Capacity Analysis of the Union Station Rail Corridor using Integrated Rail and Pedestrian Simulation

by

Yishu Pu

A thesis submitted in conformity with the requirements for the degree of Masters of Applied Science
Department of Civil Engineering
University of Toronto

© Copyright by Yishu Pu 2017
Abstract

The capacity evaluation of railway station areas is essential for accommodating future growth in demand and new rail services.

Conventional capacity analysis methodologies (analytical, optimization) have limitations due to oversimplified assumptions. While simulation tools have proven effective in analyzing complex station areas, the interactive effects between pedestrian and train movements are hardly captured properly.

The study analyzed representative analytical and railway simulation methods, and applied an integrated simulation platform – Nexus (connected with OpenTrack and MassMotion) – to perform a comprehensive capacity analysis of the Union Station Rail Corridor. A 9% drop in on-time performance was observed and passengers’ average duration at LOS F tripled with the increase of train and passenger volumes. Both length and variation of dwell time due to pedestrian movement were recognized as the main factors of performance deterioration. The study also reveals the applicability and benefits of using such integrated simulation tools in other complex transit systems.
Acknowledgements

There have been many times people looked shocked when they learnt that this is actually my second master degree. Well, that is true. I did my first master in Industrial Engineering at the University of Windsor, worked in a logistics firm in Windsor for three years before I moved to the 6ix. Why? I realized I love transporting people, and Toronto happens to have a lot of people. Oh, and yes, a big, complicated and amazing transit system too.

It is not easy to make up a mind and change a career path after spending three years in a different industry. I am extremely lucky that I have a family that is always there to support me all the way through, even though we are thousands of miles apart. I would like to give my biggest thanks to my Mom, Fan Jiang; Dad, Jianxin Pu; grandma, Yuping Jiang; and grandpa, Daan Ge, for raising me up and providing me with guidance and suggestions at every critical turn of my life. Thank you for standing by me, and backing me up with my decisions to chase my dream. I would also like to thank Mr. George Randall, my previous manager and my friend at Moe’s Transport in Windsor, for encouraging me to take the opportunity and offering me all your endorsements. It was my greatest pleasure to work for you and an amazing experience that I would never forget.

Now that I am here wrapping up my thesis, there are a few people that I would like to take a moment to appreciate. Firstly, thank you Professor Amer Shalaby for picking me as your student two years ago, believing in me, and offering me such a wonderful project to work on for my master thesis. Thank you for your guidance, suggestions and valuable inputs along the span of this project. Secondly, I would like to thank Siva Srikukenthiran for creating the Nexus platform and continue to offer me help every time I ran into problems, no matter it was at the middle of the night or on a weekend. I would also like to express my gratitude to all of the students who helped with data collection for this project, and especially Siyu Lin, who had already built a solid foundation of the models when I started the project. Without any of you, this project would not be possible.

I still remember when I made my decision to apply for this second master, I told myself that it was not going to be easy, but this could be the chance that I would be able to finally go for a career that I had always been dreaming about, and I would try my best to conquer it. It turned out that it was indeed not that easy. Fortunately, I met a bunch of awesome friends during the program at the lab and office: Greg Lue, Paula Nguyen, Bo Wen, Greg Hoy, Wenxun Hu, Teddy Lin, Moein Hosseini, Nancy Hui, Mahyar Jahangiriesmaili, Adam Weiss, Sami Hasnine, Ehab Diab, Stephanie Pham, etc. Thank you for being my friends, helping with each other and all those fun chats and conversations. Two years flew by, but hey look! We made it through, right?

Sometimes it is a gift to have friends who are willing to stick around and fight with you. I have known Shan Wu and Xiaoteng Yang since the first day I came to this country. We grew and explored the unknown land all together and helped each other. To Shan, I could not imagine a life without your company and support, especially during the time when we were both in Windsor. Life moves on, I believe everything is always going to be better if we try harder and become stronger, I believe in both of you, our friendship, and I would like you to know how important you are to me.
The biggest surprise is to meet Omar Omari and Jacek Khan at the University of Toronto. We were not in the same program, but we are bonded with magic. I would never forget all the amazing time we had together at the gym, running around downtown Toronto and Pokémon Go Hunting at the middle of the night. You guys have taught me a lot, and I really appreciate the enormous supports I have had from you. Especially Omar, my roommate and my best best friend, thanks for sticking around with me as well as all those adventures and journeys we have shared together. You know how much you mean to me, and how much I mean to you (you better anyway).

Last but not least, I would like to thank ARUP, NSERC, University of Toronto and Metrolinx for providing us with data, technical and financial support. Again, this project would not be possible without your kind endorsements.

I know I may have spent a lot of time in school or taking some detours, but all these experiences count. I am glad that I am finally on this path doing transportation, and I have no regrets of going down this road. To me, it is never too late to chase the dream. Glad that I chose to come to this country six years ago. It has been a long great journey, I am happy that I made it, actually I am happy that all of us have made it. I feel so lucky to have met all of you along this road, and I truly believe that I would not have become the person that I am right now without you. So, thank you all!

September 2017
# Table of Contents

Abstract ................................................................................................................................. ii
Acknowledgements ............................................................................................................... iii
Table of Contents .................................................................................................................. v
List of Tables ........................................................................................................................ viii
List of Figures ....................................................................................................................... ix
List of Appendices ............................................................................................................... xi
Glossary ............................................................................................................................... xii

## 1 Introduction

1.1 Background ..................................................................................................................... 1
  1.1.1 Main Concerns ........................................................................................................... 2
  1.1.2 Train Movements ..................................................................................................... 2
  1.1.3 Pedestrian Movements ............................................................................................ 2
  1.1.4 Interactive effects between train movements and pedestrian movements .......... 3
  1.1.5 Current capacity analysis practices ........................................................................ 3

1.2 Research Objectives ....................................................................................................... 3

1.3 Methodology .................................................................................................................. 4

1.4 Thesis Outline ............................................................................................................... 5

## 2 Literature Review

2.1 Capacity Definition ....................................................................................................... 6
  2.1.1 Theoretical Capacity ............................................................................................... 6
  2.1.2 Practical Capacity ................................................................................................... 6
  2.1.3 Used Capacity ......................................................................................................... 6
  2.1.4 Available Capacity ................................................................................................ 7
  2.1.5 Line Capacity, Node Capacity and Person Capacity ............................................... 7

2.2 Capacity Analysis Methods ......................................................................................... 7
  2.2.1 Analytical Methods ............................................................................................... 8
  2.2.2 Optimization Methods ........................................................................................... 9
  2.2.3 Simulation Methods ............................................................................................. 9

2.3 Dwell Time .................................................................................................................... 10

2.4 Pedestrian Modelling ................................................................................................. 11

2.5 Multi-modal Simulation ............................................................................................... 13

2.6 Reliability and Quality of Service .............................................................................. 14

2.7 Discussion and Comments ......................................................................................... 16
7.2 Passenger Alighting Behavior Modeling ................................................................. 69
  7.2.1 Problem Statement ......................................................................................... 70
  7.2.2 Relative Research ......................................................................................... 73
  7.2.3 Method ........................................................................................................... 75
  7.2.4 Model Construction ....................................................................................... 77
  7.2.5 Model Validation ......................................................................................... 78
  7.2.6 Model Implication ....................................................................................... 80
7.3 MassMotion ........................................................................................................... 81
  7.3.1 Model Setup .................................................................................................... 81
  7.3.2 Model Calibration and Validation ................................................................. 82
7.4 Nexus ..................................................................................................................... 84
  7.4.1 Model Construction ....................................................................................... 85
  7.4.2 Model Calibration and Validation ................................................................ 87
7.5 Evaluating System Performance ........................................................................... 89
8  Nexus Scenario Tests ............................................................................................... 91
  8.1 Scenario specifications ...................................................................................... 91
  8.2 Nexus Results and Discussion ......................................................................... 93
    8.2.1 Passenger Volume and Train Performance ................................................. 95
    8.2.2 Passenger Volume and LOS ................................................................. 96
    8.2.3 Further Scenarios ..................................................................................... 101
9  Conclusion, Contribution and Future Work ........................................................... 103
  9.1 Conclusion ......................................................................................................... 103
  9.2 Contribution ..................................................................................................... 104
  9.3 Future work ....................................................................................................... 106
References .................................................................................................................. 108
Appendix A: Maximum Speed Limit for USRC Area ................................................ 114
Appendix B: Current Timetable (for morning peak) .................................................. 115
Appendix C: The values pf parameters used to calculate the headways for TCQSM .... 116
Appendix D: Occupation and Interdiction Time for Analytical Methods ................. 117
Appendix E: Application and Conversion of Alighting behavior for Centralized Train Portal ........................................................................................................ 118
Appendix F: Passenger Volume Calculation for Nexus Scenario Tests ....................... 120
List of Tables

Table 2.1 LOS for Fruin Platforms and Fruin Stairways (Kittelson & Associates, Inc. et al., 2013) ............. 16
Table 3.1 Stations Involved in the Case Study and Distances to Union Station ........................................... 20
Table 3.2 Number of Trains for Services Entering Union Station ................................................................. 22
Table 5.1 Compatibility Matrix (Malavasi et al., 2014) .................................................................................. 32
Table 5.2 Total Train Trips on Each Path ......................................................................................................... 32
Table 5.3 Matrix of Occupation/Interdiction Times (Malavasi et al., 2014) ...................................................... 33
Table 5.4 Priority Matrix ................................................................................................................................. 36
Table 5.5 Train Path and Switch Definition .................................................................................................... 38
Table 5.6 Results for Current Schedule using Potthoff Method ...................................................................... 40
Table 5.7 Results for Current Schedule using DB Method .............................................................................. 40
Table 5.8 Number of GO Trains at Capacity .................................................................................................. 41
Table 5.9 Capacity Indicators for Potthoff Method ......................................................................................... 41
Table 5.10 Capacity Indicators for DB Method ............................................................................................... 41
Table 5.11 Matrix of Occupation/Interdiction (International Union of Railways, 2013) ................................. 45
Table 5.12 Sequence of Train Paths as Indicated by the Timetable (Malavasi et al., 2014) ............................ 45
Table 5.13 Inserting Train Paths for Occupancy Time Calculation in a Node .................................................. 46
Table 5.14 Finding the Number of Concatenations .......................................................................................... 48
Table 5.15 Results for Current Schedule using Compression Method ........................................................... 49
Table 5.16 Results for Capacity Evaluation using CC and OTR ..................................................................... 50
Table 5.17 Capacity Analysis Results using Three Methods .......................................................................... 51
Table 5.18 Impact of Adding 1 VIA Trip with Analytical Methods ................................................................. 52
Table 6.1 Statistical Analysis for Departure Delay .......................................................................................... 59
Table 6.2 Current Scheduled Travel Time ..................................................................................................... 63
Table 6.3 Result Comparison between Compression Method and OpenTrack ............................................... 65
Table 7.1 Average and Standard Deviation of 4 segments of Dwell Time ...................................................... 68
Table 7.2 Statistical Analysis Results for the Three Variables ....................................................................... 76
Table 7.3 Correlations among Variables ........................................................................................................ 77
Table 7.4 Alternative Models for Passenger Alighting Model ...................................................................... 77
Table 7.5 GEH Evaluation Rule (Wisconsin, 2002) ......................................................................................... 83
Table 8.1 Scenario Configurations .................................................................................................................. 93
List of Figures

Figure 1.1 Methodology Framework Flow Chart ................................................................. 5
Figure 2.1 Parameters Affecting Capacity (Abril et al., 2008) .................................................. 11
Figure 2.2 Qualitative Relationship between Reliability and Train Throughput (Kittelson & Associates, Inc. et al., 2013) ................................................................. 14
Figure 3.1 GO Train System Map (GO Transit, 2016) ............................................................. 17
Figure 3.2 Union Station Layout (PARSONS BRINCKERHOFF, 2014) ....................................... 18
Figure 3.3 Network Boundary for Simulation Analysis ........................................................... 19
Figure 4.1 GO Tracker Website (GO Transit, 2017) ................................................................. 25
Figure 5.1 Junction Area Example from TCQSM (Kittelson & Associates, Inc. et al., 2013) ............ 29
Figure 5.2 Interlocking Areas of Union Station ..................................................................... 31
Figure 5.3 Simple Station Area (Malavasi et al., 2014) ........................................................... 31
Figure 5.4 Identified Commonly Used Train Paths ................................................................. 38
Figure 5.5 Demonstration for a Simple Crossing .................................................................... 39
Figure 5.6 Physical Attributes of a Block (International Union of Railways, 2013) ....................... 43
Figure 5.7 Train Paths on a Line Sections of a Specific Schedule (International Union of Railways, 2013) ........................................................................................... 43
Figure 5.8 Capacity Consumption After Compression (International Union of Railways, 2013) .... 44
Figure 5.9 Simple Junction Area (International Union of Railways, 2013) ................................. 45
Figure 5.10 Workflow of Determining Capacity (International Union of Railways, 2013) .......... 50
Figure 6.1 Infrastructure Layout of Main network (a) and Expansion (b) for OpenTrack Model .... 55
Figure 6.2 OpenTrack Simulation Flow Chart for one train .................................................... 57
Figure 6.3 Examples of Calibrated Speed-Distance Profile ...................................................... 60
Figure 6.4 On-time Performance Comparison between Observed and Simulated .................... 61
Figure 6.5 Average Delay Comprison between Observations and Simulations ....................... 62
Figure 6.6 Example of Train Occupancy based on Generated Schedule ................................. 64
Figure 6.7 Capacity Analysis Result using OpenTrack ............................................................ 65
Figure 7.1 Segments of Dwell Time ...................................................................................... 68
Figure 7.2 Sample Passenger Flow Diagrams for each Train Arrival ....................................... 70
Figure 7.3 Demonstration of Three Types of Alighting Behavior .......................................... 71
Figure 7.4 Passenger Flow Diagrams for the Three Scenarios Demonstrated ............................ 71
Figure 7.5 Average LOS Time for Each Passenger ................................................................. 72
Figure 7.6 Average Passenger Duration Distribution on Platform ........................................... 72
Figure 7.7 Typical Cumulative Passenger - Time Diagram of a Single Train Door of an Arrival .... 75
Figure 7.8 Distribution Fitting for Three Variables ................................................................ 76
Figure 7.9 Observed Relative Frequency ............................................................................. 79
Figure 7.10 Simulated Relative Frequency .......................................................................... 79
Figure 7.11 Average and Maximum Passenger Flow Time .................................................... 80
Figure 7.12 Massmotion Model of Union Station ................................................................. 82
Figure 7.13 Passenger Volume Split across 9 Staircases for Platform 26-27 ............................. 84
Figure 7.14 Observed and Simulated Accumulative Passenger Flow for Stair #6 ..................... 84
Figure 7.15 Nexus Flow Chart ......................................................................................... 87
Figure 7.16 Validation for OTP (a), Arrival Delay (b) and Passenger Split (c) ......................... 89
Figure 8.1 Summary of Scenario Results .............................................................................. 94
Figure 8.2 Relationship between Inbound Passenger Volume and Train Arrival Delay ........................................95
Figure 8.3 Relationship between Inbound Passenger Volume and Dwell Time ......................................................96
Figure 8.4 Relationship between Scheduled Inbound Passenger Volume (per train) and Total Passenger Throughput ........................................................................................................................................97
Figure 8.5 Relationship between Inbound Passenger Volume per Train and Passenger LOS F ..........................98
Figure 8.6 Comparison of Agent Density between Scenario 1 and Scenario 5 ......................................................99
Figure 8.7 Comparison of Passenger Experienced Density between Base Model (a) and Scenario 5 (b) ..........100
Figure 8.8 Results for Further Scenarios Building off Scenario 5 .............................................................................101
List of Appendices

Appendix A: Maximum Speed Limit for USRC Area................................................................. 114
Appendix B: Current Timetable (for morning peak) ................................................................. 115
Appendix C: The values pf parameters used to calculate the headways for TCQSM .................. 116
Appendix D: Occupation and Interdiction Time for Analytical Methods .................................. 117
Appendix E: Application and Conversion of Alighting behavior for Centralized Train Portal ....... 118
Appendix F: Passenger Volume Calculation for Nexus Scenario Tests ...................................... 120
<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATR</td>
<td>Additional Time Rate</td>
</tr>
<tr>
<td>BA</td>
<td>Barrie GO Line</td>
</tr>
<tr>
<td>CC</td>
<td>Capacity Consumption</td>
</tr>
<tr>
<td>DB</td>
<td>Deutsche Bahn (Method)</td>
</tr>
<tr>
<td>GTHA</td>
<td>Greater Toronto and Hamilton Area</td>
</tr>
<tr>
<td>KI</td>
<td>Kitchener GO Line</td>
</tr>
<tr>
<td>LOS</td>
<td>Level of Service</td>
</tr>
<tr>
<td>LRT</td>
<td>Light Rail Transit</td>
</tr>
<tr>
<td>LSE</td>
<td>Lakeshore East GO Line</td>
</tr>
<tr>
<td>LSE_E</td>
<td>Lakeshore East (Express) GO Line</td>
</tr>
<tr>
<td>LSW</td>
<td>Lakeshore West GO Line</td>
</tr>
<tr>
<td>LSW_E</td>
<td>Lakeshore West (Express) GO Line</td>
</tr>
<tr>
<td>MI</td>
<td>Milton GO Line</td>
</tr>
<tr>
<td>OTR</td>
<td>Occupancy Time Rate</td>
</tr>
<tr>
<td>PHF</td>
<td>Peak Hour Factor</td>
</tr>
<tr>
<td>RH</td>
<td>Richmond Hill GO Line</td>
</tr>
<tr>
<td>SLP</td>
<td>Simulated Late Performance</td>
</tr>
<tr>
<td>SOTP</td>
<td>Simulated On-time Performance</td>
</tr>
<tr>
<td>ST</td>
<td>Stouffville GO Line</td>
</tr>
<tr>
<td>TCQSM</td>
<td>Transit Capacity and Quality of Service Manual</td>
</tr>
<tr>
<td>TTC</td>
<td>Toronto Transit Commission</td>
</tr>
<tr>
<td>UIC</td>
<td>International Union of Railways</td>
</tr>
<tr>
<td>USRC</td>
<td>Union Station Rail Corridor</td>
</tr>
</tbody>
</table>
Chapter 1

1 Introduction

1.1 Background

Railway transport is a means of transportation that transfers passengers and goods in wheeled vehicles that run on guided rail tracks. The rolling stock (train cars) of railway transport usually encounters less frictional resistance than vehicles on the road, enabling railway transport to carry multiple passenger or freight cars into longer trains. Although it is not as flexible as other modes of land transportation, railway transport can provide larger passenger or freight capacity and travels long distances connecting cities and regions at a higher speed and a more comfortable environment. It is often believed that railway transport is safer compared to other forms of land transport, and it is more energy efficient (Potter, 2003).

Railway transport became one of the most popular transport modes in the 18th and 19th century when the steam engine powered locomotives were developed. Later on, electrified trains and diesel-powered locomotives were introduced, allowing the fast development of rapid mass transit systems. However, the railway transport suffered a dramatic decline after world war II due to a fierce competition from cars. Entering the 21st century, rail transport has embraced a revival around the world due to the rising traffic jam and fuel cost. Furthermore, it is also a preferred means of land transportation due to its energy efficiency for mass transportation of passengers and goods, which can reduce emissions as an effective way of relieving the pressure of climate change. Globally, rapid urban rail transit systems are being introduced and developed, and high-speed rail has already played an important role in inter-city passenger transportation in Europe and countries like Japan and China. In North America, light rail transit (LRT) is having a major comeback at many cities as an effective measure to relieve traffic congestion in downtown areas. More closely, there are multiple rail projects undergoing in Greater Toronto and Hamilton Area (GTHA). For example, Eglinton Crosstown LRT, Finch West LRT, Hurontario LRT, Hamilton B-Line LRT. The regional transit operator, GO Transit, is also planning a major service expansion to its commuter railway network to offer more frequent services along its seven major rail lines.

The increasing demand results in an increase in scheduled train services and passenger volume. Due to lack of flexibility, railway capacity issues arise due to the conflicts of the increasing service,
especially around station areas where multiple rail services converge sharing a limited infrastructure system. In order to meet the demand, common actions are considered, including expanding and upgrading infrastructure or using existing infrastructure more efficiently. Nevertheless, the first option usually involves expensive investment as well as technical constraints such as limited space in downtown area where major railway stations are located. Therefore, it is critical to understand how the railway system works and perform a comprehensive analysis on railway capacity to identify the key problem and make the right decision.

1.1.1 Main Concerns

Analyzing railway capacity of major railway stations involves multiple complicated systems. For example, railway track infrastructure, rolling stocks, signaling system, timetable and human factors (Lindfeldt, 2015a). Each system has its own unique characteristics while interacting with each other at the same time. The main concerns of analyzing the railway capacity of major railway stations can be categorized as following sections.

1.1.2 Train Movements

With the increase of scheduled train trips, the main concern is whether the existing infrastructure could support projected volume growth and what part may be a bottleneck. A railway station, along with the corridor the station is located, is usually described as a railway node area. The main purpose of the node area is to connect the mainline tracks to the station depots or other track sections. The scale of a node area ranges from a simple terminus crossover to a complex system involving multiple mainlines and multiple station depots shared by various carriers and train configurations. Various methodologies for capacity evaluation are available, and they can be categorized into analytical, optimization, and simulation methods.

1.1.3 Pedestrian Movements

As train and passenger volume increase, the most common concern in considering this future scenario is whether the station infrastructure could support the passenger volume increase. A regular commuter rail train can carry a passenger volume up to 5000, the impact on passenger crowding on the platform when the train arrives at the railway station could be disastrous. This is especially true for stations with limited platform and staircase capacity. In these cases, not only passengers’ level of service at station could be significantly reduced, the crowding on the platform
could also pose serious safety concerns as train volume increases. A considerable number of accidents of track level injuries due to over-crowding on the platforms have been reported around the world in the past decades.

1.1.4 Interactive effects between train movements and pedestrian movements

High-frequency rail transit services are known to be extremely sensitive to delays, which would in turn affect overall train throughput. As train and passenger volume increases, the aforementioned two movements would be expected to interact on the platform level. For stations with limited platform and staircase capacity, dwell times and consequently line capacity could be adversely affected with rising levels of passenger volumes, while the train frequency and arrival patterns could adversely affect passenger crowding condition on the platform.

1.1.5 Current capacity analysis practices

It is found that many studies only focus on either train movements or pedestrian movements. The interactive effects between the two movements have been largely ignored, or rather cannot be captured by current approaches. For a complex railway station, it is equally important to study not only pedestrian and train movements, but also how the two interact in order to make the right decision of investment.

1.2 Research Objectives

The main objective of this thesis is to identify the necessity of studying both train and pedestrian movements, as well as the interactive effects between the two, when performing a comprehensive capacity analysis of a complex railway station. An integrated crowd and transit simulation model would be beneficial to assist the analysis.

In order to demonstrate such benefits, traditional railway capacity analysis of both analytical methods and railway simulation are necessary to be evaluated and applied to a complex node area, namely Toronto’s Union Rail Station. Results could then be compared among these methods to offer recommendation of their applicability, as well as to be further applied to scenarios where pedestrian movements are taken into consideration in the integrated crowd and transit simulation model.
To ensure results are comparable, consistency is required across different methods, which includes extensive data collection, accurate method application, model construction, calibration and validation. Additionally, train operations and passenger behaviors at the major railway stations need to be carefully studied to ensure the method or model applied reflect the real-world scenario appropriately.

1.3 Methodology
The methodology of the thesis includes four major stages: data collection, analytical capacity analysis methods, railway simulation, and integrated crowd and transit simulation.

The first stage is to collect necessary data for performing analysis. Certain documentations were available directly from the transit agency, however, due to the scope of study, extensive manual data collection was required additionally. A series of data collection was carefully designed and performed. The collected data would be processed and applied to the various analysis methods in this thesis.

The second stage is to select a few representative analytical methods based on popularity and simplicity. Four methods were chosen, including Transit Capacity and Quality of Service Manual, Potthoff method, Deutsche Bahn method, and Compression method. The thesis followed through detailed procedures of these methods and performed capacity analyses in the context of maximum train volume for the four methods individually. Results were compared and discussed.

During the third stage, a railway simulation model was constructed using OpenTrack, a railway simulation package. The Union Station corridor was recreated in the simulation model including track layout, signal locations, locomotives, rolling stock, train paths and timetable. The model was fully calibrated and validated. A sensitivity test was performed to obtain the capacity based on specific quality of service standard (95% on-time performance). The result was compared with the results from analytical methods and the differences were discussed.

The fourth stage is to integrate pedestrian movement with railway simulation by simulating pedestrian movement in MassMotion (pedestrian simulation package) and linking both MassMotion and OpenTrack with Nexus, the integrated crowd and transit simulation. Both MassMotion and Nexus were calibrated and validated. Built off the results from the second and
third stage, a series of scenario tests using Nexus was designed, where the interactive effects of pedestrian and train movements on total train throughput when the system is operating at capacity was effectively studied.

The general framework of the thesis can be viewed in Figure 1.1.

![Methodology Framework Flow Chart](image)

**Figure 1.1 Methodology Framework Flow Chart**

### 1.4 Thesis Outline

The thesis consists of nine chapters. Chapter 1 shows the background, main concerns, research objectives and methodology of the thesis. Chapter 2 explores current approaches of railway capacity analysis and identifies the research gap. Chapter 3 provides a detailed description of the case study - Toronto’s Union Station, where all methods of capacity analysis would be applied to. Chapter 4 describes the several types of data collection performed in order to set up the methods and simulation models. Chapter 5 discusses various analytical methods and lists the key procedures when applying these methods. Chapter 6 demonstrates the construction of a railway simulation model using OpenTrack. Chapter 7 introduces a novel approach to perform a comprehensive capacity analysis on a complex node area using the integrated crowd and transit simulation model – Nexus platform. Chapter 8 presents the scenario tests designed for the Nexus platform as well as their results. Chapter 9 concludes the outcome of the thesis and contribution; it also identifies the limitation and proposes potential areas of future work.
Chapter 2

2 Literature Review

The goal of any railway capacity analysis is to obtain the maximum number of trains that can be operated on a given section of infrastructure, during a specific time period, under certain operational conditions (Abril et al., 2008). Due to the complexity of railway system, extensive studies have been conducted by researchers to discuss definitions of railway capacity, various types of methodologies on capacity analysis and different factors affecting capacity.

2.1 Capacity Definition

The definition of the capacity is a classical problem in the industry. While variations exist from study to study, most research has identified railway capacity as a measure of the ability to move specific amount traffic (Krueger, 1999), or number of trains that can be scheduled into a timetable without conflicts (Lindfeldt, 2015b), over a defined rail line section with a given set of resources under a specific service plan or quality. Prior research efforts, however, have ascribed different meanings to capacity depending on the context or environment (Abril et al., 2008).

2.1.1 Theoretical Capacity

This is the number of trains that could run over a section in a strictly perfect, mathematically generated environment with trains running permanently at minimum headway. It is the upper limit of the capacity, and assumes traffic is homogeneous. Practically, however, it is not possible to achieve.

2.1.2 Practical Capacity

It is the practical limit of traffic volume that can be moved on a line section at an acceptable level of service reliability. It is a more realistic measure, take actual train mix, priorities and traffic bunching into consideration. As stated by Kraft (Kraft, 1982), practical capacity is usually around 60-75% of the theoretical capacity.

2.1.3 Used Capacity

It is the actual traffic volume that is being scheduled on the rail network, and it is usually lower than the practical capacity.
2.1.4 Available Capacity

It is the difference between used capacity and practical capacity, indicating the amount of traffic that can be potentially added and handled on the network. If the available capacity allows new trains to be added, it is a useful capacity; otherwise it is considered as lost capacity.

2.1.5 Line Capacity, Node Capacity and Person Capacity

Capacity can also be categorized based on the type of each defined track section (International Union of Railways, 2013) which includes line capacity and node capacity, describing the maximum number of trains that can be operated over a section of track or over a node area in the reference time without delays at traffic signals (Kontaxi & Ricci, 2010).

Another important type of capacity related to railway transport is person capacity. Transit Capacity and Quality of Service Manual (TCQSM) (Kittelson & Associates, Inc. et al., 2013) defines person capacity as the maximum number of passengers which can be carried over a defined track section in a given period of time under specified operating conditions without unreasonable delay, hazard, or restriction, and with reasonable certainty. However, the manual also states that this definition is less absolute than that of a line capacity, as person capacity is greatly determined by number of trains operated, length of the trains and loading standards. The concept of person capacity is important because it bridges train movements with human factors.

2.2 Capacity Analysis Methods

Taking into account the carrying definitions of railway capacity defined in the previous section, many methodologies have been developed for capacity evaluation with particular focus. Parkinson and Fisher(Parkinson & Fisher, 1996) conducted a review of more than 70 papers, books and reports on rail transit capacity experience and capacity analysis methodologies of North America, including both qualitative methods and quantitative methods, covering subjects including streetcar, automated guideway transit (AGT), Light Rail Transit (LRT), commuter rail, and heavy rail. Other researchers such as Abril et al.(Abril et al., 2008), Malavasi et al.(Malavasi, Molková, Ricci, & Rotoli, 2014), and Kontaxi and Ricci(Kontaxi & Ricci, 2010) categorized existing methods into analytical methods, optimization methods and simulation, they are summarized and discussed in detail in the following sections.
2.2.1 Analytical Methods

Analytical methods are designed to offer preliminary solutions and approximate results using mathematical formulae and expressions (Malavasi et al., 2014). It is a general approach to acquire overall information of the system, suitable for network planning and usually it obtains theoretical capacities.

One example is presented in the TCQSM (Kittelson & Associates, Inc. et al., 2013). As a general operational and planning guidebook for North America, it offers an in-depth demonstration of system design and an approach of calculating the minimum headway of a defined line section to obtain the maximum capacity. The calculation focuses on typical line sections and simple junction area. Peterson recommended a capacity analysis method for single-track section, in which uniformed departure time is assumed and three distinct train speeds are modeled (Petersen, 1974).

Inspired by the approach used in the Highway Capacity Manual, Lai et al. (Lai, Liu, & Lin, 2012) developed a railway capacity model by introducing the concept of base train equivalents (BTE), which converts multiple train types to a standard train type. Several approaches have been proposed by Burdett and Kozan for calculating “absolute capacity” of a rail network, taking into considerations of parameters including mix of trains, signal locations and dwell time (Burdett & Kozan, 2006).

Many analytical approaches have been developed for the capacity of node areas. De Kort et al. evaluated an approach proposed by Wakob based on queueing theory, which was in-turn an extension of Schwanhäußer’s method of assessing line capacity (De Kort, Heidergott, Van Egmond, & Hooghiemstra, 1999). Another queuing approach was suggested by Huisman et al., they presented a solvable queueing network model for rail stations and junctions (Huisman, Boucherie, & van Dijk, 2002). Next, the Union of International Railway (UIC) introduced the compression method in 2004 (International Union of Railways, 2004). The method evaluated the overall utilization and available capacity of a track section by compressing the existing schedule. However, it was criticized as only being capable of calculating the line capacity, whereas the applicability of the method in a node area is hardly mentioned (Lindner, 2011). In 2013, the second edition of UIC Code 406 (International Union of Railways, 2013) addressed this issue by introducing a new approach to allow the compression method to assess node capacity. Later, Malavasi et al. studied and compared several analytical capacity analysis methods of a node area,
including the Potthoff method and Deutsche Bahn (DB) method (Malavasi et al., 2014). Both methods assess the capacity by analyzing the average number of simultaneous movements occurring inside a node area. Kontaxi and Ricci also identified Pothoff method to be a reference method when it comes to the capacity analysis of a node area (Kontaxi & Ricci, 2010).

2.2.2 Optimization Methods

The second category, optimization methods, are designed to offer more strategic approach to solve the railway capacity problem with aims to minimize delays in the mixed speed traffic and obtain optimally saturated timetables (Abril et al., 2008). The capacity evaluated by optimization methods is usually between theoretical and practical capacity. Carey and Lockwood presented a heuristics algorithm for double track lines which considers train one at a time and solved a mixed integer linear program (Carey & Lockwood, 1995). Another approach was suggested by Higgins et al., which uses mathematical programing to schedule trains over a single line track (Higgins, Kozan, & Ferreira, 1996). Oliveira and Smith modeled the railway capacity problem as a special case of the Job-Shop Scheduling problem, in which trains are considered as jobs to be scheduled on tracks (Oliveira & Smith, 2000). Abril et al. stated that the compression method from UIC can also be considered as a timetable-dependent optimization method as it compresses all existing train paths for a section and maximize the total train throughput by carefully inserting trains into available time slots (Abril et al., 2008).

2.2.3 Simulation Methods

Simulation imitates the operation of a real-world system over time, it gives insight into the detailed process of a system and each individual movement of an object, which can be a car, a train or a pedestrian. Accurate and extensive data is required for simulations and practical capacity is usually obtained from simulation methods. Commercial simulation software packages are available including OpenTrack, RailSys and RTC, and have been deployed in a few studies on railway capacity. AECOM performed a capacity analysis of Toronto’s Union Station with RTC (AECOM, 2011); Chen and Han used OpenTrack to analyze the carrying capacity of a high-speed railway between two major cities in China (Chen & Han, 2014); Nelladal et al. assessed the capacity of a railway section in Stockholm with RailSys under the new European Train Control System (ETCS) (Nelldal, Magnarini, & Bruno, 2011).
In summary, analytical methods offer preliminary typically theoretical results; optimization methods could be used to obtain capacity-maximizing train schedules; finally, simulation is beneficial for validating the schedules produced by both analytical and optimization techniques (Abril et al., 2008). The three levels represent a general methodology for capacity management. Many studies of capacity analysis indeed follow such structure. Abril et al. used MOM system (acronym of the Spanish name: Modulo Optimizador de Mallas), developed by Barber et al. (Barber et al., 2006), to evaluate the capacity of certain Spanish railways. The MOM system can generate optimized railway schedules based on the embedded analytical and optimization approaches to evaluate the track and station capacity to meet customers’ needs (Abril et al., 2008). Nelladal et al. used compression method and STRELE-Formula to perform an analytical method first, and then applied RailSys for validating certain specific timetables and conducting further analysis (Nelldal, Magnarini, & Bruno, 2011). Lindfeldt applied the complete structure of capacity management to conduct his capacity analysis from analytical methods to RailSys, as well as an enhanced simulation package called TigerSim, which considers both static and dynamic properties of the timetables during capacity analysis (Lindfeldt, 2015b).

### 2.3 Dwell Time

Railway capacity is affected by certain parameters. UIC 2004 (International Union of Railways, 2004) discussed a qualitative relationship between capacity and its parameters, including number of trains, average speed, heterogeneity and stability. Similar conclusions were provided in many other studies, such as the result presented by Abril et al. (Abril et al., 2008) in his analysis as shown in Figure 2.1.
As can be seen that commercial stop is one of the important parameters that would affect total capacity. This includes not only the number of stops but also the duration of stopping time at the stop, which is known as the dwell time. The impact of the dwell time on a railway system capacity analysis could be substantial. In fact, TCQSM identifies it as one of the weakest links along a railway corridor as it involves the direct interaction between passenger movements and train movements, and the manual places the parameter of dwell time directly into the minimum headway calculation. Although it is believed that dwell time should not be determined with the same exactitude, in reality almost all literature references and simulations set it as a fixed value (Kittelson & Associates, Inc. et al., 2013). The most-common components of dwell time are defined as: Passenger flow time at the busiest door; un-used door-open time; and lost time between doors closed and departure. For passenger flow time, Various analytical dwell time models have been developed in previous research. To better capture the variations of dwell time, it is necessary to study the impact of pedestrian movements on boarding and alighting behaviour. Many focus on estimating the length of dwell time based on factors such as alighting and boarding volumes, through passenger volume and crowding effects. Models are usually estimated through regression (San & Masirin, 2016).

2.4 Pedestrian Modelling
For more complex stations and higher volumes, the analytical models discussed in section 2.3 fall short in their ability to account for how conflicting and potential large passenger flow through the
rest of the station can impact platform operations. They also lack the ability to incorporate station
capacity (particularly platform capacity) as part of the overall capacity of the system. This leads
to a need to explicitly simulate crowd flow with proper pedestrian modeling. Pedestrian modeling
is a relatively new field in transportation modeling, and it has been evolving through the past few
decades. During the early stage, it was a standard practice to consider pedestrian flow as aggregate
flows, assuming that all pedestrians are homogeneous. The idea soon evolved and was replaced by
agent-based approach which considers both of the agent’s geometry and location with its
movement to create more pragmatic behaviors (Hoy, Morrow, & Shalaby, 2016). Fruin studied
various pedestrian behavioral factors and developed the Level of Service (LOS) concept, which is
still being used today as a metric for evaluating pedestrians’ movements in various locations
(Fruin, 1971). Helbing and Molnar proposed a “Social Force Model” which suggests that the
pedestrian movements are affected by the relationship between each agent and other objects around
them, including other agents or obstacles (Helbing & Molnár, 1995). The relationship creates
either an attractive force or a repulsive force, determining agent’s response to the environment. In
addition, Hughes et al. distinguished human flow from classical fluid due to the fact that a crowd
has the ability to think (Hughes, 2003), while Shao and Terzopoulos proposed a pedestrian model
which develops each pedestrian into individual rather than an amorphous flow (Shao &
Terzopoulos, 2007).

Many pedestrian models place great emphasis on public transit facilities, since transit hubs,
especially large-scale interchange stations and intermodal stations, usually bear massive passenger
volume where flow conflicts are highly likely to occur. Lam et al. developed a pedestrian route
choice model between escalators and stairways in MTR stations in Hong Kong (Cheung C. Y. &
model that focuses on the pedestrian’s selection of escalators and stairways for transit platform
egress (Srikukenthiran, Shalaby, & Habib, 2014).

Pedestrian simulation tools, on the other hand, has been a powerful tool for microscopic agent-
based pedestrian models thanks to its strong computation capability. They have been
recommended by many transit operation manuals to be applied to complex transit facilities.
Commercial pedestrian simulation software packages available, such as Legion, Viswalk and
MassMotion. Most simulation models embed a variant or a combination of the aforementioned
pedestrian modelling techniques to simulate pedestrian movements in a user-defined 3D environment. A few studies on pedestrian flows in subway systems have utilized these packages. Zhao et al. analyzed pedestrian flow on Beijing’s subway line for efficiency and quality of service and examined if the infrastructure was capable of meeting peak demand at special events with Legion (Guanghua Zhao, Guanghou Zhang, Yanyan Chen, & Ping Wu, n.d.). Besides, King et al. modelled pedestrian movements at the busiest subway inter-change station in Toronto and studied the impact of different train arrival patterns on overall pedestrian congestion level (King, Srikukenthiran, & Shalaby, 2014); Hoy et al. performed a separate analysis on pedestrian movement at the passage way between Toronto’s Union Rail Station and subway station where massive transfer passenger volume occurs during the peak hours (Hoy et al., 2016). Both studies applied MassMotion as the pedestrian simulation model and analyzed pedestrians’ LOS as main performance indicators.

The benefit of using a simulation tool is that it represents the real-world process and with appropriate calibration and data input, it can gather information that is usually hard to measure in the real world, such as pedestrian density and duration at each level of service. It could also save time and cost for evaluating different scenarios and policies. However, for the pedestrian studies on transit facilities which involves transit vehicles, train arrivals and departures were assumed to be a fixed value; as a result, the impacts of pedestrian movement on dwell time and delay have not been well captured.

2.5 Multi-modal Simulation

Research discussed in the previous sections reveals that either train movement or pedestrian movement is focused in a particular analysis, with assumptions and simplifications made for the other movement. For a station area, however, both movements could potentially affect the overall capacity, and they should be treated with equal priority. Recently, research accounting for the interaction between dwell time and train throughput has started to emerge. Jiang et al. proposed a mathematical model for subway dwell time using parameters such as train headway, number of boarding and alighting passengers, and inability of train doors to close at the first time (Jiang, Xie, Ji, & Zou, 2015). The dwell time model was integrated into a simulation algorithm to constantly update the train departure time as part of a broader line capacity analysis. A similar approach was demonstrated by D’Acierno et al., where the combined analytical dwell time model and the railway
simulation with OpenTrack were applied to support timetabling development (D’Acierno, Botte, Placido, Caropreso, & Montella, 2017). Instead of analytical models, Srikukenthiran and Shalaby created a platform – Nexus – which integrates multiple micro-simulation packages to model the crowd and transit network dynamics (Srikukenthiran & Shalaby, 2017). With this method, the interaction of train and crowd flows at stations have been modelled explicitly by allowing for the two software packages to communicate to permit dynamic dwell times (determined by both dwell and line operations).

2.6 Reliability and Quality of Service

An important aspect of any capacity analysis is the measure to interpret capacity. Based on the definition of capacity, total train throughput and total passenger volume within the study period obviously should be the determining factors. However, these indicators do not or partially consider the quality of service, which can be critical in various situations. In fact, many capacity manuals and guidelines recognize that the desired level of operational reliability has a strong impact on total design capacity. For example, TCQSM states that the total delay would increase exponentially when a line approaches its capacity (Kittelson & Associates, Inc. et al., 2013) and provides a qualitative relationship between total train throughput and reliability as shown in Figure 2.2.

![Figure 2.2 Qualitative Relationship between Reliability and Train Throughput (Kittelson & Associates, Inc. et al., 2013)](image)

Many reliability measurements and studies are directly related to train operation. Abril et al. suggested that a trade-off exists between capacity and reliability (Abril et al., 2008). Sameni concluded there are three main groups of capacity measures: throughput, level of service, and asset
utilization (Sameni, Dingler, Preston, & Barkan, 2011). Many capacity analysis studies use specific reliability indicators to communicate their capacity analysis result. Nelldal et al. interpreted the capacity analysis through train delays and punctuality compared to the timetable (Nelldal et al., 2011), while AECOM applied a simulated on-time performance indicator (SOTP) as the main capacity indicator in their Union Station infrastructure capacity analysis, accounting for number of trains which arrive no later than 5 minutes than schedule (AECOM, 2011).

For a transit system, reliability is usually a main concern for both system operators as well as system users. Gittens performed a comprehensive study on various methods of quantifying reliability, suggesting that there are 5 types of reliability indicators: travel time indicators, schedule adherence indicators, headway regularity indicators, wait time indicators and composite indicators (Gittens & Shalaby, 2015). While most of the indicators are equally important to both operators and passengers, he concluded that on-time arrival of passengers at travel destinations, short wait time at the origin stop; and low variability in wait time as well as travel time are the strongest influence on passengers’ perceptions of reliability.

Passenger crowding, on the other hand, is an inevitable issue in a transit system, especially for a large-scale transit hub as well as inside transit vehicles. They have direct impact on users’ perception of the transit system’s reliability. As discussed in section 2.4 Both King et al. and Hoy et al. used the pedestrian simulation software MassMotion to perform a pedestrian circulation analysis in two of Toronto’s busiest transit hubs. King used average congestion time (duration in Level of Service F) as the main indicator while Hoy used average agent density at each level of service over time. In both cases, level of service indicators (LOS) were being used, which is a key feature of MassMotion where Fruin’s development was adopted. As stated by TCQSM, pedestrian LOS offers a useful way of evaluating the capacity and comfort of an active pedestrian space. It is based on each pedestrian’s’ standing space, perceived comfort and safety, and the ability to maneuver from one spot to another (Kittelson & Associates, Inc. et al., 2013). The LOS system is represented by six levels marked from A to F, with LOS A demonstrating an unimpeded condition while F representing an extremely undesirable state where all pedestrian movement is severely constrained. It is also noted that pedestrian capacity, which is the maximum number of pedestrians that can pass a point in a given period of time, is determined by the threshold between LOS E and F. According to the LOS system, different types of spaces would have different threshold of level
of service. For example, the thresholds for LOS of stairways and platforms are presented in Table 2.1.

Table 2.1 LOS for Fruin Platforms and Fruin Stairways (Kittelson & Associates, Inc. et al., 2013)

<table>
<thead>
<tr>
<th>LOS</th>
<th>Platforms (queueing)</th>
<th>Stairways</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Density (person/m²)</td>
<td>Space (m²/person)</td>
</tr>
<tr>
<td>A</td>
<td>x&lt;=0.826</td>
<td>x&gt;1.21</td>
</tr>
<tr>
<td>B</td>
<td>0.826&lt;x&lt;=1.075</td>
<td>1.21&gt;x&gt;=0.93</td>
</tr>
<tr>
<td>C</td>
<td>1.075&lt;x&lt;=1.538</td>
<td>0.93&gt;x&gt;=0.65</td>
</tr>
<tr>
<td>D</td>
<td>1.538&lt;x&lt;=3.571</td>
<td>0.65&gt;x&gt;=0.28</td>
</tr>
<tr>
<td>E</td>
<td>3.571&lt;x&lt;=5.263</td>
<td>0.28&gt;x&gt;=0.19</td>
</tr>
<tr>
<td>F</td>
<td>5.263&lt;x</td>
<td>0.19&gt;x</td>
</tr>
</tbody>
</table>

2.7 Discussion and Comments

Although many studies and researches suggest that the accurate definition of railway capacity has always been an issue, plenty of capacity methods have been proposed with focuses on various parameters, ranging from analytical methods to simulation methods. On the other hand, a complete study of a railway system does not only comprise of equipment and infrastructure, but also the transit system customers who use the system on a daily basis, and the interaction between the two cannot be simply ignored. However, through the literature reviews, it can be found that majority of studies have focused on line capacity, rather than station capacity, and even fewer studies have systematically compared the methods of both analytical and simulation on a complex station area. Besides, dwell time is usually assumed to be a fixed number for simplification instead of taking the actual passenger flow on the station platform side into consideration. Moreover, pedestrian movements and train movements are usually separately analyzed even though the two movements take place at the same transit facility. The interaction between the two movements is remarkably less studied. This thesis aims to explore these research gaps, and fill through using the Nexus platform to conduct a comprehensive capacity analysis of a complex railway hub.
Chapter 3

3 Description of the Case Study

3.1 Station Description

Toronto’s Union Station is Canada’s busiest multi-modal transit facility with approximately 200,000 daily passengers passing through the station. Located in downtown Toronto, the station is surrounded by the business district and entertainment district. It is the central terminal station to a variety of transit services. GO Transit, a regional commuter transit operator in the Greater Toronto and Hamilton Area, connects all seven major commuter rail lines at the station (Figure 3.1), carrying an annual passenger volume of 69.5 million. Every morning GO trains deliver thousands of commuter passengers into downtown Toronto and back to their home suburbs in the evening. Canada’s national passenger railway agency VIA Rail sets its central hub at Union Station for its eastern network. UP Express, a newly-opened airport express service connecting Toronto’s Pearson International airport with the Union Station, has its own dedicated platform located just west of the station. In addition, the station has a bus terminal with 18 GO bus lines, a major subway station, and an underground streetcar terminal with 2 streetcar lines operated by Toronto Transit Commission (TTC).

Figure 3.1 GO Train System Map (GO Transit, 2016)

Opened in 1927, the station has 14 depot tracks and 23 passenger platforms (centre and side). Each platform is approximately 350-metre long and 5-metre wide. Two bypass tracks are laid south of the train shed for equipment movements and occasional local freight movements. The layout is shown in Figure 3.2.
With consistent growth of passenger volume and demand, GO transit is planning to implement an expansion plan to provide more frequent services on its rail lines in the near future, such as Regional Express Rail and SmartTrack.

Toronto’s Union Station was chosen for this case study due to its complex infrastructure, high train and passenger volume as well as its proximity to the University of Toronto which makes it easier for data collection and observation.

3.2 Boundary and Scope
Due to the complexity of the network that is associated with the Union Station, it would be extremely difficult to model the entire GO rail network and the amount of data required could be overwhelming and impossible. A smaller portion of the network was consequently focused, which covers the area of Union Station Rail Corridor (USRC).

For analytical analysis, the boundary was limited to from the west mainlines (B, A1-A3, C1-C2, D1-D2 and two bypass tracks) to the east mainlines (E1-E4 and two bypass tracks), including the entire Union Station train shed area (all 14 station depot tracks) as well as two major interlocking areas as shown in Figure 3.2.

![Figure 3.2 Union Station Layout](PARSONS BRINCKERHOFF, 2014)

For simulation analysis, the boundary was extended to include one station prior to Union Station, including express trips as shown in Figure 3.3. The scope matches common practice when conducting a railway capacity analysis using simulation to properly model the train movements along a corridor. Main maintenance yards were also taken account of to simulate equipment moves for trains that become out of service after arriving at Union. In other words, trains in the simulation
models would not disappear at Union Station even though the service could be terminated at the station. Trains would continue to proceed to either the next specified station or one of the maintenance yards.

Compared to GO Transit, VIA rail and UP Express only share a fraction of train volume. Considering that GO Transit is planning service expansions, it is of great interest to evaluate the maximum train volume that GO Transit could achieve. Hence the study would focus on GO Transit. On the other hand, the study period was chosen to be between 8 am and 9 am where most train arrivals with the largest inbound passenger volumes occur.

### 3.3 Technical Characteristics

Based on the study scope defined in section 3.2, a total of eight stations were selected as entry stations and their distances to the Union Station are listed in Table 3.1.
Due to different topologies, each line would have sections with various shapes, curves, gradients and other factors, resulting in different speed limits. The speed limit within USRC area was obtained from CN and USRC Operating rules (O’Neill, 2013), the maximum speed limit within USRC area is listed in Appendix A.

Speed limit outside of the USRC area was not available from GO Transit directly. Data collection was designed and performed, details are described in section 4.1.

### 3.4 Operational Characteristics

#### 3.4.1 Train specifications/Rolling stocks

**GO Train**

GO transit deploys MP40 as the locomotives for the fleet. The passenger cars are Bombardier bi-level coaches with a seating capacity of up to 162 passengers per car. Each car is 25.9 metres in length and 3 metres in width. Based on GO Transit’s fact sheet and numerous official statements from Bombardier, each train car has room for over 250 standees on top of the seating capacity, which makes it possible that a completely packed 12-car train can carry over 5000 passengers when it arrives at Union Station.

**VIA Train**

VIA rail has several configurations of its train types. It uses P42DC locomotive along with seven Renaissance coaches for its Windsor-Montreal corridor trains, while for other lines such as the Canadian or super-continental train, the trains are consisted of one F40PH-2 operating, one F40PH-2 electrical power generation/deadhead plus 15 passenger cars (AECOM, 2011).
UP Express

Currently UP express trains are operated with 3-car Nippon Sharyo DMU, a model of diesel multiple unit passenger train by Nippon Sharyo. The vehicles are designed to be convertible to electric multiple unit in the future. Each car is approximately 25.9-metre long with a maximum speed of 145 km/h ("Nippon Sharyo DMU," 2017).

While all efforts have been made to obtain the official specs sheet for all trains mentioned above, however, unfortunately none of the information was made available from the transit agency directly. Instead, locomotive and engine characteristics, such as tractive effort and motive power, were referenced based on a prior report by AECOM on the USRC (AECOM, 2011).

3.4.2 Track Allocation

Union Station was undergoing a massive revitalization and construction process during the entire course of the project. With constructions, the usage of platforms has been changed after every a few months. As no official platform allocation document was received from Metrolinx, from field observation it was found that of 14 station depots at the Union Station, two depots were dedicated to VIA Rail, two to three depots were constantly out of service due to construction, and 9 depots were assigned to GO Transit.

3.5 Timetable and Schedule

Each year GO Transit makes several schedule adjustments to better meet the demand and on-going construction at the Union Station. In addition, VIA Rail and UP Express also share the tracks and platforms of Union Station and their schedules interfere with GO Transit. The schedule that would be selected as the case study was based on June 2016 when the project started. A report on weekly average passenger volume count associated with each trip was obtained from GO Transit, which as completed in 2014 (Go Transit Planning Development, 2014). After comparing each trip with GO Transit’s current schedule, despite the minor changes and adjustments that have been implemented by GO Transit throughout the year, the overall number of trains per line remained unchanged, and it was believed that the schedule could generally represent today’s condition. On the other hand, although the passenger volume continued to rise, the difference between 2014 and 2016 was believed to be almost negligible compared to the 2014 passenger volume. Besides, it was the only documentation available from GO Transit directly and no current data was available.
The total number of trains for each line for GO Transit, VIA Rail and UP Express are summarized in Table 3.2. A complete table of each trip along with its passenger volume during morning peak which would be used for base model in this thesis can be found in Appendix B.

<table>
<thead>
<tr>
<th>Line</th>
<th>Current # of trains/peak hour</th>
</tr>
</thead>
<tbody>
<tr>
<td>GO - Lakeshore West</td>
<td>2</td>
</tr>
<tr>
<td>GO - Lakeshore West - Express</td>
<td>4</td>
</tr>
<tr>
<td>GO - Lakeshore East</td>
<td>2</td>
</tr>
<tr>
<td>GO - Lakeshore East - Express</td>
<td>3</td>
</tr>
<tr>
<td>GO - Milton</td>
<td>5</td>
</tr>
<tr>
<td>GO - Kitchener</td>
<td>2</td>
</tr>
<tr>
<td>GO - Richmond Hill</td>
<td>2</td>
</tr>
<tr>
<td>GO - Barrie</td>
<td>3</td>
</tr>
<tr>
<td>GO - Stouffville</td>
<td>2</td>
</tr>
<tr>
<td>Via</td>
<td>4</td>
</tr>
<tr>
<td>UP Express</td>
<td>4</td>
</tr>
</tbody>
</table>

3.6 Current signaling system

The current signaling system was built in the 1920’s, which is a standard fixed-block three-aspect signaling system. Since 2015, the USRC has been undergoing a major signaling system improvement to bring the 90-year-old system to modern standards as an effort to minimize delays, operational bottlenecks and increase reliability using computer-based train dispatching, replacing the manual dispatching that is being used today.
Chapter 4

4 Data Collection

The scope of the project requires data from a wide range of operational data which include both train movements and pedestrian movements. Certain data such as ridership, schedule and general operation manual was obtained directly from GO Transit However, most of the operational data was not available directly. A series of data collections was consequently designed and performed.

4.1 Train Speed profile

Train speed Collection data collection occurred from between June 27- to June 30 in, 2016. Collection was conducted manually using with Android and iPhone counting applications, which logged location data with time stamp as collectors travel on the trains. Every morning during the study period, each collector boarded a GO train of on one of the seven GO rail lines between 7:30am and 8am at a station close to the city boundary of Toronto. They travelled into Toronto’s Union station while recording the data on the smartphone. This Data was stored and output as GPX files; QGIS was later used to visualize the collected data points and extract the data, from which the operational speed of each section of any all GO rail lines can be determined.

4.2 Train Path Identification

It is critical to identify the commonly-used train paths within the Union Station area, considering there are 14 station tracks (depots) and two major interlocking areas located directly on the west and east side of the station which could lead to a total possible train paths of more than 4000.

Two parts of data collections were performed using video recording. During the same collection period as the seven collectors were riding the train to travel to Union station every morning as described in section 4.1, they started video recording at train windows or doors as the train approached Union Station. For trains coming from the west side, collectors started recording after the train passed Spadina Avenue overpass; for trains coming from the east side collectors would start recording after the train passed Don River. Videos were required to capture the path each train took through the Union station’s ladder system.

These on-board recordings were supplemented by additional recordings taken from an elevated bridge located on the west side of the Union Station. During the same time period, two persons
were able to observe the west end of the entire Union Station platform as well as the west ladder system (Scott Street Interlocking) and the connecting track to the Bathurst North Yard, one of the maintenance yards located just 1 km west of the Union Station where GO transit stored some of their trains during off-peak hours. The location was ideal for capturing both revenue movements and equipment movements. Two video recording cameras were set up on the bridge facing opposite directions and filming the train movements under the bridge for four consecutive days.

All videos recorded were reviewed and analyzed to identify the path and a total of 30 and 24 of the most commonly used paths were identified for the west and east interlocking areas, respectively, for both revenue and equipment movements.

4.3 Departure and Arrival Delay
GO Transit runs a website named GO Tracker as demonstrated in Figure 4.1, where the operational status for any GO rail line is graphically presented. Each train is represented as an icon moving along a specific line, with an icon change when the train arrives at a station and a color change (to red) if it is running behind the schedule. It also provides on-time status in text for a selected station for each train on each line. Information would be provided if there is a major delay of more than 10 minutes. As defined in the study scope in section 3.2 only Union Station and the eight entry stations were selected to perform the data collection. The following information was extracted from the website for each train: arrival time at entry station; departure time at entry station and arrival time at Union Station. Delay reasons for major service disruption were also recorded if applicable. The data was collected using screen recording on several computers during morning peak from approximately 6:30 am to 9:30 am through October 2016 to March 2017. The different time period of data collection, compared to the train speed and path data, was not considered an issue since only station delay data was obtained. In addition, a longer period was deemed appropriate to generalize the study results. Relative information for each train was then obtained by reviewing the videos and following through each train. The resolution was 1 minute, in accordance with the information provided on the Go Tracker website.
4.4 Passenger Volume Count at Concourse Level and at Train Door

Passenger volume count at concourse level was collected during a weekday morning between 8am to 930am in October of 2016. This was performed by 10 people using smartphone timestamped counting apps. Each person was responsible for one of the nine staircases which connect Union Station’s platform 26-27 to the concourse level, counting passengers going both ways at the staircases.

Through multiple collections from December 2016 to March 2017, Passenger volume count at train door was collected on the platform as well as the skywalk bridge where the video recording occurred as mentioned in the previous section. For each train arrival, a random train door was selected for passenger flow counting since most GO train cars have identical specifications. Additionally, the train door selected was free of obstacles on the adjacent platform area such as staircases or elevators to ensure an uninterrupted flow from the train car.

The main purpose of passenger volume counts was to determine the maximum passenger flow rate of critical links at the station, including exit staircases and a typical GO train door. Since these are characteristic of the transit facility and with an assumption of general passenger behaviour not
changing dramatically within a relatively short period, the different time periods of collection were not considered to be an issue.

4.5 Dwell Time
Dwell time data were collected at the same time as the train door passenger count data. The main goal was to capture the duration of each critical segment of a dwell time at Union Station: 1) From train arrival to train door open; 2) from train door open to last passenger exiting; 3) from last passenger exiting to door closing; and 4) from door closing to train departure. Each go train car is equipped with an indicator light which lights up in red when the doors are open and turns off if doors are closed. It made it feasible to collect dwell time data even when the data collector was standing at a distant location, for example, the skywalk bridge on the west side of Union Station as described in section 4.2. The same counting app which could record each count with a time stamp is used.

4.6 Others
A few documents were acquired from GO Transit directly, including track layout and signal locations within the Union Station Rail Corridor as well as three of the seven GO rail lines; ridership reports; schedule and GTFS file; and an AutoCAD drawing that specified the detailed dimensions of the tracks within the railway corridor. Measurements were made using Google Maps to supplement the required dimensions for tracks and signal locations which are outside of the Union Station Railway Corridor area.
Chapter 5

5 Analytical Capacity Analysis

Following a general structure of capacity management, the thesis starts with analyzing the capacity using analytical methods. Four methods would be studied:

Transit Capacity and Quality of Service Manual (TCQSM) (2013)

Potthoff Method (1965)

Deutsche Bahn (DB) Method (1979)

UIC Compression Method (2013)

TCQSM was selected because it is considered as a general operational and planning guidebook for North America. The Potthoff method was selected as it was considered a reference method in the literature (16), and the DB method shares many similarities with it. The Compression method was selected since its latest edition was updated by the UIC to include application to the node area. It is important to understand a complicated system from studying and analyzing simple and easy-to-apply methods, which is a common feature that all these selected methods share.

Potthoff method and DB Method share common procedures, hence they are discussed together. The chapter demonstrates concepts and detailed mathematical calculations of each method and results are compared. Study period was between 8am and 9am in accordance to the study scope; dwell time was fixed to five minutes as suggested by the AECOM’s report on USRC (AECOM, 2011). All trains were assumed to have through movements at the Union Station area; only number of GO trains were adjusted to evaluate capacity, while all VIA rail trips and UP Express trips were still considered during the study period and remained at the same volume. A dedicated platform was assigned to each line.

5.1 Transit Capacity and Quality of Service Manual (TCQSM)

TCQSM provides deterministic formulas which estimate the minimum headways at each railway link based on operational performance and acceptable level of service. Capacity is then determined by the line section that requires the maximum minimum headway. The parameters taken into for
identifying the weakest link include: Dwell time at the controlling station along the rail line; minimum train separation allowed by the primary train control system; right-of-way type; turnbacks; junctions; power supply constraints; train length limitations and track layout within terminals. A total of eight steps are suggested by TCQSM to calculate the minimum headway of a line section.

The first step is to determine the non-interference headway, including minimum train separation time, controlling station dwell time and operating margin, as given by the following formula:

\[
 t_{cs} = \sqrt{\frac{2(L_t+d_{eb})}{a+a_gG_0}} + \frac{L_t}{v_a} + \left(\frac{1}{f_{br}} + b\right)\left(\frac{v_a}{2(d+a_gG_i)}\right) + \left(\frac{a+a_gG_0}{2v_a}\right)^2\left(1 - \frac{v_a}{v_{max}}\right) + t_{os} + t_jl + t_{br}
\]

(1)

\[
 t_{cs} = \frac{L_t+P_e}{v_a} + \left(\frac{1}{f_{br}} + b\right)\left(\frac{v_a}{2(d+a_gG_i)}\right) + \left(\frac{a+a_gG_0}{2v_a}\right)^2\left(1 - \frac{v_a}{v_{max}}\right) + t_{os} + t_jl + t_{br}
\]

(2)

\[
 h_{ni} = t_{cs} + t_{d, crit} + t_{om}
\]

(3)

where:

- \( t_{cs} \): train control separation (s)
- \( h_{ni} \): Non-interference headway
- \( L_t \): longest train length (m)
- \( d_{eb} \): distance from the front of stopped train to start of station exit block (m)
- \( v_a \): station approach speed (m/s)
- \( v_{max} \): maximum line speed
- \( f_{br} \): braking safety factor
- \( b \): separation safety factor
- \( t_{os} \): time for overspeed governor to operate on automatic systems
- \( t_{j} \): time lost to braking jerk limitation
- \( t_{br} \): brake system reaction time
- \( a \): initial acceleration (m/s²)
- \( d \): deceleration (m/s²)
- \( a_g \): acceleration due to gravity (m/s²)
- \( G_i \): Grade into station, downgrade = negative
- \( G_0 \): Grade out of station, downgrade = negative
- \( l_v \): line voltage as percentage of specification
- \( P_e \): positioning error (moving block only)
- \( t_{d, crit} \): average dwell time at the controlling station (s)
- \( t_{om} \): Operating margin

Equation (1) is for calculating fixed-block and cab signaling throughput; while equation (2) is for moving block systems. When calculating minimum headway of a mainline area, dwell time does
not need to be considered, the minimum headway would be determined by minimum train separation time and operating margin. For a station area, the minimum headway would account for the dwell time.

The next step is to determine the minimum headway associated with the right-of-way (ROW) type. Three types of ROW are considered, including single track with two-way operation; on-street operation (streetcar, LRT); and station departures adjacent to grade crossings. The final minimum headway would be the maximum value of the three.

The third step is to determine the headway at a junction area. TCQSM offers a headway calculation based on a simple crossing area as shown in Figure 5.1.

![Figure 5.1 Junction Area Example from TCQSM (Kittelson & Associates, Inc. et al., 2013)](image)

Based on the example described, the following formula is given when a train is blocked by a switch when traveling at main line:

\[
h_j = t_{cs} + \sqrt{\frac{2(L_t + n f_{sa} d_{ts})}{a}} + \frac{v_{max}}{a+d} + t_{sw} + t_{om}
\]

(4)

Where:
- \( h_j \): limiting headway at junction (s)
- \( d_{ts} \): track separation (m)
- \( f_{sa} \): Switch angle factor
- \( t_{sw} \): switch throw and lock time (s)

The formula provides certain insight of how the minimum headway would be affected at a single branch off or crossing area.
Furthermore, power supply constraints must be checked and satisfied. The final controlling headway \(h_c\) would be the maximum of all the headways discussed above in various sections along a railway line. The final train throughput would be simply the inverse of the minimum headway:

\[
T = \frac{3600}{h_c}
\]

Where:

- \(T\): line capacity (trains/h)
- \(h_c\): controlling headway (s/train)

The manual does require extra steps to verify the terminal layover time for turnback trains. Since the general assumption made in this thesis is that all trains would have through movements at the station area, it will not be discussed in this section.

Following the formulas provided by TCQSM, it can be calculated that for station area the minimum headway = 7.5 minutes, and for main lines the minimum headway = 2.5 min. The values of parameters used to calculate the headways are listed in Appendix C.

It can be seen from the formulas outlined in this section that TCQSM offers detailed calculation for line capacity, taking into considerations of all relevant parameters. However, for a junction area the formula is only capable of calculating the headway of a single branch off or crossing area. For the case of Union Station, as illustrated in Figure 5.2, there are two complex ladder systems located directly on the west side and east side of the Union Station platform area respectively, namely John St. Interlocking and Scott St. Interlocking. Obviously, the formulae provided by TCQSM were not able to offer a realistic solution of the capacity of the junction areas of this kind, in fact, the TCQSM suggests that it would be more beneficial to utilize other methods or simulation models for such complex network.
5.2 Potthoff method and Deutsche Bahn method

As stated by Kontaxi and Ricci, Potthoff method has become a reference method for analyzing node capacity by studying the regular occupation time and extra occupation time at the node due to conflicts of train paths (Kontaxi & Ricci, 2010). It studies the problem from a university point of view while Deutsche Bahn method tackles the problem from an industrial perspective. There are many common features and procedures in calculating the capacity using the two methods, hence they will be discussed together in this section. To begin with, both methods assume that trains could arrive at any instant of a study time period $T$ with the same probability. As a direct result, there is no need for a timetable when applying these two methods.

The first step of the two methods is to identify all possible train paths existing in the specified node area. An example of a simple station area is demonstrated by Malavasi as shown in Figure 5.3. There are 10 possible train paths and they are arranged in a matrix where rows and columns are associated with these train paths identified, as shown in Table 5.1.
Table 5.1 Compatibility Matrix (Malavasi et al., 2014)

<table>
<thead>
<tr>
<th></th>
<th>1-I</th>
<th>1-II</th>
<th>1-IV</th>
<th>4-III</th>
<th>4-IV</th>
<th>III-2</th>
<th>IV-2</th>
<th>I-3</th>
<th>II-3</th>
<th>IV-3</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-I</td>
<td>a</td>
<td>s</td>
<td>s</td>
<td></td>
<td>d</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1-II</td>
<td>s</td>
<td>a</td>
<td>s</td>
<td></td>
<td>d</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1-IV</td>
<td>s</td>
<td>a</td>
<td>u</td>
<td>x</td>
<td>u</td>
<td>d</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4-III</td>
<td>a</td>
<td>s</td>
<td>d</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4-IV</td>
<td>u</td>
<td>s</td>
<td>a</td>
<td>d</td>
<td>u</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>III-2</td>
<td>x</td>
<td>d</td>
<td>a</td>
<td>z</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IV-2</td>
<td>u</td>
<td>d</td>
<td>z</td>
<td>a</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>I-3</td>
<td>d</td>
<td></td>
<td></td>
<td>a</td>
<td>z</td>
<td>z</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>II-3</td>
<td>d</td>
<td></td>
<td></td>
<td>z</td>
<td>a</td>
<td>z</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IV-3</td>
<td>d</td>
<td>x</td>
<td>u</td>
<td>z</td>
<td>z</td>
<td>a</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The letter in each cell of matrix represents the type of conflict between the two intersected train paths:

- “a” – between a path and itself
- “x” – intersection of paths
- “z” – converging routes
- “s” – diverging routes
- “d” – consecutive routes;
- “u” – frontal collision routes

The empty cell in the matrix indicates that there is no conflict between the two train paths.

After identifying the train paths, the next step is to gather information of the total number of trips that would utilize each train path $i$, denoted as $n_i$, the information is presented in Table 5.2. Total number of trips is the summation of trips of individual paths: $N = \sum n_i$.

Table 5.2 Total Train Trips on Each Path

<table>
<thead>
<tr>
<th>Route</th>
<th>1-I</th>
<th>1-II</th>
<th>1-IV</th>
<th>4-III</th>
<th>4-IV</th>
<th>III-2</th>
<th>IV-2</th>
<th>I-3</th>
<th>II-3</th>
<th>IV-3</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td># of movements</td>
<td>56</td>
<td>55</td>
<td>0</td>
<td>112</td>
<td>8</td>
<td>112</td>
<td>8</td>
<td>56</td>
<td>55</td>
<td>0</td>
<td>462</td>
</tr>
</tbody>
</table>

The following step is to determine the occupation time $t_{ij}$ of the paths based on the compatibility matrix identified in Table 5.1. Cells indicating the incompatibility of two train paths would require a value of occupation time or interdiction time. In other words, it is the period of time that a trip on path $j$ has to wait when a trip on path $i$ is taking the incompatible path. A similar table layout as the compatibility matrix is used, while the cell in the matrix would be replaced by the occupation
or interdiction time \((t_{ij})\) as shown in Table 5.3. When \(i = j\), it represents the occupation time of a trip on path \(i\); otherwise it indicates the interdiction time for a trip on path \(j\) when path \(i\) is occupied. The value is highly dependent on the specific infrastructure layout.

<table>
<thead>
<tr>
<th></th>
<th>1-I</th>
<th>1-II</th>
<th>1-IV</th>
<th>4-III</th>
<th>4-IV</th>
<th>III-2</th>
<th>IV-2</th>
<th>I-3</th>
<th>II-3</th>
<th>IV-3</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-I</td>
<td>3.7</td>
<td>1.95</td>
<td>1.37</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1-II</td>
<td>0.93</td>
<td>1.73</td>
<td>0.7</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1-IV</td>
<td>1.85</td>
<td>1.85</td>
<td>3.93</td>
<td>0</td>
<td>4.11</td>
<td>1.47</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>4-III</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1.45</td>
<td>0.64</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.64</td>
</tr>
<tr>
<td>4-IV</td>
<td>0</td>
<td>0</td>
<td>3.6</td>
<td>1.54</td>
<td>3.34</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>III-2</td>
<td>0</td>
<td>0</td>
<td>0.92</td>
<td>0.82</td>
<td>0</td>
<td>1.31</td>
<td>1.31</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>IV-2</td>
<td>0</td>
<td>0</td>
<td>2.06</td>
<td>0</td>
<td>1.8</td>
<td>2.83</td>
<td>2.83</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>I-3</td>
<td>2.64</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>3.07</td>
<td>3.07</td>
<td>3.07</td>
<td>3.07</td>
<td>3.07</td>
</tr>
<tr>
<td>II-3</td>
<td>0</td>
<td>0.96</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1.28</td>
<td>1.28</td>
<td>1.28</td>
<td>1.28</td>
<td>1.28</td>
</tr>
<tr>
<td>IV-3</td>
<td>0</td>
<td>0</td>
<td>2.46</td>
<td>2.64</td>
<td>2.64</td>
<td>0</td>
<td>0</td>
<td>3.07</td>
<td>3.07</td>
<td>3.07</td>
</tr>
</tbody>
</table>

From this point, there are a few differences between the Pothoff and DB methods. The two methods would be individually discussed.

5.2.1 Pothoff Method

The key capacity indicators for the Pothoff method are defined as follows in the following paragraphs.

The average number of trips that can simultaneously run within the node area is defined by \(n_{med}\):

\[
n_{med} = \frac{N^2}{\Sigma(n_i \cdot n_j)}
\]

(6)

Where:

- \(N\): total number of trips \((N = \Sigma n_i = \Sigma n_j)\)
- \(n_i, n_j\): number of trips associated with path \(i\) and path \(j\)

The average occupancy time \((t_{med})\) is the time that \(n_{med}\) trains can simultaneously travel within the node area:

\[
t_{med} = \frac{\Sigma(n_i \cdot n_j \cdot t_{ij})}{\Sigma(n_i \cdot n_j)}
\]

(7)
With equation (6) and (7), the system can be represented as that \( n_{med} \) trains simultaneously circulate within the node area for a \( t_{med} \) time.

The method also proposes a way to calculate total delay that is imposed due to incompatibility of the conflicting paths within the nodes:

\[
R_{ij} = \frac{n_i n_j t_{ij}^2}{2T}
\]  

where:

\( R_{ij} \): average delay

The total time of occupation is calculated by equation (9) and the coefficient of utilization of the station is defined in equation (10).

\[
B = \frac{N}{n_{med} \cdot t_{med}} \tag{9}
\]

\[
U = \frac{B}{T} \tag{10}
\]

Finally, the total delay considering simultaneous movements of \( n_{med} \) trains in the system is defined as the ratio between total delay \( \sum R_{ij} \) and \( n_{med} \), and it has to fulfill the condition that:

\[
\frac{B+R}{T} = \frac{n_{med} t_{med} + \sum R_{ij}}{T} \leq 1 \tag{11}
\]

Equation (11) can also be represented as the capacity indicator of the Potthoff method since the total occupation time and delay cannot exceed the length of study period \( T \).

**5.2.2 Deutsche Bahn method**

Deutsche Bahn method, on the other hand, has another approach to determine capacity.

The method first determines the index \( k \), the probability with which the trips relating to the node are mutually exclusive. It only affects the pair of paths that are incompatible with each other. In other words, they are the cells in the compatibility matrix (Table 5.1) which are denoted with a letter symbol.

\[
k = \sum \frac{n_i n_j}{N^2} \tag{12}
\]
It also uses the definition of the total time of occupation, which describes the node area is occupied by trips:

\[
B = \frac{\sum(n_i n_j t_{ij})}{N} = \frac{N}{N^2 \sum(n_i n_j)} \frac{\sum(n_i n_j t_{ij})}{\sum(n_i n_j)} = \frac{N}{n_{med}} \cdot t_{med} \tag{13}
\]

As shown from equation (13), Deutsche Bahn method shares the same definition as that of Potthoff’s. It can also be calculated in function of the average blocking time as defined in equation (14):

\[
E(t) = \frac{\sum(n_i n_j t_{ij})}{\sum(n_i n_j)} \tag{14}
\]

The equation shares the same expression as the definition of \( t_{med} \) in Potthoff’s method, and equation (13) can re-written as:

\[
B = k \cdot N \cdot E(t) \tag{15}
\]

The utilization of the node is denoted as coefficient \( h \), which is essentially the same coefficient \( U \) defined in equation (10):

\[
h = \frac{B}{T} \tag{16}
\]

The difference is that DB method has a general guideline for the coefficient \( h \), suggesting a value range between 0.45 and 0.7 as from the most unfavorable scenarios to the most favorable scenarios, accounting for the quality of service.

There is another parameter defined in the methodology which is called the average tolerance time. It is the maximum blocking time \( t_{ij} \) to avoid that a trip on path \( i \) delays the successive trip on path \( j \).

\[
E(r) = \frac{(T-B)}{k \cdot N} \tag{17}
\]

DB method proposes a priority matrix to incorporate the priority associated with each type of trains or carriers. The matrix attains the same structure as the compatibility matrix, with each indicating the priority relationship between a pair of train paths. For instance, a priority matrix corresponding to the simple example introduced in Table 5.1 and Table 5.3 is demonstrated in Table 5.4.
Table 5.4 Priority Matrix

<table>
<thead>
<tr>
<th></th>
<th>1-I</th>
<th>1-II</th>
<th>1-IV</th>
<th>4-III</th>
<th>4-IV</th>
<th>III-2</th>
<th>IV-2</th>
<th>I-3</th>
<th>II-3</th>
<th>IV-3</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-I</td>
<td>G</td>
<td>G</td>
<td>G</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1-II</td>
<td>G</td>
<td>G</td>
<td>G</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1-IV</td>
<td>G</td>
<td>G</td>
<td>G</td>
<td>V</td>
<td>V</td>
<td>V</td>
<td></td>
<td>R</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4-III</td>
<td>G</td>
<td>V</td>
<td>V</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4-IV</td>
<td>R</td>
<td>R</td>
<td>G</td>
<td>V</td>
<td></td>
<td></td>
<td></td>
<td>R</td>
<td></td>
<td></td>
</tr>
<tr>
<td>III-2</td>
<td>R</td>
<td>R</td>
<td>G</td>
<td>V</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IV-2</td>
<td>R</td>
<td>R</td>
<td>R</td>
<td>G</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>I-3</td>
<td>V</td>
<td></td>
<td></td>
<td>G</td>
<td>R</td>
<td>R</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>II-3</td>
<td>V</td>
<td></td>
<td>V</td>
<td>G</td>
<td>R</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IV-3</td>
<td>V</td>
<td>V</td>
<td>V</td>
<td>V</td>
<td>V</td>
<td>G</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The letter symbols in the table above is denoted as:

- **G**: same priority
- **V**: higher priority
- **R**: lower priority

With the matrix, the interdiction time of a train on path i that imposes to a train on path j will be:

\[
P_{ij} = \frac{n_in_j(t_{ij} + d_{ij})^2}{2T}
\]

\[
P_b = \sum P_{ij}
\]

where:

\[d_{ij} = t_{ij}\text{ if path i has a priority over j;}
\]

\[d_{ij} = -t_{ij}\text{ if path i has a lower over j;}
\]

\[d_{ij} = 0\text{ if they share the same priority}
\]

The equation becomes the average delay \(R_{ij}\) defined in Potthoff’s method as described in equation (8) when the two paths share the same priority.

In addition, DB method also defines an approach to calculate the average number of trains in the waiting queue to evaluate operation quality:

\[
L_z = \frac{k \cdot P_b \cdot x^2}{T - x \cdot B}
\]

where:

\[x\text{ is a scale factor.}\]
According to the methodology, the maximum carrying capacity is reached when 60% of the trains wait in the queue before entering the node area \((L_z = 0.6)\). The value of \(x\) can be calculated based on such guideline, and the carrying capacity can be represented by \(N_z\):

\[
N_z = \frac{N \times T'}{T}
\]  

where:

- \(T'\): extended window period
- \(T\): original study window

If an analysis is focused on just single period of time \((T' = T)\), the capacity can otherwise consider to be reached when \(x \leq 1\).

As it is possible to observe that Potthoff method and Deutsche Bahn method share many similar approaches and the capacity parameters proposed by these two methods are interchangeable. The main difference between the two methods is that Deutsche Bahn method takes priority and quality of service into consideration when calculating the capacity.

5.2.3 Application to Union Station

Both Potthoff and DB methods were applied to preliminarily evaluate the capacity of Union Station. As described in section 5.1, Union Station has two complex interlocking areas located directly at the west and east side of the station area. Based on the infrastructure characteristics and track layouts, the total number of possible combination of paths can add up to 4000. After carefully reviewing the footages from the train path video recordings performed in section 4.2, 30 and 24 commonly used train paths were identified for west interlocking and east interlocking areas respectively, as shown in Figure 5.4.
The identified train paths were shared by GO trains, VIA Rail trains, and UP Express trains. Certain paths could be affected by the station dwell time.

With the identified train paths, there were still considerably large tables when constructing compatibility matrices and occupation/interdiction time matrices (30 x 30 and 24 x 24 for west and east interlocking areas respectively). It would be time consuming to fill all the cells up in these tables one by one. Therefore, an easier approach was required to identify the conflicts between each pair of paths.

A tool was created to automatically recognize the conflicts. The idea was that the conflicts arise when two train paths overlap at a same line section, a switch or a crossover area. When defining a train path, it was required to indicate all the switches the path would pass through, including starting track section of platform depot and ending track section or platform depot as illustrated in Table 5.5.

<table>
<thead>
<tr>
<th>Path ID</th>
<th>Line</th>
<th>Rev/Equip</th>
<th>Track Paths</th>
<th>Direction</th>
<th>Main Line/Switches/Depot</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>LSW</td>
<td>Rev</td>
<td>D2-SL2-UD14</td>
<td>East</td>
<td>D2 556A 561 591 596 600 586 587 Depot14</td>
</tr>
<tr>
<td>2</td>
<td>LSW</td>
<td>Rev</td>
<td>D2-SL2-UD13</td>
<td>East</td>
<td>D2 556A 561 591 596 600 586 587 686 Depot13</td>
</tr>
<tr>
<td>3</td>
<td>LSW-E</td>
<td>Rev</td>
<td>D1-SL2-UD13</td>
<td>East</td>
<td>D1 547 561 591 596 600 586 587 686 Depot13</td>
</tr>
</tbody>
</table>

If a line section, switch and crossover area was indicated by two and more than two train paths, all paths could potentially be conflicted with each other. The tool would highlight the cell in the final compatibility matrix where the corresponding paths intersect, making it easy to input the value. If no conflict is detected between a pair of train paths, the intersected cell would remain blank.
For the value of occupation and interdiction time $t_{ij}$ required in the methods, a simplified calculation method is used in this case as introduced by Malavasi et al. (Malavasi et al., 2014). A typical scenario is illustrated in Figure 5.5.

![Figure 5.5 Demonstration for a Simple Crossing](image)

The occupation time $t_1$ and $t_2$ of the trains on path 1 and path 2 respectively are assumed to be constant during the study period $T$; the probability of the train arrivals is uniformly distributed along the period. Under these assumptions, a train which finds itself blocked by another train due to path conflict must spend a wait time from 0 to the occupation time related to the train on the other path of the section. If acceleration and deceleration is neglected, the maximum time that a train must wait for the other is defined as:

$$t_{ij} = \frac{d_i + l_i}{v_i}$$

(22)

Where:

- $d_i$: track length from the previous signal location of the conflict point to the release point on path $i$
- $l_i$: length of train on path $i$
- $v_i$: average speed of train on path $i$

Even though the characteristics of path $j$ is not directly reflected in the equation, the calculation is specific to the layout of the point where the two train paths of interest intersect, hence the value of $t_{ij}$ would not be the same for any train paths that are conflicted with path $i$.

On the other hand, since most of the paths defined in the Union Station case directly start from or terminate at a platform area, it is critical to consider the dwell time at the platform area and incorporate it into the occupation and interdiction time matrix. Same applies to the main line
sections, the minimum train separation time of the next line section right after the conflicted point would also have an impact on the total occupation time and it should be considered properly.

The final tables of the occupation and interdiction time for west interlocking and east interlocking areas are presented in Appendix D.

In addition to the challenges discussed above when applying Potthoff and Deutsche Bahn methods, a few other statements should be made before performing the analysis. Due to the complex infrastructure layout of Union Station, it would be extremely difficult to conduct an analysis that include the west interlocking area, station area and the east interlocking all together. The two interlocking areas would be treated separately, with considerations to the station dwell time each path may encounter with as well as the minimum train separation time each path connects with. Based on the current schedule as shown in Table 3.2, the capacity analysis results using both Potthoff and Deutsche Bahn (DB) methods are presented in Table 5.6 and Table 5.7.

Table 5.6 Results for Current Schedule using Potthoff Method

<table>
<thead>
<tr>
<th>Potthoff</th>
<th>$n_{med}$</th>
<th>$T$</th>
<th>$t_{med}$</th>
<th>B(min)</th>
<th>U20h</th>
<th>$\sum R_{ij}$</th>
<th>$\sum R_{ij}/n_{med}$</th>
<th>$(B+R)/T$</th>
</tr>
</thead>
<tbody>
<tr>
<td>W.I.</td>
<td>3.24</td>
<td>60.00</td>
<td>2.87</td>
<td>33.67</td>
<td>0.56</td>
<td>58.65</td>
<td>18.12</td>
<td>0.86</td>
</tr>
<tr>
<td>E.I.</td>
<td>1.80</td>
<td>60.00</td>
<td>2.27</td>
<td>32.81</td>
<td>0.55</td>
<td>24.57</td>
<td>13.66</td>
<td>0.77</td>
</tr>
</tbody>
</table>

Table 5.7 Results for Current Schedule using DB Method

<table>
<thead>
<tr>
<th>DB</th>
<th>$k$</th>
<th>E(t)</th>
<th>B</th>
<th>h</th>
<th>E(r)</th>
<th>$L_x$</th>
<th>T</th>
<th>$P_b$</th>
<th>$x$</th>
</tr>
</thead>
<tbody>
<tr>
<td>W.I.</td>
<td>0.31</td>
<td>2.87</td>
<td>33.67</td>
<td>0.56</td>
<td>2.24</td>
<td>0.60</td>
<td>60.00</td>
<td>53.25</td>
<td>1.00</td>
</tr>
<tr>
<td>E.I.</td>
<td>0.56</td>
<td>2.27</td>
<td>32.81</td>
<td>0.55</td>
<td>1.88</td>
<td>0.60</td>
<td>60.00</td>
<td>24.57</td>
<td>1.06</td>
</tr>
</tbody>
</table>

where:

- W.I.: West Interlocking area
- E.I.: East Interlocking area

The result from Potthoff method shows that currently west interlocking area is operating at a higher volume than the east interlocking. The values of $(B+R)/T$ are smaller than 1, yet they are quite close indicating that the station area could possibly be able to handle only a limited number of more trains. On the other hand, the value of $x$ for west interlocking area from DB method is already at 1, indicating that at the current level of train volume the west interlocking is already at capacity while east interlocking is extremely close to capacity with an $x$ value of 1.06. This is expected as discussed in the previous section, essentially Potthoff and Deutsche Bahn methods have similar
approaches while Deutsche Bahn method produces the result with consideration of certain service quality criteria.

The final capacity of the entire station area was determined by inserting trains into the system based on the current schedule. Only GO trains were inserted, while the volume of VIA Rail trains and UP Express trains remained the same. Since each interlocking area was evaluated separately, consistency when inserting any train trip should be carefully maintained as any addition of the train trip would add occupation on both interlocking areas. Based on the key capacity indicator discussed in the previous section, the system was considered to reach its capacity when any of the two interlocking areas reaches \((B + R)/t \geq 1\) for Porrhoff method, or \(x \leq 1\) for Deutsche Bahn method. The final number of trains at capacity from both methods are listed in Table 5.8, and the capacity indicators of the two methods are demonstrated in Table 5.9 and Table 5.10.

As expected Porrhoff method reveals a higher train volume than Deutsche Bahn method, with 31 GO trains and 26 GO trains respectively for the two methods. It should be noted that for DB method, a minor adjustment was made to the original schedule by reducing one train from BA line. The capacity it freed up was able to accommodate two more trains on the lakeshore lines before reaching the capacity.

### Table 5.8 Number of GO Trains at Capacity

<table>
<thead>
<tr>
<th>Method</th>
<th>Total</th>
<th>LSW</th>
<th>LSW_E</th>
<th>LSE</th>
<th>LSE_E</th>
<th>MI</th>
<th>KI</th>
<th>RH</th>
<th>BA</th>
<th>ST</th>
</tr>
</thead>
<tbody>
<tr>
<td>Potthoff</td>
<td>31</td>
<td>3</td>
<td>5</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>DB</td>
<td>26</td>
<td>3</td>
<td>4</td>
<td>3</td>
<td>3</td>
<td>5</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>

### Table 5.9 Capacity Indicators for Potthoff Method

<table>
<thead>
<tr>
<th>Potthoff</th>
<th>(n_{med})</th>
<th>T</th>
<th>(t_{med})</th>
<th>B(min)</th>
<th>U20h</th>
<th>(\sum R_{ij})</th>
<th>(\sum R_{ij}/n_{med})</th>
<th>(B+R)/T</th>
</tr>
</thead>
<tbody>
<tr>
<td>W.I.</td>
<td>3.34</td>
<td>60</td>
<td>2.78</td>
<td>36.69</td>
<td>0.61</td>
<td>68.81</td>
<td>20.61</td>
<td>0.96</td>
</tr>
<tr>
<td>E.I.</td>
<td>1.86</td>
<td>60</td>
<td>2.33</td>
<td>40.25</td>
<td>0.67</td>
<td>37.03</td>
<td>19.96</td>
<td>1.00</td>
</tr>
</tbody>
</table>

### Table 5.10 Capacity Indicators for DB Method

<table>
<thead>
<tr>
<th>DB</th>
<th>(k)</th>
<th>E(t)</th>
<th>B</th>
<th>h</th>
<th>E(r)</th>
<th>L_z</th>
<th>T</th>
<th>(P_b)</th>
<th>x</th>
</tr>
</thead>
<tbody>
<tr>
<td>W.I.</td>
<td>0.30</td>
<td>2.86</td>
<td>33.32</td>
<td>0.56</td>
<td>0.56</td>
<td>2.29</td>
<td>0.60</td>
<td>60.00</td>
<td>53.62</td>
</tr>
<tr>
<td>E.I.</td>
<td>0.54</td>
<td>2.32</td>
<td>33.94</td>
<td>0.57</td>
<td>0.57</td>
<td>1.78</td>
<td>0.60</td>
<td>60.00</td>
<td>27.17</td>
</tr>
</tbody>
</table>
5.3 Compression Method

Compression method was introduced by International Union of Railways (UIC). It was first presented in UIC Code 406 (International Union of Railways, 2004), while at that time it was mainly focused on capacity analysis of a line section. In the latest edition, UIC 406 capacity leaflet (International Union of Railways, 2013), the concept was extended to cover node areas as well. The method offers the information regarding the capacity usage of the infrastructure, and it only requires the data from existing timetable and can be applied easily. Similar to TCQSM, the method also requires a rail network to be divided into smaller sections and each section should be assessed individually and compared. Five general steps are defined by UIC:

- Define the scope of infrastructure and timetable
- Define each section for evaluation
- Calculate capacity consumption
- Evaluate capacity consumption for each section
- Assess available capacity

5.3.1 Compression for a Line Section

In order to fully understand the compression method, it is beneficial to start with the principles of the method on a line section before applying to a node area.

As a general rule, the train paths to be included should start at the beginning of the line section within the study time period, and the paths should be included completely along the line section if their start points lie within the time period.

The method is based on a blocking time model. Railway network is divided into sections marked by track-side signals, and each section is defined as a block. The purpose of such signal block is to ensure safety so that when one block is occupied by a train, the following train or train that shares a path that is conflicted with the section would not be allowed to enter. For a single block, it is comprised of three basic elements: reservation time, actual occupation time and release time. Detailed components can be seen in Figure 5.6. In compression method, the occupancy time includes the period from the beginning of reservation to the final release time.
A line section is consisted of one or multiple block sections. On a unidirectional single track between location A and C, the train paths on a time-distance diagrams over a period length of 2 hours is shown in Figure 5.7. The train paths are based on an existing schedule, each line represents one trip on the train path, and each square on a trip is a block section. The figure also offers a good example of the criteria of including or excluding certain trips when performing a capacity analysis. The main idea of the compression method is that based on the timetable, available capacity could still exist in between any pair of trips. Hence, capacity consumption is then calculated by compressing all of the blocks during the defined line section and time period while maintaining the original sequence of trips as well as the shape of the train paths in the time-distance diagram.
In other words, the original occupation. Practically, the first train path can be inserted as a final train path at the end of the sequence to make up for any unaccounted time between the last trip and the end of the study period. The starting point of the final trip (inserted first trip) is the end of the occupancy time. The final occupancy time is measured from the start of the first train until the start of the last train, as shown in Figure 5.8.

![Figure 5.8 Capacity Consumption After Compression (International Union of Railways, 2013)](image)

The method calculates the final occupancy time without considering any buffer time or safety margin to indicate a level of service. To incorporate quality of service, UIC proposes a concept called Additional Times, which is to limit capacity consumption by a given percentage. The details of the additional times would be discussed later in this chapter.

5.3.2 Compression for a Node Area

For a node area, the same concept could be applied while certain adjustments are required to be made to take into consideration the complexity of the junction area, possibility of parallel paths as well as the conflicts among the train paths.

The procedure starts with identifying all possible train paths in an interlocking area. For a simple junction area as presented in Figure 5.9, a matrix is set up by listing the identified train paths against all excluded paths as shown in Table 5.11. As can be easily seen from the content of the matrix, it is essentially the same occupation and interdiction matrix as introduced by Potthoff and DB in the previous section.
Table 5.11 Matrix of Occupation/Interdiction (International Union of Railways, 2013)

<table>
<thead>
<tr>
<th>Excluded Trip k</th>
<th>pA</th>
<th>PB</th>
<th>aP</th>
<th>aF</th>
<th>FB</th>
<th>fA</th>
<th>bF</th>
<th>bP</th>
</tr>
</thead>
<tbody>
<tr>
<td>pA</td>
<td>1.7</td>
<td>1.4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PB</td>
<td>1.4</td>
<td>1.7</td>
<td>1.4</td>
<td>1.4</td>
<td>1.7</td>
<td>1.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>aP</td>
<td>1.5</td>
<td>1.8</td>
<td>1.3</td>
<td>1.3</td>
<td>1.3</td>
<td>1.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>aF</td>
<td>2.4</td>
<td>2.2</td>
<td>2.4</td>
<td>2.4</td>
<td>2.9</td>
<td>2.4</td>
<td>2.4</td>
<td>2.4</td>
</tr>
<tr>
<td>fB</td>
<td>2.4</td>
<td>2</td>
<td>2.4</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>fA</td>
<td>2.4</td>
<td>2</td>
<td>2.4</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>bF</td>
<td>2.3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2.3</td>
<td>1.7</td>
</tr>
<tr>
<td>bP</td>
<td>1.8</td>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
<td>1.8</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The following step is to provide a sequence of paths as in the timetable to be evaluated. A example is provided in Table 5.12. This step is rather critical as it is a required input for the compression method. In contrast, such timetable is not necessary for the Potthoff and DB method. The first row indicates the time when the train path starts. It is possible to have two train paths starting at the same time since parallel paths exist, while an arbitrary order should still be assigned for the two paths.

Table 5.12 Sequence of Train Paths as Indicated by the Timetable (Malavasi et al., 2014)

<table>
<thead>
<tr>
<th>min</th>
<th>3</th>
<th>6</th>
<th>9</th>
<th>12</th>
<th>15</th>
<th>18</th>
<th>21</th>
<th>24</th>
<th>27</th>
<th>33</th>
<th>36</th>
<th>39</th>
<th>42</th>
</tr>
</thead>
<tbody>
<tr>
<td>Path</td>
<td>pB</td>
<td>pA</td>
<td>fB</td>
<td>pA</td>
<td>fB</td>
<td>pA</td>
<td>bP</td>
<td>aP</td>
<td>fA</td>
<td>fB</td>
<td>aP</td>
<td>fB</td>
<td>pA</td>
</tr>
<tr>
<td>Order</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>8</td>
<td>9</td>
<td>10</td>
<td>11</td>
<td>12</td>
<td>13</td>
</tr>
</tbody>
</table>

With the scheduled sequence, it is possible to calculate the occupancy time. The train paths can be added into calculation with reference to the defined sequence. With every entry, all excluded train paths should be listed with the interdiction or occupation time value from Table 5.11, indicating the earliest time that a train on any of the excluded train path can start while the actual path is taken in the node. For example, as shown in Table 5.13, a trip on path pB starts first at the node at time 0. While the train starts moving on the path pB, the next train on pA and fB cannot start until time
1.4 and time 1.7 respectively. Consequently, when the second train on path pA is about to enter the node (2nd entry of the table), the time for begin of occupation for path pA is shown as 1.4. Similarly, all trips that are conflicted with path pA should be considered when the train on pA is running, and it should also consider the earliest time for the path to start in the previous iteration. For example, when the train on path pA is running, the next train on path pA cannot start until time 3.1 because previously when path pB is running, pA cannot start until time 1.4; while when the second train on pA is running the next train on pA cannot start until 1.7 minutes later as indicated in the occupation and interdiction matrix in Table 5.11, hence 1.4+1.7=3.1.

Table 5.13 Inserting Train Paths for Occupancy Time Calculation in a Node

<table>
<thead>
<tr>
<th>Order</th>
<th>Trip</th>
<th>Begin of occupation</th>
<th>pA</th>
<th>pB</th>
<th>aP</th>
<th>aF</th>
<th>fB</th>
<th>fA</th>
<th>bF</th>
<th>bP</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>pB</td>
<td>0</td>
<td>1.4</td>
<td>1.7</td>
<td>1.4</td>
<td>1.4</td>
<td>1.7</td>
<td>1.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>pA</td>
<td>1.4</td>
<td>=1.4+1.7</td>
<td>=1.4+1.4</td>
<td>*/1.4</td>
<td>*/1.4</td>
<td>*/1.4</td>
<td>=1.4+1.7</td>
<td>*/0</td>
<td>*/0</td>
</tr>
<tr>
<td>3</td>
<td>fB</td>
<td>1.7</td>
<td>*/3.1</td>
<td>=1.7+2.4</td>
<td>=1.7+2.4</td>
<td>=1.7+2.4</td>
<td>=1.7+2.4</td>
<td>=1.7+2</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Possible simultaneous train movements are taken into consideration, as can be seen from the table above that when a certain trip is occurring, multiple excluded trips can start at the same time with the same Begin of Occupation value.

There are a few rules when performing the calculation: each trip should start as soon as the previous trip based on the exclusion time and no buffer time is considered. The total occupancy time is the beginning time of occupation of the last trip entered in the table. A higher value should always be attained for any iteration of the exclusion path. Similar to the procedure for the line section, the first trip may be inserted at the bottom of the calculation table as the last trip. If the inserted first trip is still not excluded by the last trip, the second or even the third trip needs to be added. The final occupancy time rate (OTR) can be calculated as:

\[
\text{Occupancy Time Rate} \% = \frac{\text{Occupancy Time}}{\text{Defined Time Period}} \times 100\%
\]

(23)

UIC states that OTR is not the final criteria for evaluating capacity consumption since the OTR does not consider buffer time or safety margin to incorporate quality of service into measurements. It proposes a parameter named Additional Time Rate (ATR) as defined in equation (24). This acts to limit the permitted capacity consumption by a given percentage.
Additional Time Rate \[\%\] = \left[\frac{100}{\text{Occupancy Time Rate}} - 1\right] \times 100 \tag{24}

The final capacity consumption (CC) value is then calculated as follows:

\[
\text{Capacity Consumption} \ [\%] = \frac{\text{Occupancy Time} \times (1 + \text{Additional Time Rate})}{\text{Defined Time Period}} \times 100
\tag{25}
\]

A line section is considered to reach its capacity if its capacity consumption value reaches 100%; and the line section with the highest capacity consumption value should be the representative line section.

The equation outlined in (24) above is for calculating the additional time rate for a line section. For a node section, a concatenated occupancy rate is suggested instead, which is defined as \(\phi\):

\[
\phi(\text{Concatenation Rate}) = \frac{K}{Z} \times 100\%
\tag{26}
\]

where:

- \(K\): number of concatenations
- \(Z\): total number of trips within the study period

The number of concatenations \(K\) can be obtained by tracing the starting points backwards from the last begin of occupation until the first begin of occupation as shown in Table 5.14. In this example, there are 17 trips from the original timetable to be compressed, the 18\(^{th}\) trip is the first trip that is inserted again at the bottom to avoid “open end”. Assuming an evaluation time period of 60 minutes, the occupancy time rate for the schedule is: \(\frac{18}{60} \times 100\% = 30\%\). On the other hand, the total number of concatenations \(K\) is 9, concatenation rate \(\phi = \frac{K}{Z} \times 100\% = \frac{9}{17} \times 100\% = 52.94\%\).
However, there are some issues when evaluating the capacity of a node area using the capacity consumption with concatenation rate. One of the main concerns is that the purpose of calculating additional time is not very clear. The leaflet states that it is intended to reflect the required quality of service, yet there is no description regarding what kind of quality of service it is intended for, or the possible capacity indicator it is designed for, such as average delay or on-time performance.

On the other hand, the leaflet also states that there is little empirical data concerning appropriate occupancy time rates since the method is quite new, and the values must be confirmed by calculation before they are applied universally. Additionally, there has been little study performed using the latest compression method on a node area, hence the accuracy and magnitude of the additional time rate is hard to verify, so is the level of service that the additional time is supposed to reflect.

In this regard, both OTR and CC were applied as two key capacity indicators. Two individual analyses were performed to determine the maximum train volume when considering and not considering the quality of service defined in the compression method. The disadvantage of using OTR is that it does not account for the quality of service as no buffer time is considered; however, this allowed for obtaining a theoretical capacity as opposed to a practical capacity.
5.3.3 Application to Union Station

As discussed in the previous section, the matrices of occupation and interdiction time is the same table as used in Pothoff and DB methods. The OTR needs to be calculated for west and east interlocking separately, with considerations of the dwell time and minimum train separation that each path is connected with. The base schedule (current schedule) is evaluated first, results are shown in Table 5.15.

<table>
<thead>
<tr>
<th>Indicator</th>
<th>West Interlocking</th>
<th>East Interlocking</th>
</tr>
</thead>
<tbody>
<tr>
<td>Occupancy Time Rate (OTR)</td>
<td>75%</td>
<td>54%</td>
</tr>
<tr>
<td>Concatenation Rate</td>
<td>32%</td>
<td>54%</td>
</tr>
<tr>
<td>Additional Time Rate</td>
<td>215%</td>
<td>87%</td>
</tr>
<tr>
<td>Capacity Consumption (CC)</td>
<td>35%</td>
<td>63%</td>
</tr>
</tbody>
</table>

The OTR is determined by the track section that has the maximum occupancy, while the resulting concatenation rate, additional time rate and capacity consumption were calculated. The additional time rate would be used to evaluate maximum capacity of the node area.

The maximum capacity of the station area was determined by inserting more trains into the schedule until any of the two interlocking areas has reached 100%, with considerations to parallel train paths. Since timetable is required for this method, one assumption was made to simplify the process: every GO line was scheduled with a uniformed headway at every station depot at Union. Timetable optimization and generation were not within the scope of the study and the purpose of generating the timetable is to demonstrate the method and possible congestion situation.

A general procedure for inserting trips into the timetable to evaluate capacity using CC is given by UIC as shown in Figure 5.10.
The flowchart can also be applied to determine capacity using OTR by simply replacing CC with OTR. The main concept is that the capacity is considered to be reached when any addition of train paths to any GO line would result in an overall OTR or CC of 100% or over 100% through trial and error.

The results for the capacity in the context of maximum train volume using CC and OTR are shown in Table 5.16.

<table>
<thead>
<tr>
<th>Critical Indicator</th>
<th>Evaluating Capacity based on CC</th>
<th>Evaluating Capacity based on OTR</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>West Interlocking</td>
<td>East Interlocking</td>
</tr>
<tr>
<td>Max. Train Volume</td>
<td>50</td>
<td>55</td>
</tr>
<tr>
<td>Occupancy Time Rate (OTR)</td>
<td>73%</td>
<td>85%</td>
</tr>
<tr>
<td>Concatenation Rate</td>
<td>17%</td>
<td>47%</td>
</tr>
<tr>
<td>Additional Time Rate</td>
<td>215%</td>
<td>87%</td>
</tr>
<tr>
<td>Capacity Consumption (CC)</td>
<td>34%</td>
<td>98%</td>
</tr>
</tbody>
</table>
5.4 Results and Discussion

The final GO train volumes at system capacity for the analytical methods, along with the volume of the current schedule, are shown in Table 5.17. The results from TCQSM are not included as the method would not be able to analyze a complex node area through calculating minimum headway.

<table>
<thead>
<tr>
<th>Method</th>
<th>Total</th>
<th>LSW West</th>
<th>LSW E (Express)</th>
<th>LSE</th>
<th>LSE E (Express)</th>
<th>MI</th>
<th>KI</th>
<th>RH</th>
<th>BA</th>
<th>ST</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current Schedule</td>
<td>25</td>
<td>2</td>
<td>4</td>
<td>2</td>
<td>3</td>
<td>5</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>Potthoff</td>
<td>31</td>
<td>3</td>
<td>5</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>DB</td>
<td>26</td>
<td>3</td>
<td>4</td>
<td>3</td>
<td>3</td>
<td>5</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Compression (OTR)</td>
<td>55</td>
<td>6</td>
<td>7</td>
<td>6</td>
<td>6</td>
<td>5</td>
<td>6</td>
<td>6</td>
<td>7</td>
<td>6</td>
</tr>
<tr>
<td>Compression (CC)</td>
<td>50</td>
<td>6</td>
<td>7</td>
<td>6</td>
<td>6</td>
<td>5</td>
<td>4</td>
<td>6</td>
<td>4</td>
<td>6</td>
</tr>
</tbody>
</table>

In applying the DB method, a minor adjustment was made to the original schedule, specifically removing one train from the BA line. This was done to free up capacity to accommodate two additional trains on the Lakeshore lines.

The results show that the Potthoff method estimated a higher train volume than the DB method when the system reached capacity; also, the compression method using OTR produced a higher estimate of the node capacity than CC.

This was expected as neither the Potthoff method nor compression method with OTR considers quality of service when analyzing the capacity. In contrast, the DB method considers the system at capacity when 60% of the trains wait in the queue before entering the node area, while the compression method with CC uses ATR to create a buffer between each movement within the node area.

Furthermore, the resulting train volume of the compression method was substantially higher than those of the Potthoff and DB methods. One likely reason is related to the requirement of the compression method for a timetable, which makes it possible to arrange the sequence of different trips in a node area such that the available capacity is highly utilized. In contrast, the Potthoff and DB methods do not require a timetable, assuming trains could arrive at any instant with the same probability. While this assumption facilitates a more simplified application of the method, the results would be highly averaged. A simple example could fully illustrate the difference between these methods.
If the system was at capacity according to the result from DB (26 trains) and compression with CC (50 trains) respectively, the effect of adding one VIA trip to the system is demonstrated in Table 5.18.

Table 5.18 Impact of Adding 1 VIA Trip with Analytical Methods

<table>
<thead>
<tr>
<th>Method</th>
<th>Capacity Indicator</th>
<th>West Interlocking</th>
<th>East Interlocking</th>
<th>Add 1 VIA trip</th>
<th>West Interlocking</th>
<th>East Interlocking</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pothoff</td>
<td>(B+R)/T</td>
<td>0.85</td>
<td>0.81</td>
<td>0.90</td>
<td>0.96</td>
<td></td>
</tr>
<tr>
<td>DB</td>
<td>x</td>
<td>1.00</td>
<td>1.02</td>
<td>0.97</td>
<td>0.88</td>
<td></td>
</tr>
<tr>
<td>compression</td>
<td>OTR</td>
<td>73%</td>
<td>85%</td>
<td>73%</td>
<td>85%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>CC</td>
<td>34%</td>
<td>98%</td>
<td>34%</td>
<td>98%</td>
<td></td>
</tr>
</tbody>
</table>

With the addition of the VIA trip, the capacity indicators increased for the Pothoff method, decreased to drop below the capacity threshold for the DB method, while the overall OTR and CC of the compression method remained the same. This was because the capacity indicator of the compression method was determined by the maximum occupancy of all train tracks within the same section; in other words, it was the bottleneck. Potential volume increase was still possible without affecting the overall occupancy time rate or capacity consumption. This proved that the Pothoff and DB methods average the values for all the trips, which means that any additional trip would contribute to total delays and capacity if it intersected with any of the other paths in the node. On the other hand, for the compression method, it was possible to maximize the capacity with careful scheduling on a timetable.

The Pothoff, DB and Compression methods all utilize a matrix of occupancy and interdiction time to indicate the conflicts between pairs of train paths. This renders the application of these methods simpler, in that only a pair of paths needs to be focused on at a time to identify conflicts; on the other hand, the size of the matrix grows exponentially with the increase of possible train paths, and the accuracy of the values in the matrix is critical to the final capacity evaluation. The Pothoff and DB methods are simpler for application as they do not require a timetable. Their results, however, are highly averaged, which might underestimate the available capacity. On the other hand, a timetable is required and critical for the capacity evaluation using the Compression method. It is possible to identify the bottleneck with the Compression method by tracing back the concatenation, and it could theoretically achieve maximum capacity with proper scheduling.
However, the application of ATR, as proposed by the UIC to incorporate level of service, needs to be further studied to determine its proper magnitude as the value could strongly influence the final train volume at capacity.
Chapter 6

6 Railway Simulation

As many previous researches and manuals have recognized that as the complexity of the system increases, the difficulty of analyzing the capacity of a node area using mathematical approaches could grown exponentially, and a simulation tool would be necessary. A simulation is a representation of the real-world, it could replicate many behaviors and actions and evaluate the performances and scenarios which are usually hard and costly to recreate physically, providing that the simulation model is configured properly. On the other hand, extensive data collection is required to ensure the accuracy of a simulation model, hence comprehensive calibrations and validations are necessary. In general, the process of setting up a simulation model includes data collection, model construction, model calibration, and model validation. Further scenario tests can be built on successful validation of the base model.

Toronto’s Union Station Rail Corridor is considered to be a very complicated system due to the two interlocking systems located directly on both sides of the station area, 14 station track depots, hundreds of switches that contribute to a total possible combinations of train paths to be over 4000 in the areas. A simulation tool would be beneficial in capacity analysis for a railway corridor of this scale. In this study, a railway simulator OpenTrack is selected for fulfilling the task. OpenTrack is developed at ETH Zurich and by OpenTrack Railway Technology Ltd., the package allows to model, simulate and analyze various rail systems on a microscopic level from defining locomotive and train characteristics to constructing the detailed network of the railway system and configuring the signaling system. The simulation model includes calculations of the precise train movements under these constraints, following a specified timetable, distributions of delays and various performance factors.

6.1 Model Construction

The specific data required for setting up the OpenTrack model include train speed profile, train path identification, departure delays, and train configuration information as described in section 4.1, section 4.2 and section 4.3.
The infrastructure model was created by defining track layouts, lengths, signals, station areas, switches and other properties including gradients, power supply, tunnel section and radius. Such information was obtained from GO Transit directly for areas within the Union Station Rail Corridor (USRC).

The train speed profile collected was used to set the maximum speed for each track section along all of the seven GO Rail lines. Maximum speed limit within the USRC corridor was acquired from USRC Operation Manual as introduced in section 3.3.

The scope of the infrastructure model followed the definition of the study as indicated in section 3.2 which covered one station prior to Union Station, including express trips. The final infrastructure model constructed in OpenTrack is shown in Figure 6.1. It was consisted of a main file with stations that were one stop away from Union, and an expansion network that covered all the stations where express trains started.

Figure 6.1 Infrastructure Layout of Main network (a) and Expansion (b) for OpenTrack Model
OpenTrack requires that a hierarchy of train paths to be defined including route (signal to signal); path (station to station) and itinerary (start and end point of a train trip). A course or a trip then can be simulated based on the structure of the defined path of the infrastructure, since there could be various the combinations of different paths between the same origin and destination. As previously applied in section 5.2 and 5.3 the video recordings of train paths were carefully studied and a total of 30 and 24 commonly used train paths were identified for west interlocking and east interlocking areas respectively. These paths were used to be assigned to each line to represent the regular train paths for each line passing through the Union Station.

Train profiles were defined as described in section 3.4 Locomotive and engine characteristics such as tractive effort and motive power were configured based on a prior report by AECOM on the USRC. It was assumed that each GO train was consisted of one locomotive and 12 cars; each VIA train was consisted of one locomotive and 6 cars; and each UP Express train was consisted of three cars.

The simulation was first based on the current timetable as the base model for calibration and validation. The current timetable was illustrated in Table 3.2. With 25 arrivals for GO trains, six trains would continue their trips along lakeshore west or lakeshore east lines, the rest would become out of service as soon as they arrive at the Union Station and clear the passengers off the train. These trains were assumed to leave for the three depots (Willowbrook, Bathurst North and Don Yard). Due to lack of data, it was assumed that each yard had unlimited capacity to accommodate as many out-of-service trains as possible. Another concern was that based on the operation schedule obtained from GO Transit, it was noticed that there was a “internal departure schedule” for both revenue movements (carrying passengers) and equipment movements (trains that head to the yard), possibly to avoid conflicts at the interlocking area. Unfortunately, the in-depth reasoning for such internal departure schedule was not clear as no internal information was available. In order to realistically reflect the effect of such internal departure time, it was determined that for each trip that did not have a published departure time after their arrivals at Union (trains becoming out of service), the internal departure time for these trains would be 5 minutes after their published arrival time at the station. Connecting trips at Union would not be affected as they always had published arrival and departure time at the Union Station.
The dwell time at the station was assumed to be 5 minutes, as indicated by the USRC report by AECOM as well as GO Transit’s reference. Considering the effect of the internal departure time outlined in the section above, the final dwell time would be 5 minutes at minimum, depending on how early the train arrived at the station. In other words, if a train arrived at the Union Station and became out of service, it would dwell at the platform for 5 minutes. At the end of the 5-minute period, it would check whether the current time was later than the internal departure time, and it would depart right away if it was, otherwise the train will be held until the internal departure time. The general work flow chart of the simulation for one trip is shown in Figure 6.2.

The study period would focus between 8am and 9am for an hour. Simulation would run from 7am to 10am to include 1 hour before and after for warming up the system.
6.2 Departure Delay Statistical Analysis

One of the critical advantages of a simulation package is the capability of capturing the stochasticity of the system. Departure delay at entering stations is a major input of such stochasticity. There are multiple delays in a railway network, Sipilä (Sipilä, 2010), Nelldal et al. (Nelldal et al., 2011) and Lindfeldt (Lindfeldt, 2015b) identified that types of delays could include entry delay, dwell time extensions, departure delay and running time extension. All studies used entry delay as an input and then validate and evaluate the system by assessing the arrival delay at the downstream stations. This thesis focused on the departure delay from where trains were released in accordance with the scope of the study (one station away from Union). In fact, due to the scope definition, entry delay and departure delay for this case were identical as only two stations were involved and the virtually every train within the study scope were released from the station that was one station away from Union. Dwell time extension and running time extension were not modelled in this study due to lack of data. Besides, considering the scope, the lengths of line sections for each GO line were quite short and the travelling delays occurred could almost be negligible.

The delay data collected in section 4.3 was used to model the departure delay. The first step was to exclude all on-time trips. The reason being was that based on observation, all GO trains would be held until their published schedule time at any station if they were ahead of schedule. In this regard, the on-time trains were limited by the schedule, and there was no obvious randomness that can be applied to these trips.

The remaining trips were grouped by each line and each station to account for both local trips and express trips. Statistical analysis was performed on each station and a fitted distribution was determined using R Studio. The results are shown in Table 6.1.
The fitted distributions would be applied to each departure stations for the simulation runs, and they were the main input for the system stochasticity.

6.3 Model Calibration and Validation

All types of data discussed in the sections above were used to construct and calibrate the model.

Before model calibration, it is critical to ensure the simulated speed along the entire trip should match the actual speed in order to attain a realistic travel time for each trip. It is an effective way to examine the accuracy of the maximum speed configured for each line section. However, it was observed that there were certain variations of the actual train speed within the same track section from trip to trip, and trains might come to a complete stop at locations due to operation disruptions. As a result, speed-distance diagrams were compared. Since running time extension was not applied, every trip of a specific line would produce the same result, hence only one trip for each line was required to be compared between the simulated speed-distance diagram and the actual observation. The results of train speed-diagrams for Lakeshore East Line between Danforth GO Station and Union Station, as well as Richmond Hill Line between Oriole Station and Union Station are presented in Figure 6.3.

(a) Speed profile comparison for Lakeshore East Line (Danforth to Union)
As can be seen from the graphs that the simulated train speed between origin and destination matched closely with the observed speed-distance profile. It should be noted that no modifications of the speed limit within the USRC area was made since original input from the operation manual, indicating that all trains strictly adhered to the operation rules within the USRC area. This procedure could also help to validate the modelled distance of line sections as it clearly outlined the total distance of each line within the study scope.

Model calibration involved adjusting the signal's performance factor, which acts to scale the accelerating power and maximum speed. The analyzed departure delays were applied to the starting station of each line to incorporate stochasticity of the real-world operation using Monte-Carlo simulation. It was believed that with accurate model construction and calibration, the resulting arrival delay at Union Station should follow a similar distribution. The metric of On-Time Performance Indicator (OTP) was applied to evaluate the arrival delays. The on-time performance was commonly defined as the proportion of trains that arrive no later than a specific range of the scheduled arrival time over the total number of trains scheduled during the study period:

\[
OTP = \left( \frac{\text{# of trips arrive within a specified range of schedule time}}{\text{total # of trips scheduled}} \right) \times 100\% \tag{27}
\]

It was learnt that GO Transit defines the threshold of OTP to be no later than 5 minutes for its operation. From the data collected in section 4.3 it was calculated that GO trains have an overall on-time performance of 96.4%. Trips with major delays were excluded as they were highly likely to be related to service disruptions or accidents, which was not within the scope of this study. The
Validation of the OpenTrack simulation model was performed based on the evaluation of the resulting simulated average delay value as well as the simulated on-time performance (SOTP). Wight simulations runs were performed to obtain an average result. A random delay value would be selected for each line at each run in accordance with the corresponding fitted distribution. Validation was performed on the base model with the current schedule. VIA Rail trains and UP Express trains were considered and modelled in the simulation since they physically utilized and shared the tracks with GO transit, and a certain level of interference or conflicts was expected. The result of SOTP is shown in Figure 6.4.

![Figure 6.4 On-time Performance Comparison between Observed and Simulated](image)

The total on-time performance values as well as values for individual lines were compared. As can be seen from the graph that simulated on-time performance for individual line matches the observed values at an acceptable level, with the maximum difference smaller than 9%. The overall on-time performance values between the observation and simulation are almost identical, indicating a goodness of fit.

The disadvantage of on-time performance is that is only evaluates on a value that is based on an manually-defined threshold, the delay variations below the threshold and the magnitude of the
delays are neither well captured. For example, a train arriving 3 minutes earlier than schedule and a train arriving 4 minutes later than schedule would be both considered as “on-time”, while a train arriving 6 minutes later would considered to be “Late”, so is a train that is arriving 30 minutes late. Hence, the simulated average delay distribution should also be compared between the observation and simulation results, as there is no such threshold affecting the result. The average delay is summarized and compared in Figure 6.5.

![Relative Freq for Arrival Delay](image)

Figure 6.5 Average Delay Comparison between Observations and Simulations

Since the total number of observations and total number of simulation trips were not equal, relative frequency was used to compare the results. From the result shown in the figure above, it can be seen that the average delays of both observations and simulations were following a same general trend and they matched at an acceptable level.

### 6.4 Sensitivity Test

OpenTrack performs a simulation run for approximately 30 seconds. Due to its efficiency, it is possible to perform a sensitivity test by incrementally increasing train volume until overall severe delays are observed. Capacity of the rail corridor can be obtained by considering the delay and simulated on-time performance defined in the previous section.

In order to perform the sensitivity test, a few assumptions need were made. Similar to base model, all trains were assumed to have through movements to maximize the throughput, which was also consistent with the applications using analytical methods. Dwell time at Union Station was fixed at 5 minutes, while no internal departure schedule was considered so that trains would not be constrained. The designated depot at Union Station for each line would be the same, no extra depots would be used with the volume increase. All trains would follow the current identified
commonly-train paths. Scheduled travel times between stations were extracted from current GO schedule, which is shown in Table 6.2. VIA and UP Express trips were still represented in the sensitivity test while remaining at the same train volume. Uniformed headway was assumed for each train depot and GO line, similar to the compression method as described in section 5.3.3

Table 6.2 Current Scheduled Travel Time

<table>
<thead>
<tr>
<th>Line</th>
<th>Direction</th>
<th>Origin Station</th>
<th>Destination</th>
<th>Normal Travel Time (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LSW</td>
<td>Inbound</td>
<td>EXHIBITION</td>
<td>UNION</td>
<td>11</td>
</tr>
<tr>
<td>LSW_E</td>
<td>Inbound</td>
<td>CLARKSON</td>
<td>UNION</td>
<td>25</td>
</tr>
<tr>
<td>LSE</td>
<td>Inbound</td>
<td>DANFORTH</td>
<td>UNION</td>
<td>14</td>
</tr>
<tr>
<td>LSE_E</td>
<td>Inbound</td>
<td>PICKERING</td>
<td>UNION</td>
<td>33</td>
</tr>
<tr>
<td>KI</td>
<td>Inbound</td>
<td>BLOOR</td>
<td>UNION</td>
<td>12</td>
</tr>
<tr>
<td>MI</td>
<td>Inbound</td>
<td>KIPLING</td>
<td>UNION</td>
<td>20</td>
</tr>
<tr>
<td>BA</td>
<td>Inbound</td>
<td>YORK UNIVERSITY</td>
<td>UNION</td>
<td>24</td>
</tr>
<tr>
<td>RH</td>
<td>Inbound</td>
<td>ORIOLE</td>
<td>UNION</td>
<td>29</td>
</tr>
<tr>
<td>ST</td>
<td>Inbound</td>
<td>DANFORTH</td>
<td>UNION</td>
<td>14</td>
</tr>
<tr>
<td>LSW</td>
<td>Outbound</td>
<td>UNION</td>
<td>EXHIBITION</td>
<td>7</td>
</tr>
<tr>
<td>LSE</td>
<td>Outbound</td>
<td>UNION</td>
<td>DANFORTH</td>
<td>10</td>
</tr>
</tbody>
</table>

The sensitivity test was built on the current schedule. Trains were inserted into the schedule until all designated depots reach the minimum headway as calculated in TCQSM from section 5.1. OpenTrack also produces a useful report which indicates the occupation of a defined track section. Each station depot section was defined to generate the occupation report so that the utilization of each station depot could be better understood. The occupation time is calculated as follows:

\[
OR_j = \Sigma_k \frac{\text{Reservation time for train i on track section } j + \text{Occupation Time for train i on track section } j}{\text{Length of study period}}
\]  

(28)

The procedure of inserting trains can be described as follows:

1. Start with the current schedule

2. From previous iteration, check SOTP for each line, select the line with the highest SOTP to insert

3. If multiple lines share the same SOTP, check their associated depot utilization. Select the one with the lowest depot occupation rate to insert
4. Create new schedule, check the station occupation graph based on the new schedule and adjust the arrival time if there is a potential conflict

5. Run 10 simulations with departure delays drawn from the fitted distributions

6. Obtain result. Terminate when all depots reach minimum headway, otherwise repeat the procedure from point 2.

However, inserting trains one after another can be very time-consuming. A schedule generation tool was created to speed up the process. The input required includes minimum headway for each line based on the designated depots and their corresponding first and last arrivals at Union. The tool would then take the information and generate a complete schedule for each line, assuming uniformed headway; an XML-formatted document that OpenTrack could read/import directly to create courses; and a timetable file OpenTrack could read and import to create the schedule for each course. An example is demonstrated in Figure 6.6 for the generated schedule occupancy at Union Station.

![Scheduled Union Station Terminal Track (Depot) Occupancy](image)

Figure 6.6 Example of Train Occupancy based on Generated Schedule

### 6.5 Results and Comparison with Analytical Methods

Starting at 25 arrivals, a total of 39 configurations are tested with one train inserted to one line every time. The system reaches its capacity when the overall SOTP falls under 95% threshold. Result is presented in Figure 6.7.
Both SOTP and average arrival delay results were reported in the graph above. It can be seen that both curves share a similar trend indicating the impact on total delay. The SOTP dropped dramatically with the increase of train volume, while the simulated average delay increased exponentially with the increase of train volume. The figure resembles the figure introduced by TCQSM as discussed in Figure 2.2, illustrating relationship of service reliability and train volume with quantitative values. With 95% SOTP threshold, a train volume of 39 trains (arrivals at Union) was determined as the capacity.

A comparison was made between the result of compression method (using OTR) and OpenTrack as shown in Table 6.3.

Table 6.3 Result Comparison between Compression Method and OpenTrack

<table>
<thead>
<tr>
<th>Method</th>
<th>Total Trains</th>
<th>LSW</th>
<th>LSW_E</th>
<th>LSE</th>
<th>LSE_E</th>
<th>KI</th>
<th>MI</th>
<th>BA</th>
<th>RH</th>
<th>ST</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compression (OTR)</td>
<td>55</td>
<td>6</td>
<td>7</td>
<td>6</td>
<td>6</td>
<td>5</td>
<td>6</td>
<td>6</td>
<td>7</td>
<td>6</td>
</tr>
<tr>
<td>OpenTrack</td>
<td>39</td>
<td>4</td>
<td>5</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>Ratio (%)</td>
<td>71%</td>
<td>67%</td>
<td>71%</td>
<td>67%</td>
<td>67%</td>
<td>80%</td>
<td>83%</td>
<td>67%</td>
<td>57%</td>
<td>83%</td>
</tr>
</tbody>
</table>
The compression method revealed a much higher total train volume at capacity than OpenTrack. Based on the discussion in section 5.3 and 5.4 the compression method with OTR provided a more theoretical way to calculate the capacity of a railway section, as it did not account for any buffer time and assumed fixed schedules for trip start and ending; it also compressed all trips as much as possible, assuming the next trip to be started right after the previous one. Furthermore, with careful scheduling it was possible to reach the theoretical maximum capacity. On the other hand, OpenTrack offered a more realistic result by taking the stochasticity into consideration as it attempted to replicate the real-world operation, and it can be considered a practical capacity based on operation rules and acceptable level of service. The result of the two methods confirmed that practical capacity is around 60% to 75% of the theoretical capacity from the previous researches.

When studying a complex station area, simulation has great advantages as it takes the entire system into consideration instead of separating west and east interlocking areas as in the analytical methods. It simulates realistic train movements rather than using hypothetical occupancy time, and it represents actual conflicts among multiple trains in a dynamic manner instead of determining conflicts between individual pairs of paths. Furthermore, it is easy to perform scenario tests or evaluate specific policies by adjusting certain parameters in the simulation model, which is not always possible in analytical methods. Comprehensive system performance analyses are also available using simulation approaches.

However, both analytical and the simulation methods assume that the dwell time to be a fixed value of 5 minutes, which ignores the variation and possible impact from pedestrian movements. A varying dwell time would be expected to have certain impact on capacity as the station area, where dwell time occurs, is usually considered to be a weak link. Further studies should be performed to explore such impact.
Chapter 7

7 Railway and Pedestrian Simulation using Nexus

As discussed in the previous two chapters, a fixed value of dwell time was assumed for Union Station, which is the common practice for most of the railway capacity analysis today. However, as has been identified by many studies the dwell time is largely dependent on the pedestrian movements and the infrastructure limits of the station. With an increased passenger volume, a longer dwell time could be expected, and it could in turn have an impact on train delays or even total train throughput when the system is being operated close to or at capacity. On the other hand, passengers are the main users of a transit system, it is important to consider their experienced level of and service as well as safety when they are traveling through the system. The system would be less attractive to users if majority of them have to spend extra long time at a congested platform just trying to exit the station, and it would ultimately discourage passenger from taking the transit system in the long term. As discussed in section 2.4 many pedestrian models have been developed to study the pedestrian movements. For a complex transit hub like Union Station, however, it is beneficial to investigate with a simulation package. Simulation could not only represent the pedestrian movements, but also capture the complex interaction between pedestrian and the environment.

The study focused on the Union Station Rail Corridor, hence the pedestrian movements at Union Station were studied. More specifically, the pedestrian movements related to train dwell time would be studied as the goal of the study was to analyze the impact of pedestrian movements on total capacity.

7.1 Dwell Time Modeling

As identified to be the weakest link along a railway corridor, dwell time is the critical time period where trains making connection with stations, allowing passengers to interchange between platform side and track side. It is necessary to fully analyze and distinguish each section of the dwell time properly.

As discussed in section 2.3 dwell time is usually consisted of passenger flow time, including alighting and boarding, and un-used lost time. The lost time can be made up of several sub-
segments, such as the time from train arriving at the station completely to doors opening; door opening and closing time; and the time from doors closing until train departing the station. In this study a similar definition was adopted. The entire period of dwell time was divided into four segments: Train arrival to door open; door open to last passenger exits; last passenger exits to door close; and door close to train departure. Each segment is shown in Figure 7.1.

It should be stated that the door opening and closing time were not considered as they were relatively small with little to none variations compared to the other components. Besides, the end of the first segment already covered the door opening time partially, so was the third segment for the door closing time.

Dwell time data was manually collected as described in section 4.5 in accordance with the segments defined in the paragraph above. Based on the assumptions made in this study, only observations of through trains which became out of service at Union Station were selected for further analysis. The average values and standard deviations of the four segments are presented in Table 7.1.

<table>
<thead>
<tr>
<th>Segment</th>
<th>Train Arrival to door open (Sec)</th>
<th>Door Open to Last Passenger exits (Sec)</th>
<th>Last Passenger exits to Door Close (sec)</th>
<th>Door Close to Train Departure (sec)</th>
<th>Total (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>9.38</td>
<td>140.07</td>
<td>62.34</td>
<td>89.86</td>
<td>5.03</td>
</tr>
<tr>
<td>Std. Dev.</td>
<td>6.8</td>
<td>43.08</td>
<td>69.55</td>
<td>68.61</td>
<td>1.66</td>
</tr>
</tbody>
</table>

Figure 7.1 Segments of Dwell Time
As can be seen from the table that the total average length of dwell time was 5.03 from 85 records, matching the assumed 5-minute dwell time from AECOM and Metrolinx as well as the rail simulation analysis performed in this study. A statistical analysis has been performed for segment 1 using R, showing that it followed a lognormal distribution with a log mean of 1.99 and a log standard deviation of 0.79. However, the rest of segments could not be simply analyzed statistically. Segment 2 largely depends on the number of passengers each train carries; furthermore, the data collected for segment 3 and 4 in fact accounted for the effect of the “internal departure schedule” discussed in section 6.1 as most trains were held until their scheduled departure time for either equipment movements or revenue movements. In this regard, simply utilizing distribution fitting would ignore such effect and cause potential errors. On the other hand, it is important to take segment 3 and 4 into consideration as they reflect certain safety rules or operation policies GO Transit has in place. It is not hard to understand that any transit agency would allow a certain amount of time allocated after last passenger exits to ensure that no one is still left on the train, especially for a train that becomes out of service after arriving at a station and head to a yard for maintenance. Unfortunately, such information was not directly obtainable from GO Transit. A fixed length of time is assumed for this period. Considering that a 5-minute dwell time was applied to the rail simulation model, using the average value of segment 1 and 2 from the observed data, the time allocated for this fixed length of time for segment 3 and 4 can be calculated as: 5*60-9.38-140.07=150.54 sec or 2.5 minutes. The actual application of this duration would be discussed in section 7.4.1

7.2 Passenger Alighting Behavior Modeling

During the data collection for passenger count at train door, an interesting phenomenon was observed for each train arrival at Union Station. There was a certain portion of passengers alight right away while others choose to alight later. A few examples of the observed passenger flow diagrams for these arrivals are exhibited in Figure 7.2. This is a unique behavior to a terminal station like Union, possibly due to passengers’ perceptions that the train would not leave immediately due to the extra-long dwell time at a terminal station. The behavior could affect density and crowding on the platform differently as well as the total passenger flow time especially for trains that become out of service after arriving at Union, as trains cannot leave if passengers are still on board.
With the increase of train and passenger volume, the impact of the behavior on platform density and passenger flow time could be even bigger especially when trains arrive at adjacent platforms.

7.2.1 Problem Statement

An experiment was set up to illustrate such effect. A simple floor space was laid out in MassMotion as shown in Figure 7.3. Agents were released from the right side of the floor space (train car), crossing the link to the other floor (platform) and exiting at the portal on the left side. Three scenarios were tested:

1. All passengers were generated simultaneously at the portal and exit right away, which is commonly observed at intermediate stations
2. Portion of passengers were generated simultaneously at the portal and exit right away, while the rest of passengers were generated later and spaced out to alight (with a slower alighting rate), mimicking the behavior observed at Union
3. All passengers were generated one after another with a spawning rate within the same time period as scenario 2.
In all three scenarios, 100 agents were generated. The passenger flow diagrams of these scenarios are shown in Figure 7.4.

Scenario 2 revealed a similar curve as what was observed at a train door at Union Station, while the total duration of passenger flow time in scenario 1 was significantly shorter. Although the duration for passenger flow time in scenario 3 was the same as scenario 2, it did not represent the crowding pattern for the first portion of passenger who alight right away the same way as scenario 2.
2. The impact on platform density and passenger duration on the platform for the three scenarios are shown in Figure 7.5 and Figure 7.6.

As can be seen scenario 1 revealed the longest duration at LOS F as all of the passengers were trying to alight at the same time while its total average duration in the system was the longest possibly due to the passenger congestion created at the narrow parts (link and portal); on the other hand, scenario 3 has the shortest total duration, and on average almost no passenger spend any time at level of service F, indicating that a controlled release rate could effectively mitigate the passenger congestion as well as platform crowding. Scenario 2 had a combined effect of scenario 1 and scenario 3, with its results positioning in the middle.
If the actual pedestrian model implemented the passenger behavior adopted in scenario 1, the duration of passenger flow time would be significantly underestimated, while the crowding could be overestimated; in contrast, scenario 3 could offer a better prediction on total passenger flow time yet the crowding effect on the platform would be underestimated. Hence, it is important to properly model the passenger behavior so that both crowding as well as passenger flow time could be properly represented.

The goal was to establish a simple model that was able to predict the total length of passenger flow time and identify the turning point where passengers start to slow down for a given number of total passengers. It also was capable of capturing the different flow rates during the alighting process. The final model should be implemented in a pedestrian simulation model for further investigation on the resulting platform crowding and passengers’ LOS.

### 7.2.2 Relative Research

Previous research has been conducted to model dwell time. As discussed in section 2.3 common approaches to model the dwell time share a form as expressed in:

\[
    t_{pf_{di}} = b_i' \cdot \tau_b + a_i' \cdot \tau_a + c
\]

\[
    t_{pf} = \max(t_{pf_{di}})
\]

Where:

- \( t_{pf_{di}} \): total passenger flow time at door \( i \)
- \( b_i' \): number of boarding riders through the most heavily used boarding door
- \( a_i' \): number of alighting riders through the most heavily used alighting door
- \( \tau_b, \tau_a \): boarding time and alighting time per person (second/person)

Some models have incorporated crowding effects and through passengers inside transit vehicles. Regression methods, particularly linear regression methods, are commonly used to estimate the coefficients. These methods are useful for estimating dwell time at intermediate stations where the dwell time is relatively short. However, for a terminal station, the result would be a single linear curve if implementing these traditional dwell time model, since there would be no boarding passengers or through passengers for trains that become out of service upon arrival. Such implementation would lead to either scenario 1 and scenario 3 as demonstrated in the previous section, and such scenarios could not properly represent the fast alighting passengers and slow
alighting passengers, neither can them reveal the crowding effects or the accurate dwell time length.

On the other hand, fire evacuation models were referenced as it is found that there are some similarities between the two. To start off, it was recognized in some fire evacuation studies that certain unrealistic assumptions and simplifications were made in the previous research, such as that all building occupants immediately begin to evacuate the building and seek exits upon hearing a fire alarm or sensing a fire (Kuligowski, 2008). This is not typically true, as building occupants usually take some time to react to the situation and then take actions, for example, notifying other household members, getting dressed, or taking important stuff. This is usually defined as occupant’s pre-movement time, and it varies largely from person to person. (Proulx & Fahy, 1997) suggested that it is essential to include a reasonable delay for occupants to start their evacuation at the time of fire alarm sounding. In their study, they found that there is a large variation in delays to start evacuation through a series of studies on the apartment building fire drills. Results are stochastic, buildings with the similar size (population) could produce different total evacuation time. Later on, (Ko, 2003) conducted a study on human behaviors at different stages during a fire evacuation, including fire alarm ringing, perception and interpretation time, and pre-movement times as well as the actual movement time. It was also found that the majority of the population responding within a reasonable time, but the distribution having a long tail to account for the “stragglers” who take much longer to complete tasks. (Vistnes, Grubits, & He, 2005) further studied and categorized all possible behaviors occurred during a fire evacuation, they proposed a model that quantifies the response and delay periods using probability distribution functions and Monte Carlo simulation techniques. The model produces the probability distribution of pre-movement time and the related parameters.

The applicability of the fire evacuation models in this thesis mainly lies in the delay in the pre-movement before occupants or passengers actually take actions. The start of fire alarm ringing is equivalent to the arrival of trains at Union; each train arrival can be considered as an evacuation process; certain portion of passengers could be assigned to alight the train right away, yet others would be occupied with fulfilling other tasks (i.e., storing laptops, packing bags, or waking up from naps).
Fire evacuation simulation tends to simulate the process for one specified building, with predefined number of occupants and it would be easier to apply one single unified distribution. However, for the case of Union Station, each train arrival should be considered as an evacuation, with different number of occupants and various percentage of uncertain passengers who choose to stay for an uncertain period of time. Hence the distribution fitting process in this case cannot just focus on the duration, instead the flow rate as well as the turning point would be more appropriate for statistical analysis.

7.2.3 Method

With the data collected in section 4.4 each record of train arrival was carefully studied by plotting the passenger flow diagram. A typical cumulative passenger – time diagram of a single train door of an arrival is shown in Figure 7.7. The concept was to represent the observed alighting curve with two linear lines of different flow rates for segment a (fast alighting passengers) and segment b (slow alighting passengers) respectively, and a turning point where passengers start to slow down.

Turning point ρ was selected based on visual inspection; linear regression was performed on the resulting segment a and segment b respectively; $R^2$ values for the slopes of both lines were

![Figure 7.7 Typical Cumulative Passenger - Time Diagram of a Single Train Door of an Arrival](image-url)
examined. Through this process, a few variables were extracted to represent the passenger flow at one train door for each arrival: Total passengers ($TP$); Turning point (%, $\rho$); Passengers in segment a ($TP_a$); Segment a flow rate ($f_a$); Passengers in segment b ($TP_b$); and segment b flow rate ($f_b$).

However, this process was only focused on the trains that became out of services after they arrive at Union since all connecting trains have published departure time, and passengers’ behavior could be different, and the actual alighting flow could be interrupted by the boarding passenger flow as they alight. On the other hand, the total number of records collected from the data collection for connecting trains were not sufficient enough to perform any further analysis as they only accounted for less than 25% of the total train volume.

As discussed previously, the total number of passengers change from train to train, hence it is necessary to focus on the flow rates and turning point. Statistical analysis was performed for the three variables: $\rho$, $f_a$, and $f_b$, results are shown in Figure 7.8. All three variables follow lognormal distributions and pass the chi square test as shown in Table 7.2.

One interesting finding from the statistical analysis was that the segment a passengers (fast alighting), they do not necessarily alight at a steady maximum flow rate at the train door, instead
a distribution with an average value of 60 passengers/door and a maximum value of 100 passengers/door were observed. The maximum value would be set as the cap flow limit for the train door in the pedestrian simulation to be discussed in the next section. Since each set of variables were extracted from the same arrival record, correlations among these variables should be studied. Results are shown in Table 7.3.

<table>
<thead>
<tr>
<th>Alternative</th>
<th>Description</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base</td>
<td>From observation</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Purely stochastic - random turning point; ( \rho ), random segment a flow rate; ( f_a ), random segment b flow rate; ( f_b )</td>
<td>All 3 variables will be drawn from the fitted distributions</td>
</tr>
<tr>
<td>2</td>
<td>Random turning point; ( \rho ), random segment a flow rate; ( f_a ), linear relation between number of passengers alight during segment b (( TP_b )) &amp; segment b flow rate (( f_b ))</td>
<td>Linear regression relationship is expressed as: ( f_b = TP_b \cdot 0.907 - 0.525 ) ( = TP \cdot (1 - \rho) \cdot 0.807 - 0.525 )</td>
</tr>
<tr>
<td>3</td>
<td>Direct linear relation between total number of passenger flow time: ( t_{flow} ) and total passenger</td>
<td>Linear regression relationship is expressed as: ( t_{flow} = TP \cdot 0.693 + 0.921 )</td>
</tr>
<tr>
<td>4</td>
<td>Random turning point; ( \rho ), fixed segment a flow rate (from overall regression), and linear regression between number of passengers alight during segment b (( TP_b )) &amp; segment b flow rate (( f_b ))</td>
<td>Linear regression relationship is expressed as: ( f_b = TP_b \cdot 0.921 + 0.264 - TP \cdot \rho \cdot 0.921 + 0.264 ) ( f_b ) is the same as in alt. 2</td>
</tr>
</tbody>
</table>
The model would utilize Monte-Carlo simulation. The main input would be the total number of passengers alighting at each train door \((TP)\), and the passenger number from the observed records would be used to validate the model. The process would generate and determine the portion of passengers alighting right away upon arrival \((\rho)\); flow rate for these passengers to alight \((f_a)\), as well as the flow rate for the type b passengers to alight \((f_b)\). Total passenger flow time for train door \(i\) can then be calculated as:

\[
 t_{pfdi} = \frac{TP \cdot \rho}{f_a} + \frac{TP \cdot (1-\rho)}{f_b}
\]  

The simulated passenger flow time would be compared with the observed records, distributions, average and maximum values of the total passenger flow time were evaluated to determine the most-fitted model.

### 7.2.5 Model Validation

A 3D histogram was applied to show the sprawl of the total passenger time over the combination of total number of passengers at one train door \((TP)\) and the total duration of passenger flow time, since the duration would differ largely even with a similar number of passengers from train to train due to the stochasticity in the system. Besides, relative frequency was used since the number of observed records and simulated records were different. The distribution of observed passenger number and passenger flow time is shown in Figure 7.9. The two pictures demonstrate the same graph from different angles.
The result for the four alternative models are shown in Figure 7.10.

It can be seen from the results that alternative 1 spread out the entire space, certain records were even out of the scope. Alternative 2, 3, 4 have similar trends as the observed values. However, alternative 3 was more centred and clustered along a linear line, which is reasonable since alternative 3 was basically a direct linear relationship between the total passenger volume and the total duration. The results of alternative 4 revealed that for the same number of passengers, the total
duration of passenger flow time would be longer. Alternative 2 has the peak density at approximately the same location as the observed data, and the sprawl could be seen to follow a similar trend as observation with acceptable variations.

Additionally, the average and maximum passenger flow time for the four alternatives as well as the observed records are exhibited in Figure 7.11.

![Model Comparison](image)

Figure 7.11 Average and Maximum Passenger Flow Time

The result shows that alternative 1 has the worst performance as the maximum passenger flow time unreasonably skyrocketed. This is possibly due to that all three variables were set to be drawn from the distribution while ignoring the correlation among them. Alternative 2 has the closest value to the observation. In fact, alternative 2 implemented a linear relationship between $TP_b$ and $f_b$, which captured the strong correlation value indicated in the correlation analysis, which helped to keep the total passenger flow time within a reasonable range.

Considering the distribution as well as the average and maximum value from the results, alternative 2 was chosen to be the best model.

### 7.2.6 Model Implication

The model indicates that the urgency individuals must alight is related to the total number that need to alight; namely they would want to ensure they did not miss their chance to leave before the train departs. On the other hand, it might also be possible that since operators know how long
the scheduled station time is, if they see more passengers remain on board and are slow to alight, they might make more announcements to rush people off the train. As revealed from fire evacuation literature, people are more sensitive to verbal warning, hence they tend to leave faster.

With the process implemented in the model, the model could capture and represent the fast alighting passengers and slow alighting passengers, as well as the total passenger flow time. The model would be implemented in the pedestrian model for all non-connecting trains at Union Station (trains that become out-of-service upon arrival at Union).

### 7.3 MassMotion

The passenger flow at a transit facility can be affected by many factors such as infrastructure layout and train arrival patterns. However, the flow could be further complicated by elements such as narrow platforms and barriers. Traditional dwell time model could not capture such limitation, neither can it capture passengers’ level of service or congestion metrics as a simulation. In fact, TCQSM recommends a pedestrian simulation software if the system becomes large and complex.

Massmotion is an advanced 3D pedestrian simulation and crowd analysis tool developed by Oasys, a division of Arup. The agent-based micro-simulation package uses a combination of dynamic route selection and a variant of the Social Forces algorithm to model pedestrian movements. A cost tree is developed for each agent depending on the surrounding environment. Agents apply the social forces model every 0.2 second to assess and respond to their current locations and set the new position for the current time step (Hoy et al., 2016). These processes allow agents to navigate through a building automatically and respond dynamically to evolving operational conditions.

### 7.3.1 Model Setup

The construction of the infrastructure model in MassMotion involves building up a complete 3D model of the Union Station. A previous Union Station model has been developed and calibrated by Arup, and it was applied in this thesis with certain modifications to match the scope of the study. The complete platform and concourse level of the station were included; the locations of stopped trains at platforms were fixed since the variations were usually within a few metres. Each train car contained one portal to allow inbound passengers to be generated and outbound
passengers to be dissipated. A complete infrastructure model of the station can be found in Figure 7.12.

Figure 7.12 Massmotion Model of Union Station

Additionally, passengers were modelled to enter and exit the station areas via 15 exit portals around the station boundary. The split of the passenger volumes of the 15 exits for both inbound and outbound flows was based on the cordon counts set up at the exact same locations in the calibrated model from Arup. Maximum flow rates at critical links (train doors, ramps and staircases) were assigned according to the analyzed result of the data collection. Furthermore, any stopped train at Union Station that was adjacent to two platforms on both sides of the train were assumed to open both sides of the doors at the same time, except platforms that were out of service. Certain agent properties (size, walking speeds) were set as default values in the simulation.

7.3.2 Model Calibration and Validation

Calibration of the model included adjusting queue and waiting costs at platforms and staircases; and altering certain agent characteristics such as body radius and direction bias. The calibration procedure focused on the passenger flow at each staircase for platform 26-27 and the passenger split among its nine staircases. An iterative process of adjusting the values of parameters was
conducted through trial and error. GEH statistical method was applied to calibrate the model (Wisconsin, 2002).

The GEH statistic is a formula commonly used in traffic engineering, traffic forecasting and traffic modeling for comparing two sets of traffic volumes (Karakikes, Spangler, & Margreiter, 2017). It was developed by Geoffrey E. Havers. The concept is applicable to pedestrian simulation, with pedestrian volume being treated as traffic volume. The GEH formula is shown in equation (32).

\[ G_H = \sqrt{\frac{2(m-c)^2}{m+c}} \]  

(32)

where

\[ m: \text{the traffic volume from the traffic model (vehicles per hour)}; \]
\[ c: \text{the real-world traffic count (vehicles per hour)} \]

It is suggested for individual traffic flows or pedestrian flows, the following rules in Table 7.5 can be applied (Wisconsin, 2002):

<table>
<thead>
<tr>
<th>GEH less than 5</th>
<th>Acceptable fit, probably OK.</th>
</tr>
</thead>
<tbody>
<tr>
<td>GEN between 5 and 10</td>
<td>Caution: possible model error or bad data.</td>
</tr>
<tr>
<td>GEH greater than 10</td>
<td>Warning: high probability of modeling error or bad data.</td>
</tr>
</tbody>
</table>

In order to successfully calibrate a model, a total of three general acceptance criteria should be met. Broadly speaking, the model should conform in the following ways:

1. The modelled traffic or pedestrian volumes match the observed volume within acceptance thresholds
2. The modelled travel times and speeds are similar to the actual observations
3. The modelled travel patterns or pedestrian paths are realistic for the entire system

The GEH formula was applied to evaluate the first point, while visual inspections were required to ensure the second and third points were satisfied.

Using the GEH statistical method, the model was calibrated when at least 85% of the nine staircases for each of the eight repetitions (different seeds) passed the GEH test. The result of one of the eight repetitions of the passenger split among the nine staircases is shown in Figure 7.13.
An acceptable match was observed with the maximum difference of less than 2% between the observed and simulated passenger volume.

To validate the model, the modelled and observed flows were examined, and the result revealed a close match between the two at each of the platform staircases. A passenger flow diagram of staircase 6 at platform 26-27 can be found in Figure 7.14.

7.4 Nexus

Nexus is a connected platform to link together existing separate simulators, for modelling surface transit, rail and stations, in order to simulate operations in multi-modal transit networks (Srikukenthiran & Shalaby, 2017). Nexus was designed to capture the dynamics of crowd and transit vehicles at a network level for disruption management support and capacity analysis. Agents travel between simulators as they make their way from their origins to destinations based
on a path assignment engine in the Nexus platform. Each connected simulator is coordinated by Nexus through their application programming interfaces (API), while specific analysis output and results are still available from the individual simulators. For this study, a software was written to allow OpenTrack to link up with Nexus, enabling detailed movement of trains through the complex track and signal layout of the USRC, and train dwell to be specified by either boarding and alighting behaviour in MassMotion or signal operation in OpenTrack. Further information on the mechanics of how the software links to Nexus can be found in (Srikukenthiran & Shalaby, 2017).

### 7.4.1 Model Construction

The Nexus platform coordinates various simulators while each simulator performs its own simulation assignment at the same time, hence the parameter settings of individual simulator were applicable to the Nexus Simulation providing that they have been calibrated and validated properly. In addition to the OpenTrack and MassMotion models, a few more inputs were necessary to ensure that the Nexus simulation worked coherently. A General Transit Feed Specification (GTFS) dataset was required to build network structure including transit agency, station with entrances and exits, transit networks, schedules and trips. The purpose was to connect and map each component of various simulators correspondingly. Each trip carried a passenger volume, while each passenger had his or her own itinerary of Origin-Destination (OD) and arrival time. For a microsimulation, a complete list of each passenger’s basic information including OD and arrival time was required. A program was coded using Python to generate a list of each passenger information based on the passenger volume and their OD for each train. This list was then fed into Nexus as a main input to route passengers through various simulators using the path assignment engine embedded in the Nexus platform. Passengers departing from Union Station were assumed to enter the MassMotion simulation model 10 minutes prior to their scheduled train departure via the 15 exits and entrances, and they would wait on their designated platform until the train arrives. Passenger departing from all other stations were assumed to enter the simulation 6 minutes prior to the scheduled departure time for the specific station. A simplified mathematical pedestrian model was assumed for these stations as they have significantly simpler structure than the Union Station and pedestrian movements at these stations were out of scope. At platform level, priority was given to alighting passengers, all boarding passengers were set to commit to wait until alighting passengers were cleared. In addition, UP Express trains and VIA trains were modelled
to represent track occupancy, no passenger volumes were attached to any of their trips due to a significant lower volume, and the UP Express platform is separate from the main Union Rail platforms. The dwell time components, passengers alighting behavior for out-of-service trains, and departure delays were all built into the Nexus platform and would be applied based on scenario requirement. As discussed in 7.1 the duration of segment 3 and 4 of dwell time was 2.5 minutes. Due to simulation software input limit (only an integer was allowed as an input), however, both 2 minutes and 3 minutes were tested for Nexus, the result of 2 minutes provided a better result and it matched the observation data better. Considering that 3 minutes could add to an average dwell time of approximately 5.5 minutes, potentially resulting in a certain amount of unnecessary dwell time which could potentially create artificial bottleneck at the station area. A fixed value of 2 minutes was used for the duration of segment 3 and 4 of dwell time.

A flow chart of a train trip using Nexus simulation is shown in Figure 7.15.
7.4.2 Model Calibration and Validation

As Nexus links separate simulation models, the calibration procedure was completed when it was performed for each of the individual component models as detailed in earlier sections. To validate the base model, this thesis applied the GTFS dataset with the same schedule as used in the base model of OpenTrack analysis. The passenger volume of each trip during the study period was extracted from GO Transit’s annual Weekday Cordon Counts report (Go Transit Planning Development, 2014). Departure delays at entry stations, passenger alighting behavior at Union Station for out-of-service trains, 2-minute buffer time for dwell segment 3 and 4, as well as internal departure time for equipment movement were considered and applied for the base model. A conversion of the alighting behavior model was required, since the original model constructed was
specifically for the passenger flow at one train door, while the portal that generated passengers upon train arrival in the pedestrian simulation was set up as one portal per train car. The conversion of the model is demonstrated in Appendix E. Eight repetitions were performed to obtain average results. To validate the base model, on-time performance, average delay and passenger volume split among the nine staircases of platform 26-27 were examined. The results from Nexus were compared with the OpenTrack base model as well as the observation Figure 7.16 to demonstrate the differences.

(a) Observed OTP and STOP for OpenTrack and Nexus

(b) Observed arrival delay and simulated arrival delay for OpenTrack and Nexus
The differences among the observed total OTP and total SOTP for OpenTrack and Nexus were within 1%, although the SOTP for individual line varies. The general trends of simulated arrival delays for OpenTrack and Nexus followed the observed values. There were some discrepancies between the results from OpenTrack and Nexus, possibly due to the variations of dwell time in the Nexus model. A maximum of 3% difference was observed among the observed passenger volume split and simulated splits for MassMotion and Nexus. Overall, the model was deemed well calibrated.

7.5 Evaluating System Performance

Using Nexus allows for train delay values to be extracted from OpenTrack and pedestrian’s LOS to be captured from MassMotion. As described in section 2.6, LOS is based on pedestrian’s standing space, perceived comfort and safety, and the ability to maneuver from one spot to another. With the six levels defined and demonstrated in Table 2.1, it is important to evaluate LOS F as it represents extreme overcrowding and could cause severe safety hazards, especially on the narrow platforms and staircases at Union Station.

The system evaluation, therefore, focused on train performance at Union Station, and passenger LOS analysis at the platform and each platform staircase. Overall, the performance indicators reported are summarized in the following paragraphs. The final reported value of each indicator is the average of eight repetitions for one specific scenarios, for all GO trains.
**Simulated On-time Performance (SOTP, %):**

The proportion of trains that arrive no later than five minutes of the published schedule arrival time during the peak hour.

**Simulate average arrival delay at Union (min):**

The amount of delay occurred compared to the published schedule arrival time during the peak hour.

**Average dwell time (min):**

The duration of each train stopping at the platform at Union Station from arrival to departure.

**Hourly inbound and outbound passenger volume (Person):**

The total person throughput for inbound and outbound passengers per hour for the entire station, summed over all GO train arrivals.

**Average percentage of inbound and outbound passengers per second at LOS F (%):**

For each second during a study period, passengers can be categorized into six service levels based on their surrounding density as defined in Table 2.1. This indicator reports the average value of the proportion of passengers at LOS F during the entire period (8am to 9am). The scope includes the entire platform area and platform staircases.

**Average duration at LOS F for each inbound and outbound passenger (Sec)**

For each passenger at the simulation, he or she would spend different amount of time at each level of service from entering to exiting the study scope. The indicator reports the average value of the duration of time that each passenger spends at LOS F during the study period. The scope includes the entire platform area and platform staircases.
Chapter 8

8  Nexus Scenario Tests

8.1  Scenario specifications

The result of the OpenTrack sensitivity test was the maximum train volume based on infrastructure limit of the track layout with an assumption of 5-minute dwell time. However, the assumption of the dwell time largely limited the capability of studying the effect of the dwell time variations. It is known that when a system is operating at capacity, any variation could cause an amplified impact on system performance. For a complex transit facility with limited space, the impact could be greater. The Nexus platform could effectively study the interactive effects between train and pedestrian movements as demonstrated in the previous sections. In particular, the goal was to illustrate the necessity of such a system for capacity analysis to account for the interactions between a complex rail system and a multi-platform station. It was therefore necessary to study how passenger volume increases would impact the train arrival delays as well as passengers’ experienced LOS.

As discussed earlier in the literature review (section 2.1.5), the definition of person capacity incorporates passenger factors into capacity calculation, and TCQSM offers an approach to calculate the person capacity for a rail route when operated at line capacity based on vehicle capacity and peak hour factor (PHF) as shown in equation (33).

\[ P = T \cdot N_c \cdot P_c \cdot (PHF) \]  

(33)

where

- \( P \): design person capacity (p/h)
- \( T \): line capacity (trains/h)
- \( N_c \): number of cars per train (cars/train)
- \( P_c \): maximum schedule load per car (p/car)
- \( PHF \): peak-hour factor (PHF)

The PHF reflects the uneven demand over an peak hour. It is defined as:

\[ PHF = \frac{P_h}{4P_{15}} \]  

(34)

where

- \( P_h \): passenger volume during the peak hour (persons)
\( P_{15} \): passenger volume during the peak 15 minutes

In this context, it is easy to calculate the person capacity for the rail route section along Union Station corridor by multiplying the obtained line capacity, the design capacity of the train, and the PHF. The line capacity has been obtained from OpenTrack sensitivity test (39 trains per hour); the design capacity of the train can be calculated as: 12 cars \( \times \) (162 seats + 256 standees) = 5016 spaces/train. The only factor that would be affecting the final person capacity is the PHF. TCQSM suggests a value of 0.49 for GO transit based on observation. Besides, heavy rail usually carries a PHF value of 0.8 and 0.6 for commuter rail operated by electric multiple-unit trains, as suggested by TCQSM as well. The PHF is usually determined by loading standard and passenger’s standing space on the transit vehicle is taken into consideration. Obviously, this approach does not consider the station capacity and passenger movements inside the station. This might not be an issue if the station has relatively big capacity, however, it could pose potential safety risks if the platform space is restricted, which is Union Station’s case.

In this study, the passenger volume would be increased by adjusting the value of PHF. A series of scenario tests were designed to evaluate such effect. Firstly, the GO train volume would be increased to the maximum train volume result from the OpenTrack sensitivity test (39 trains), with each train carrying equivalent or less passenger volume than current passenger level through simple averaging (PHF=0.34); then passenger volume would be increased by adjusting the PHF to 0.49 as stated by TSQSM for GO Transit. From this point PHF would be increased by 0.1 stepwise to schedule more passengers into the system until severe average arrival delays and long LOS F durations were observed. A 0.05 step was also applied if the overall performance showed a sign of drastic deterioration. An example of the calculation for such passenger volume increase is provided in Appendix F. All scenarios described above assumed the passenger alighting behavior at terminal station for out-of-service trains, and 2-minute buffer for segment 3 and 4 of the dwell time. Outbound passenger volume at Union Station was increased in proportion to the inbound passenger volume based on the current condition. For the worst scenario observed, two further scenarios would be tested by removing the 2-minute buffer, followed by eliminating the passenger alighting behavior (no passenger would be delaying to alight) to study how much better the system could perform. A complete scenario configuration is shown in Table 8.1.
8.2 Nexus Results and Discussion

A total of seven scenario tests were performed. Simulation run time ranges from 45 minutes per run to over 3 hours, depending on the total number of agents in the simulation. The simulation outputs were stored as report documents (for OpenTrack) which can be viewed and modified by Microsoft Excel or notepad; and “mmdb” file (for MassMotion) which stored detailed agent information and can be further analyzed using the built-in analysis tools in MassMotion. The size of the mmdb file ranges from 4 GB to 20 GB per simulation run, depending on the number of agents in the simulation.

Since a total of nine performance indicators have been defined in section 7.5 for each scenario, a radar chart (Figure 8.1) was applied to display an overall result of all the scenarios as well as the base model for Nexus simulation. They were the averaged results from the eight repetitions of each scenario. Each axis in the chart represents a performance indicator, while the scale of these indicators is different. Generally, the scale ranges from 0 (centre) to the corresponding maximum value at the outer edge. The scale for average delay is ranged from -3 (centre) to 2 since trains can arrive earlier on average and the delay value could consequently be a negative number. All axes are arranged from a lower value in the centre to a higher value at the outer edge, with most of the indicators revealing a declining performance as the value increases. The only exception is the SOTP, which indicates an improved performance as the value increases. To make this indicator coherent with the rest, a conversion has been applied by extracting the SOTP value from 100% to obtain a “Simulated Late Performance (SLP)”. The actual SOTP values are listed in bracket for each scenario in the chart for reference. Data are labeled for scenario 1 to 5 and the OpenTrack sensitivity test.
In general, the radar chart indicates a deteriorating performance from scenario 1 to 5, as the total scheduled inbound and outbound passenger volumes increase. The base model obtains the exception, with its overall performance remained the same or slightly lower than scenario 1. This was essentially due to that the base model retained an uneven-headway schedule as today while scenario 1 assumed an even headway, and the base model also considered the “internal departure schedule” for every movement which resulted in a longer average dwell time. On the other hand, although the train volume in scenario 1 was pushed to be equivalent to the OpenTrack sensitivity test result for scenario 1, the average passenger volume per train remained the same or even lower due to simple averaging based on current passenger volume, which effectively reduced the pedestrian congestion on the platform and staircases areas. Traditional train simulation packages, on the other hand, are not able to measure any passenger behavior related indicators within the same simulation run.
Further investigating the radar chart, any two axes could form a relationship between the two indicators. Since inbound passengers were the main variable adjusted among the first 5 incremental scenarios, relationships between the inbound passengers and multiple performance indicators were extracted and analyzed in the following sections.

8.2.1 Passenger Volume and Train Performance

Figure 8.2 reveals the relationship between inbound passenger volume per train and the average train arrival delay at Union Station. A 9% drop in SOTP and a 2-minute increase in average train arrival delay were observed. Additionally, the standard deviation of average delay increased even faster, which is consistent with the behaviour of certain stochastic queueing systems such as M/M/1. All of the curves indicated exponential drop or increase as the passenger volume per train increased, similar to the relationship between train performances and train volume increases as indicated from the result of OpenTrack sensitivity test Figure 6.7.

![SOTP, Average Delay with the increase of IB Psg Volume](image)

**Figure 8.2 Relationship between Inbound Passenger Volume and Train Arrival Delay**

The relationship between scheduled inbound passenger volume per train and dwell time is shown in Figure 8.3. A similar trend as the average delay was observed in the chart, with both average dwell time and its standard deviation rising with the inbound passenger volume. It was also noted that the proportion of trips that have more than 5-minute dwell time increased almost linearly with the increase of inbound passenger volume.
Interestingly, as soon as the inbound passenger volume increased to a level where dwell time exceeded 5 minutes, the corresponding SOTP started to drop below 95%. This is consistent with the findings from the original OpenTrack analysis since the train volume used in Nexus simulation was the same as the maximum capacity obtained from OpenTrack sensitivity test, where a fixed dwell time of 5 minutes was assumed. This proved that there is a direct impact of the length of dwell time on the overall on-time performance.

On the other hand, it can be observed that the SOTP for the OpenTrack sensitivity test was higher than Nexus, even for scenarios where the averaged dwell time in Nexus were smaller than five minutes. Considering all other settings between the two were identical, the variations in dwell time caused by pedestrian movements under congested conditions is likely the main contributing factor, and its impact on average delay becomes greater as it grows.

8.2.2 Passenger Volume and LOS

The radar chart also shows the average hourly total inbound passenger volume (person throughput), which rises as the scheduled inbound train passenger volume increases. Further investigating the relationship between scheduled inbound passenger volume per train and the total passenger throughput for both inbound and outbound passengers (Figure 8.4), the rate of the increase of the inbound passenger volume tends to slow down as the scheduled inbound passenger volume increases, which matches the decreasing SOTP as shown in the graph.
One possible reason could be that as the SOTP drops, the actual number of trains arriving at the station would be smaller during the peak hour, hence the actual number of inbound passengers arriving at the Union Station cannot keep up with the scheduled inbound passenger volume per train linearly. On the other hand, with the decline of the increasing rate of total arriving passengers during peak hour, the number of delayed passengers is expected to rise due to the drop in SOTP, and the total delay time (\textit{number of passengers} \times \textit{delay}) could grow exponentially considering the passenger volume each delayed train carries.

It should be noted that the tendency looks rather weak from the graph, although the theory makes sense. More experiments should be done by further increasing the schedule inbound passenger volume per train to verify.

The increasing passenger volume also led to a 30% increase in the average percentage of inbound passengers per second at LOS F, as well as an additional 60 seconds spent by each inbound passenger at LOS F for all platforms and staircases. Similar increases were observed for outbound passengers as shown in Figure 8.5, since all outbound passengers were assumed to arrive at Union
10 minutes before departure time, and they would wait on the platform until train arrives. The platform became more crowded when each train arrived with more passengers and each outbound passenger was expected to experience such surge of crowding more frequently as the train frequency arose.

Figure 8.5 Relationship between Inbound Passenger Volume per Train and Passenger LOS F

Another interesting finding from the graph is that the average percentage of inbound passengers per second at LOS F tend to obtain a similar trend as the total passenger throughput as discussed previously (Figure 8.4). This could be due to the similar reason that the drop of SOTP resulted in a reduced arrival rate of passengers arriving at the Union Station during the study period, hence the averaged percentage of people per second at LOS F throughout the study period also increased at a reduced rate. The average duration at LOS for each inbound and outbound passenger grew at an equal or increasing pace with the growth of scheduled inbound passenger volume per train, indicating that number of passengers on-board the train could have a direct impact on the duration of LOS F, as for each train arrival more passengers would be trying to alight and exit the platform at the same time. Figure 8.6 exhibits the difference between scenario 1 and scenario 5 on the agent density. The graph only represents the result from one simulation run from scenario 1 and scenario 5 respectively, with the rest obtaining similar results. The figure is also the main data source that generated the value for average percentage of people per second at LOS F. With the increase of passenger volume, a significant increase of the percentage of passengers at LOS F can be observed (scenario 5). It should be noted that the scales for the four graphs are different.
In regard to the base model, two LOS heat maps in platform and staircase areas were compared in Figure 8.7, where a substantially larger LOS F portion of the platform area can be observed in scenario 5 than the base model, indicating that the crowding levels worsened by increasing the train and passenger volumes. The empty platforms were for VIA Rail, the passenger volumes of which were not considered due to insignificant volumes as discussed in section 857.4.1.
Most of these congested areas were around staircases, the narrowest portion of the platform. By further inspecting the simulation video playback, it was discovered that many passengers were blocked inside of the train car due to the congestion on the platform, especially when two trains...
arrived around the same time at adjacent platforms which created an immense crowding at the exits. The increased duration at LOS F does not only represent a worsening of the travel experiences by passengers. Considering the narrow platforms, it could also potentially pose safety hazards at those locations. Such results could not be obtained from a mathematical dwell time model.

8.2.3 Further Scenarios

Building off scenario 5 (worst scenario in terms of SOTP, average delay and passenger LOS F duration), for the final two scenarios, the two-minute dwell buffer time was removed and agents were set to alight immediately, rather than the portion delaying, effectively reducing the dwell time. The results of certain key performance indicators among scenario 5, 5A and 5B are exhibited in Figure 8.8.

![Figure 8.8 Results for Further Scenarios Building off Scenario 5](image)

With the average dwell time dropping from 6.24 minutes to 4.75 minutes and 4.39 minutes respectively, The SOTP for scenario 5A and 5B increased by 8% and 9% and the average delay decreased accordingly. The further improvement of scenario 5B suggests a positive impact on train performance if minimizing passengers’ alighting time, which can be enforced by repeating
announcements by train conductors and on-site transit officers. However, the corresponding
duration at LOS F for inbound passenger increased by 14 seconds as more passengers were
alighting at the same time which exacerbated the congestion on the platform. This implies that
modifications would be required for the identified congested area on the platform to ensure an
acceptable LOS for passengers under such a policy.
Chapter 9

9 Conclusion, Contribution and Future Work

9.1 Conclusion

A capacity analysis of a complex railway station corridor was performed following a general structure of capacity management.

Analytical methods were first studied and applied to the case study of Toronto’s Union Station. The results varied largely among different methods in regard to the total train volume at capacity. It was found that depending on the assumptions, whether quality of service is taken into consideration, or the recommended values of specific parameters, the various methods tend to underestimate, or overestimate the capacity. In many cases, simplifications have been assumed for the analytical methods in order to be performed, which overlook the complexity of the system. Analytical methods could be an effective way for conducting a capacity analysis over a node or corridor under specific circumstances (such as long-term planning or a simple station and corridor area) due to its simplicity. However, they are not sufficient to capture the stochasticity of a complex area.

Railway simulation has great advantages as it takes the entire system into consideration instead of dividing the corridor or station areas into multiple sections as in the analytical methods. It simulates realistic train movements (including acceleration and deceleration) rather than using hypothetical occupancy time, and it represents actual conflicts among multiple trains in a dynamic manner instead of determining conflicts between individual pairs of paths. Furthermore, it is easy to perform scenario tests or evaluate specific policies by adjusting certain parameters in the simulation model, which is not always possible in analytical methods. Comprehensive system performance analyses are also available using simulation approaches.

The dwell time in both analytical methods and railway simulation method was assumed to be a fixed value. However, the dwell times are variable and largely dependent on the pedestrian movements and the architecture of the platform. As passenger volume increases, a longer dwell time should be expected. This can in turn have an impact on train delays or even total train throughput when the system is being operated close to or at capacity. On the other hand, as
passengers are the main users of any transit system, it is important to consider their experienced level of service and safety as they make their way through the system. As a result, future research should focus on studying the impact of pedestrian movements on the total train throughput and train delay when the system is operating at capacity, as well as pedestrian-focussed metrics.

Using Nexus, a connected platform to link together existing separate simulators, the interactive effects of train and pedestrian movements can be well captured, while each simulator could work both cooperatively and individually. A 9% drop in train’s on-time performance was observed and passengers’ average duration at LOS F almost tripled with increasing passenger volume. The impact of passenger volume increase on train OTP is similar to the train volume increase, where OTP drops exponentially as volume rises. Both length and variations of dwell time were shown to contribute to the deteriorating performance especially when the system was operating at capacity. To improve performance, shortening the dwell time by reducing dwell buffer time and encouraging passenger to alight faster; this, however, would need to be coupled with modifications to expand the identified congested area on the platform to ensure an acceptable passenger LOS.

9.2 Contribution

**Performed a comprehensive comparative analysis among various analytical and simulation methods on the capacity of a node area**

The thesis adopted the general structure of capacity management, which includes analytical, optimization, and simulation method. As the first step of the complete study, the thesis performed a comprehensive analysis to compare various representative capacity analysis methods (in the analytical and simulation categories) to determine railway capacity, particularly in the context of a complex node area. Most prior research has focussed on line capacity only, while even fewer studies have compared the methods of both analytical and simulation on a complex node area. The results from this part of the study were then applied as the target train volume for the integrated rail and pedestrian simulation for scenario tests.

**Affirmed that practical capacity is around 60% to 75% of the theoretical capacity**

The dwell time in both analytical methods and railway simulation method was assumed to be a fixed value, which is a common practice for many railway capacity analysis methods. As
simulation usually represent practical capacity while analytical methods usually represent theoretical capacity, with this assumption of the fixed dwell time for both analytical methods and simulation methods, the railway simulation using OpenTrack performed in this thesis affirmed that the practical capacity is around 60% to 75% of the theoretical capacity. To be more precise, the result from OpenTrack sensitivity test is 71% of the result from compression method using the Occupancy Time Rate indicator.

**Observed unique terminal passenger alighting behavior, proposed a simple initial model**

A passenger alighting behavior at the terminal station was observed for trains become out of service upon arrival at the station, where a portion of passengers alight right away while others alight slower, possibly due to the longer dwell time at the terminal station. The impact of such behaviors on total passenger flow time and passenger level of service at platform area was demonstrated. A simple model was proposed by representing the observed passenger flow with two linear segments of different flow rates for the fast alighting passengers (a) and slow alighting passengers (b), respectively, split at a turning point. Correlation and statistical analyses were performed. The model requires the input of total passengers alighting at the specific door, and generates the turning point, flow rate for fast alighting passengers and flow rate for slow alighting passengers. The model was implemented in the pedestrian model for all non-connecting trains at Union Station in the pedestrian simulation model.

The model is preliminary due to limited access to necessary data. Future improvements are required with more factors to be considered.

**Identify the benefit of using integrated simulation model**

Through the extensive data collection, analytical methods implementation, simulation model construction, calibration and validation, various results from different methodologies have been compared and their advantages and disadvantages were discussed. Analytical methods are simple to apply while their results may vary largely due to the level of simplification each has assumed; railway simulation benefits from its realistic representation of train movements with specific infrastructure configurations, which could overcome the disadvantages of over-simplifications in the analytical methods. However, the assumption of a fixed dwell time at critical station in both
analytical and railway simulation methods neglects the effect of the duration and variation of dwell time. To properly study the cause of the dwell time variation, the integrated simulation model, Nexus, was applied to link up the rail simulator (OpenTrack) and pedestrian simulator (MassMotion) to study the interactive effects. Through a series of scenario tests, the result proved that pedestrian movements do affect the train capacity.

**PHF Determination**

The passenger volume in the scenario tests was increased by adjusting the PHF value, which was originally depended on the loading standard and passenger’s standing space on the transit vehicle. The result of this study shows that when determining the PHF, not only the loading standard on transit vehicle should be considered, the capacity and passenger experienced LOS at the station should also be carefully studied as it would in turn affect overall train delays and pose safety hazards especially for infrastructure with limited space.

**9.3 Future work**

The thesis performed a comprehensive railway system capacity analysis using traditional analytical methods, rail way simulations, and it illustrated the advantages of using the Nexus platform at a complex transit facility, in which the two-way interaction between trains and station at the platform were well captured. However, there is a scope of future work that can be further studied and investigated.

Firstly, the thesis mainly focused on analytical methods and simulation methods. From a complete capacity management point of view, optimization methods could be investigated as well to obtain the maximum train through and compare against other methods. This way the characteristics of various type of methods could be analyzed more comprehensively, and it could also offer an alternative approach to generate an optimal timetable which can be integrated into the simulation model.

The second part of future work is mainly for the assumptions and simplifications made when constructing the simulation models. For example, the capacity of maintenance yards should be considered instead of assuming it to be unlimited. As a result, the train movements at Union Station...
can be more realistically represented, where not just through trains should be considered, but also turn-back trains at the Union Station due to capacity constraint at the yards.

The thesis observed the unique behavior for alighting passengers from out-of-service trains at a terminal station. While the model served the purpose of predicting the total length of passenger flow time as well as representing the crowding effect of two different groups of alighting passengers, it was a highly-simplified model which only depended on the total number of alighting passengers due to limited access to data. As identified in the literature review of fire evacuation studies, the delay of individual passengers could be a result of several factors, for example, how often the conductor has made announcements; how late or early passengers are to their work; and possible activities when train arrives at the terminal station. By identifying these factors, the model can be better utilized to predict the flow time and crowding conditions, as well as to understand such behavior so that effective actions can be taken to reduce dwell time to further enhance capacity.

The scope of the study on the train station for analyzing pedestrian movements only included platform areas and staircases that connect the platform with the concourse level. Unlimited capacity was assumed for the space on the concourse level. However, it should be cautious that the layout of the concourse may also pose challenges to the person throughput and may cause potential pedestrian congestion at areas with limited space inside the transit facility. The future work could increase the scope of the study by including complete structure of the building instead of just the platform and staircases. More data would be required to perform such analysis.

Since the benefits of using Nexus, the integrated transit and crowd simulation platform, have been identified, further scenarios can be tested such as adjusting station layout, merging platforms, and changing signaling system. The simulation platform would also be able to comprehensively evaluate the system performance given a proposed operational (train) schedules and projected passenger demand. In addition, the simulation platform can also be further applied to study other congested or complex transit facilities such as interchange subway stations with limited station capacity while the service frequency is high enough to be very sensitive to delays.
References


movement-analysis-at-railway-stations--procedures-and-evaluation-of-Wakobs-approach--or--cauth/7/bhgbege


# Appendix A: Maximum Speed Limit for USRC Area

<table>
<thead>
<tr>
<th>MAXIMUM SPEEDS MPH</th>
<th>GO</th>
<th>VIA</th>
<th>Freight</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>WEST ZONE BETWEEN</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mile 0.0 and west limit signs Mile 1.2</td>
<td>60</td>
<td>20</td>
<td>15</td>
</tr>
<tr>
<td>Tracks A2, A3</td>
<td>60</td>
<td>60</td>
<td>15</td>
</tr>
<tr>
<td>Westward Movements</td>
<td>60</td>
<td>20</td>
<td>15</td>
</tr>
<tr>
<td>Eastward Movements</td>
<td>60</td>
<td>60</td>
<td>15</td>
</tr>
<tr>
<td>Mile 0.0 to west limit Sign Mile 1.0</td>
<td>60</td>
<td>60</td>
<td>15</td>
</tr>
<tr>
<td>Tracks D1 and D2</td>
<td>60</td>
<td>60</td>
<td>15</td>
</tr>
<tr>
<td>Mile 0.0 to Mile 1.1 Bathurst St Bridge</td>
<td>45</td>
<td>45</td>
<td>15</td>
</tr>
<tr>
<td>All other tracks including B Track, C1 Track, C2 Track and Galt South Track</td>
<td>45</td>
<td>45</td>
<td>15</td>
</tr>
<tr>
<td>Mile 1.1 Bathurst St Bridge to West limit signs Mile 1.9</td>
<td>30</td>
<td>30</td>
<td>15</td>
</tr>
<tr>
<td>All other tracks including B Track, C1 Track, C2 Track and Galt South Track</td>
<td>30</td>
<td>30</td>
<td>15</td>
</tr>
<tr>
<td><strong>EAST ZONE BETWEEN</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mile 0.0 and east limit signs Mile 1.4</td>
<td>30</td>
<td>30</td>
<td>15</td>
</tr>
<tr>
<td>Tracks E1, E2, E3 and E6</td>
<td>30</td>
<td>30</td>
<td>15</td>
</tr>
<tr>
<td>Mile 1.4 and Mile 1.7</td>
<td>30</td>
<td>30</td>
<td>15</td>
</tr>
<tr>
<td>Tracks E3 and E6</td>
<td>30</td>
<td>30</td>
<td>15</td>
</tr>
<tr>
<td>Mile 1.4 and east limit signs Mile 2.1</td>
<td>25</td>
<td>25</td>
<td>10</td>
</tr>
<tr>
<td>Tracks E1 and E2</td>
<td>25</td>
<td>25</td>
<td>10</td>
</tr>
<tr>
<td>Mile 0.0 and east limit sign Mile 1.7</td>
<td>30</td>
<td>30</td>
<td>15</td>
</tr>
<tr>
<td>Tracks E4 and E5</td>
<td>30</td>
<td>30</td>
<td>15</td>
</tr>
<tr>
<td>Westward movements</td>
<td>45</td>
<td>40</td>
<td>15</td>
</tr>
<tr>
<td>Eastward movements</td>
<td>45</td>
<td>40</td>
<td>15</td>
</tr>
</tbody>
</table>
## Appendix B: Current Timetable (for morning peak)

<table>
<thead>
<tr>
<th>Trip #</th>
<th>Line</th>
<th>Departure Station</th>
<th>Departure Time</th>
<th>Arrival Station</th>
<th>Arrival Time</th>
<th>Duration (min)</th>
<th>Population</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Lakeshore West</td>
<td>Exhibition</td>
<td>7:34</td>
<td>Union</td>
<td>7:45</td>
<td>11</td>
<td>1589</td>
</tr>
<tr>
<td>2</td>
<td>Lakeshore East</td>
<td>Union</td>
<td>7:48</td>
<td>Danforth</td>
<td>8:13</td>
<td>10</td>
<td>11</td>
</tr>
<tr>
<td>3</td>
<td>Lakeshore West</td>
<td>Clarkson</td>
<td>7:25</td>
<td>Union</td>
<td>8:00</td>
<td>10</td>
<td>2309</td>
</tr>
<tr>
<td>4</td>
<td>Lakeshore West</td>
<td>Clarkson</td>
<td>7:35</td>
<td>Union</td>
<td>8:00</td>
<td>25</td>
<td>1067</td>
</tr>
<tr>
<td>5</td>
<td>Lakeshore East</td>
<td>Union</td>
<td>8:03</td>
<td>Danforth</td>
<td>8:13</td>
<td>10</td>
<td>62</td>
</tr>
<tr>
<td>6</td>
<td>Lakeshore West</td>
<td>Exhibition</td>
<td>8:04</td>
<td>Union</td>
<td>8:15</td>
<td>11</td>
<td>1609</td>
</tr>
<tr>
<td>7</td>
<td>Lakeshore East</td>
<td>Union</td>
<td>8:18</td>
<td>Danforth</td>
<td>8:28</td>
<td>10</td>
<td>81</td>
</tr>
<tr>
<td>8</td>
<td>Lakeshore West</td>
<td>Clarkson</td>
<td>7:55</td>
<td>Union</td>
<td>8:20</td>
<td>25</td>
<td>3027</td>
</tr>
<tr>
<td>9</td>
<td>Lakeshore West</td>
<td>Clarkson</td>
<td>8:05</td>
<td>Union</td>
<td>8:30</td>
<td>25</td>
<td>615</td>
</tr>
<tr>
<td>10</td>
<td>Lakeshore East</td>
<td>Union</td>
<td>8:33</td>
<td>Danforth</td>
<td>9:03</td>
<td>10</td>
<td>47</td>
</tr>
<tr>
<td>11</td>
<td>Lakeshore West</td>
<td>Exhibition</td>
<td>8:34</td>
<td>Union</td>
<td>9:04</td>
<td>11</td>
<td>2085</td>
</tr>
<tr>
<td>12</td>
<td>Lakeshore East</td>
<td>Union</td>
<td>8:48</td>
<td>Danforth</td>
<td>9:18</td>
<td>10</td>
<td>84</td>
</tr>
<tr>
<td>13</td>
<td>Lakeshore West</td>
<td>Clarkson</td>
<td>8:25</td>
<td>Union</td>
<td>9:00</td>
<td>25</td>
<td>1643</td>
</tr>
<tr>
<td>14</td>
<td>Lakeshore West</td>
<td>Clarkson</td>
<td>8:35</td>
<td>Union</td>
<td>9:00</td>
<td>25</td>
<td>799</td>
</tr>
<tr>
<td>15</td>
<td>Lakeshore East</td>
<td>Union</td>
<td>9:03</td>
<td>Danforth</td>
<td>9:13</td>
<td>10</td>
<td>35</td>
</tr>
<tr>
<td>16</td>
<td>Lakeshore West</td>
<td>Exhibition</td>
<td>9:04</td>
<td>Union</td>
<td>9:15</td>
<td>11</td>
<td>1201</td>
</tr>
<tr>
<td>17</td>
<td>Lakeshore East</td>
<td>Union</td>
<td>9:17</td>
<td>Danforth</td>
<td>9:27</td>
<td>10</td>
<td>28</td>
</tr>
<tr>
<td>18</td>
<td>Lakeshore East</td>
<td>Danforth</td>
<td>7:31</td>
<td>Union</td>
<td>7:45</td>
<td>14</td>
<td>1931</td>
</tr>
<tr>
<td>19</td>
<td>Lakeshore West</td>
<td>Union</td>
<td>7:48</td>
<td>Exhibition</td>
<td>8:00</td>
<td>7</td>
<td>136</td>
</tr>
<tr>
<td>20</td>
<td>Lakeshore East</td>
<td>Pickering</td>
<td>7:22</td>
<td>Union</td>
<td>7:55</td>
<td>33</td>
<td>2396</td>
</tr>
<tr>
<td>21</td>
<td>Lakeshore East</td>
<td>Pickering</td>
<td>7:32</td>
<td>Union</td>
<td>8:05</td>
<td>33</td>
<td>1789</td>
</tr>
<tr>
<td>22</td>
<td>Lakeshore West</td>
<td>Union</td>
<td>8:13</td>
<td>Exhibition</td>
<td>8:20</td>
<td>7</td>
<td>253</td>
</tr>
<tr>
<td>23</td>
<td>Lakeshore East</td>
<td>Danforth</td>
<td>8:06</td>
<td>Union</td>
<td>8:20</td>
<td>14</td>
<td>1619</td>
</tr>
<tr>
<td>24</td>
<td>Lakeshore East</td>
<td>Pickering</td>
<td>7:52</td>
<td>Union</td>
<td>8:25</td>
<td>33</td>
<td>1500</td>
</tr>
<tr>
<td>25</td>
<td>Lakeshore East</td>
<td>Danforth</td>
<td>8:31</td>
<td>Union</td>
<td>8:45</td>
<td>14</td>
<td>1500</td>
</tr>
<tr>
<td>26</td>
<td>Lakeshore West</td>
<td>Union</td>
<td>8:48</td>
<td>Exhibition</td>
<td>9:18</td>
<td>7</td>
<td>206</td>
</tr>
<tr>
<td>27</td>
<td>Lakeshore East</td>
<td>Pickering</td>
<td>8:22</td>
<td>Union</td>
<td>8:55</td>
<td>33</td>
<td>1508</td>
</tr>
<tr>
<td>28</td>
<td>Lakeshore East</td>
<td>Danforth</td>
<td>9:01</td>
<td>Union</td>
<td>9:15</td>
<td>14</td>
<td>814</td>
</tr>
<tr>
<td>29</td>
<td>Lakeshore West</td>
<td>Union</td>
<td>9:18</td>
<td>Exhibition</td>
<td>9:25</td>
<td>7</td>
<td>159</td>
</tr>
<tr>
<td>30</td>
<td>Milton</td>
<td>Kipling</td>
<td>7:42</td>
<td>Union</td>
<td>8:02</td>
<td>20</td>
<td>2103</td>
</tr>
<tr>
<td>31</td>
<td>Milton</td>
<td>Kipling</td>
<td>7:55</td>
<td>Union</td>
<td>8:15</td>
<td>20</td>
<td>1747</td>
</tr>
<tr>
<td>32</td>
<td>Milton</td>
<td>Kipling</td>
<td>8:07</td>
<td>Union</td>
<td>8:27</td>
<td>20</td>
<td>1981</td>
</tr>
<tr>
<td>33</td>
<td>Milton</td>
<td>Kipling</td>
<td>8:18</td>
<td>Union</td>
<td>8:38</td>
<td>20</td>
<td>2369</td>
</tr>
<tr>
<td>34</td>
<td>Milton</td>
<td>Kipling</td>
<td>8:28</td>
<td>Union</td>
<td>8:48</td>
<td>20</td>
<td>1664</td>
</tr>
<tr>
<td>35</td>
<td>Milton</td>
<td>Kipling</td>
<td>8:40</td>
<td>Union</td>
<td>9:00</td>
<td>20</td>
<td>753</td>
</tr>
<tr>
<td>36</td>
<td>Kitchener</td>
<td>Bloor</td>
<td>7:40</td>
<td>Union</td>
<td>7:52</td>
<td>12</td>
<td>1609</td>
</tr>
<tr>
<td>37</td>
<td>Kitchener</td>
<td>Bloor</td>
<td>8:08</td>
<td>Union</td>
<td>8:20</td>
<td>12</td>
<td>1597</td>
</tr>
<tr>
<td>38</td>
<td>Kitchener</td>
<td>Bloor</td>
<td>8:38</td>
<td>Union</td>
<td>8:50</td>
<td>12</td>
<td>1137</td>
</tr>
<tr>
<td>39</td>
<td>Richmond Hill</td>
<td>Oriole</td>
<td>7:14</td>
<td>Union</td>
<td>7:41</td>
<td>27</td>
<td>1035</td>
</tr>
<tr>
<td>40</td>
<td>Richmond Hill</td>
<td>Oriole</td>
<td>7:44</td>
<td>Union</td>
<td>8:13</td>
<td>29</td>
<td>1735</td>
</tr>
<tr>
<td>41</td>
<td>Richmond Hill</td>
<td>Oriole</td>
<td>8:14</td>
<td>Union</td>
<td>8:43</td>
<td>29</td>
<td>2011</td>
</tr>
<tr>
<td>42</td>
<td>Barrie</td>
<td>York UNIVERSITY</td>
<td>7:25</td>
<td>Union</td>
<td>7:47</td>
<td>22</td>
<td>667</td>
</tr>
<tr>
<td>43</td>
<td>Barrie</td>
<td>York UNIVERSITY</td>
<td>7:41</td>
<td>Union</td>
<td>8:03</td>
<td>22</td>
<td>2380</td>
</tr>
<tr>
<td>44</td>
<td>Barrie</td>
<td>York UNIVERSITY</td>
<td>7:55</td>
<td>Union</td>
<td>8:19</td>
<td>24</td>
<td>613</td>
</tr>
<tr>
<td>45</td>
<td>Barrie</td>
<td>York UNIVERSITY</td>
<td>8:11</td>
<td>Union</td>
<td>8:33</td>
<td>22</td>
<td>1904</td>
</tr>
<tr>
<td>46</td>
<td>Barrie</td>
<td>York UNIVERSITY</td>
<td>8:41</td>
<td>Union</td>
<td>9:03</td>
<td>22</td>
<td>1596</td>
</tr>
<tr>
<td>47</td>
<td>Stouffville</td>
<td>Danforth</td>
<td>7:38</td>
<td>Union</td>
<td>7:50</td>
<td>12</td>
<td>1737</td>
</tr>
<tr>
<td>48</td>
<td>Stouffville</td>
<td>Danforth</td>
<td>7:48</td>
<td>Union</td>
<td>8:00</td>
<td>12</td>
<td>1234</td>
</tr>
<tr>
<td>49</td>
<td>Stouffville</td>
<td>Danforth</td>
<td>8:20</td>
<td>Union</td>
<td>8:32</td>
<td>12</td>
<td>2246</td>
</tr>
<tr>
<td>50</td>
<td>Stouffville</td>
<td>Danforth</td>
<td>8:48</td>
<td>Union</td>
<td>9:00</td>
<td>12</td>
<td>2177</td>
</tr>
</tbody>
</table>
Appendix C: The values of parameters used to calculate the headways for TCQSM

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Parameter Definition</th>
<th>Unit</th>
<th>Applied Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$l_{sa}$</td>
<td>Longest train length</td>
<td>m</td>
<td>331.53</td>
</tr>
<tr>
<td>$d_{sb}$</td>
<td>Distance from front of stopped train to start of exit block</td>
<td>m</td>
<td>10</td>
</tr>
<tr>
<td>$v_{max}$</td>
<td>Maximum line speed</td>
<td>km/h</td>
<td>16</td>
</tr>
<tr>
<td>$v_s$</td>
<td>Station approach speed</td>
<td>km/h</td>
<td>16</td>
</tr>
<tr>
<td>$f_{br}$</td>
<td>Braking safety factor (percent service braking rate)</td>
<td>NA</td>
<td>0.75</td>
</tr>
<tr>
<td>$t_{og}$</td>
<td>Overspeed governor operating time (automatic system) or driver sighting and reaction time (manual system)</td>
<td>s</td>
<td>3</td>
</tr>
<tr>
<td>$t_{br}$</td>
<td>Time lost to braking jerk limitation</td>
<td>s</td>
<td>0.5</td>
</tr>
<tr>
<td>$t_{br}$</td>
<td>Brake system reaction time</td>
<td>s</td>
<td>1.5</td>
</tr>
<tr>
<td>$a_i$</td>
<td>Initial service acceleration rate</td>
<td>m/s²</td>
<td>1.3</td>
</tr>
<tr>
<td>$d$</td>
<td>Service deceleration rate</td>
<td>m/s²</td>
<td>1.3</td>
</tr>
<tr>
<td>$a_g$</td>
<td>Acceleration due to gravity</td>
<td>m/s²</td>
<td>10</td>
</tr>
<tr>
<td>$G_i$</td>
<td>Percent grade into station</td>
<td>%</td>
<td>0</td>
</tr>
<tr>
<td>$G_o$</td>
<td>Percent grade out of station</td>
<td>%</td>
<td>0</td>
</tr>
<tr>
<td>$l_{s}$</td>
<td>Percent of specification line voltage</td>
<td>%</td>
<td>0.9</td>
</tr>
<tr>
<td>$D$</td>
<td>Three-aspect separation safety factor</td>
<td>NA</td>
<td>2.4</td>
</tr>
<tr>
<td>$t_{dwell}$</td>
<td>Average dwell time at the controlling station</td>
<td>min</td>
<td>5</td>
</tr>
<tr>
<td>$L_{st}$</td>
<td>Length of single-track section</td>
<td>m</td>
<td>300</td>
</tr>
<tr>
<td>$N_{st}$</td>
<td>Number of stations on single-track section</td>
<td>NA</td>
<td>1</td>
</tr>
<tr>
<td>$V_{maxst}$</td>
<td>Maximum speed reached in single-track section</td>
<td>km/h</td>
<td>32</td>
</tr>
<tr>
<td>$t_{dwell}$</td>
<td>Average station dwell time in single-track section</td>
<td>s</td>
<td>600</td>
</tr>
<tr>
<td>$S_{m}$</td>
<td>Speed margin</td>
<td>NA</td>
<td>1.1</td>
</tr>
<tr>
<td>$t_{sw}$</td>
<td>Switch throw and lock time</td>
<td>s</td>
<td>6</td>
</tr>
<tr>
<td>$d_{st}$</td>
<td>Track separation</td>
<td>m</td>
<td>10</td>
</tr>
<tr>
<td>$f_{sw}$</td>
<td>Switch angle factor</td>
<td>NA</td>
<td>9.62</td>
</tr>
</tbody>
</table>
### Appendix D: Occupation and Interdiction Time for Analytical Methods

#### Occupation and Interdiction Time for West Interlocking Area

<table>
<thead>
<tr>
<th>Path #</th>
<th>Occupation and Interdiction Time for West Interlocking Area</th>
<th>Path #</th>
<th>Occupation and Interdiction Time for West Interlocking Area</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### Occupation and Interdiction Time for East Interlocking Area

<table>
<thead>
<tr>
<th>Path #</th>
<th>Occupation and Interdiction Time for East Interlocking Area</th>
<th>Path #</th>
<th>Occupation and Interdiction Time for East Interlocking Area</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

117
Appendix E: Application and Conversion of Alighting behavior for Centralized Train Portal

The alighting behavior model needs to be applied in MassMotion, and need to be differentiated between trains opening one side of doors and trains opening both sides of doors, which is illustrated in the following paragraphs. The input of the model is total passenger volume that a train carries into the Union station. The model generates certain number of passengers to be released first (as passengers who choose to get off right away) with a flow rate, and the rest of the passengers to alight with another flow rate, which are all defined in the following paragraphs.

Two distribution draws are required in this process, and these need to be generated per train arrival at Union, along with the alighting behavior model which is illustrated below.

a) Distribution for the turning point (to determine % of passengers who will alight right away)
   The final selected break point is denoted as \( p \), \( 0 < p < 1 \). The distribution type is universal for all trips; each arrival needs a draw from the distribution, which is estimated to follow a lognormal distribution with a log mean of -0.3741426 and log standard deviation of 0.1628057.

b) Distribution for the flow rate for the passengers who will alight right away
   The final selected flow rate for segment a denoted as \( f_a \) (passengers/minute). The distribution type is universal for all trips; each arrival needs a draw from the distribution, which is estimated to follow a lognormal distribution with a log mean of 4.1264366 and log standard deviation of 0.2355809.

Note that this distribution draw only applies to the train door due to the original data collection, a conversion is needed when releasing these people from the centralized portal at each train car as the MassMotion model is currently configured. The conversion is illustrated in the following paragraphs.

For trains opening only one side of the doors (2 doors per car), the dispersing rate inside of the train car (the portal) would be \( f_{a-2} = f_a \cdot 2 \) (passengers/min); For trains opening both sides of the doors (4 doors per car), the dispersing rate inside of the train car (the portal) would be \( f_{a-4} = f_a \cdot 4 \) (passengers/min);

The formulation for the flow rate for passengers who choose to alight slowly (\( f_b \)) at one train door is discussed in section 7.2.4. Assuming total passenger volume for train \( i \) to be \( v_i \), all train are assumed to have 12 train cars, so each train car carries a passenger load of: \( v_i/12 \) passengers (assuming equal load). For these passengers, \( p \) of them will be assigned to alight right away, hence \( v_i/12 \cdot (1 - p) \) is the number of passengers who choose to exit slowly after all passengers from segment a have alighted (need to be dispersed later, starting approximately at time:

1) for trains opening only one side (2 doors): \( t_{bp-2} = \frac{(\frac{v_i}{12}p)/2}{f_a} = \frac{\frac{v_i}{12}p}{f_a-2} \)
2) for trains opening both sides (4 doors): \( t_{bp-4} = \frac{(\frac{v_i}{12}p)/4}{f_a} = \frac{\frac{v_i}{12}p}{f_a-4} \).

The flow rate of these passengers (segment b) alighting has a direct relationship with the total number of these passengers. For each train door, the relationship is described as:

\[ f_b = (\# \text{ of people alight during segment b of that train door}) \times 0.807 - 0.525 \]
The coefficients in the formula are estimated through regression.

For a train opening only one side of the doors (2 doors per car), at each train door:

\[ f_b = \left( \frac{v_i}{12} \cdot (1 - p)/2 \right) \times 0.807 - 0.525, \]

The dispersing rate inside of the train car (the portal) would be:

\[ f_{b-2} = f_b \cdot 2 = \left[ \left( \frac{v_i}{12} \cdot (1 - p)/2 \right) \times 0.807 - 0.525 \right] \times 2 \text{ passengers/min} \]

For a train opening both sides of the doors (4 doors per car), at each train door:

\[ f_b = \left( \frac{v_i}{12} \cdot (1 - p)/4 \right) \times 0.807 - 0.525, \]

The dispersing rate inside of the train car (the portal) would be:

\[ f_{b-4} = f_b \cdot 4 = \left[ \left( \frac{v_i}{12} \cdot (1 - p)/4 \right) \times 0.807 - 0.525 \right] \times 4 \text{ passengers/min} \]
Appendix F: Passenger Volume Calculation for Nexus Scenario Tests

The passenger volume assignment for scenario 1 was based on simple averaging of the passenger volume for the current schedule as shown in Appendix B. Section 8.1 described that the passenger volume for scenario 1 remained at the same or less as the base model, the value was determined by current passenger volume of related lines and trips between related times. For example, if a new trip is scheduled for Lakeshore West Express at 8:15am from Clarkson Station, it would refer to the current schedule and look for the two trips on Lakeshore West Express line which are right before and right after the new trip (trip 9 and trip 13), and take the average passenger volume of these two trips as its own passenger volume: \( \frac{615 + 1643}{2} = 1129 \) passengers. If the start time of the additional train is earlier or later than the earliest and latest train of the current schedule, it would take the passenger volume of the earliest and latest train of the current schedule directly.

For scenario 2 to 5, the passenger volume increase was dependent on the design capacity and assigned PHF. In scenario 2, the inbound passenger volume is calculated as: \( N_c \cdot P_c \cdot (PHF) = 5016 \times 0.49 = 2458 \) spaces/train for each arrival. Outbound passenger volume would proportionally increase in regard to the inbound train volume. The current schedule has an average outbound passenger volume of 69 passengers/train/peak hour outbound on Lakeshore East line and 1583 passengers/train/peak hour Inbound on Lakeshore East; 230 passengers/train/peak hour outbound on Lakeshore West line vs 1549 passengers/train/peak hour inbound on Lakeshore West. Since all Inbound trains would increase their passenger load to 2458 passengers/train, growth factors for Lakeshore East and Lakeshore West is 1.55 and 1.58 respectively for Inbound trains. The growth factors were applied to the corresponding Outbound trains, and the new passenger volume for outbound trains would be 106 passengers/train and 364 passengers/train for lakeshore east and lakeshore west trains respectively. The same procedure was applied to the rest of scenarios where passenger volume was necessary to be increased.