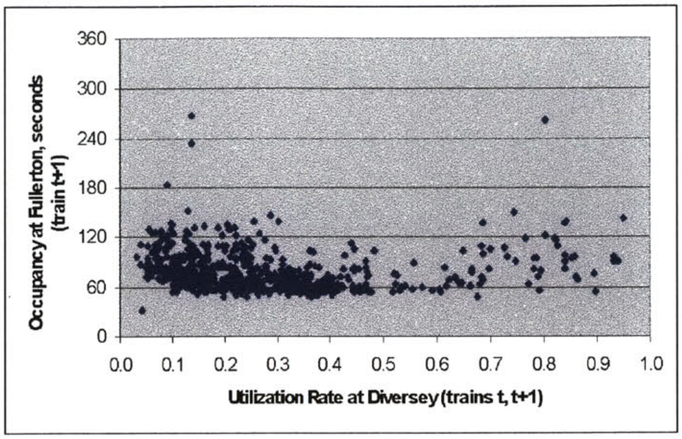


840
780
720
660
600
540
480
420
360
300
240
180
120
60
0
Occupancy at Wellington, seconds (train t+1)
0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0
Utilization rate at Wellington (trains t, t+1)

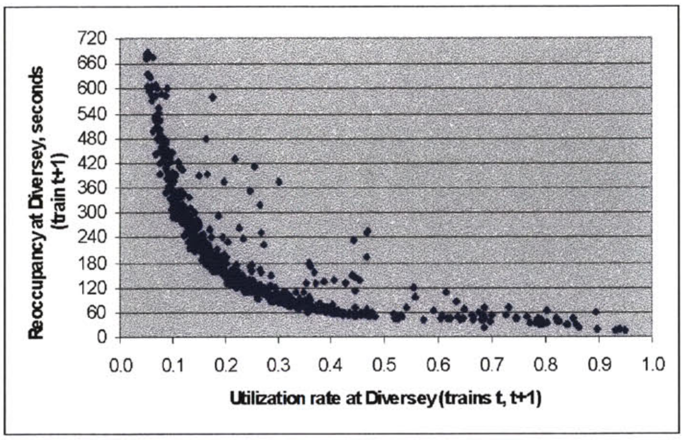

Frequency
0
20
40
60
80
100
120
140
160
180
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Utilization Rate at Wellington


Run time Fullerton to Diversey, seconds (train t+1)
0
20
40
60
80
100
120
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
Utilization rate at Diversey (trains t, t+1)

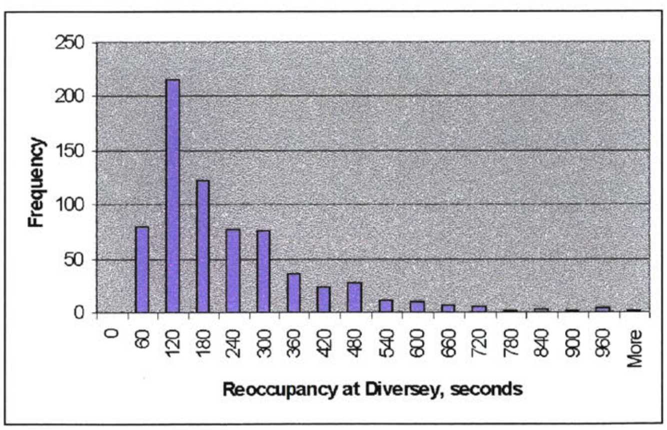

Frequency
0
100
200
300
400
500
600
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
More
Run time Fullerton to Diversey, seconds



360
300
240
180
120
60
0
Occupancy at Fullerton, seconds (train t+1)
0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0
Utilization Rate at Diversey (trains t, t+1)

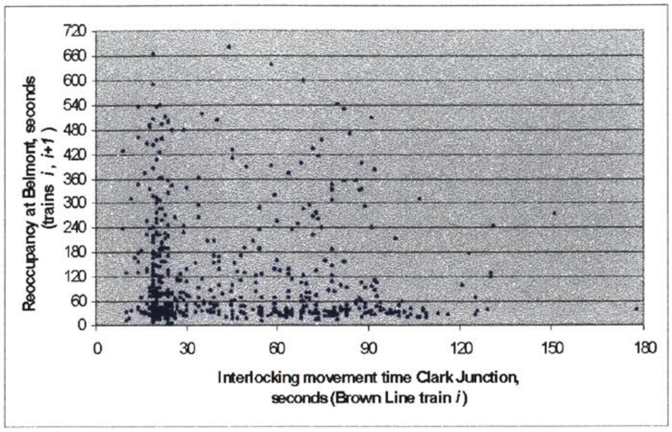


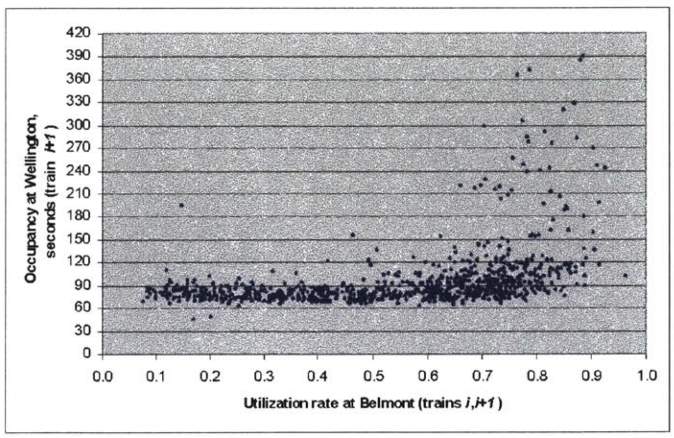
720
660
600
540
480
420
360
300
240
180
120
60
0
Reoccupancy at Diversey, seconds (train t+1)
0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0
Utilization rate at Diversey (trains t, t+1)

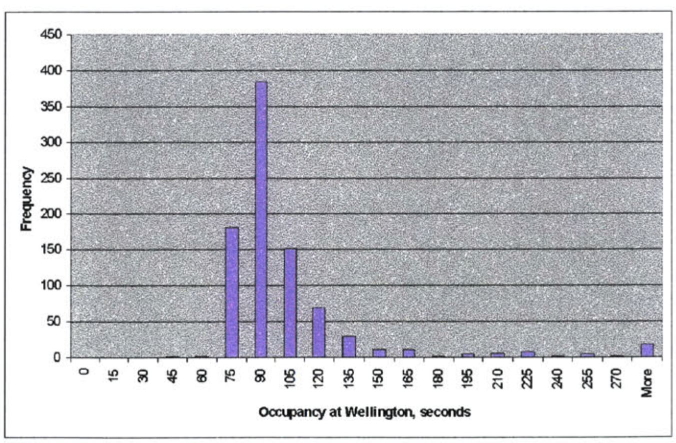


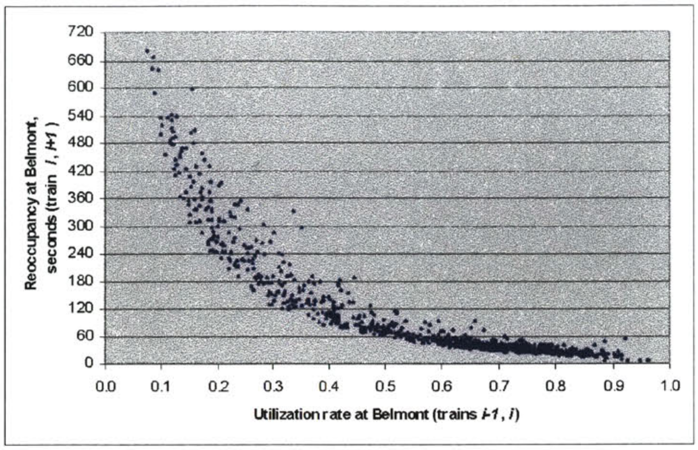
250
200
150
100
50
0
Frequency
0 60 120 180 240 300 360 420 480 540 600 660 720 780 840 900 960 More
Reoccupancy at Diversey, seconds

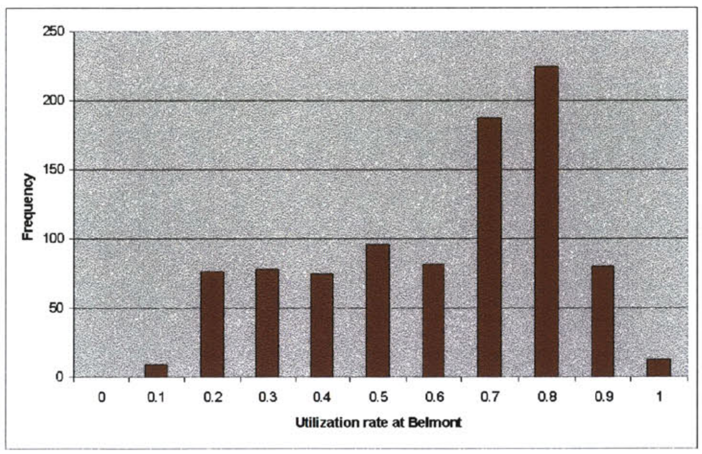
B.2 Queueing relations on track NM4

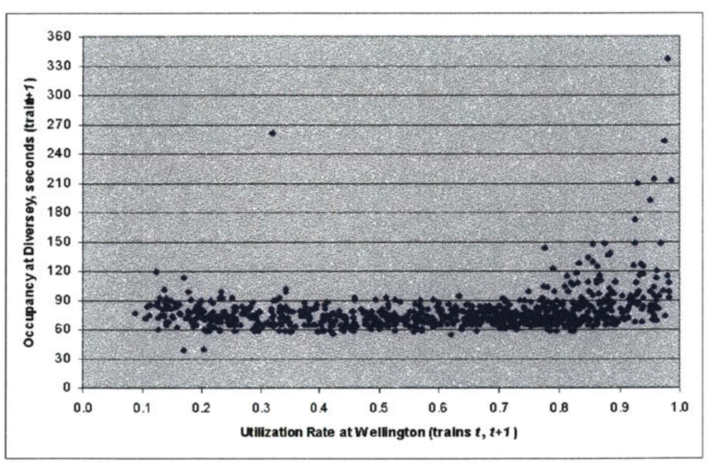


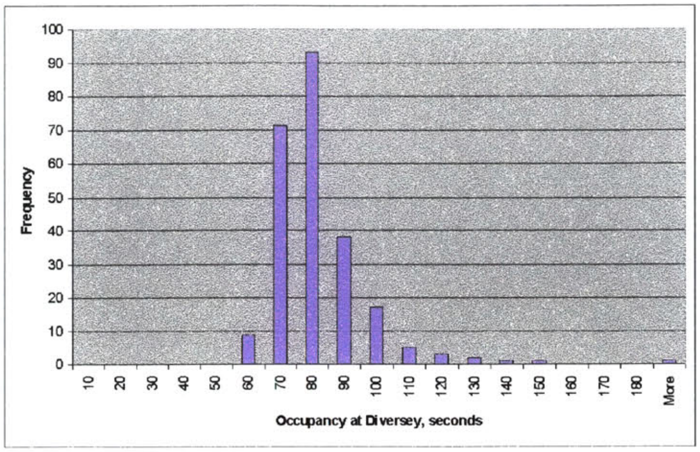


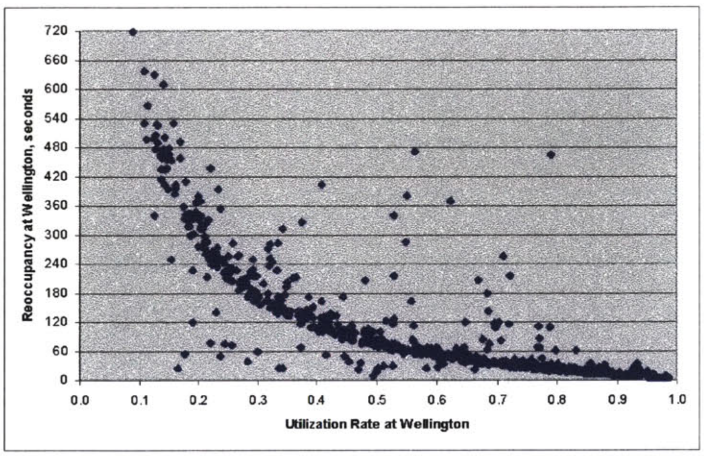


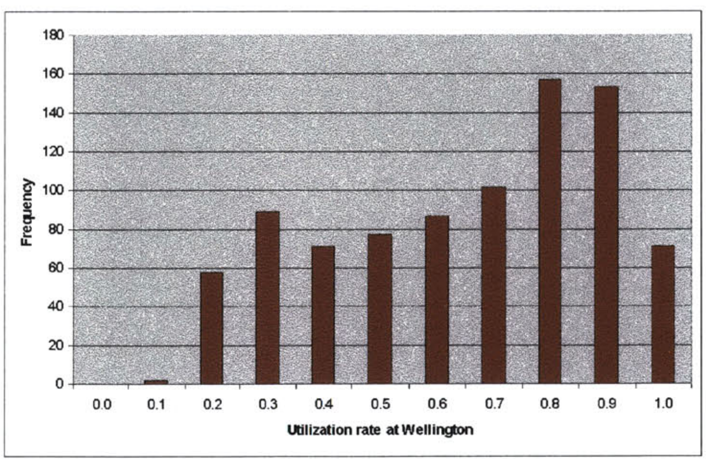

Reoccupancy at Belmont, seconds (train i, i+1)
Utilization rate at Belmont (trains i-1, i)
720
660
600
540
480
420
360
300
240
180
120
60
0
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0

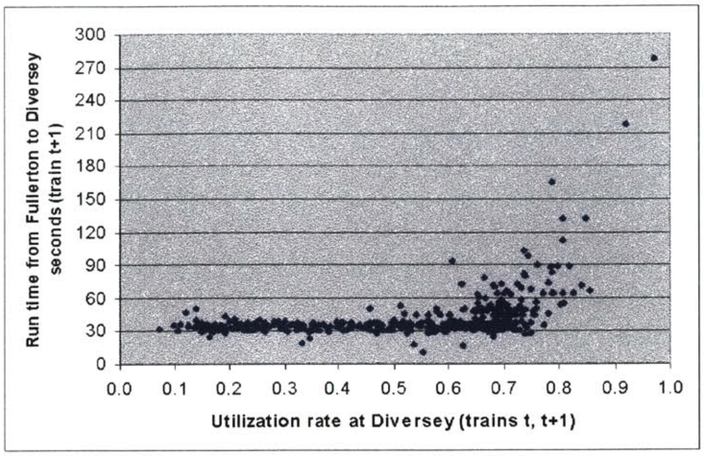

Frequency
Utilization rate at Belmont
250
200
150
100
50
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1

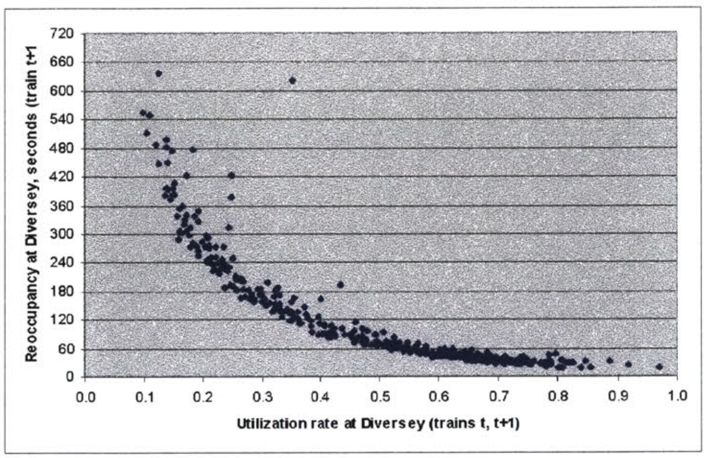

Occupancy at Diversey, seconds (train t+1)
Utilization Rate at Wellington (trains t, t+1)
360
330
300
270
240
210
180
150
120
90
60
30
0
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0


Frequency
Occupancy at Diversey, seconds
More


Reoccupancy at Wellington, seconds
Utilization Rate at Wellington

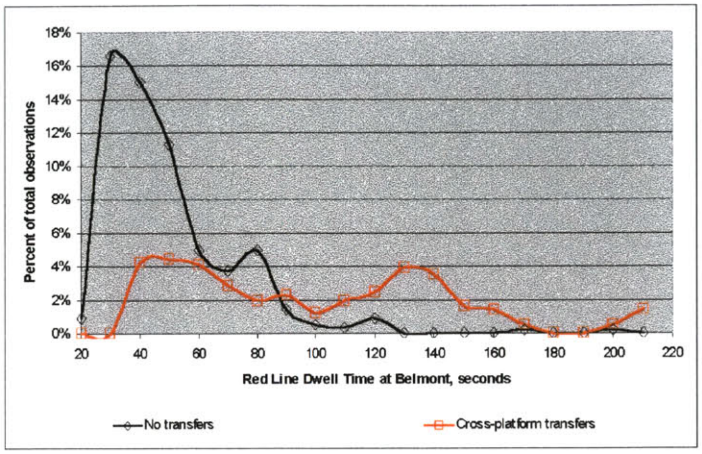

Frequency
Utilization rate at Wellington

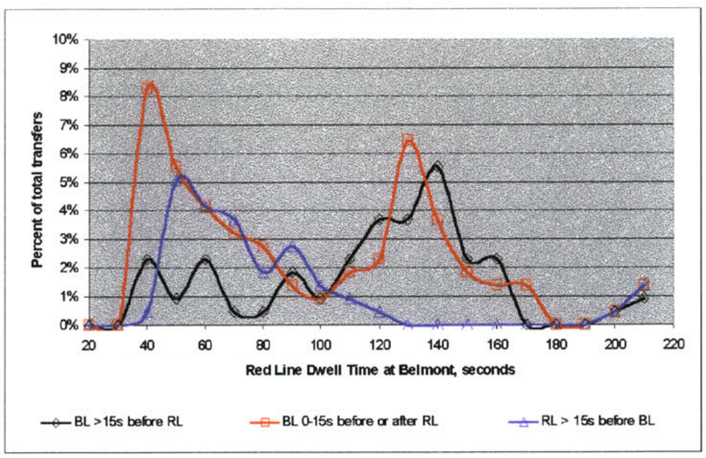

Run time from Fullerton to Diversey seconds (train t+1)
Utilization rate at Diversey (trains t, t+1)

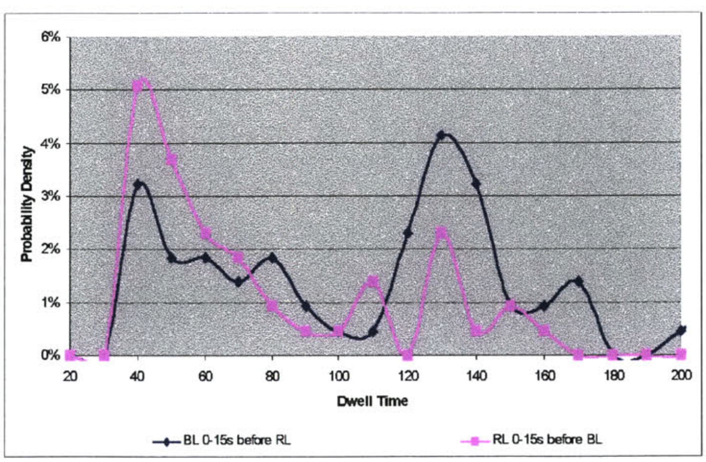

Reoccupancy at Diversey, seconds (train t+1
Utilization rate at Diversey (trains t, t+1)

Appendix C

C.2 Northbound Red Line distributions







C.2 Northbound Brown (Purple) Line distributions