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TIMETABLE MANAGEMENT TECHNIQUE IN RAILWAY CAPACITY ANALYSIS: DEVELOPMENT OF THE HYBRID OPTIMIZATION OF TRAIN SCHEDULES (HOTS) MODEL

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TIMETABLE MANAGEMENT TECHNIQUE IN RAILWAY CAPACITY ANALYSIS: DEVELOPMENT OF THE HYBRID OPTIMIZATION OF TRAIN SCHEDULES (HOTS) MODEL

By

Hamed Pouryousef

A DISSERTATION

Submitted in partial fulfillment of the requirements for the degree of

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List of Abbreviations

AAR:	The Association of American Railroads
Acela Express:	High Speed Train Service along the Northeast Corridor (USA)
AMTRAK:	The Intercity Passenger Train Operator in the U.S.
APB:	Absolute Permissive Block
AREMA:	The American Railroad Engineering and Maintenance-of-Way Association
Arena:	A General Simulation Package
Avg.:	Average
AweSim:	A General Simulation Package
Banverket:	The Swedish National Rail Administration
BNSF:	A Class 1 Railroad Company in the U.S.
CMS:	A Rail Simulation Package (UK)
CN:	Canadian National Railway
CP (CPR):	Canadian Pacific Railway
Cplex:	A General Optimization Software (USA)
CSX:	A Class 1 Railroad Company in the U.S.
CTC:	Centralized Traffic Control
Davis:	An Equation to Calculate the Train Resistance
DB:	Deutsche Bahn (German Federal Railways)
DB Netz AG:	German Federal Railways-Infrastructure Manager
DC:	The District of Columbia (USA)
DEMIURGE:	A Rail Simulation Package (France)
DOT:	Department of Transportation (USA)
EMU:	Electric Multiple Unit
EQ.:	Equation
ETCS:	European Train Control System
ETMS:	European Traffic Management System
EU:	European Union
F1DT:	Flexibility on Early Departure Time (HOTS Model)
F2DT:	Flexibility on Late Departure Time (HOTS Model)
FRA:	Federal Railroad Administration (USA)
Gams:	A General Optimization Software (USA)
GB:	Gigabyte
HOTS:	Hybrid Optimization of Tran Schedules
HS:	High Speed

HSL:	High Speed Line
HSR:	High Speed Railway
ICE:	Intercity Express (German High Speed Trains)
JRC:	Joint Rail Conference (USA)
KCS:	The Kansas City Southern Railway (A Class 1 Railroad in the U.S.)
LINGO:	A General Optimization Software by Lindo Systems, Inc. (USA)
LOS:	Level of Service
LP:	Linear Programming
Matlab:	A General Simulation and Optimization Software
MAX.:	Maximum
MDOT:	Michigan Department of Transportation
MIN.:	Minimum
Min:	Minute
Minitab:	A General Simulation Package
MIP:	Mixed Integer Programing
MILP:	Mixed Integer Linear Programming
MPH:	Mile per Hour
MTU:	Michigan Tech University
MultiRail:	A Rail Simulation Package (USA)
NB:	Northbound
NEC:	Northeast Corridor
NLP:	Non-Linear Programming
NS:	Norfolk Southern Railway (A Class 1 Railroad Company in the U.S.)
NS:	Nederlandse Spoorwegen (Dutch National Railways)
NURail:	National University Rail Center (USA)
OBB:	Österreichische Bundesbahn (Austrian Federal Railways)
OD:	Origin-Destination
OpenTrack:	A Rail Simulation Package (Switzerland)
OR:	Operations Research
PC:	Personal Computer
PTC:	Positive Train Control
RAILCAP:	A Rail Simulation Package (Belgium)
RAILSIM:	A Rail Simulation Package (USA)
RailSys:	A Rail Simulation Package (Germany)
RAM:	Random Access Memory
RCA:	Root Cause Analysis

RCET:	The Railroad Capacity Evaluation Tool
ROMA:	A Rail Simulation Package (Italy)
RTC:	Rail Traffic Controller (A Rail Simulation Package- USA)
SB:	Southbound
SBB:	Schweizerische Bundesbahnen (Swiss Federal Railways)
SCAN:	Strategic Capacity Analysis for Network
SD:	Speed-Delay
SEC:	Second
SIMONE:	A Rail Simulation Package (The Netherlands)
SLS PLUS:	A Rail Simulation Package (Germany)
Sum:	Summation
TOC:	Theory of Constraints
TRB:	Transportation Research Board (USA)
TT:	Timetable
UIC:	Union Internationale des Chemins de fer. (International Union of Railways)
UIUC:	University of Illinois at Urbana-Champaign
UK:	United Kingdom
UP (UPRR):	Union Pacific Railroad (A Class 1 Railroad Company in the U.S.)
U.S. (USA):	United States of America
USC:	University of Southern California
Viriato:	A Rail Simulation Package (Switzerland)
WSDOT:	Washington Department of Transportation

Preface

This dissertation is a collection of four submitted papers for peer-reviewed journals and conference proceedings; and one paper which has been prepared for journal submission. **Chapter 1** *"Railroad Capacity Tools and Methodologies in the U.S. and Europe"* was published (March. 2015) by the Journal of Modern Transportation (Springer). An earlier, peer-reviewed version of this paper was presented at the 2013 Transportation Research Board (TRB) annual meeting and was included in the conference proceedings. The paper includes a review of more than 60 different papers on industrial and academic research and projects related to the rail capacity tools and methodologies in the U.S. and Europe, as well as identification of differences and similarities of the rail systems. Pouryousef was the primary author of the manuscript while White and Lautala provided suggestions to the draft paper and participed in the editorial process.

Chapter 2, *"Hybrid Simulation Approach for Improving Railway Capacity and Train Schedules"* is based on developing a hybrid (combined) approach that uses two commercial rail simulation packages (RTC and RailSys) in a single track case study. The objective of this part of the research was to understand the challenges and benefits of applying a European based simulation over a U.S. based case study. Pouryousef was the primary author of this paper and developed experience with the two commercial railway simulation software packages used in the study, including building a respective database, and running and analyzing the results of the simulation. He also prepared a methodology for a hybrid simulation process using both software versions, and applied the process to a case study. Lautala helped finalize the research methodology, and led the manuscript editing process. An earlier, peer-reviewed version of this paper was presented in 2013 at the Joint Rail Conference (JRC) and was included in the conference proceedings. The paper was submitted for potential publication by the Journal of Scheduling (Springer) in March, 2015.

Chapter 3, *"Evaluating Two Capacity Simulation Tools on Shared-use U.S. Rail Corridor"* was presented during 2014 Transportation Research Board (TRB) Annual Meeting and published in the peer-reviewed conference proceedings. Pouryousef contributed to this paper by developing the case study of a multiple-track corridor (Washington, D.C. - Baltimore) in RailSys, using a RTC's database from Amtrak. He also led the simulation component, as well as interpreting and analyzing the simulation results derived from RTC and RailSys. Pouryousef prepared the manuscript, while Lautala led the technical review over the entire manuscript, and contributed in editing the paper.

Chapter 4, *"Capacity Evaluation of Directional and Non-directional Operational Scenarios along a Multiple-Track U.S. Corridor"* was presented during 2015 TRB Annual Meeting and published in the peer-reviewed conference proceedings. Pouryousef (author of the dissertation) developed the methodology, collected the data, constructed the simulation database in RailSys, run the simulation, and analyzed/interpreted the results. He also prepared the manuscript. Lautala reviewed the research steps and analytical results and contributed the technical review and editing of the manuscript.

Chapter 5, *“Development of Hybrid Optimization of Train Schedules (HOTS) Model for Railway Corridors”* is the final part of this research and it has been submitted to the Journal of Rail Transport Planning and Management (Elsevier) in April 2015. Pouryousef is the primary author and contributor by providing the literature review on rescheduling and timetable management models, developing a methodology based on a hybrid simulation-optimization approach, Hybrid Optimization of Train Schedules (HOTS) model, and implementing the entire model structure and mathematical formulation of optimization model in LINGO software. He also constructed several case studies to examine the performance of the HOTS model. Pouryousef prepared the manuscript, while Lautala and Watkins reviewed the manuscript and led technical modifications and edits.

Acknowledgments

During the last five years that I spent in Michigan Tech I have worked with several wonderful people who kindly helped me to develop my research and dissertation. Hereby, I would like to extend my great gratitude toward them.

First of all, I am grateful to my advisor, Dr. Pasi Lautala who encouraged and supported me to come to the Michigan Tech to continue my higher education in rail transportation. Pasi was always patient, supportive and helped me in the technical and academic aspects of my research as well as providing several opportunities for me to attend different conferences, workshops and meetings related to my research area. Also, I had this opportunity to take Railroad Track Design class led by Pasi which was one of the best academic courses I have ever attended, very informative and practical, and I learned a lot about rail transportation in the U.S. Without Pasi's help and his great support, I would not have been able to complete my studies and finish my dissertation.

Also, I would like to show my great appreciation toward my PhD committee members, Dr. William Sproule, Dr. David Watkins and Dr. Joern Pachl who helped me through my research by providing comments, and suggestions to improve my dissertation in the different steps of my research. This experience was a great opportunity for me to develop my knowledge in several aspects of transportation, modeling and optimization, and rail transportation. I should thank Dr. Sproule, for his detailed review of several papers along the way. I also really enjoyed the public transit class led by Dr. Sproule and learned about the different aspects of public transportation in the U.S. Dr. Watkins kindly reviewed my proposal as well as my optimization model and gave me several great comments and feedback. I also had this opportunity to take Dr. Watkins' Optimization Methods class, which was very helpful, and practical for me to refresh my knowledge and accelerate my skills on this area. Dr. Joern Pachl was also very supportive through my research and I learned about train simulation, timetable management and train scheduling aspects from his publications and our conversations.

I appreciate the funding sources that supported my research and travel to several academic events and conferences. The Michigan Tech. Rail Transportation Program (RTP) and National University Rail (NURail) Center, (a US DOT-OST Tier 1 University Transportation Center) provided significant support to my research and academic activities. I also acknowledge the academic and financial support I received from AREMA and Michigan Tech rail alumni by providing several rewards through AREMA annual scholarship. I also appreciate the support and attention I received from the Civil and Environmental Engineering (CEE) Department, as well as Michigan Tech Transportation Institute (MTTI). Special thanks goes to Dr. David Hand, the Chair of Department, Dr. Ralph Hodek, the director of MTTI, as well as Dr. Kuilin Zhang, William Leder, Rashelle Sandell, Amanda Cadwell, Angela Keranen, and David Nelson. I also appreciate Pamela Hannon, the coordinator of RTP and MTTI for her kind support, and assistance during the years that I spent with RTP.

I would like to also thank my colleagues and friends in other universities who encouraged and helped during my research as I learned the different aspects of timetable management and rail capacity topics. Dr. Christopher Barkan, Dr. Rapik Saat, Conrad Ruppert, Jr., Tyler Dick, and Samuel Sogin (UIUC), Dr. Joseph Sussman (MIT), Dr. David Clarke (UTK), Dr. Giorgio Medeossi (University of Trieste-Italy), and Thomas White encouraged and helped throughout my research and I truly appreciate their attention and comments.

Several companies, government and industrial representatives helped in parts of my dissertation, especially the simulation and optimization aspects. First I appreciate the assistance provided by Amtrak, including information and database of Northeast Corridor (NEC) that was made available for this research. Without this data, I could not accomplish this research. Special thanks go to Davis Dure and Stan Slater for the great assistance and feedback I received for the NEC case study. I would like to also thank Eric Wilson (Berkeley Simulation Software, LLC), Sonja Perkuhn and Gabriele Löber (RMCon), Daniel Huerlimann (OpenTrack), Mark Wiley (Lindo Systems, Inc.), Karen McClure (FRA), Kurt Schultze (Schultze + Gast Ingenieure) for providing academic licenses for different simulation and optimization software packages, (RTC, RailSys, OpenTrack, LINGO, SU capacity planning tools, and SLS, respectively) and for their great support during my research at Michigan Tech. In addition, Michigan DOT has helped with information and datasets from Michigan rail corridor. I really appreciate kind support and attention I received from Tim Hoeffner and Mohammed Alghurabi during this work.

Also, I would like to thank John Kleiber, a senior undergraduate in the CEE department, for his help in developing the simulation databases and models used in my dissertation. Without his assistance, it would have been difficult to finalize all scenarios of simulation case studies. I'd like to also thank Mary Pachmayer for her kindly review and editorial corrections.

In addition to the technical support of this research, I cannot forget my family and friends in Iran. Special thanks go to my dear parents and my family, for their love, for encouraging and supporting me during the years that I was far away from them and busy with my research.

The most important and greatest appreciation goes to my dear wife, Hosna. Thank you so much for your love, your patience and perfect atmosphere you provided during these years, while you were also busy with your studies and university commitments, as well as taking care of our lovely daughter Lillian. Without your great support I would not be able to complete my research.

Finally, I would like to thank everyone who reads the dissertation and I hope at least some parts of it can be useful for the reader, today or tomorrow.

To My Parents, My Wife: Hosna
And Our Little Lovely Daughter: Lillian

Abstract

There are two general approaches to improve the capacity in a rail corridor, either by applying new capital infrastructure investment or by improving the operation of the rail services. Techniques to evaluate the railway operation include modeling and optimization through the use of commercial timetable management and rail simulation tools. However, only a few of the existing tools include complete features of timetable management techniques (e.g. timetable compression) are equipped with an optimization model for rescheduling and timetable improvement and this is especially true when it comes to the U.S. rail environment that prevalently uses unstructured operation practices.

This dissertation explores an application of timetable (TT) management techniques (e.g. rescheduling and timetable compression techniques) in the U.S. rail environment and their effect on capacity utilization and level of service (LOS) parameters. There are many tools and simulation packages used for capacity analysis, by both European and the U.S. rail industry, but due to the differences in the operating philosophy and network characteristics of these two rail systems, European studies tend to use timetable-based simulation tools (e.g. RailSys, OpenTrack) while the non-timetable based tools (e.g. RTC) are commonly used in the U.S. **(Chapter 1).** This research study investigated potential benefits of using a “Hybrid Simulation” approach that would combine the advantages of both the U.S. and European tools. Two case studies (a single track and a multiple-track case study) were developed to test the hybrid simulation approach, and it was concluded that applying timetable management techniques (e.g. timetable compression technique) is promising when implemented in a single track corridor **(Chapter 2)**, but it is only applicable for the multiple track corridors under directional operation pattern **(Chapter 3).** To address this, a new heuristic rescheduling and rerouting technique was developed as part of the research to convert a multiple track case study from non-directional operation pattern to a fully directional operation pattern **(Chapter 4).**

The knowledge and skills of existing software, obtained during the development and testing of “Hybrid Simulation”, was used to develop an analytical rescheduling/optimization model called “Hybrid Optimization of Train Schedules” (HOTS) **(Chapter 5)**. While the results of the “Hybrid simulation approach” are promising, the method was also time consuming and challenging, as all respective details and database of the given corridors had to be replicated in both simulation tools. The “HOTS Model” could provide the same functions and features of train rescheduling, but with much less efforts and challenges as in the hybrid simulation. The HOTS model works in conjunction with any commercial rail simulation software and it can reschedule an initial timetable (with or without conflict) to provide a “Conflict-Free” timetable based on user-defined criteria. The model is applicable to various types of rail operations, including single, double and multiple-track corridors, under both directional and non-directional operation patterns. The capabilities of the HOTS model were tested for the two case studies developed in the research, and its outcomes were compared to those obtained from the commercial software. It was concluded that the HOTS model performed satisfactorily in each of the test scenarios and the model results either improved or maintained the initial timetable characteristics. The results are promising for the future development of the model, but limitations in the current model structure, such as station capacity limits, should be addressed to improve the potential of applying the model for industrial applications.

Keywords: *Railway Capacity, Railway Simulation, Train Schedules Optimization, Timetable Compression, Shared-use Corridor*

Introduction

Research Background

A growing demand for passenger and freight transportation, combined with limited available capital to expand the United States (U.S.) rail infrastructure are challenging the rail system's ability to carry the necessary train traffic. These capacity challenges are further exacerbated by the fact that most operations take place on the corridors in which the passenger and freight rail services are shared and this increases the heterogeneity and the complexity of operations.

There are several ways to define railway capacity, but in general it is the capability of a line segment to carry a specific mix and volume of traffic (passenger and/or freight) while meeting service quality goals for each type of traffic [1, 2]. The concepts of railway capacity and the objective to maximize its utilization are global, but the differences among the rail systems throughout the world affect the capacity and related analysis. For example, European and U.S. systems have historically differed in such aspects as the infrastructure ownership, operational philosophy, and the traffic services. As the U.S. continues to develop higher speed passenger services with similar characteristics to those in European shared-use lines, some of the differences may diminish and common methods and tools used for capacity will become more popular.

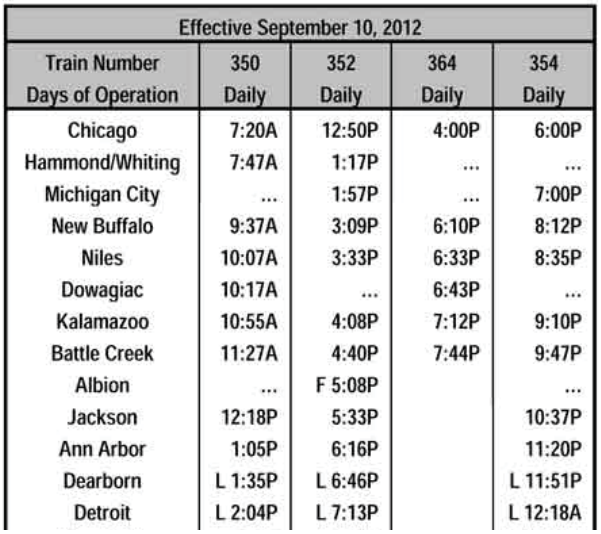
Capacity analysis is a process that uses either analytical, simulation, or combined methods to estimate the capabilities of the line segment/network to meet its objectives. Analyses are also used to investigate the effects of one, or both of the two available approaches to improve the capacity, capital infrastructure investments, or adjustments to operational parameters. In the U.S., the past capacity analysis work has concentrated on evaluating or determining the need for infrastructure improvements, but this research focuses on investigating rescheduling and timetable management techniques, similar to operational analysis approaches that are more commonly undertaken in Europe.

Timetable Management

Timetable management, such as train scheduling, rescheduling, and a particular type of rescheduling, called timetable compression, are common techniques to improve the timetables with an objective to increase capacity and allow for additional trains along a given corridor. In this technique a segment of the route is selected for compression of the existing train-paths, while considering the minimum headways and acceptable buffer times between the trains. After compressing the timetable, the unutilized capacity can be used by new train-paths, until the given time period is saturated by the train-paths and buffer times [2, 3].

Two common tools that can assist in illustrating timetable management analyses are timetables and stringlines which were developed to present the logical progression of trains along rail corridors soon after the rail transportation industry was established in early 19th century. The timetable demonstrates the schedule of all trains which are operated in a given corridor by presenting departure\arrival times of each individual train at each station/stop point (Table I-1) The timetable includes information of three main parameters for scheduling; the train, the time, and location (stop point) [1, 4].

Table I-1- An example Timetable (2012 Amtrak service between Chicago and Detroit)



Effective September 10, 2012				
Train Number	350	352	364	354
Days of Operation	Daily	Daily	Daily	Daily
Chicago	7:20A	12:50P	4:00P	6:00P
Hammond/Whiting	7:47A	1:17P	...	...
Michigan City	...	1:57P	...	7:00P
New Buffalo	9:37A	3:09P	6:10P	8:12P
Niles	10:07A	3:33P	6:33P	8:35P
Dowagiac	10:17A	...	6:43P	...
Kalamazoo	10:55A	4:08P	7:12P	9:10P
Battle Creek	11:27A	4:40P	7:44P	9:47P
Albion	...	F 5:08P		...
Jackson	12:18P	5:33P		10:37P
Ann Arbor	1:05P	6:16P		11:20P
Dearborn	L 1:35P	L 6:46P		L 11:51P
Detroit	L 2:04P	L 7:13P		L 12:18A

A stringline chart (or “Graph diagram”, or simply “Graph”) represents the same information as the timetable, but it is provided in a time-distance diagram format (Figure I-1). One axis of a stringline diagram typically refers to the “Time”, while the other axis refers to the “Location”. In this report, horizontal axis represents time and vertical a location (a typical format in North America). Each sloping line of the diagram represents the movement of individual train or other authorized rolling stock over time, in both directions. Stationary trains are shown as a horizontal line [5].

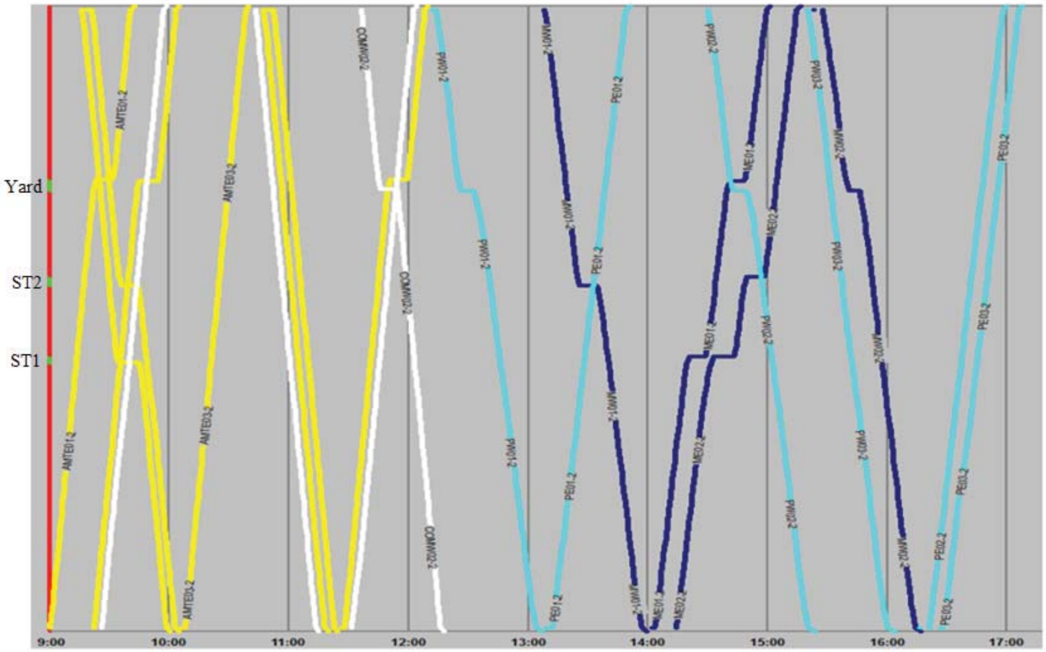


Figure I-1- An example stringline of a single-track corridor

In addition to reviewing the progress of individual train movements, stringlines are useful for in identifying potential conflicts between trains. For instance, the sloping lines (trains) of a single-track stringline (Figure I-1) can only meet (cross) each other at legitimate stop points (station, siding, yard); otherwise it is interpreted as a conflict that should be resolved to provide a conflict-free schedule [4, 5] (Figure I-2). On multiple track sections, identifying and interpreting a conflict is not as easy as a single-track case, since trains may use different tracks and therefore appear to cross each other outside the stations/yards/sidings. (Figure I-3) It should be pointed out that “timetable” was used, interchangeably, for both stringline and timetable through the dissertation.

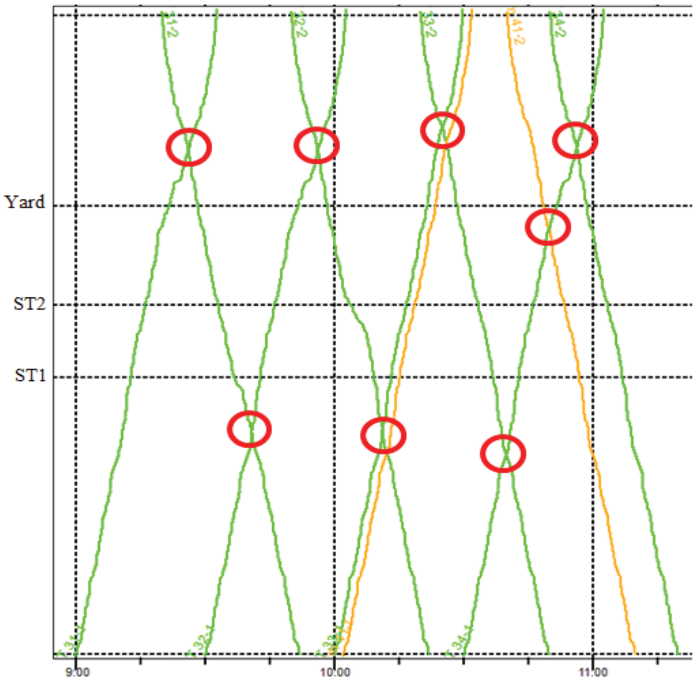


Figure I-2- An example stringline with several train conflicts highlighted by circles

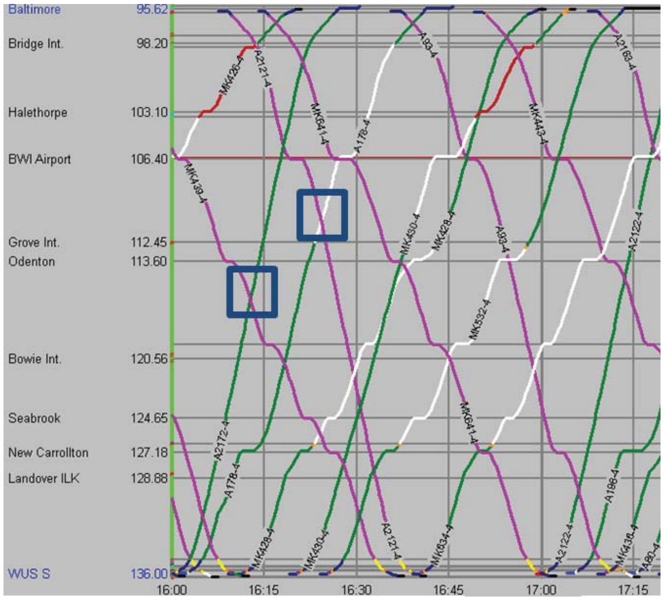


Figure I-3- An example of multiple-track corridor stringline with train meets outside of station\siding using different tracks highlighted

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Research Objectives and Methodology

This research concentrated on operational capacity analysis of railway corridors. The main goal was to investigate whether benefits could be gained from cross-pollination of U.S. and European capacity analysis methodologies, techniques, and tools. The research was structured around five core objectives, as described below:

1) To investigate the similarities and differences between the U.S. and European rail networks and the impact on capacity methodologies and tools used in each region (Chapter 1)
2) To identify the challenges, advantages and disadvantages of applying European tools and methodologies in the U.S. rail environment (Chapter 2, 3, 4)
3) To determine whether there would be quantifiable benefit to applying timetable compression and timetable management techniques or tools (like RailSys or OpenTrack) in shared-use corridors in the U.S. (Chapter 2, 3, 4)
4) To investigate a "hybrid simulation approach" where non-timetable based (RTC) and a timetable-based packages are used in a complimentary way for analysis (Chapter 2, 3, 4)
5) To develop a model that uses operational management techniques (e.g. timetable compression technique and rescheduling) in conjunction with current simulation packages (e.g. RTC, RailSys) and provides additional capabilities not available in these packages for capacity analysis. (Chapter 5)

Several methods and techniques were used in the research the address the objectives. the main methods included:

1) A comprehensive literature review of different methods and tools to perform capacity analysis (Chapter 1)
2) Acquisition of three simulation packages commonly used in both European and the U.S. rail environment; RTC, RailSys and OpenTrack (Chapter 2, 3, 4)
3) Application of simulation packages on a single track and a multiple-track case studies to examine challenges/benefits, and learn more about timetable management features available (Chapter 2, 3, 4)
4) Development of a standalone analytical model, Hybrid Optimization of Train Schedules (HOTS), as an improvement to capacity analysis framework. (Chapter 5)

CHAPTER 1

1- Railroad Capacity Tools and Methodologies in the U.S. and Europe[1]

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[1] : This chapter is a reprint of the open-access article published by Journal of Modern Transportation-Springer: "*Pouryousef, H., P. Lautala, T. White (2015). Railroad capacity tools and methodologies in the U.S. and Europe, Journal of Modern Transportation 23(1): 30-42.*"
An earlier edition of this chapter was also published in TRB 2013 conference proceedings (with permission granted by TRB): "*Pouryousef, H., P. Lautala, et al. (2013). Review of Capacity Measurement Methodologies; Similarities and Differences in the U.S. and European Railroads 2013 TRB Annual Meeting Washington-DC.*"

1-1- Abstract

A growing demand for passenger and freight transportation, combined with limited capital to expand the United States (U.S.) rail infrastructure, are creating pressure for a more efficient use of the current line capacity. This is further exacerbated by the fact that most passenger rail services operate on corridors that are shared with freight traffic. A capacity analysis is one alternative to address the situation and there are various approaches, tools and methodologies available for application. As the U.S. continues to develop higher speed passenger services with similar characteristics to those in European shared-use lines, understanding the common methods and tools used on both continents grows in relevance. There has not as yet been a detailed investigation as to how each continent approaches capacity analysis, and whether any benefits could be gained from cross-pollination. This paper utilizes more than fifty past capacity studies from the U.S. and Europe to describe the different railroad capacity definitions and approaches, and then categorizes them, based on each approach.

The capacity methods are commonly divided into analytical and simulation methods, but this paper also introduces a third, “combined simulation-analytical” category. The paper concludes that European rail studies are more unified in terms of capacity, concepts and techniques, while the U.S. studies represent a greater variation in methods, tools and objectives. The majority of studies on both continents use either simulation, or a combined simulation-analytical approach. However, due to the significant differences between operating philosophy and network characteristics of these two rail systems, European studies tend to use timetable-based simulation tools as opposed to the non-timetable based tools commonly used in the U.S. rail networks. It was also found that validation of studies against actual operations was not typically completed, or was limited to comparisons with a base model.

Keywords: Railroad Capacity, Simulation, Railroad Operation, the U.S. and European Railway Characteristics

1-2- Introduction

Typically, the capacity of a rail corridor is defined as the number of trains that can safely pass a given segment within a period of time. The capacity is affected by variations in system configurations, such as track infrastructure, the signaling system, operating philosophy, and rolling stock.

The configuration differences between European and the U.S. rail systems may lead to different methodologies, techniques, and tools to measure and evaluate the capacity levels. There are high utilization corridors in Europe where intercity passenger, commuter, freight, and even high speed passenger services operate on shared tracks, and all train movements follow their predefined schedule in highly structured daily timetables that may be planned a full year in advance. On the contrary, the prevalent operations pattern on current shared corridors in the U.S. follows unstructured (improvised) philosophy, where schedules and routings (especially for freight trains) are often adjusted on a daily or weekly basis. Recently, the U.S. has placed an increasing emphasis on the development of new higher speed passenger services, or to incrementally increase the speeds of current passenger services on selected shared corridors [6]. At the same time, the slower speed freight rail transportation volumes are also expected to increase [7]. These increases in volumes and operational heterogeneity can be expected to add pressure for higher capacity utilization of the U.S. shared-use corridors. Capacity measurement and analysis approaches (and their methods and tools) will play a crucial part in preparing the U.S. network for these changes. To maximize the efficiency of future improvements, such as new passenger and high speed rail services, the accuracy and applicability of capacity tools and methods in the U.S. environment need to be carefully evaluated. Whether the analytical and operational approaches utilized in Europe would provide any benefits for the U.S. shared-use corridors should also be reviewed.

This paper starts by identifying the various definitions of capacity and by discussing the similarities and differences between the U.S. and European rail systems that may affect both the methods and outcomes of capacity analysis. It will also identify different approaches to conduct the analysis and concludes with an examination of several past capacity studies from both continents.

1-3- What is Capacity?

1-3-1- Capacity Concept and Definitions

The definition used for rail capacity in the literature varies based on the techniques and objectives of the specific study. For instance, Barkan and Lai [8] defined capacity as "a measure of the ability to move a specific amount of traffic over a defined rail corridor in the U.S. rail environment with a given set of resources under a specific service plan, known as level of service (LOS)". They listed several infrastructure and operational characteristics which affect capacity levels, including length of subdivision, siding length and spacing, intermediate signal spacing, percentage of number of tracks (single, double and multi-tracks), heterogeneity in train types (train length, power-to-weight ratios). In another paper, Tolliver [9] introduced freight rail capacity as the number of trains per day for typical track configurations depending on several factors, such as track segment length, train speed, signal aspects and signal block length, directional traffic balance, and peaking characteristics. The American Railroad Engineering and Maintenance-of-Way Association (AREMA) offers a simplified approach for line capacity that estimates practical capacity by multiplying theoretical capacity (Ct) and dispatching efficiency (E) of the line ($C= Ct \times E$). AREMA's method for calculating theoretical capacity and dispatching efficiency require consideration of various factors, such as number of tracks, the operations rules (single or bi-direction operation), stopping distance between trains (or headway), alignment specifications (grade, curves, sidings, etc.), trains specifications (type of train, length, weight, etc.), maintenance activities requirements, and the signaling and train control systems [10]. A capacity modeling guidebook for the U.S. shared-use corridors, released by the Transportation Research Board (TRB), defines capacity as "the capability of a given set of facilities, along with their related management and support systems, to deliver acceptable levels of service for each category of use." Similar to the other capacity definitions, TRB notes that different parameters and variables should be considered in the capacity analysis, such as train dispatching patterns, train type and consist, signaling system, infrastructure and track maintenance system, etc. [5].

In Europe, the most common method for capacity analysis is provided by the International Union of Railways (UIC) code 406. According to UIC 406, there is no single way to define capacity, and the concerns and expectations vary between different points of view by railroad customers, infrastructure and timetable planners, and railroad operators. UIC also emphasizes that the capacity is affected by interdependencies and the interrelationships between the four major elements of railway capacity including average speed, stability[2], number of trains, and heterogeneity[3], as shown in Figure 1-1 [3]. According to the figure, a rail line with various types of trains on the same track (mixed traffic operations or shared-use corridor) has a higher heterogeneity level compared to the urban metro (subway) system with dedicated right-of-way and homogeneous operations. While the average speed of a mixed traffic corridor might be higher than a dedicated metro line, the various train types reduce the stability of train schedules, as well as the total number of trains that can operate on the corridor, due to increased headway requirements.

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[2] The state of keeping the same train schedule by providing time margins/buffers between trains arrival/departures; despite of minor delay which may occur during operation.

[3] Diversity level of train types which are in operation along a shared-use corridor

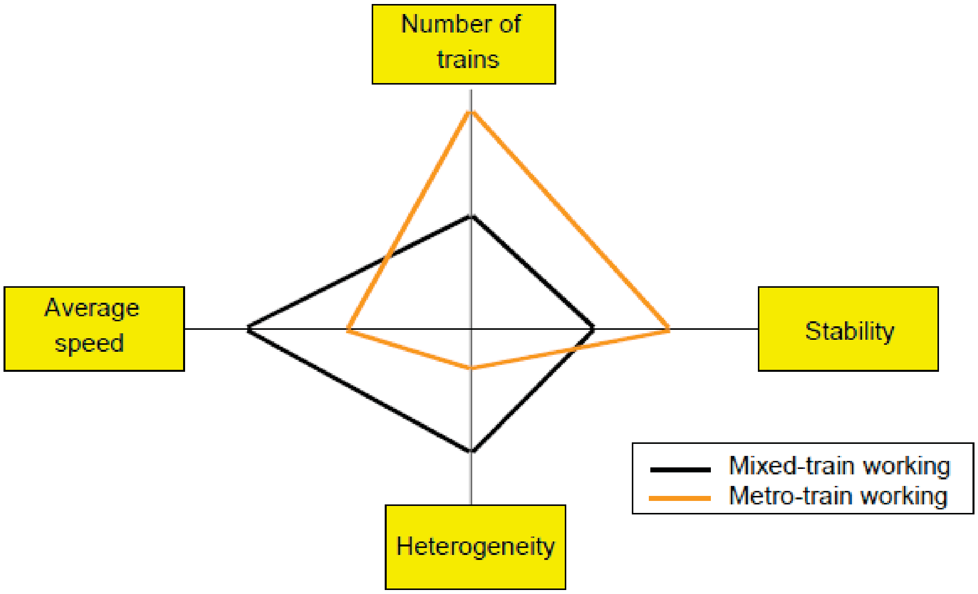

Figure 1-1- Capacity balance according to UIC code 406 definition [3]

According to UIC, the absolute maximum capacity, or "Theoretical Capacity", is almost impossible to achieve in practice and it is subject to:

- Absolute train-path harmony (the same parameters for majority of trains)
- Minimum headway (shortest possible spacing between all trains)
- Providing best quality of service [3].

In addition to the UIC literature, research conducted as part of European Commission's “Improve Rail” project produced a definition of ultimate capacity that was similar to the UIC's theoretical capacity definition, but placed higher emphasis on the train schedules and running time [11].

1-3-2- Capacity Metrics

The literature categorizes the main metrics of capacity level measurements into three groups: throughput (such as number of trains, tons, train-miles), level of service (LOS) (terminal/station dwell, punctuality/reliability factor, and delay), and asset utilization (velocity, infrastructure occupation time or percentage) [12]. In 1975, The Federal Railroad Administration (FRA) introduced a parametric approach developed by "Peat, Marwick, Mitchell and Company" to measure capacity in the U.S. rail network based on delay units (hours per 100 train-miles) [9]. The European rail operators typically use throughput metrics (number of trains per day or hours) to measure the capacity levels, although punctuality and asset utilization metrics are also applied as secondary units [11, 13].

1-4- Differences between the U.S. and European Rail Systems

The U.S. and European rail networks have several similarities, such as mixed operations on shared-use corridors, and using modern signaling and traffic control systems (e.g., developing ETCS in Europe and PTC in the U.S.). On the other hand, significant differences also exist and they may change the preferred methodologies, tools and the outcomes of capacity analysis.

Figure 1-2 and the following discussion uses the literature review to highlight several key differences between infrastructure, signaling, operations and rolling stock in Europe and the U.S.

	The U.S. Rail Network	Europe Rail Network
Infrastructure	Private ownership of rail infrastructure Bidirectional double-tracks / single track Longer sidings/yards Higher axle loads Many existing grade crossings	Public ownership of rail infrastructure Directional double-tracks Shorter distance between sidings/yards Larger radius horizontal curves
Signaling	Few corridors still under manual block operation	Majority of corridors under signaling systems Cab signaling & automated train stop aspects
Operations	Freight traffic (Majority) Unstructured operations pattern	Passenger traffic (Majority) Structured operations (freight, passenger) Higher punctuality for passenger and freight trains (short delays)
Rolling Stock	Longer and heavier freight trains Diversity of freight trains	Faster and more modern passenger trains (HSR) Diversity of passenger trains

Figure 1-2- The main differences in the U.S. and Europe rail systems

1-4-1- Infrastructure Characteristics

- **Public vs. Private Ownership of Infrastructure**: The ownership of rail infrastructure is one of the important differences between Europe and the U.S. rail networks. More than 90% of the infrastructure is owned and managed by private freight railroads in the U.S., while in Europe almost all infrastructure is owned and managed by governments or public agencies. In addition, operations and infrastructure are vertically separated in Europe while in the U.S., the majority of operations (mainly freight) are controlled by the same corporations who own the infrastructure. The ownership and vertical separation have wide impact in the railroad system. Perhaps the greatest effect is on the prioritization of operations and accessibility for operating companies, but other aspects, such as operations philosophy, maintenance strategy and practices, signaling and train control systems, rolling stock configuration, and capital investment strategies are also affected [9, 14].
- **Single vs. Double-Track:** More than 46% of rail corridors in Europe are at least double-track [15, 16], while approximately 80% of the U.S. rail corridors are single-track [7, 9].
- **Directional vs. Bidirectional:** Most of the U.S. double tracks operate in bidirectional fashion and use crossovers along the corridor, while directional

operation with intermediate sidings and stations is the common approach in Europe [9].

- **Distance between Sidings:** The distances between stations and sidings in the European rail network are generally shorter than in the U.S. The average distance between sidings / stations throughout the European network (total route mileage versus number of freight and passenger stations) is approximately four miles between sidings / stations in both UK and Germany [16, 17]. On double track sections passing sidings are typically further apart than in Europe, often more than twice the average European distance [14, 18].
- **Siding Length:** Siding/yard tracks in the U.S. are typically longer than the European rail network, but in many cases are still not sufficient for the longest freight trains operating today [14, 19].
- **Track Conditions:** Typically, railroad structure in the U.S. is designed for higher axle loads, but has tighter horizontal curves (smaller radius) and lower maximum speed operations than the European rail network [14, 19].
- **Grade Crossings:** There are approximately 227,000 active grade-crossings along the main tracks in the U.S. [20, 21], while there are few grade-crossings on the main corridors in Europe, partially due to higher train speeds. High frequency of grade crossings and difficulty of their elimination cause operational and safety challenges for increased train speeds in the U.S. [22].

1-4-2- Signaling Characteristics

- **Manual blocking vs. signaling systems**: Manual blocking is absent on main passenger corridors in the U.S. today, but relatively common on lower density branch ones, including some of the lines proposed for passenger corridors. In Europe, most shared-use corridors are equipped with one of the common signaling systems [23].
- **Cab Signaling:** A more significant difference is the extensive use of cab signaling and enforced signal systems, such as ETMS and ATS in Europe. Implementation of automatic systems is limited in the U.S., despite the current effort to introduce the Positive Train Control (PTC) on a large portion of corridors [14].

1-4-3- Operation Characteristics

- **Improvised vs. Structured Operation:** While some specific freight trains (mainly intermodal) have tight schedules, the U.S. operations philosophy is based on the improvised pattern with no long-term timetable or dispatching plan. On the passenger side, the daily operation patterns of many Amtrak and commuter trains are also developed without details, anticipating improvised resolution of conflicts among the passenger trains, or between passenger and freight trains. In Europe, almost all freight and passenger trains have a regular schedule developed well in advance, known as structured operations [24].
- **Freight vs. Passenger Traffic:** The majority of U.S. rail traffic is freight, while the majority of European rail traffic is passenger rail [9, 25].

- **Delay vs. Waiting Time:** Delay (deviation of train arrival/departure time from what was predicted/planned) and waiting time (scheduled time spent at stations for passing or meeting another train) are two fundamental concepts in the railroad operations. The waiting time concept is typically used in Europe to manage rail operations, due to the structured operations pattern with strict timetables. Delay is more commonly used in the U.S. capacity analysis as the main performance metric, while it is limited in Europe to the events that are not predictable in advance [24].
- **Punctuality:** The punctuality criteria of trains are quite different in the U.S and Europe. Amtrak's trains are considered on-time if they arrive within 15 minutes of a scheduled timetable for short distance journeys (less than 500 miles) or within 30 minutes for long distance trains (over 500 miles). In 2011, Amtrak’s train punctuality was 77% for long-distance trains, 84% for short-distance trains, and 92% for Acela trains on Northeast Corridor. According to Amtrak, more than 70% of passenger train delays were caused either by the freight trains performance or infrastructure failure [26]. The passenger trains in Europe have shorter average delay per train. For instance, Network Rail in the UK reported that approximately 90% of all short-distance passenger trains had less than five minutes deviation from planned timetable, while for long-distance trains, the same was true for deviation less than 10 minutes [27]. In Switzerland, more than 95% of all passenger trains are punctual with an arrival delay of five minutes or less [28]. The punctuality of European freight trains in 2003 was reported to be approximately 70% [29].

1-4-4- Rolling Stock Characteristics

- **Train configuration (length and speed):** Typically freight trains in the U.S. are longer and heavier than freight trains in Europe. Based on the Association of American Railroads (AAR), the typical number of cars in a U.S. freight train varies between 63-164 cars in the West and 57-110 cars in the East, while the typical number in Europe is 25-40. From speed perspective, the average speed of intercity passenger trains in Europe is significantly faster than in the U.S. [7, 14, 19]. Freight trains also typically operate on higher speeds and with less variability in Europe.
- **Diversity of Freight vs. Passenger Trains:** The U.S. rail transportation is more concentrated on the freight trains than Europe, and there is a great diversity between the types, lengths, etc. of freight trains. On the passenger side, Europe has more diverse configurations (such as speed, propulsion, train type, power assignment, HSR services, diesel and electric multiple unit (EMU) trains) in comparison to the U.S. [7, 23].

While the principles of rail capacity remain the same in all rail networks, the characteristics reviewed above all have an effect on capacity and its utilization. What remains unclear is how these differences have been considered in various capacity analysis tools and methodologies used and how much they limit the applicability of the U.S. tools in the European environment and vice versa. This paper introduces some of the common tools and methodologies, including examples of their use in past studies, but excludes any direct comparisons between the capabilities of individual tools. A more detailed (case study based) comparative analysis of selected U.S. and European simulation tools and methodologies is provided by the authors in separate papers [30, 31].

1-5- *Capacity Measurement, Analytical, Simulation and Combined Approaches*

Generally speaking, there are two main approaches to improve the capacity levels; either by applying new capital investment toward upgraded or expanded infrastructure, or by improving operational characteristics and parameters of the rail services [32]. In either approach, it is necessary to assess and analyze the benefits, limitations and challenges of the approach, often done through capacity analysis. The literature classifies capacity analysis approaches and methodologies in several different ways. Although the approaches differ, the input typically includes infrastructure and rolling stock data, operating rules and signaling features. Abril, et al. [33] classified the capacity methodologies as analytical methods, optimization methods, and simulation methods. Joern Pachl [34] divided the capacity methodologies into two major classes: analytic and simulation. Similar categorization was used in research conducted by Murali on delay estimation technique [35]. Khadem Sameni, and Preston, et al., [12] categorized capacity methods to timetable based and non-timetable based approaches. The capacity guidebook developed by TRB also divides capacity evaluation methods to two approaches: simple analysis, and complex simulation modeling [5]. Finally, in research conducted at the University of Illinois, Sogin, Barkan, et al., [8, 36] classified capacity methods as theoretical (analytical), parametric, and simulation methods. Overall, the analytical and simulation methods are the most common methods found in the literature. For our review, we divided methods into three groups; analytical, simulation, and combined. Although the term "combined methodology" was not used commonly in the reviewed literature, it was added as a new class to address the fact that many reviewed studies took advantage of both analytical and simulation methods.

1-5-1- Analytical Approach

The **analytical approach** typically uses several steps of data processing through mathematical equations or algebraic expressions and is often used to determine theoretical capacity of the segment/corridor. The outcomes vary based on the level of complexity of the scenario and may be as simple as the number of trains per day, or a combination of several performance indicators, such as timetable, track occupancy chart, fuel consumption, and speed diagrams. Analytical methods can be conducted without software developed for railroad applications, such as Microsoft Excel, but there are also analytical capacity tools specifically developed for rail applications. One example is SLS PLUS in Germany, which is used in the German rail network

(DB Netz AG) for capacity estimation through analytical determination of the performance, asynchronous simulation and manual timetable construction [37]. Figure 1-3 presents the different levels of analytical approach and how complexity can be added to the process to provide more detailed results. In some cases, analytical models are called optimization methods or parametric models, taking advantage of different modeling features, such as probabilistic distribution or timetable optimization. The latter method, timetable optimization, is typically achieved by using specialized software or simulation tools [33, 34].

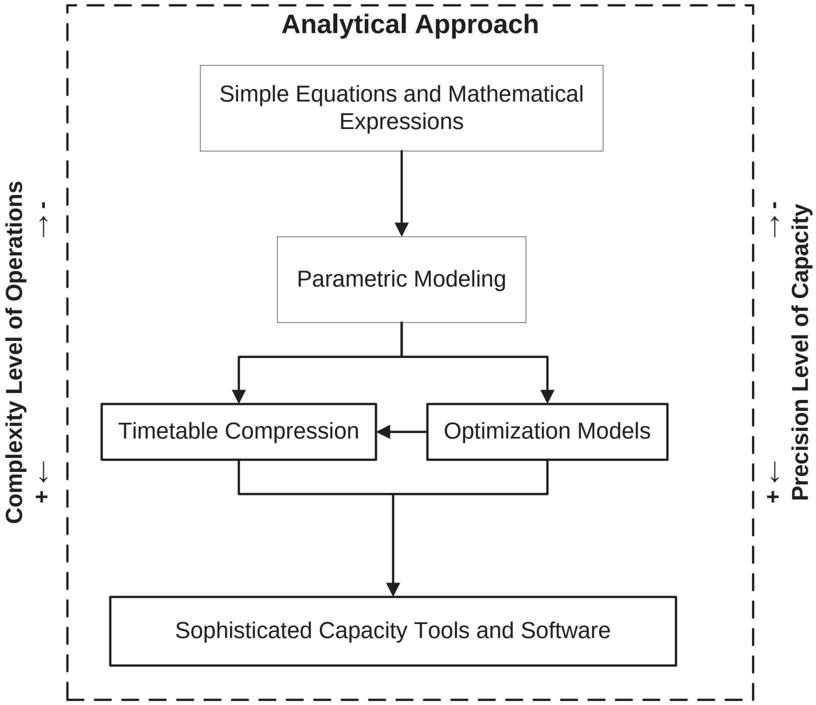

Figure 1-3- Levels of analytical approaches for capacity analysis

Timetable compression method is one of the main analytical approaches in Europe to improve the capacity levels, especially on the corridors with pre-determined timetables (structured operation pattern). A majority of techniques and tools for improving the capacity utilization in Europe, including the UIC method (leaflet 406), are partly developed based on timetable compression. [3, 13, 38-40]. The UIC's method modifies the pre-determined timetable and reschedules the trains as close as possible to each other [33]. Figure 1-4 provides an example of the methodology where a given timetable along a corridor with quadruple tracks (Scenario a) is first modified by compressing the timetable (Scenario b) and then further improved by optimizing the order of trains (Scenario c). As demonstrated in the figure, the third scenario could provide a higher level of theoretical capacity in comparison to the scenarios a, and b [13].

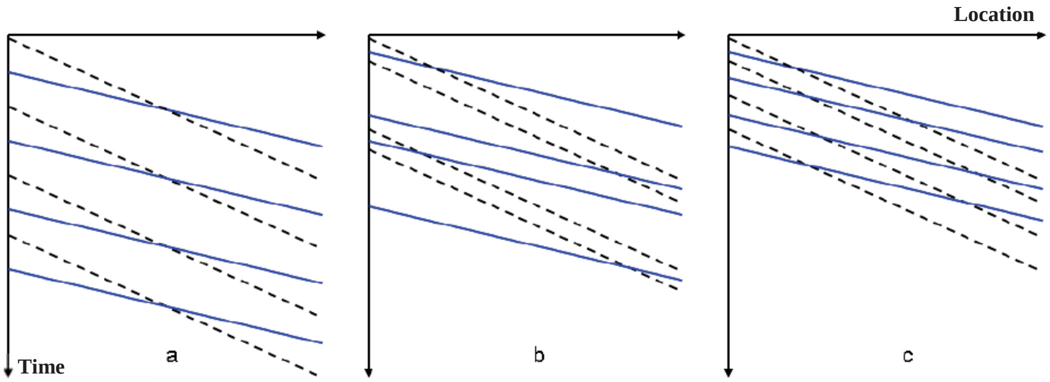

Figure 1-4 - Actual timetable for a quadruple-track corridor (a) compressed timetable with train order maintained (b) compressed timetable with optimized train order (c) (Note: chart layout follows typical European presentation and solid and dot lines represent different types of trains) [13]

1-5-2- Simulation Approach

Simulation is an imitation of a system's operation which should be as close as possible to its real-world equivalent [33]. In this approach, the process of simulation is repeated several times until an acceptable result is achieved by the software. The data needed for the simulation are similar to the analytical methods, but typically at a higher level of detail. The simulation practices in rail industry started in the early 1980s through the development of models and techniques, such as dynamic programming and branch-and-bound, proposed by Petersen, as well as heuristic methods developed by Welch and Gussow [33]. Today, the simulation process utilizes computer tools to handle sophisticated computations and stochastic models in a faster and more efficient way. **The simulation approaches** use either **general simulation** tools, such as AweSim, Minitab, and Arena [35, 41]; or **commercial railroad simulation** software specifically designed for rail transportation, such as RTC, MultiRail, RAILSIM, OpenTrack, RailSys, and CMS [12, 33]. The use of general simulation tools requires the user to develop all models, equations and constraints step by step (often manually). This requires more expertise, creativity and effort, but it can also offer more flexible and customization when it comes to results and outputs. The commercial railroad simulation tools offer an easier path toward development of different scenarios, in addition to providing a variety of outputs in a user-friendly way, but the core decision models and processes are not easily customizable or reviewable, which may reduce the flexibility of applying these tools.

The commercial railroad simulation software typically revolves around two key simulation components; 1) Train movement, and 2) Train dispatching. The first component uses railroad system component data provided as an input, such as track and infrastructure characteristics (curvature and grades), station and yard layout, signaling system, and rolling stock characteristics, to calculate the train speed along the track. Train dynamics are typically determined based on train resistance formulas, such as Davis equation, and train power / traction. The dispatching simulation component typically emulates (or attempts to emulate) the action of the dispatcher in traffic management, but in some cases, it can be also used as part of a traffic management software to help traffic dispatchers to manage and organize the daily train schedules (Figure 1-5) [24].

According to Pachl, the simulation method can also be divided into asynchronous and synchronous methods. Asynchronous simulation software is able to consider stochastically generated train paths within a timetable, following the scheduling rules and the train priorities. In synchronous simulation, the process of rail operations is followed in real time sequences, and the results are expected to be closely aligned with real operations. In contrast to the asynchronous method, synchronous methods cannot directly simulate the scheduling, or develop a timetable, without use of additional computer tools and programs to create a timetable [34]. The outputs of simulation software typically include several parameters such as delay, dwell time, waiting time, elapsed time (all travel time), transit time (time between scheduled stops), trains speed, and fuel consumption of trains [24, 33].

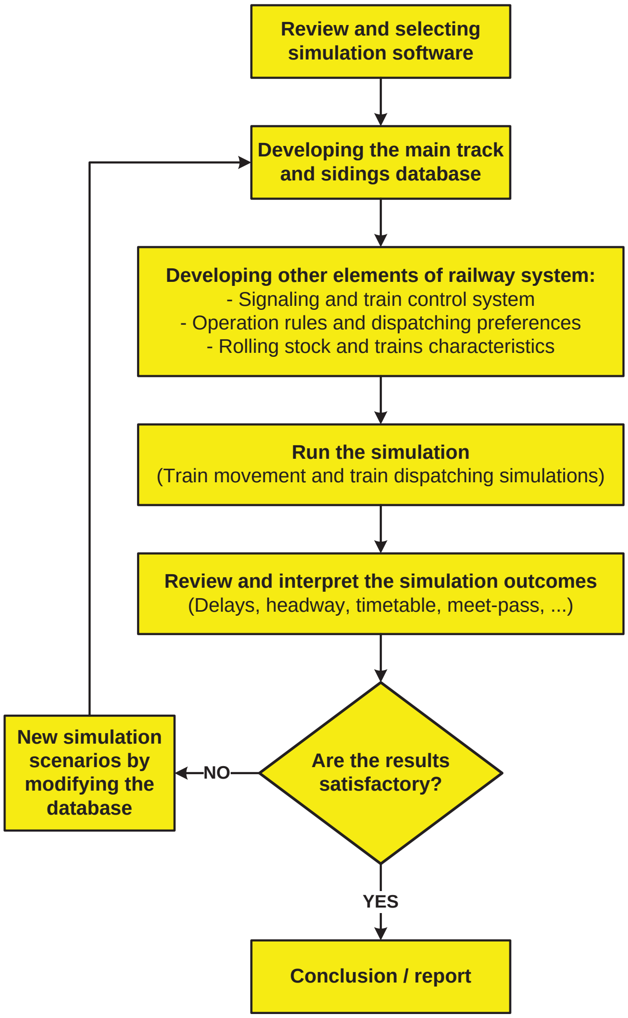

Figure 1-5- Steps for railway capacity analysis in commercial simulation approach

Simulation Methods: Timetable Based vs. Non-timetable Based

The commercial railroad simulation software can be classified in two groups; non-timetable based or timetable based. The non-timetable based simulations are typically utilized by railroads that use the improvised (unstructured) operation pattern without an initial timetable, such as the majority of the U.S. rail network. In this type of simulation, after loading the input data in the software, the train dispatching simulation process uses the departure times from the initial station that are provided as part of the input data. The software may encounter a problem to assign all trains and request assistance from the user to resolve the issue by manually adjusting the train data, or by modifying the schedule constraints [12, 24]. The Rail Traffic Controller (RTC), developed by Berkeley Simulation Software is the most common software in this category, used extensively by the U.S. rail industry [12].

The simulation procedure in timetable based software (typically used in Europe) is based on the initial timetable of trains, and the objective is to improve the timetable as much as possible. The UIC's capacity approach is often one of the main theories behind the timetable based simulation approach. The simulation process in this methodology begins with creating a timetable for each train. In the case of schedule conflict between the trains, the user must adjust the timetable until a feasible schedule is achieved. However, the user actions are more structured compared to the improvised method, and is implemented as part of the simulation process [24]. There are several common software tools in this category, such as MultiRail (U.S.), RAILSIM (U.S.), OpenTrack (Switzerland), SIMONE (The Netherlands), RailSys (Germany), DEMIURGE (France), RAILCAP (Belgium), and CMS (UK) [12, 33]. A comprehensive capability review of various simulation tools is outside the scope of this paper, but three simulation packages (RTC, RailSys and OpenTrack) are briefly introduced to demonstrate some key differences between non-timetable based and timetable based software.

The Rail Traffic Controller (RTC), developed by Berkeley Simulation Software is the most common software in the non-timetable based category, used extensively by the U.S. rail industry [12]. RTC was launched in the U.S. (and North American) rail market in 1995 and has since been continuously developed and upgraded. Since majority of the U.S. train services (particularly freight trains) have frequent adjustments in their daily schedules, RTC has several features and tools for simulating the rail operations in non-scheduled environment, including train movement animation, automated train conflict resolution, and randomization of train schedule. The dispatching simulation component of RTC is based on a decision support core, called “meet-pass N-train logic”. For any dispatching simulation practice, “meet-pass N-train logic” will decide when the given trains should exactly arrive and depart from different sidings, based on the defined train priorities and preferred times of departure. The simulation outcomes may include variation between the simulated departure times and preferred times [42]. Besides its decision core fitting the U.S. operational philosophy, RTC has other system characteristics, such as attention to grade crossing, that make it well suited to the U.S. market.

RailSys, developed by Rail Management Consultants GmbH (RMCon) in Germany, is an operation management software package that includes features, such as timetable construction/slot management, track possession planning, and simulation. It has been in the market since 2000 and it is one of the commonly used timetable-based simulation software in Europe. The capacity feature of RailSys uses the UIC code 406 which is based on the timetable compression technique [43, 44]. OpenTrack is another common simulation package in Europe. It was initially developed by Swiss Federal Institute of Technology-Zurich (ETH-Zurich) and has since 2006 been supplied by OpenTrack Railway Technology Ltd. OpenTrack is also a timetable-based simulation tool with several features, such as automatic conflict resolution based on train priority, routing options and delay probabilistic functions, as well as several outputs and reporting options, such as train diagram, timetable and delay statistics, station statistics, and speed/time diagram [45, 46].

1-5-3- Combined Analytical-Simulation Approach

In addition to the analytical and simulation approaches, a **combined analytical-simulation method** can also be used to investigate the rail capacity. Parametric and heuristic modeling (in analytical approach) are more flexible when creating new aspects and rules for the analysis. On the other hand, updating the railroad component input data and criteria tends to be easier in the simulation approach, and the process of running the new scenarios is generally faster, although simulation may place some limitations when adjusting the characteristics of signaling or operation rules. A combined simulation-analytical methodology takes advantage of both methodologies' techniques and benefits, and the process can be repeated until an acceptable set of outputs and alternatives is found. (Figure 1-6) There are several ways to combine analytical and simulation tools. For instance, finding a basic and reasonable schedule of trains through simulation, followed by analytical schedule can be considered as one example of combined analytical-simulation approach. Another example would be application of a simplistic analytical model to provide the basic inputs, such as determining the type of signaling system, or developing train schedule, followed by more extensive and detailed analysis in commercial rail simulation tools.

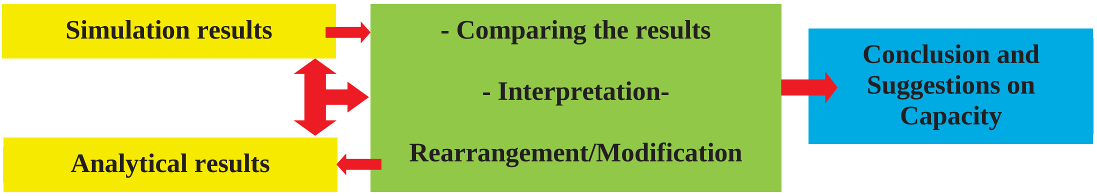

Figure 1-6 - Basic diagram of combined analytical-simulation approach for capacity analysis

1-6- Review of Capacity Studies in the U.S. and Europe

The approaches, methodologies and tools highlighted in previous section have been applied in numerous U.S. and European capacity studies. The team reviewed 51 total studies using all three approaches (17 analytical studies, 22 simulation studies and 12 combined simulation-analytical approaches). 25 of them that had sufficient detail of the study approach and respective results were used to conduct a detailed assessment of studies conducted in Europe versus in the U.S.

1-6-1- Studies with Analytical Approach

One of the first analytical models was developed by Frank in 1966 by studying the delay levels along a single track corridor considering both directional and bidirectional scenarios. He used one train running between two consecutive sidings (using manual blocking system) and a single average speed for each train to calculate the number of possible trains (theoretical capacity) on the given segment [47]. Petersen expanded Frank’s idea in 1974 by considering two different speeds, independent departure times, equal spacing between sidings, and constant delays between two trains [48]. Chen et al (1990) and Parker et al (1990) continued Petersen’s research by taking into account different speed patterns, varied dispatching policies, and partially double track network with meet and pass scenarios [35]. Higgins et al developed a model in 1998 for urban rail networks to evaluate the delays of trains by considering different factors such as trains’ schedule, track links, sidings, crossings, and the directional/bidirectional operation patterns throughout the network [49].

De Kort et al analyzed the capacity of new corridors in 2003 by applying an optimization method and considering uncertainty of demand levels on the planned route [50]. Ghoseiri, et al introduced a multi-objective train scheduling model of passenger trains along single and multiple tracks of rail network, based on minimizing the fuel consumption cost as well as minimizing the total passenger-time of trains [51]. Burdett and Kozan developed analytical techniques and models in 2006 to estimate the theoretical capacity of a corridor based on several criteria, such as mixed traffic, directional operation pattern, crossings and intermediate signals along the track, length of the trains, and dwell time of trains at sidings or stations [52]. Wendler used queuing theory and the semi-Markov chains in 2007 to provide a technique of predicting the waiting times of trains based on the arrival times, minimum headway of trains and the theory of blockings [53]. Lai and Barkan introduced an enhanced technique of capacity evaluation tools in 2009 based on the parametric modeling of capacity evaluation, which was initially developed by CN Railroad. The Railroad Capacity Evaluation Tool (RCET), developed by Lai and

Barkan, can evaluate the expansion scenarios of network by estimating the line capacity and investment costs, based on the future demand and available budget [8].

Lindner, recently, reviewed the applicability of timetable compression technique, UIC code 406, to evaluate the corridor and station capacity. He used several case studies and examples to conclude that UIC code 406 is a good methodology for evaluating the main corridor capacity, but it may encounter difficulties with node (station) capacity evaluation [54]. Corman et al conducted another study in 2011 to analyze an innovative approach of optimization of multi-class rescheduling problem. The problem focused on train scheduling with multiple priority classes in different steps, using the branch-and-bound algorithm [55].

In addition to specific studies on railroad capacity, a book edited by Hansen and Pachl, containing several articles and sections conducted by different railroad studies mostly by European universities and academic centers, was released in 2008 as one of the latest resources of timetable optimization and train rescheduling problem. The book covers articles on various topics, such as cyclic timetabling, robust timetabling, use of simulation for timetable construction, statistical analysis of train delays, rescheduling, and performance evaluation [1].

1-6-2- Studies with Simulation and Combined Approach

While the analytical studies that have been conducted since 1960s, studies with simulation and combined approaches found in the literature appeared several years later. One of the first general simulation studies was conducted by Petersen et al. in 1982 by dividing a given corridor to different track segments where each segment represented the distance between two siding / switches [56]. Kaas developed another general simulation model in 1991, called “Strategic Capacity Analysis for Network” (SCAN), by defining different factors of simulation which could determine the rail network capacity [57]. In another study, Dessouky et al. (1995) used a general simulation model for analyzing the track capacity and train delay throughout a rail network. Their model included both single and double-track corridors, as well as other network parameters, such as trains length, speed limits and train headways [58]. Sogin et al, recently used RTC to simulate several case studies at University of Illinois, Urbana-Champaign. One of the studies evaluated the impact of passenger trains along U.S. shared-use double track corridors, considering different speed scenarios. They concluded that increasing speed gap between the trains can result in higher delays [59].

The Missouri DOT used the combined analytical-simulation approach in 2007 to analyze the rail capacity on the Union Pacific (UP) corridor between St. Louis to Kansas City to improve the passenger train service reliability and to reduce the freight train delay. Six different alternatives were generated based on a Theory of Constraints (TOC) analysis[4] and then compared with each other using the Arena simulation method. A set of recommendations and capital investment for each proposed alternative were proposed with respect to delay reduction [41].

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[4] : TOC is a management technique that focuses on each system constraints based on five-step approach to identify the constraints and restructure the rest of the system around it. These steps are: 1) identify the constraints, 2) decision on how to exploit the constraints, 3) subordinate everything around the above decision, 4) elevate the system’s constraints, 5) feedback, back to step 1.

In another project, Washington DOT (WSDOT) conducted a master plan in 2006 to provide a detailed operation and capital plan for the intercity passenger rail program along Amtrak Cascades route. The capacity of the corridor was also evaluated using the combined simulation-analytical approach. First, analytical methods were used to determine the proposed infrastructure. Then, the proposed traffic and infrastructure were simulated with RTC software to test the proposed infrastructure and operational results. After running simulation on RTC software, a heuristic (analytical) method, called Root Cause Analysis (RCA), was applied to evaluate the simulation output. The objective of RCA method was to identify the real reason of a delay along the rail corridor by comparing the output reports of each delayed train with other train services and to re-adjust the simulation outputs to be more accurate, in addition to locating infrastructure bottlenecks which caused the capacity issues and delays [60].

The Swedish National Rail Administration (Banverket) carried out a research project in 2005 to evaluate the application of the UIC capacity methodology (timetable compression) for the Swedish rail network. RailSys software was used for the simulations and the research team analytically evaluated the capacity consumption, its relationship with time supplements (or buffer times) and the service punctuality. The research concluded that the buffer times are absolutely necessary for the service recovery, in case of operation interruption. When there is no buffer time, the service punctuality can be significantly degraded due to increased capacity consumption. Banverket also confirmed the validity of the framework and the results of the UIC's approach and asked their experts and consultants to implement this analytical approach in their network [39].

In research conducted through combined analytical-simulation approach, Medeossi et al applied stochastic approach on blocking times of trains to improve the timetable planning by using OpenTrack simulation software. They redefined timetable conflicts by considering a probability for each train conflict as a function of process-time variability. The method repeatedly simulated individual train runs on a given infrastructure model to show the occupation staircase of trains in different color spectrum while each color represents the probability of trains' conflict which should be resolved [61].

Recently, a new "Web-based Screening Tool for Shared-Use Rail Corridors" was developed in the U.S. by Brod and Metcalf to perform a preliminary feasibility screening of proposed shared-use passenger and freight rail corridor projects. The outcomes can be used to either reject projects, or move them to more detailed analytical/simulation investigations. The concept behind the tool is based on a simplified simulation technique which does not provide optimization features or complex simulation algorithms. The tool requires development of basic levels of infrastructure, rolling stock and operation rules (trains schedule) of the given corridor and a conflict identifier assists the user in identifying locations for a siding or yard extension needed to resolve the conflict between existing and future train services [62].

1-6-3- Detailed Assessment of Selected Studies

Only a subsection of reviewed studies offered sufficiently detailed explanation of the study approach and respective results, so they could be divided into smaller subcategories for comparison purposes. Table 1-1 and the following discussion summarize the approach, tools used, study purpose, types of outcomes, and validation methods of the 25 studies selected for more detailed comparison.

Table 1-1- Category / subcategory breakdown of 25 selected studies in the U.S. and Europe [7, 8, 12, 13, 24, 28, 32, 35, 38, 39, 41, 59-72]

Category / Subcategory		The U.S. (13 Studies)	Europe (11 Studies)
Capacity Approach	*Analytical*	4 Studies [7, 8, 32, 35]	-
	Simulation	5 Studies [59, 63, 64, 66, 67]	5 Studies [13, 28, 39, 69, 71]
	Combined analytical-Simulation	5 Studies [12, 24, 41, 60, 62]	6 Studies [38, 61, 65, 68, 70, 72]
Tools/ Software	*Only Mathematical/ Parametric modeling*	3 Studies [7, 8, 32]	-
	General Simulation software	3 Studies [35, 41, 62]	-
	Timetable based simulation software	-	11 Studies [13, 28, 38, 39, 61, 65, 68-72]
	Non-Timetable based simulation software	8 Studies [12, 24, 59, 60, 63, 64, 66, 67]	-
Purpose of Research	*New methodology development/methodology approval*	5 Studies [8, 12, 24, 32, 62]	7 Studies [13, 28, 38, 39, 61, 68, 70]
	Master plan/capacity analysis	3 Studies [7, 41, 60]	-
	Academic research/project	6 Studies [35, 59, 63, 64, 66, 67]	4 Study [65, 69, 71, 72]
Type of outcomes /solutions	*Delay analysis/improvement*	3 Studies [35, 59, 63]	1 Study [71]
	Infrastructure development,	1 Study [7]	-
	Rescheduling/ operation changes	2 Studies [24, 64]	4 Studies [28, 38, 65, 69]
	Combination of above solutions	4 Studies [41, 60, 66, 67]	2 Study [70, 72]
	New Tools / methodology approval	4 Studies [8, 12, 32, 62]	4 Studies [13, 39, 61, 68]
Validation of simulation results	*Base Model*	6 Studies [7, 12, 32, 59, 63, 64]	3 Studies [28, 38, 39]
	Base and Alternative results	7 Studies [8, 24, 41, 60, 62, 66, 67]	7 Studies [13, 61, 65, 68, 69, 71, 72]
	No Comparison	1 Study [35]	1 Study [70]

Approach: Most studies used either simulation or combined analytical-simulation approaches. However, research conducted by Association of American Railroads (AAR) [7], University of Illinois at Urbana-Champaign (UIUC) [8, 32] and University of Southern California (USC) [35], applied analytical-only methodologies.

Tools and Software: All European studies used timetable based simulation software (e.g. RailSys, OpenTrack, ROMA) while the U.S. studies relied on other tools like optimization/parametric modeling (UIUC and USC) [7, 8, 32], general simulation software (e.g., Arena) [41], web-based screening tools [62], and non-timetable based rail capacity software (RTC).

Purpose of Research: Three main purposes were identified for studies: 1) introducing new methodology for capacity evaluation, 2) evaluating the capacity status of a given corridor as part of a corridor master-plan development, and 3) academic research on various capacity issues. The majority of European studies (Denmark, Austria, Germany, the Netherlands and Sweden) were conducted by industry or academic research teams to justify and evaluate the UIC's approach (UIC code 406) for capacity evaluation [13, 38, 39, 69, 72] while the objectives of the U.S. studies included all three subcategories.

Type of Outcomes or Solutions: The outcomes and solutions obtained from the U.S. studies included variety of different types such as delay analysis (UIUC by using RTC and USC by using Awesim/Minitab), rescheduling and recommendations related to current operations (UIUC and White) [24, 64], infrastructure development, and combination of all outcomes mentioned above (typically as part of a master plan). In addition, new tools and parametric models were also developed as the final outcome of three U.S. studies (mainly by UIUC). The outcomes of European studies were not as diverse, as they either approved the application of UIC's capacity methodology to be used on their network [13, 39], or suggested network rescheduling and operational changes (the timetable compression concept) [28, 38, 65, 69, 72]. One of the common conclusions of various studies was the identification of operational heterogeneity as a major reason of delay, especially in the U.S. rail network with unstructured operation pattern.

Validation of Simulation Results: None of the studies using analytical method compared the results to a real-life scenario, but some of the simulation-based studies validated the results with one of the following three types of comparisons:

- *No comparison*: No specific information or comparison was provided between simulated results and actual practices. As presented in Table 1-1, approximately one third of the studies (9 out of 25) did not validate the simulation results, either because the study was not based on actual operational data, or comparison was not conducted as part of the research.
- *Base Model*: Only the results of a base model were compared with the real data. More than half of the studies (14 out of 25) compared the simulation results only with the base model.
- *Base and alternative results*: In addition to base model comparison, the alternative outcomes were compared with the real data. Only two studies belonged to this category.

1-7- Summary and Conclusions

This paper has provided an overview of capacity definitions, alternative analysis approaches and tools available to evaluate capacity. It has also highlighted the key similarities and differences between the U.S. and European rail systems and how they affect related capacity analysis. Finally, the paper has reviewed over 50 past capacity studies and selected 25 of them for more detailed investigation,

The review revealed no single definition of railroad capacity. Rather, the definition varies based on the techniques and objectives of the specific study. The capacity analysis approaches and methodologies can also be classified in several ways, but are most commonly divided into analytical and simulation methods. This paper also introduced a third “combined” approach that uses both analytical and simulation approaches.

While the objective of capacity analysis is common, there are several differences between the U.S. and European rail systems that affect the approaches, tools and outcomes of analysis. Europe tends to use a structured operations philosophy and thus uses often timetable based simulation approaches for analysis, while the improvised U.S. operations warrant non-timetable based analysis. Other factors, such as differences in ownership, type and extent of double track network, distance between and length of sidings, punctuality of service, dominating type of traffic (passenger vs. freight), and train configuration also affect the analysis methods and tools.

The review of over 50 past studies revealed that a majority of analyses (approximately 65% of studies) utilized either simulation or combined simulation-analytical methods, while the remainder relied on analytical methods. Although the general simulation tools and modeling approaches have been used, most studies use commercial simulation software either in the U.S. (non-timetable based) or in Europe (timetable based). Based on the more detailed review of 25 of the studies, European capacity analysis tends to be linked to the UIC 406 method, while the U.S. does not seem to have as extensive principles as the European case studies, but the methodologies vary more from one study to another. The outcomes of European studies were also less diverse than in the U.S., and commonly suggested rescheduling and operation changes as the solutions for capacity improvement. Also, the studies showed limited effort in comparing the simulation results to the actual conditions (the validation step), especially after recommended improvements were implemented. Only two studies did the full validation, 14 out of 25 only compared the results with the base model, and the remaining one third of the studies had no validation process. Overall, it was found that there was no major divergence between approaches or criteria used for capacity evaluation in the U.S. and Europe. However, there are differences in the tools used in these two regions, as the tool designs follow the main operational philosophy of each region (timetable vs. non-timetable) and include features that concentrate on other rail network characteristics for the particular region.

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CHAPTER 2

2. Hybrid Simulation Approach for Improving Railway Capacity and Train Schedules[5]

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2-1- Abstract

For rail corridors with high demand, maximizing the utilization of available capacity is of utmost importance. Two operational methodologies to assist in reaching the goal are train rescheduling and timetable management. These methodologies have been commonly applied in the highly structured European rail system, but their potential benefits to the less structured U.S. system have received little attention. Railway simulation is one approach to investigate the potential, but unlike in Europe, commercial rail simulation tools in the U.S. rarely offer the functionality needed for automated timetable improvements. This paper investigates the use of timetable management techniques in the U.S. environment through a hybrid simulation approach, where output from a non-timetable based simulation tool developed in the U.S., (Rail Traffic Controller or RTC) is used as input for optimization effort in a timetable-based tool developed in Europe, RailSys. The improved timetable (RailSys output based on timetable compression technique) is then validated in the RTC to confirm the effects of rescheduling on level of service (LOS) parameters and capacity utilization. The case study analysis revealed that ten minute maximum dwell time provided the best corridor capacity utilization. Also, by applying the hybrid simulation approach, the LOS was improved, as unnecessary stops were reduced by 55%, delays reduced by 85%, and maximum dwell time was reduced from 60 minute to 10, while the timetable duration was increased by only 18% compared to the initial schedule. The research also emphasized on the trade-off between LOS criteria and capacity utilization levels, as if LOS is improved, capacity utilization may get degraded; and vice versa.

Keywords: Railway Simulation, Timetable Management, Train scheduling, Railway Capacity, Timetable Compression Technique

2-2- Introduction

The majority of passenger rail services in the United States (U.S.) operate on shared-use corridors with significant freight rail services. The European passenger rail services also operate on shared-use corridors, but the infrastructure conditions and the operation priorities and patterns typically favor passenger operations [6, 7]. The increasing demand for train traffic is creating pressure to add capacity in the U.S. either through the construction of new tracks and lines, or through improved operational strategies. This necessitates evaluation of capacity improvement alternatives, so the best alternative gets selected for implementation.

Capacity analysis is one of the main tools to evaluate the benefits. While the concept of capacity and the objective to maximize its utilization are global, the configuration differences between the European and the U.S. rail systems (such as the infrastructure ownership and the operations philosophy) lead to the use of different methodologies, techniques, and tools for capacity evaluation. More information on these differences and how they affect the capacity studies is provided by Pouryousef, et al, 2013 [73]. This paper provides a brief synopsis of methods and tools to evaluate capacity and the level of service (LOS)[6] of trains, but concentrates on introducing a new capacity analysis concept, called "Hybrid Approach", where commercial rail simulation software from U.S. and Europe are used together for the analysis. Since the European simulation software is better equipped with timetable management features, it is used to improve the initial timetable. The results are brought back to the

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[6] Level of service (LOS): The timetable characteristics with importance to the customer/clients and, defining the quality of service from timetable standpoint. Common parameters include number of stops, maximum dwell time and total dwell time.

U.S. based simulation tool to confirm that the recommendations are implementable. This differs from traditional analysis, as it takes advantage of the complementary features offered by each tool, and the output of one software is used as input in the other software. A case study using a single-line rail corridor is presented to demonstrate the approach and the outcomes and challenges are included in the discussion.

2-3- Capacity Analysis

The capacity There is no standard definition for railway capacity, but one alternative is the number of trains that can safely pass over a given segment of the line within selected time period [3]. Various definitions, metrics, methodologies and tools are applied for evaluating the capacity and its utilization in Europe and North America, mainly due to the differences of rail network characteristics between the two continents [73]. Three critical differences are the ownership of infrastructure, the predominant traffic type (freight vs. passenger), and the operation philosophy. More than 90% of the infrastructure is owned and managed by private freight railroads in the U.S. while in Europe infrastructure is almost completely owned and managed by governments or public agencies. The U.S. operations are predominantly for freight transportation and prevailing operations philosophy for the majority of freight trains and even some passenger and commuter services is based on the improvised pattern (no repeatable dispatching plan in-advance). In Europe, passenger trains dominate the corridors and almost all trains (freight and passenger) follow structured operations with a regular schedule developed months in advance [24]. The reasons above, combined with variations in other characteristics, such as rolling stock and signaling systems all affect capacity and related analysis, including tools and techniques used to accomplish the task.

The literature mainly divides capacity analysis approaches to analytical and simulation methods [8, 12, 33-36], although a combined analytical-simulation approach that takes advantage of both analytical and simulation methods has also been used in past studies [68, 74]. The simulation methods typically utilize either **general simulation** tools or **commercial railway simulation** software that has been specifically designed for rail transportation [12, 33]. The commercial railway simulation software can be divided into two major categories: **Non-timetable based** and **Timetable based software**. Both incorporate two main components: "Train movement simulation" to calculate the train speed along the track, and "Train dispatching simulation" to emulate the actions of the actual dispatcher as closely as possible [24]. The non-timetable based simulations are typically used in railways which operate based on unstructured operation pattern without initial timetable, such as the majority of the U.S. rail network. The Rail Traffic Controller (RTC), developed by "Berkeley Simulation Software, LLC" is the most common software in this category and is used extensively by the U.S. rail industry [12, 24]. The simulation procedure in the timetable based software, which is typically used in Europe, is based on the initial timetable of trains and often includes simulation tools to improve the timetable as much as possible. RailSys, developed by Rail Management Consultants

GmbH in Germany, is one example of a timetable-based simulation package. More details of different simulation tools has been provided by Pouryousef, et al, 2013 [73].

Table 2-1 provides a sample of recently published capacity studies in the U.S. and Europe, and shows the difference between tools commonly used for analysis. RTC has been the software of choice for all U.S. studies while several timetable-based packages have been used in Europe. In addition to the software highlighted in the Table, there are other simulation tools used in the U.S., especially used by rail transit and commuter services (e.g. MultiRail, RailSim), as well as in Europe (e.g. OpenTrack, Viriato, SLS, RAILCAP, CMS). A review of Table 2-1 indicates that train delay analysis is a common performance metric for capacity evaluation in the U.S. which is also recommended by the Federal Railroad Administration [9]. Europeans have a variety of different methodologies to evaluate the railway performance, but most of them utilize on timetable management techniques. The technique applied as part of this research, called timetable compression, is one of the commonly used techniques in Europe for both simulation and analytical approaches and was developed to improve the capacity levels by readjusting the operational characteristics. In other words, the technique is applicable mainly on corridors with pre-scheduled timetables and predetermined routes for most daily trains (structured operation philosophy) and its objective is to modify the pre-determined timetable by rescheduling the trains as close as possible to each other [3, 13, 38-40]. While U.S. shared corridors rarely operate under structured operation philosophy, the daily schedules for passenger trains rarely change, making the shared use corridors more applicable for the technique.

Table 2-1- Review of selected capacity simulation studies (academic research) conducted in the U.S. and Europe

Authors		Simulation Package	Applied Technique/Method through Simulation
The U.S. (5 Studies)	Khadem Sameni, et al, 2011 [12]	RTC	Evaluated a new metric of capacity (profit-generating capacity) for the intermodal and bulk train services in the U.S. by applying different heterogeneity scenarios between these two trains
	Sogin, et al 2012 [59]	RTC	Delay analysis of freight trains along a double-track case study based on applying various speed scenarios and number of passenger and freight trains
	Sogin, et al 2013 [75]	RTC	Compared single and double track performance (train delay analysis) by changing traffic volume, passenger train speed and heterogeneity level of freight and passenger trains
	Atanassov, et al 2014 [66]	RTC	Evaluated the additional capacity of different scenarios of adding double track segments to the existing single track, based on delay analysis of freight trains
	Shih, et al 2014 [67]	RTC	Compared different scenarios of single track lines with sparse siding options, in terms of freight train delay
Europe (5 Studies)	Schlechte, et al 2011 [68]	OpenTrack	Used simulation package to obtain microscopic level results and to convert the results to macroscopic level for further timetable development/improvement by using a specific algorithm, and then the new timetable was retransformed again to the simulation for further analysis
	Gille & Siefer, 2013 [69]	RailSys	Used simulation package through a 3-step method of capacity improvement: 1- obtaining max. level of occupancy, 2- running the simulation and determining the service quality, 3- adjustment of max. level of occupancy
	Medeossi & Longo, 2013 [70]	OpenTrack	Developed an approach of estimating the stochastic inputs of simulation to be more practical and simple for generating realistic simulation scenarios
	Sipila 2014 [71]	RailSys	Applied simulation package to evaluate different train run time scenarios (vs. minimum run times) based on delay analysis
	Goverde, et al 2014 [72]	ROMA	Used timetable compression technique (UIC method) for computing capacity of corridors with scheduled trains, while for unscheduled (disturbed) traffic conditions, Monte Carlo simulation technique was used for the analysis. (Both applied via ROMA which combines alternative graphs of train-paths)

2-4- Hybrid Simulation Approach

The objective of the study was to test the use of timetable management tools to the capacity analysis in the U.S. environment. The methodology included development of a "hybrid analysis concept" that takes advantage of the strengths of both timetable and non-timetable based software. The tools used in the study included RTC as the non-timetable based simulation tool and RailSys as the timetable-based tool. Figure 2-1 presents key features of each simulation package. RTC has the capability to use preferred departure times, train dispatching simulation process, and its automatic train conflict resolution to develop the initial timetable (stringline), while RailSys can use its timetable compression technique (based on UIC code 406) to improve and optimize the initial timetable for more efficient capacity utilization.

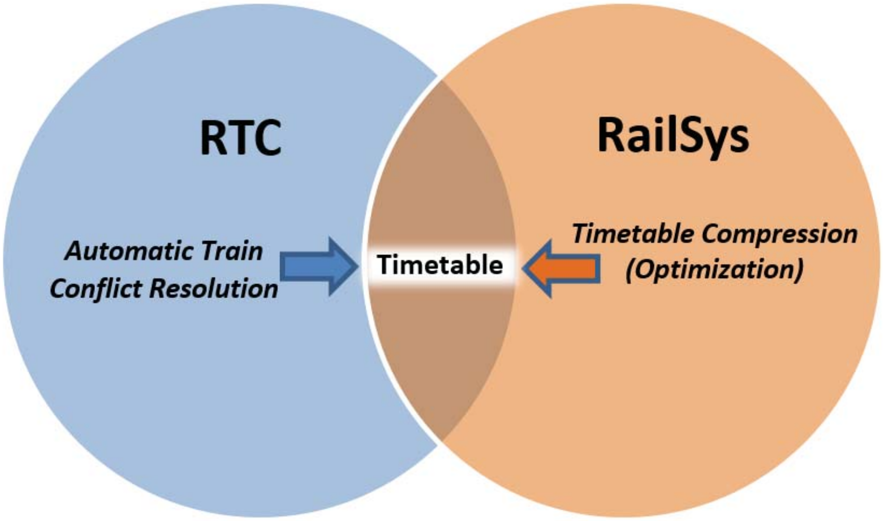

Figure 2-1- The main features of RTC and RailSys for timetable development

The hybrid approach uses the initial timetable developed in the RTC as input for RailSys and attempts to improve the outcomes of original RTC simulation by RailSys timetable compression technique that adjusts the operational parameters. After adjustment, the improved timetable developed by RailSys, is imported as input to RTC to validate the results in a tool widely accepted in the U.S. rail environment. (Figure 2-2)

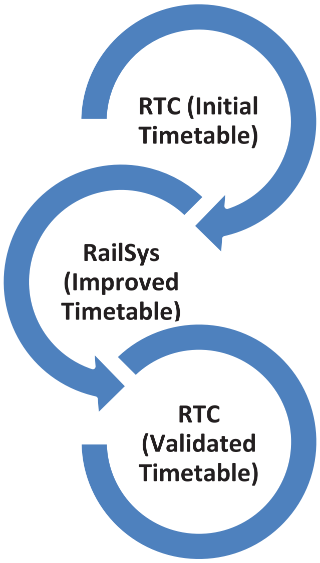

Figure 2-2- Main outputs of each step in a "Hybrid Approach"

Figure 2-3 illustrates the hybrid simulation approach on step-by-step basis. Step 1 represents the development of the initial timetable using RTC. Step 2 improves the RTC's timetable by using RailSys compression techniques, and Step 3 validates the new timetable in the RTC.

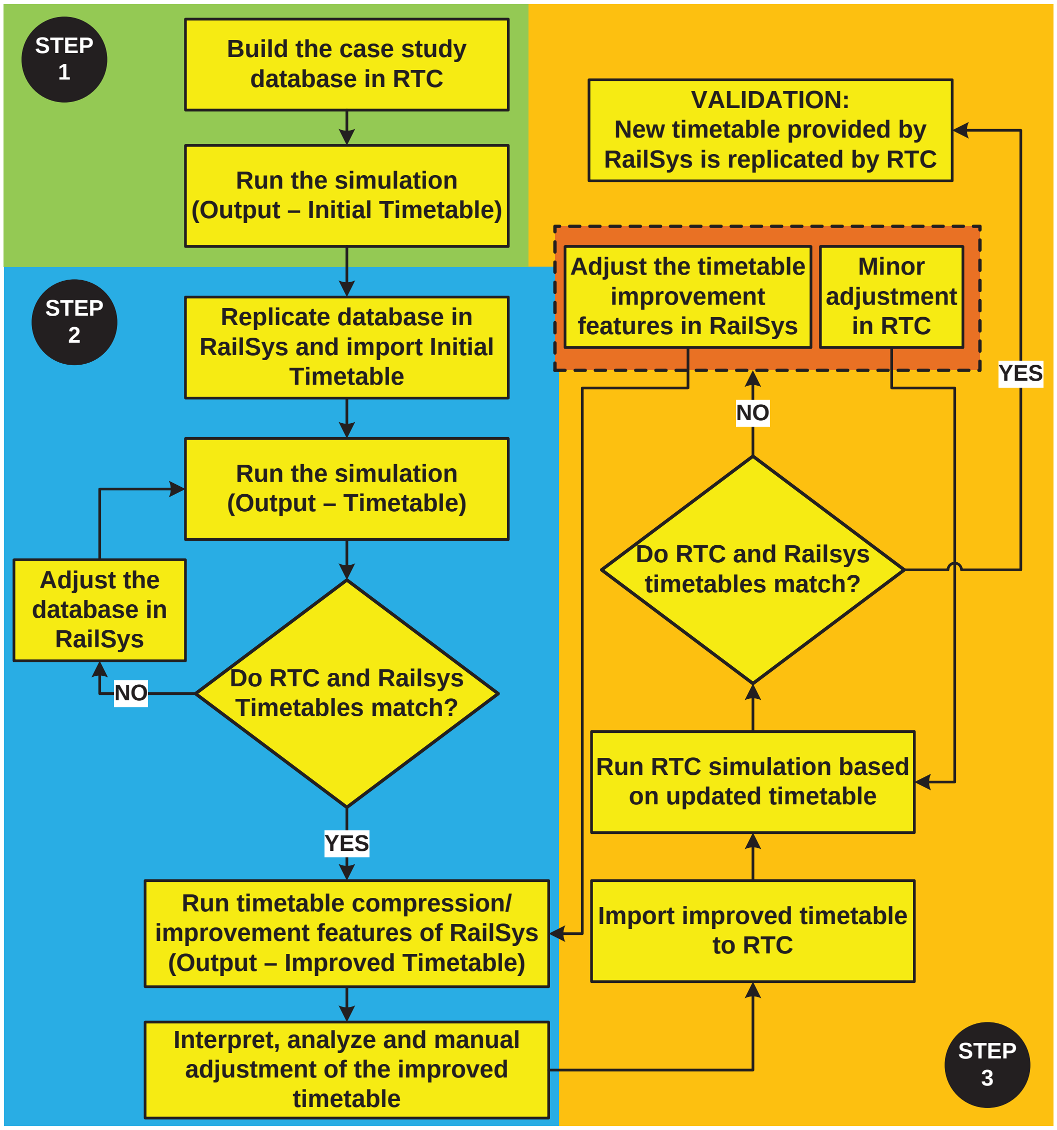

Figure 2-3- Flowchart of hybrid simulation (RTC-RailSys-RTC)

As presented in Figure 2-3, the hybrid approach requires conversion of the database from RTC to RailSys and checking that the key simulation outcomes match with each other. There are four categories in the database and the level of conversion criteria and difficulty vary. Table 2-2 provides a synopsis of the replication process and the challenges in making the respective databases. The conversion of infrastructure and operation rules consists mainly of unit conversion (English to metric), but the conversion of train and signaling characteristics is a much more involved and challenging task and may require specific adjustments in individual parameters.

Table 2-2- Summary of database conversion from RTC to RailSys

Category	Conversion Criteria	Difficulty Level	Main Adjustments
Operation rules	Match	Easy	Unit conversion
Trains	Maintain trains run times	Complicated	Train consist, Power, Max speed, Train resistance
Signaling	Maintain routes and run times	Complicated	Signal features, Interlocking, Blocks
Infrastructure	Match	Easy	Unit conversion

The validation process depends on the parameters that need to be matched. In the case study, the main objective was to maintain the same schedule and run time of trains, as well as to confirm that there were no deviations in train routings. The deviations in these parameters were used to determine if further adjustments were required in the parameters.

2-5- *Case Study*

A case study was developed as part of the research to demonstrate the hybrid approach. The case study used an actual rail line in the U.S. that is currently used for excursion passenger trains, but train and signaling parameters were hypothetical. The input data was developed for each simulation package and included all four database categories; operations rules, trains, signaling, and infrastructure.

The line was a 30 mile long single track segment with three sidings/yards for meet/pass and stop purposes (Figure 2-4). The vertical track profile and locations of the sidings were precisely derived from an existing corridor data, but the horizontal curves were not considered, as their impact on the train speed was not considered essential for the simulation results. Table 2-3 summarizes the infrastructure parameters for the case study.

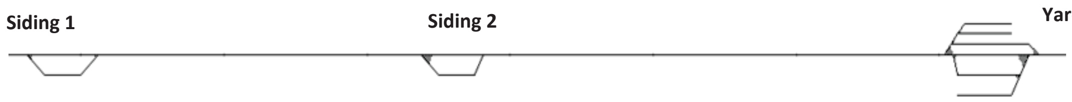

Figure 2-4- A simple scheme of sidings and yard located along the case study

Table 2-3- Details of case study infrastructure

Segment Length	30 miles, single track
Sidings/yards	2 sidings + 1 yard
Max. grade	1.78%
Curvature	Horizontal curves neglected
Length of sidings	0.34 - 0.42 miles
Turnout #	# 11

The signaling system was absolute permissive block (APB) for single track operation with four-aspect signaling along the main blocks. The length of blocks varied between 1.2 and 2.5 miles and all sidings/ yard tracks were equipped with controlled interlocking systems.

Four types of trains were considered in the case study: intercity passenger (4 daily pairs), commuter passenger (2 daily pairs), merchandise freight (2 daily pairs) and intermodal freight trains (3 daily pairs). It was assumed that the characteristic and configuration of trains in each specific category was uniform and each train was operated in both westbound and eastbound directions. All passenger and commuter trains were propelled by a single diesel-electric locomotive and all freight trains were loaded in both directions. Since the type and configuration of locomotives were different in the RTC and RailSys database, some of the characteristics of selected locomotives in RTC (such as power, weight, length, axle load, acceleration/ deceleration rate, resistance) were imposed and adjusted in the RailSys database as a new type of locomotive.

There were several relevant operation rules for simulation, such as the train priority, speed limits, stop patterns, and preferred time and order of train departures. The train priority (in descending order) was commuter trains, passenger trains, intermodal, and merchandise trains. The maximum speed of passenger/commuter trains was 60 mph, and freight trains 50 mph. In addition, the initial speed of all trains was 30 mph when they reached the track segment that started the simulation process. There were no planned stops for any trains, but passenger, commuter or merchandise trains were allowed to stop at the sidings due to the meet-pass logic. The intermodal freight trains were allowed a meet-pass stop only in the yard tracks since the length of this type of trains was longer than the siding lengths. In the case study, there were no predefined arrival/departure timetables, although some preferred departure times were considered.

2-6- *Outcomes and Discussion*

2-6-1- Replicating Initial Timetable

Figure 2-5 presents the initial simulation results obtained from RTC in distance-time diagram format (string-line). No manual improvement was applied to the outputs. As noted earlier, there were no planned stops for the trains, but several stops were suggested by RTC for meet-passes in the sidings to resolve train conflicts. The simulated arrival/departure times showed a deviation from the preferred train dispatching times that were provided to develop the initial schedule, due to RTC automatic decision making features that resolved the conflicts between trains provided in the initial plan.

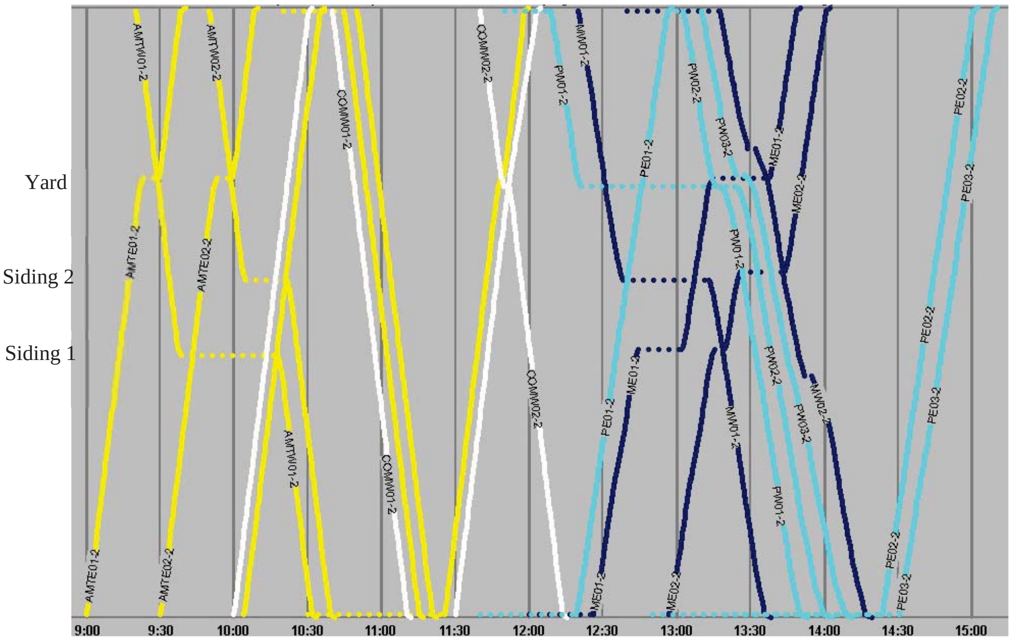

Figure 2-5- Simulated train timetable (stringline) in RTC (Commuter: White, Passenger: Yellow, Intermodal: Blue, freight: Navy blue)

The initial preferred train departure times did not consider all factors of scheduling, so some times were adjusted by the RTC. As presented in Table 2-4, trains with higher priority (commuter and passenger) had lower deviation between their requested and simulated departure times. The departures with deviated time have been highlighted in table cells by "*" and "**"for eastbound and westbound columns, respectively. There was also conflict between requested departure time of passenger 3 and commuter 1 (eastbound direction), as both trains were requested to depart at 10:00. RTC solved the time conflict by maintaining the initial schedule of commuter train (with higher priority) and delaying passenger train for three minutes at the entry point of the line. Similar situation occurred between Intermodal 2 and Freight 2 along eastbound direction (both were planned to depart at 12:50). RTC changed departure times of both trains to facilitate necessary meet-pass events. After the changes, the high priority commuter trains had one short stop in a siding due to the meet-pass enforcement, while passenger trains faced more frequent and longer delays in the sidings and in the entry points of the line (Figure 2-5). The same trend was noticed for freight and intermodal train schedules with even more delays and longer meet-pass time in the sidings, since the priority of these two types of trains was lower than passenger and commuter trains. However, the merchandise freight trains had lower delays in comparison to the intermodal freight trains, although the priority of intermodal trains was slightly higher than merchandise train. This may be due to the fact that merchandise trains had more flexibility for meet-pass stop locations, while intermodal trains were limited to stopping in the yards with sufficient siding lengths to fit the full train.

Table 2-4- Comparison between planned and simulated departure times in RTC

Train	Planned departure-Eastbound	Simulated departure-Eastbound	Planned departure-Westbound	Simulated departure-Westbound
Pass1	9:00	9:00	9:20	9:20
Pass2	9:30	9:30	9:50	9:50
Pass3	10:00 *	10:03 *	10:20 **	10:45 **
Pass4	10:30 *	11:27 *	10:50	10:50
Comm1	10:00	10:00	10:40	10:40
Comm2	11:30	11:30	11:40	11:40
Interm1	11:40 *	12:20 *	11:50 **	12:08 **
Interm2	12:50 *	14:23 *	13:00 **	13:02 **
Interm3	13:20 *	14:30 *	13:10	13:10
Freight1	12:00 *	12:25 *	12:20	12:20
Freight2	12:50 *	12:55 *	12:40 **	13:15 **

The output from the RTC simulation was used as input in RailSys simulation (Figure 2-6). There were some minor deviations between arrival/departure times in RailSys and RTC, due to differences between rolling stocks and signaling features/equations of each simulation package, such as tractive effort of engines, acceleration, deceleration, and braking diagram. Despite these differences, approximately 96% of timetable characteristics (order of trains, stop patterns, departure/arrival times) were identical in RailSys when compared to the output obtained from RTC.

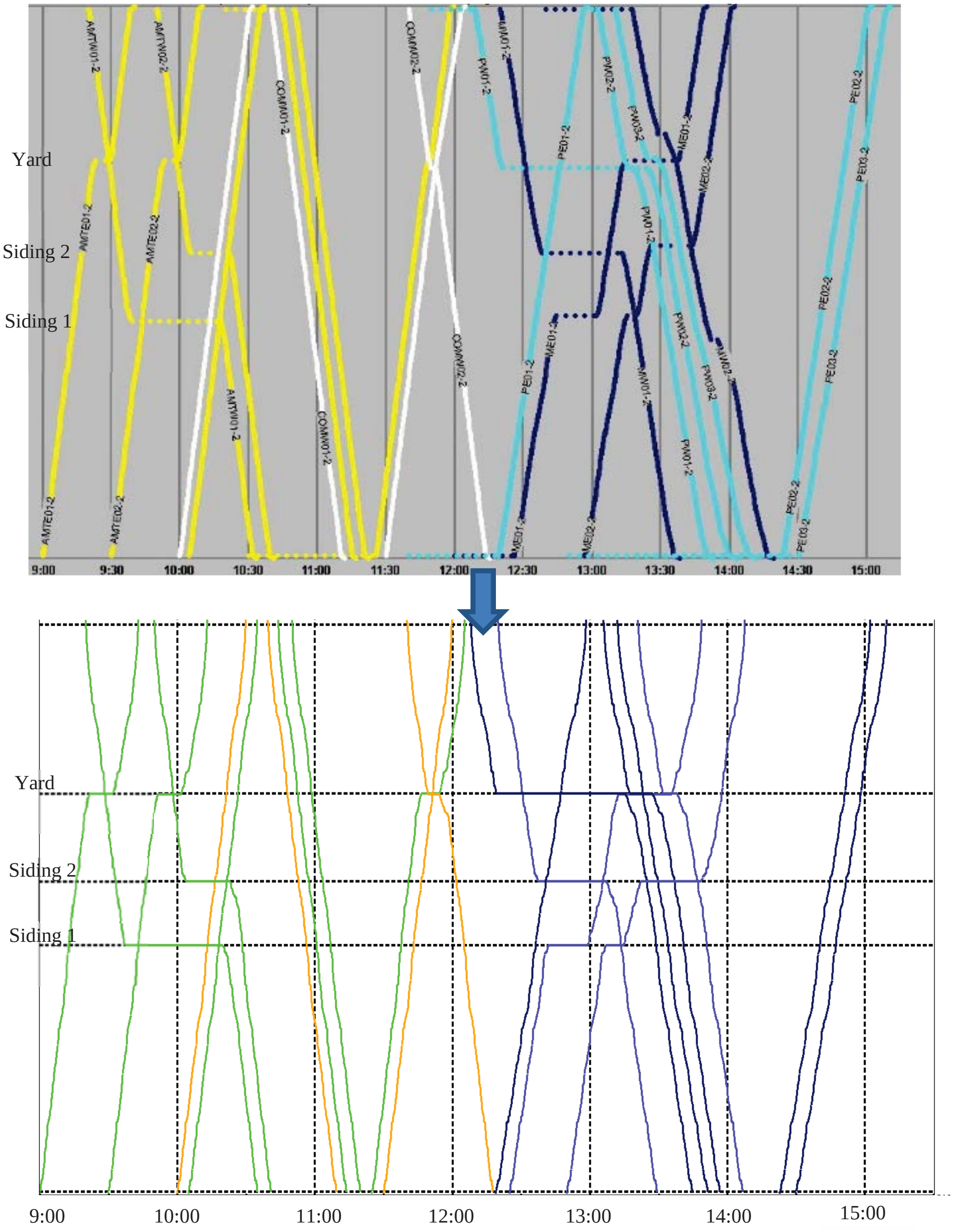

Figure 2-6- The output of RTC stringline (top) was replicated in RailSys as input (bottom)

2-6-2- Timetable Improvement

Once the accuracy of the replicated database was confirmed, RailSys capabilities were used to improve and compress the initial timetable based on predefined patterns and algorithms. RailSys uses UIC 406 compression technique to automatically adjust an initial timetable and improve the capacity utilization levels. RailSys has several factors that had to be defined prior to the timetable compression such as:

- Overtaking option in the sidings
- Maximum dwell time of trains in the sidings
- The initial timetable from RTC (used as input)
- Selection between compression technique (Austrian method, OBB, or German method, DB)
- Timetable duration (the portion of timetable which is planned to be adjusted)

The case study used the OBB compression algorithm and allowed overtaking option at maximum two stations. OBB was selected over DB algorithm as it maintained the number of simulated trains obtained from RTC results. The simulation was completed for four different total timetable durations, ranging from eight to eleven hours and each duration was simulated with seven different maximum dwell times. Figure 2-7 presents the capacity utilization of the improved timetable for all simulated scenarios. As shown in Figure 2-7, dwell times has significant impact on overall capacity utilization levels. Based on the analysis (Figure 2-7), capacity utilization is minimized in our case study if 10 minute maximum dwell time is allowed for the trains, regardless the total duration of timetable. However, the "10-

hour duration” is selected for any further capacity utilization calculation through this research because, according to Figure 2-7, the practical threshold of capacity utilization (70%), recommended in different railway literature [3, 34, 73], was observed under 10-minute maximum dwell time scenario. Therefore, ten-hour timetable duration, and ten-minute maximum dwell time were selected for all improvement scenarios.

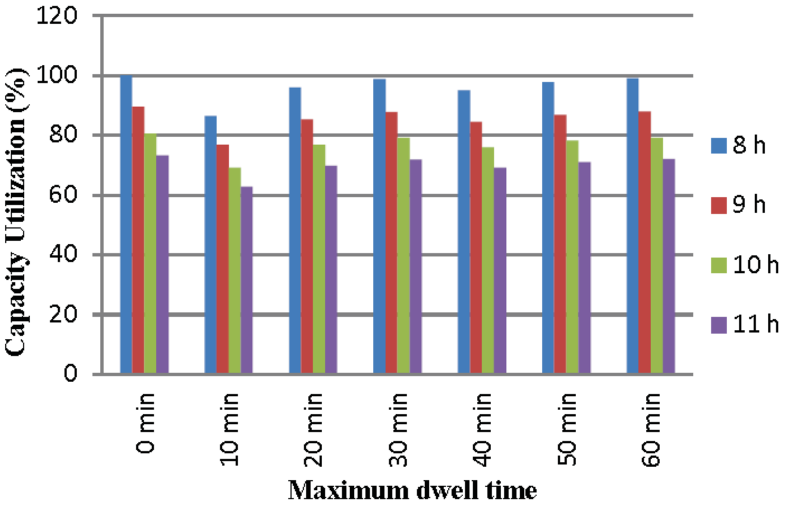

Figure 2-7- Capacity utilization percentage based on different timetable durations and maximum allowable dwell times

Based on its definition, the LOS is maximized, if both train stops and total dwell times are kept to zero. Figure 2-8 demonstrates the improved timetable developed by RailSys that uses maximized LOS values for “10 hour timetable duration”. However, the total duration of timetable in this scenario was almost two hours longer than the RTC’s outcomes, as disallowance of train stops and dwell times decreased the overall capacity utilization.

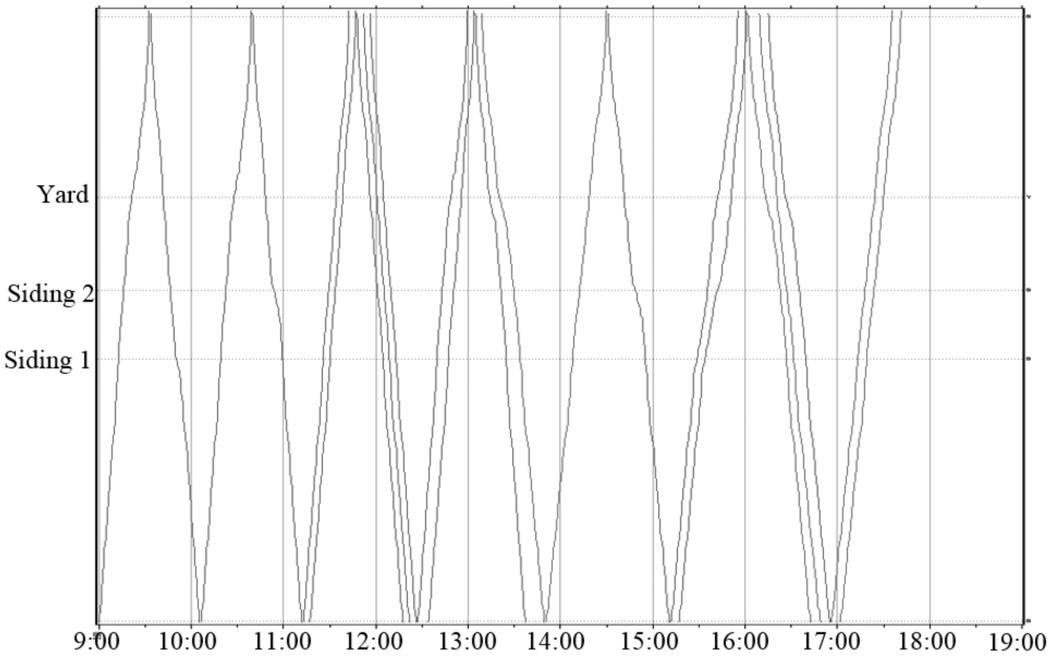

Figure 2-8- Improved timetable (stringline) in RailSys based on “no dwell time” scenario (Best LOS)

Figure 2-9 presents the timetable with “10 minute maximum dwell time”, which has been compressed by approx. 60 minutes, compared to Figure 2-8. However, the total duration of “10 minute dwell time” scenario (Figure 2-9) is still longer than the initial timetable of RTC (approx. 57 minutes); due to the fact that the LOS parameters have been significantly improved. This demonstrates the trade-off between LOS parameters and total duration of timetable (or capacity utilization), as by improving the LOS, the capacity utilization might be degraded; and vice versa.

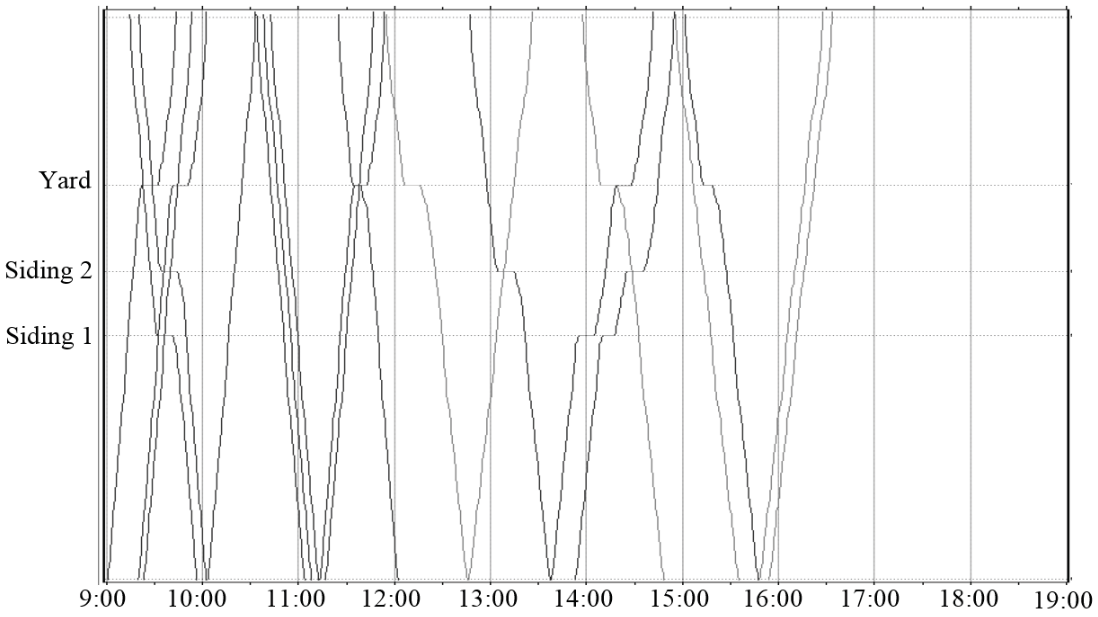

Figure 2-9- Improved timetable (stringline) in RailSys with 10 minute maximum dwell time

Table 2-5 compares the differences in train departure times between initial and "10 minute dwell time" scenarios. The train order was maintained the same as in the initial schedule for both eastbound and westbound directions.

Table 2-5- Train departure times; initial and adjusted timetable developed by RailSys (10 minute dwell time scenario)

Train	Initial departure-Eastbound	Improved departure-Eastbound	Initial departure-Westbound	Improved departure-Westbound
Pass1	9:00	9:00	9:34	9:20
Pass2	9:30	10:07	10:40	9:50
Pass3	10:05	11:18	11:53	10:44
Pass4	11:25	12:28	11:57	10:50
Comm1	10:00	11:12	11:48	10:40
Comm2	11:30	12:35	13:05	11:40
Interm1	12:19	13:51	13:10	12:08
Interm2	14:23	16:17	16:03	13:06
Interm3	14:30	17:03	16:10	13:12
Freight1	12:25	15:12	14:31	12:20
Freight2	12:50	15:18	16:16	13:21

Although RailSys tools performed well in improving the timetable, a review of the outputs revealed a few occasions where trains were stopped for a siding without a reason (Figure 2-10-top). It was speculated that RailSys maintained the unnecessary stops, as they were needed to resolve the train conflicts in the initial schedule. Manual timetable adjustments were made to eliminate the unnecessary stops. The new improved timetable (RailSys compression technique + manual improvements) reduced the overall duration of timetable by approx. 25 minutes as illustrated in Figure 2-10-bottom.

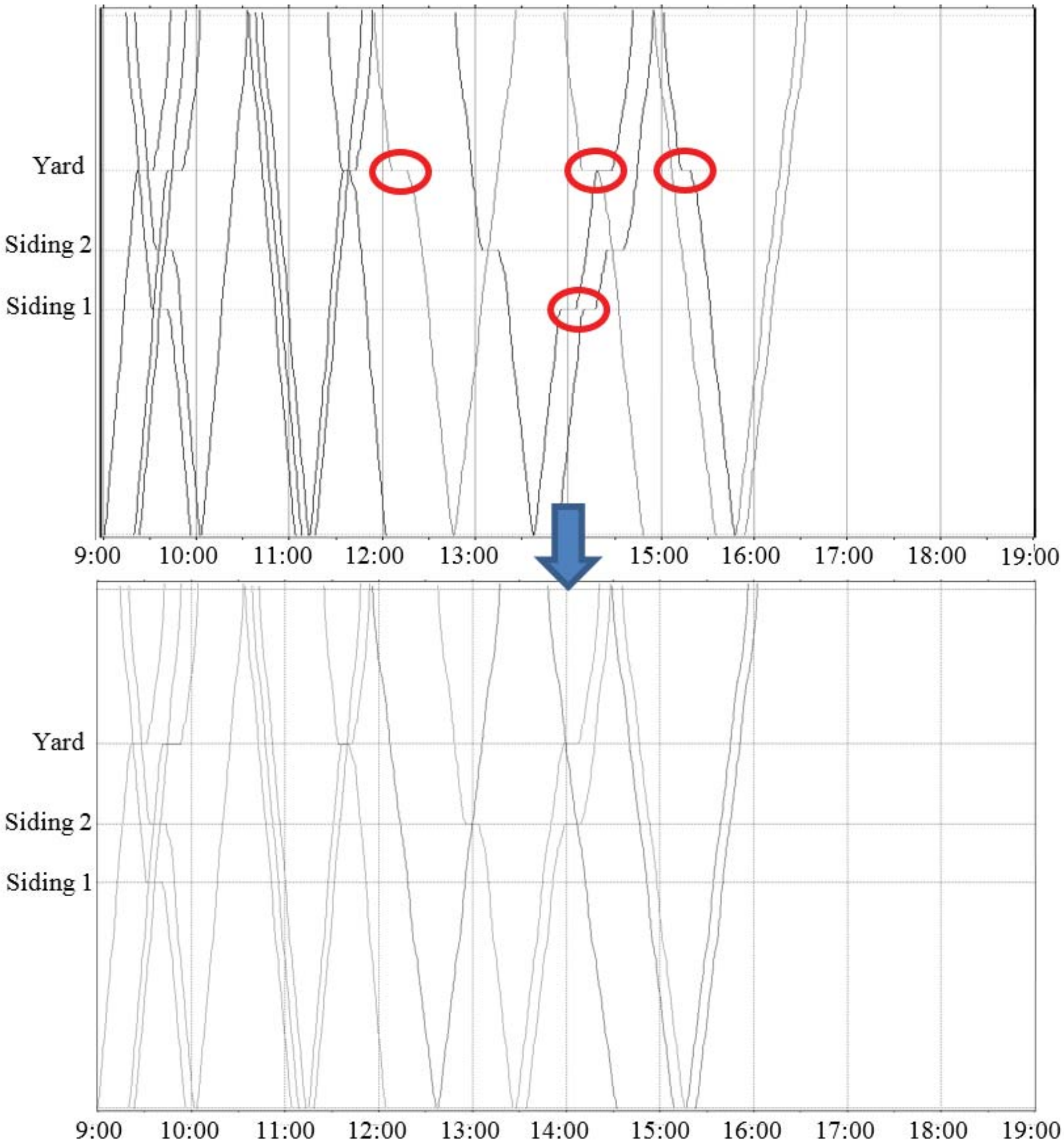

Figure 2-10- The unnecessary stops (red circles) in adjusted timetable (top) were manually removed (bottom)

2-6-3- Additional Capacity Provided by Compression Technique

As Manual removal of unnecessary stops reduced the overall timetable duration by 25 minutes (Figure 2-10), although it is still longer than the initial timetable obtained from RTC (Figure 2-5). While the final timetable, shown in Figure 2-10-bottom, provides a lower LOS values for the existing trains than the scenario of best LOS (Figure 2-8), it offers a lower capacity utilization that allows new trains to be added to the corridor. Table 2-6 shows various opportunities for different types of new trains that can be added to the compressed timetable. All new trains are equally distributed between eastbound and westbound directions, have no stops and have minimum three minute headway between departure and arrival times of two consecutive trains. Table 2-6 shows the number of new trains by type that could be added to the timetable improved by RailSys (Figure 2-10).

Table 2-6- Comparison between different scenarios of capacity utilization after adding new trains to the existing services based on "10 h timetable duration"

New Trains	Total new trains	Eastbound/ Westbound	Capacity utilization
Mixed traffic	4	2/2	89.6 %
Only Intermodal	4	2/2	91.2 %
Only Freight	4	2/2	91.2 %
Only Commuter	5	3/2	96.5 %
Only Passenger	5	3/2	96.4 %

Figure 2-11 demonstrates an example of five new passenger trains added to the existing services after timetable compression. While this example adds all the new trains on the end of the schedule, they could also be added between existing traffic. Naturally, each such addition would require another round of analysis to determine the effects on the existing traffic.

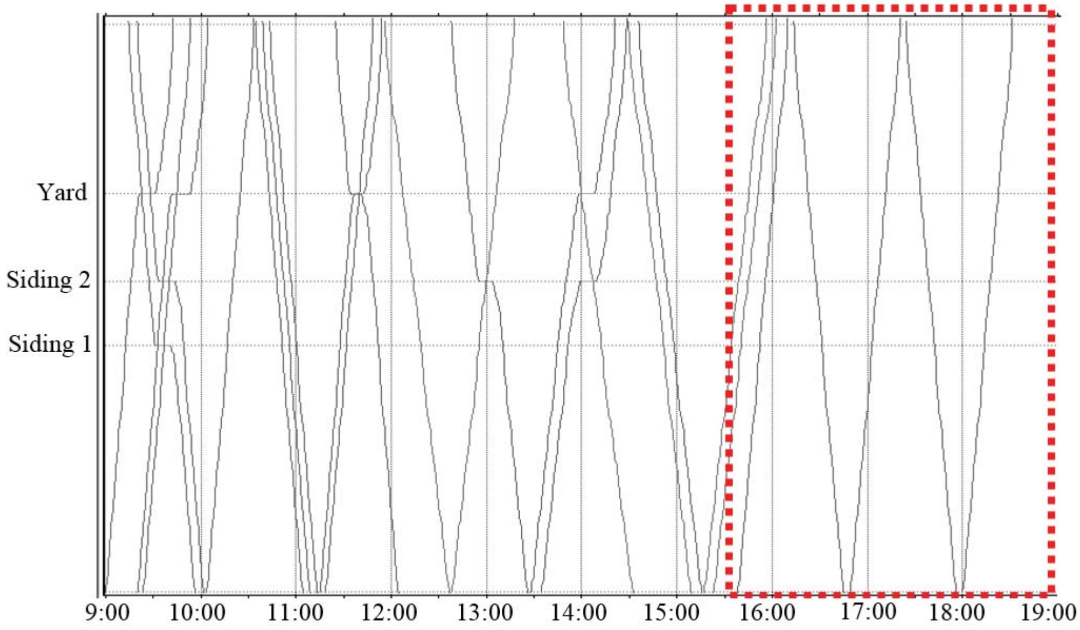

Figure 2-11- An example of five new passenger trains added to the end of compressed timetable

2-6-4- Validation of Improved Timetable

As illustrated in Figure 2-2, the final step of the hybrid process was to validate the new timetable by running it through RTC. This step is necessary, if there is a concern on the replicability and accuracy of the results obtained from RailSys. Figure 2-12 shows the timetable by RailSys (Figure 2-10-bottom) after validation in RTC. All trains were successfully dispatched in RTC with the same order and same stop patterns. However, the differences between signaling and rolling stock characteristics of RTC and RailSys, caused some minor deviation between arrival/departure times and in dwell times (approx. 1-4 minutes deviation). These deviations caused approx. 40 minutes longer timetable duration in RTC (Figure 2-12-bottom). In addition to overall duration, the order of trains, stop patterns, and departure/arrival times were compared and the results showed a 93% match between RTC and RailSys.

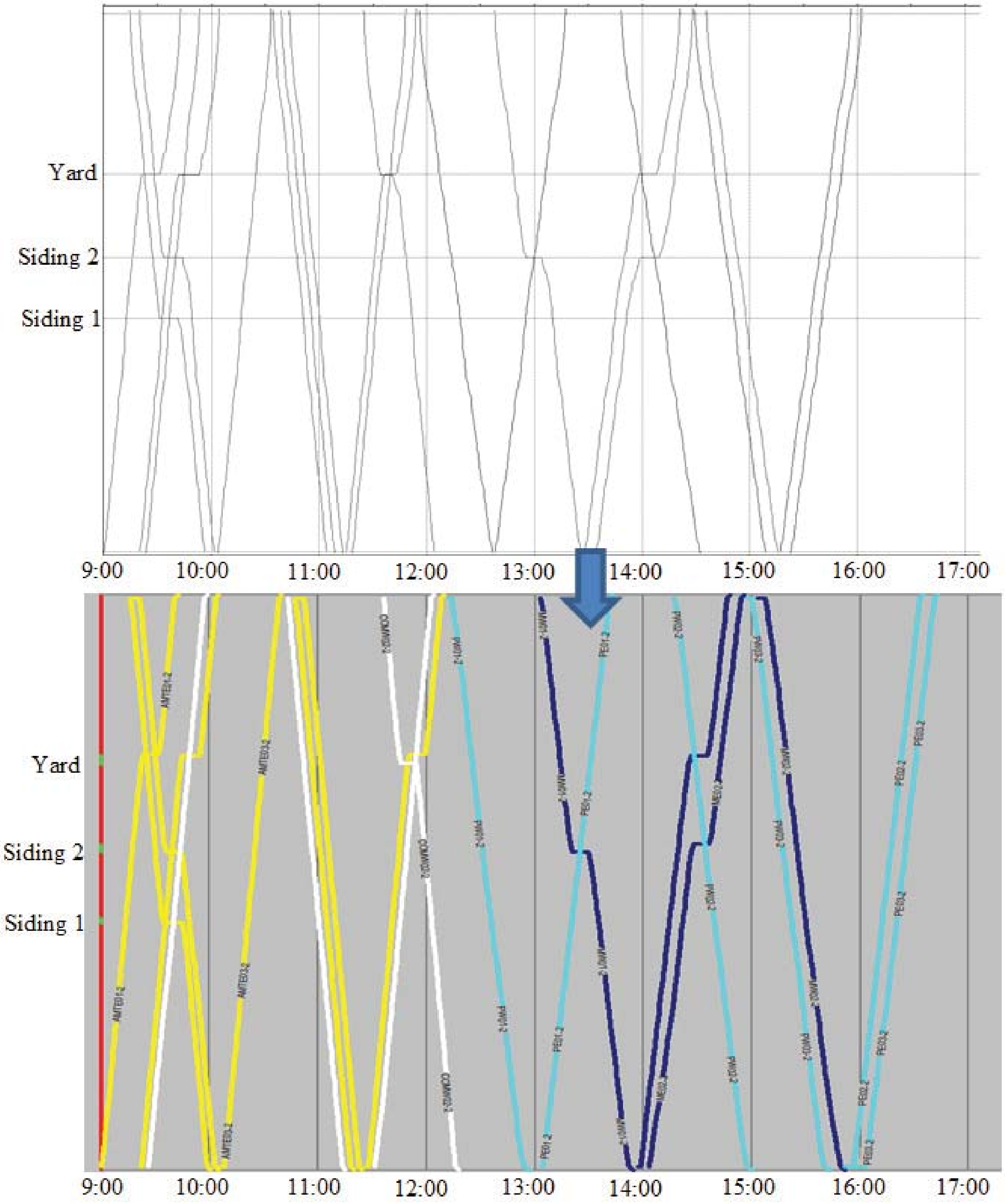

Figure 2-12- The RailSys final stringline (top), validated/replicated RTC stringline (bottom)

The hybrid simulation approach was successful in improving the level of service (LOS) parameters of the initial timetable. It was also successful in improving the capacity utilization (reducing the timetable duration), in comparison to the best LOS scenario of the case study (Figure 2-8), when certain train stops/dwell times were allowed. Table 2-7 summarizes the timetable characteristics derived from outcomes of the hybrid simulation approach for ten-minute dwell time. The table reveals that there are significant improvements in LOS parameters (maximum dwell time, number of stops, and total delays), but the timetable duration (capacity utilization) was increased by approximately 72 minutes from the initial timetable in RTC. It emphasizes the importance of analyzing the trade-off between LOS criteria and capacity utilization levels, as if LOS is improved, capacity utilization might be degraded (especially when capacity utilization is over 70%); and vice versa.

Table 2-7- Comparison between initial and improved timetables (10 minute max. dwell time) through hybrid approach of the research

Criteria	Initial Timetable		Improved Timetable	
	Developed by RTC	Replicated in RailSys	Developed by RailSys	Validated in RTC
Max dwell time (LOS)	61’	60’	10’	10’
Number of stops (LOS)	20	20	9	9
Total delays (LOS)	702’	685’	84’	105’
Timetable duration (Capacity utilization)	6h 30’	6h 30’	7h 02’	7h 42’
Matching % with original timetable	-	96%	-	93%

2-7- Summary and Conclusions

This paper has provided a brief introduction to the railway capacity, capacity analysis, and the use of commercial railway simulation software. The paper also introduced a hybrid simulation approach that attempts to improve level of service (LOS) criteria and capacity utilization through operational (scheduling) adjustments. The method uses the strengths of both timetable (RailSys) and non-timetable based software (Rail Traffic Controller or RTC). The approach used the output of RTC as input in RailSys and the timetable compression technique offered by RailSys to improve the initial timetable. The improved results of RailSys were validated in RTC to confirm their repeatability in the U.S. software. The approach was tested on a case study corridor and it revealed that ten minute maximum dwell time provided the best corridor capacity utilization. The unnecessary stops were reduced by 55%, delays reduced by 85%, and maximum dwell time was reduced from 60 to 10 minutes. As a trade-off, the total timetable duration was increased by 72 minutes (18%). This emphasizes the trade-off between LOS parameters and capacity utilization levels, as increased capacity utilization (reduced timetable duration) has typically adverse effect on LOS parameters; and vice versa.

The hybrid simulation developed as part of the research provided satisfactory results, but the process was time-consuming and the fact that RailSys is originally developed in Europe made the conversion to North American rolling stock and signaling features relatively challenging in RailSys. The conversion also caused minor differences between the results of simulation packages. The outcomes of the study suggest that timetable compression technique, currently used predominantly in

Europe, may have potential to be successfully applied in the U.S. rail environment, if appropriate model and algorithm is developed to address the respective network and operational characteristics of the U.S. rail environment.

2-8- Acknowledgments

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CHAPTER 3

3. Evaluating Two Capacity Simulation Tools on Shared-use U.S. Rail Corridor[7]

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3-1- Abstract

Most passenger rail services in the United States (U.S.) operate on corridors that are shared with freight traffic. As the demand for passenger and freight transportation grows and emphasis is placed on increased speed and on-time performance of passenger services, the available capacity becomes even more consumed. When higher speed passenger trains are mixed with freight, the increased heterogeneity from expanding speed differential creates further challenges for reliable operations. Based on the experiences in the other parts of the world (particularly in European rail corridors), the required density and reliability is typically secured through structured/planned/scheduled operations instead of the unstructured, or improvised, operations philosophy that is currently prevalent in the U.S.

There are several tools and methodologies available in both the European and U.S. rail environments that utilize user defined infrastructure specifications, operational rules, signaling systems and rolling stock characteristics to evaluate capacity. This paper introduces the main components of two simulation software packages, U.S. developed Rail Traffic Controller (RTC) and European RailSys, and applies them both to a shared-use case study corridor in the U.S. The outputs from each package are compared and the non-timetable based software output (RTC) is applied in the timetable based software (RailSys) as input to form a hybrid model that allows the utilization of timetable compression techniques.

The research revealed that simulation outputs from both software packages are very similar, if the trains can be operated according to initial arrival/departure times

on the corridor. However, RTC's database and timetable parameters are easier to implement, while RailSys has more timetable management features and options that can be used to improve an existing timetable when introducing new trains running along the corridor.

3-2- Introduction

Railway capacity is a complex concept and rail organizations around the world use various definitions for capacity. One simple definition of capacity is the number of trains that can safely pass along a given segment through a period of time. Capacity is affected by different system configurations, such as: 1) Track infrastructure; 2) Signaling system; 3) Operations philosophy; and 4) Rolling stock. Differences between the U.S. and European rail systems, such as system ownership and type and extent of double track network, also affect capacity and its utilization [73]. Simulation software is commonly applied to evaluate the capacity utilization, but the characteristics and features of each package must be adjusted to meet the characteristics of the specific network being investigated. The configurations and parameters mentioned above may be considered at various level of detail, mainly based on the region where the software is used. The same is true for the logic behind core decisions made by simulation software and how much detail is included when building the required database of a given case study.

A review of capacity simulation tools commonly used in the U.S. and Europe can help researchers to evaluate the potential advantages and challenges of expanding the application of these tools to the other side of Atlantic. Since some of the software packages are based on timetables and some are not, there is also a potential to utilize these tools collaboratively in a hybrid approach where initial simulation results on non-timetable software can be used as inputs on the timetable based software to investigate further improvements in capacity utilization and timetable development.

This paper focuses on two major simulation tools from the U.S. and Europe, RTC and RailSys, respectively, to evaluate the use of a hybrid approach on a real-life case study in the U.S. In the first part of the paper, different tools and methodologies for capacity analysis will be briefly reviewed in both the European and U.S. rail environments. The case study used for this research (section of Northeast Corridor) will be briefly introduced in the second part of the paper including review of inputs; infrastructure, signaling, rolling stock, and operations characteristics. The research presented in this paper considered the selected section as a stand-alone piece of infrastructure, neglecting any continuation of routes in either end. The objective of the research was not to evaluate or recommend any changes to current NEC operations, but rather to use actual infrastructure and train operational data to understand the capabilities of simulation tools and theories behind them in larger context.

The third part of the paper provides an overview on the main features and components of RTC and RailSys, as well as explanation of different scenarios applied in the capacity analysis on the case study. It also reviews the outcomes of using both simulation tools on the given case study. Finally, the conclusions and next steps of the research are briefly summarized in the last part of the paper.

3-3- Review of Capacity Methodologies and Tools

Several methodologies and tools can be used to evaluate the capacity utilization of any rail corridor or system. Typically, methodologies can be classified in three main approaches; analytical, simulation and combined analytical-simulation. Analytical and simulation approaches are most commonly found in the literature,[12, 33-35] but there are also several examples of the combined approach that requires the use of both analytical and simulation tools. More details regarding capacity methods have been explained by Pouryousef, et al [73].

There are several parameters which affect the capacity utilization and different tools place varying weight on individual parameters and attributes, mainly based on the network and operating characteristics of the region they were designed for. Although the U.S. and European rail networks have several similarities, the differences between these two regions affect the selection of capacity tools and methodologies and how they incorporate infrastructure, signaling, operation rules and rolling stock specifications. More detailed description about key differences between network characteristics in Europe and the U.S and their impact on capacity are discussed by Pouryousef, et al. [73] and 2010 Sameni, et al [40].

The **commercial rail simulation packages,** such as RTC, Railsim, OpenTrack, RailSys, and CMS [12, 33], are commonly used tools to evaluate capacity and rail operations features in many rail networks including Europe and North America. They are typically divided to two major groups; 1) **non-timetable based** vs. 2) **timetable based** software. The non-timetable based simulations are typically applied in railways which are operated based on the unstructured or improvised operation pattern and may have no initial train timetable, such as the majority of the U.S. rail network. The simulation procedure in the timetable based software (typically used in Europe) uses the initial timetable provided for each specific train in the beginning of simulation to improve the capacity utilization and level of service attributes of the original timetable. In the case of schedule conflict between trains, the user must change the timetable until the feasible schedule is achieved; however, the user interference is not arbitrary as in the improvised method, but it is implemented as part of the simulation process [24]. More details on these two types of simulations are explained in a separate paper by Pouryousef and Lautala [30].

3-4- Case Study of the U.S. Shared-Use Corridor

3-4-1- Objective

While several simulation tools are used in both the U.S. and European rail networks, the impact of tool selection on the outcomes has rarely been researched. In addition, the potential to combine the strengths of two separate tools might offer benefits over a single tool, even though the increased input effort may limit such use in industry applications. To address these issues, the study was conducted with an objective to 1) run two simulation tools on a single U.S shared-use corridor case study and highlight the advantages and challenges of using each tool and 2) apply a hybrid approach (combining the input/output of these two packages) to improve the outcomes of one or both simulations.

3-4-2- Review of Case Study Characteristics

The case study selected for the research was a short segment of the Northeast Corridor (NEC) between Baltimore and Washington, DC. The selected segment is one of the most congested and complicated corridors in the U.S. rail network, in terms of:

- Number of trains per day,
- Diversity of train types,
- Operation of the only high speed train service in the U.S. (Acela Express),
- Complexity of signaling systems (both wayside and cab signaling systems), and
- Number of tracks along the corridor (Sections with triple and quadruple tracks).

The research used all existing tracks, sidings, crossovers and signaling systems along the section. All existing passenger and commuter trains running along this segment of the corridor (141 daily trains in both directions) have been considered, although the initial analysis presented in this paper used 40 randomly selected trains, to reduce the complexity and research time required during the first phase of the study. The objective is to replicate the study with full schedule of 141 daily trains in the next phase. Courtesy of Amtrak, the researchers were able to secure a complete RTC database as input, which was also used to develop the four database categories in the RailSys simulation software.

Infrastructure Characteristics

The case study's infrastructure contains 40.6 miles of triple track, (about 5 miles of quadruple and about 1.5 miles of double track rail) with several crossovers and intermediate stations/ platforms along the corridor (Figure 3-1). Horizontal and vertical alignments were accurately developed for both RTC and RailSys input database and are summarized in Table 3-1.

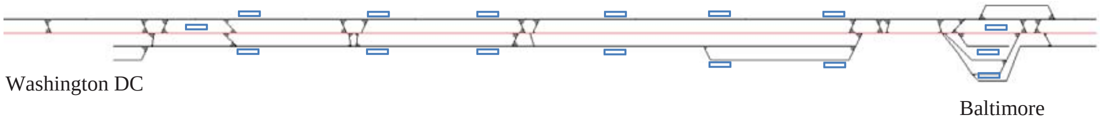


Figure 3-1- Snapshot of the case study infrastructure between Washington DC-Baltimore

Table 3-1- Details of case study infrastructure

Corridor Length	40.6 miles
Sidings/yards	2 main yards + 7 station platforms
Max. vertical grade	2.12%
Curvature	0.01 - 7.27 degrees
Length of double track	1.48 miles
Length of triple track	33.94 miles
Length of quadruple track	5.18 miles
Turnout #s	# 32.5, # 15 (one crossover)

Signaling Characteristics

The signaling system included a wayside system under CTC, together with a cab signaling system. These two systems have been integrated and work in unison to improve the capacity and safety levels of the corridor. All trains running through NEC are required to be equipped with working cab signals. In case of failure of the cab signals en route, the dispatcher grants permission for movement in the absolute block between each interlocking, with a 79 mph speed limit.

Rolling Stock Characteristics

Four types of trains have been considered in the case study; Long-distance passenger, commuter, Regional Amtrak, and high speed trains (Acela). The characteristics of each train type have been closely derived from the actual configurations of current rail services along the corridor. It should be pointed out that NEC (including the Baltimore-Washington, DC section) is one of the few electrified corridors in the U.S. Therefore, some of the trains considered in this case study (including Acela trains) are electrified and use overhead power supply system. Since the type and configuration of pre-programmed locomotives are fairly different in the RTC and RailSys database, some of the main characteristics of locomotives (such as power, weight, length, axle load, acceleration/ deceleration rate, and resistance) were included in the RailSys database as new locomotive type. The main characteristics of rolling stock used in the case study are presented in Table 3-2.

Table 3-2- Main features of case study's trains

Train	Daily trains (pairs)	# of cars	Trailing weight (ton)	Trailing length (feet)
Acela	10	6	378	649
Long-distance Amtrak	10	9	450	816
Regional Amtrak	10	7	385	744
Commuter	10	5	175	483

Operation Rules

There are several operation rules for simulation, such as the train's priority, speed limits, stopping patterns, and preferred time and order of train departures. The priority of different types of trains in diminishing order was Acela Express, commuter trains, Regional and long-distance passenger trains. In the case study, the maximum speed of Acela trains was 137 mph, but its practical speed was calculated by the software based on the track profile and reduced speed limits along the track, e.g. due to crossovers. Intercity passenger trains were limited to 110 mph; while commuter trains were limited to 90 mph. The initial speed of all trains from Washington, DC toward Baltimore (Northbound direction) was 30 mph when they reached the track segment starting the simulation process. For the southbound direction, the initial speed of trains had to be maintained in 30 mph for approximately 1.2 miles, due to the technical requirements along Baltimore- Bridge interlocking section. There are various stop patterns by different trains, but all trains stop at Baltimore and DC. For example, some Acela trains have no other planned stops at the intermediate sidings/platforms. The predefined arrival/departure times and preferred priority of trains have been considered for all trains according to daily operation practices.

3-5- Capacity Analysis, Review of Train Timetable

3-5-1- Brief Introduction of Applied Tools

RTC and RailSys used in the research are two well-established commercial railway capacity analysis tools. Table 3-3 provides a comparison of some of the features and characteristics of RTC and RailSys.

Table 3-3- Comparison between RTC and RailSys [30]

Criteria	RTC	RailSys
Developer	Berkeley Simulation Software, LLC, (USA)	Rail Management Consultants GmbH (RMCon) (Germany)
Features and Modules	- Animation of traffic flow - Time-distance diagrams (stringline) - TPC profile - Track occupancy chart - Detailed train status - Timetable at various level of detail - Operating statistics at the individual train level or summarized by train type or at a system-wide level - Graphical network interface	-Infrastructure manager -Timetable construction -Capacity Management (UIC code 406) - Track Possession planning -Simulation Manager -Rolling stock circulation planning - Graphical Timetable -Platform and track occupation diagram - Graphical network interface -Delay statistics
Simulation Category	Non-timetable based simulation	Timetable based simulation (UIC code 406)
Capacity Metrics	Delay statistics, Track occupation time, time-distance diagram	Delay statistics, infrastructure occupation time, optimized timetable
Example Users	Class 1 RRs: (UPRR, BNSF, CSX, NS, KCS, CN, CP, Amtrak), U.S. railway consultants, urban rail transit agencies	Many European rail operators and consultants, international rail companies

RTC was launched in the North America's rail market in 1995 and has since been continuously developed and upgraded for a variety of simulation practices. RTC can be categorized as non-timetable based simulation software used predominantly for improvised operation philosophy conditions (the dominant operations approach in the U.S. rail environment). It is developed by Berkeley Simulation Software and it is the most common package in this category, used extensively by the U.S. rail industry. In this type of simulation, after loading the input data in the software, the train dispatching simulation process improvises the train departure times from the originating station provided as part of the input data. However, it can also receive the preferred, or scheduled, arrival and departure times of different trains for the simulation process through user input. The dispatching simulation component of RTC is based on a decision support core, called “meet-pass N-train logic”. For any dispatching simulation practice, “meet-pass N-train logic” will decide when the given trains should exactly arrive and depart from different sidings, based on the defined train priorities and preferred times of departure. The simulation outcomes may include variation between the simulated departure times and preferred times [42].

RailSys developed by Rail Management Consultants GmbH (RMCon) in Germany, is an operation management software package tool that includes infrastructure data management, timetable construction/slot management, track possession planning, and simulation features. It has been in the market since 2000 and it is one of the most common timetable-based simulation software used in Europe. The capacity feature of RailSys uses the UIC code 406 which is based on the timetable compression technique. Given train timetables, a segment of the route is selected to automatically compress the utilized train-paths, while considering the minimum headways and acceptable buffer times between the trains. The compression technique always begins at the start of the calculation period and ends after the calculation period is fully occupied by the last possible train. The remaining usable level of capacity is identified by the number of new train-paths available, until the given time period is saturated by the train-paths and buffer times [43, 44].

3-5-2- Outcomes of RTC Simulation

The case study simulation results obtained from RTC are presented in distance-time diagram format (train string-line) (Figure 3-2). Since the RTC database and schedule were prepared by Amtrak authorities, there is no deviation between the simulated arrival/departure times and the requested times (the initial departure/arrival times requested by software user) in RTC's database.

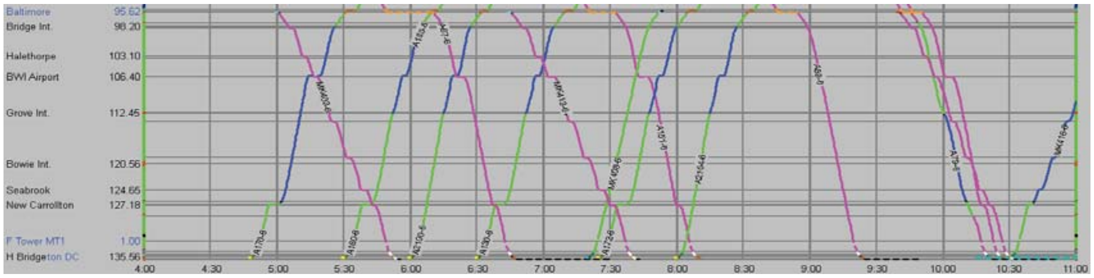


Figure 3-2- Simulated train string-line schedule in RTC, 4 am -11 am, (each color represents different track)

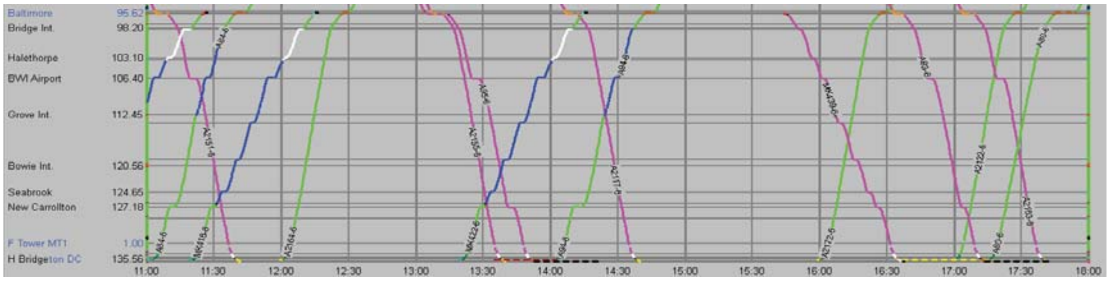


Figure 3-2 – (Continued) Simulated train string-line schedule in RTC, 11 am -6 pm

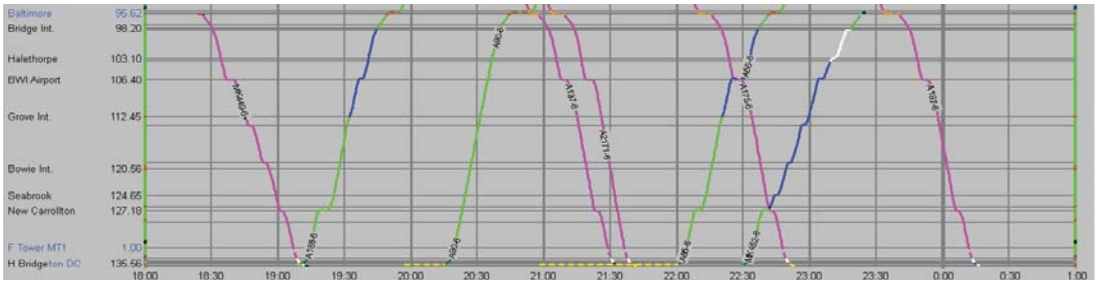


Figure 3-2 – (Continued) Simulated train string-line schedule in RTC, 6 pm -12 am

Although the schedule of all simulated trains in RTC followed precisely the requested times of the input, RTC does not have a complete package of tools to determine a schedule conflict between two or more trains before running the simulation. During the simulation, the software automatically resolves each schedule conflict as a dispatcher would resolve them, based on “meet-pass N-train logic”, and displays the impacts of the conflict resolutions both graphically and in terms of run times. In case a conflict between trains is identified by the software, a user intervention is needed to modify the schedule of trains and avoid the conflict. Such interventions are facilitated by the user-friendly animation tools of RTC which can help the software users to understand and analyze updates on train routing and signaling features, as necessary.

3-5-3- Outcomes of RailSys Simulation

The infrastructure characteristics (including main lines, gradient, curvatures, crossovers and sidings), rolling stock (type and number of trains), signaling systems (both permissive and cab-signaling systems) and operation rules (preferred timetable of trains, stop patterns of each train, speed limit along crossovers, train priorities) were developed in RailSys based on the database and network characteristics obtained from RTC simulation software. RailSys implementation required certain conversions, such as conversion of track curvatures from degree to radius and adjustment of rolling stock characteristics to SI units. Figure 3-3 shows the string-line train schedules of simulated trains in RailSys.

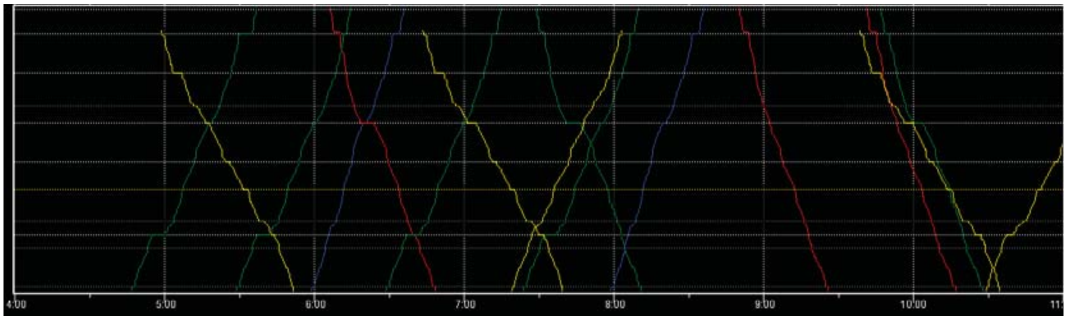


Figure 3-3- Simulated train string-line schedule in RailSys, 4am -11 am, (Green: Regional Amtrak, Red: Long-distance Amtrak, Blue: Acela, Yellow: Commuter)

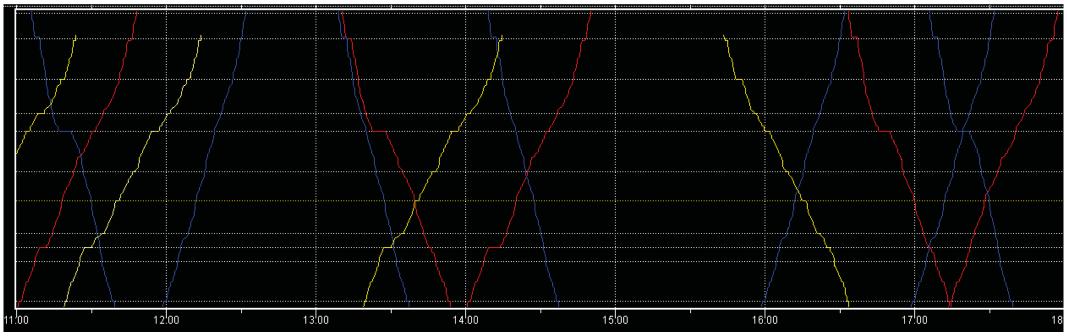


Figure 3-3 (Continued) Simulated train string-line schedule in RailSys, 11am -6 pm

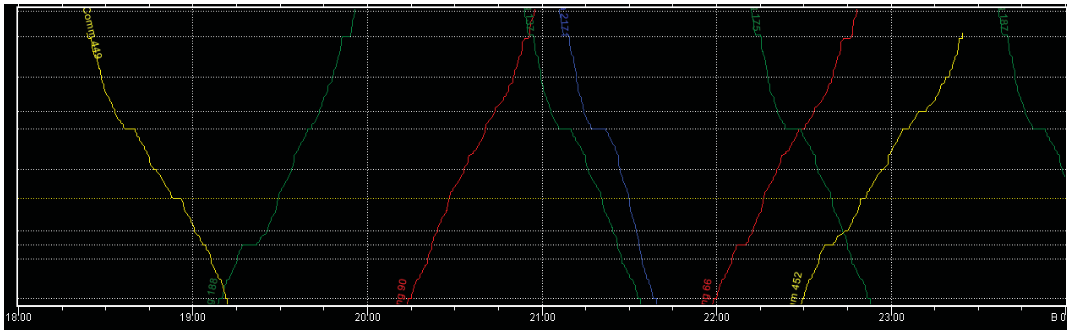


Figure 3-3 (Continued) Simulated train string-line schedule in RailSys, 6 pm -12 am

As presented in Figure 3-3, train schedules in RailSys match the same arrival and departure times as in RTC with some minor deviations between arrival/departure times (from couple of seconds up to approximately two minutes). The deviations were caused by variations of simulated train running times along the corridor, mainly due to minor differences between rolling stock and signaling features/equations in RailSys vs. RTC (such as tractive effort of engines, acceleration, deceleration, braking diagram, etc.). Overall, the simulated outcomes obtained from RailSys matched almost 90% of the requested departure/arrival times.

In some cases the tracks used by each train in RailSys differed from those in RTC, as the train routing in multiple-track corridors is dependent on user decisions. The general principle of train routing in RailSys was to allocate the first track for southbound trains (Baltimore to DC) and use the second, third and fourth tracks for northbound trains (DC to Baltimore). The second track was also used for non-stop trains (Acela or long-distance Amtrak trains) in both directions. There were significant differences how trains were routed through the stations. For example, at Baltimore, all 40 trains used in the research were routed along tracks 1 through 4, while tracks 5-7 saw no activity. On the other hand, at BWI all tracks were utilized by trains, since they were in reality extensions of the main line tracks. There were also significant differences between percentages of occupation of each track. The average percentage a track was occupied varied between 1.42% and 7.28%, during whole operation hours, and between 3.55% and 25.48% per hour during peak times.

3-6- Capacity Analysis and Applying Timetable Compression Technique on the Case Study

Since the requested times for trains were already developed by Amtrak, both RTC and RailSys successfully used the input to develop train schedules/timetables. To analyze the capability of selected tools to address a revision to daily operations, two different scenarios were introduced:

- **Scenario 1:** A new freight train with potential conflict with other train schedules
- **Scenario 2:** Evaluating the timetable compression technique of the existing schedule (RailSys only)

3-6-1- Scenario 1: New Freight Train

A demand frequently arises to run a new freight/passenger service along the existing tracks, in addition to the current trains. In this scenario, a new southbound freight train was introduced to depart around 9:50 am from Baltimore to Washington, DC. There were no requested intermediate stops and its departure time could be changed, if there were any schedule conflict. As shown in Figure 3-4, RTC dispatched the freight train after all other current passenger and commuter trains, (around 12:10 am next day instead of 9:50 am) due to the fact that the priority of this train was much lower than other trains and earlier dispatch would have introduced conflicts between the schedules of new and current trains (assuming no change in train priority). However, RTC could resolve the conflict differently, if train priorities were manually adjusted.

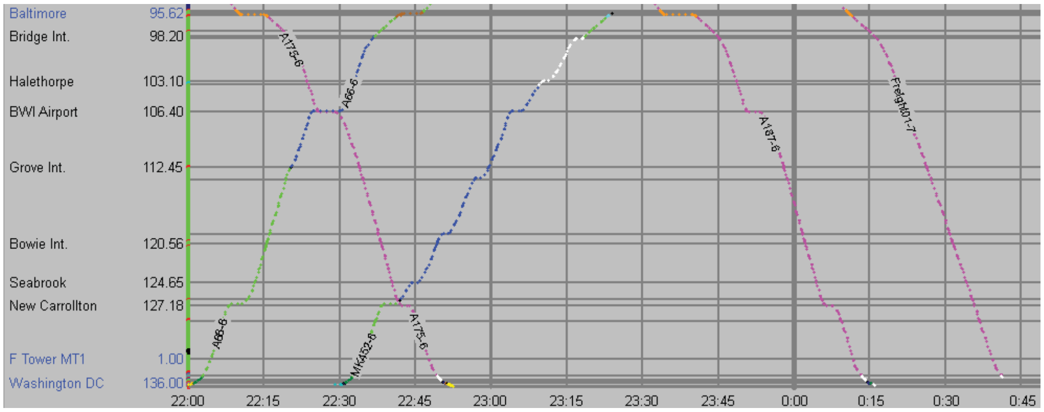
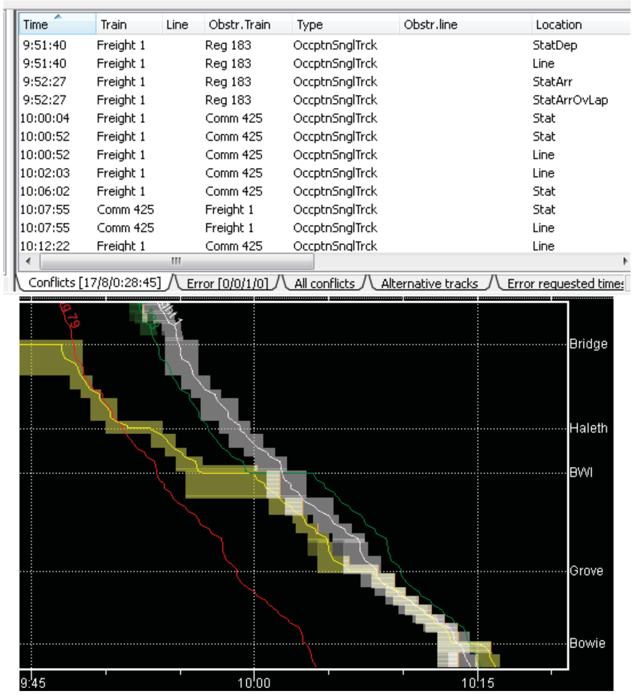


Figure 3-4- The simulated freight train was dispatched in RTC after all other trains, despite its initial requested departure time assumed at 9:50 am

RailSys recognized the conflicts between the new and current trains as well and used its supportive features of train conflict management to identify (graphically and in table-based format) where these conflicts took place (Figure 3-5).



Time	Train	Line	Obstr.Train	Type	Obstr.line	Location
9:51:40	Freight 1		Reg 183	OccptnSnglTrck		StatDep
9:51:40	Freight 1		Reg 183	OccptnSnglTrck		Line
9:52:27	Freight 1		Reg 183	OccptnSnglTrck		StatArr
9:52:27	Freight 1		Reg 183	OccptnSnglTrck		StatArrOvLap
10:00:04	Freight 1		Comm 425	OccptnSnglTrck		Stat
10:00:52	Freight 1		Comm 425	OccptnSnglTrck		Stat
10:00:52	Freight 1		Comm 425	OccptnSnglTrck		Line
10:02:03	Freight 1		Comm 425	OccptnSnglTrck		Line
10:06:02	Freight 1		Comm 425	OccptnSnglTrck		Stat
10:07:55	Comm 425		Freight 1	OccptnSnglTrck		Stat
10:07:55	Comm 425		Freight 1	OccptnSnglTrck		Line
10:12:22	Freight 1		Comm 425	OccptnSnglTrck		Line

Figure 3-5- RailSys train conflict management tool output (graphical and tabular formats)

The software allows user to resolve the conflicts by adjusting the departure/arrival times, by rerouting the trains, and/or by considering any conditional stop in the sidings to provide any meet-pass opportunity. As depicted in Figure 3-6, the freight train was successfully dispatched in RailSys by adjusting the departure time of freight train to 10 am instead of 9:50 am, and by rerouting some of the other trains via crossovers along different segments of the corridor.

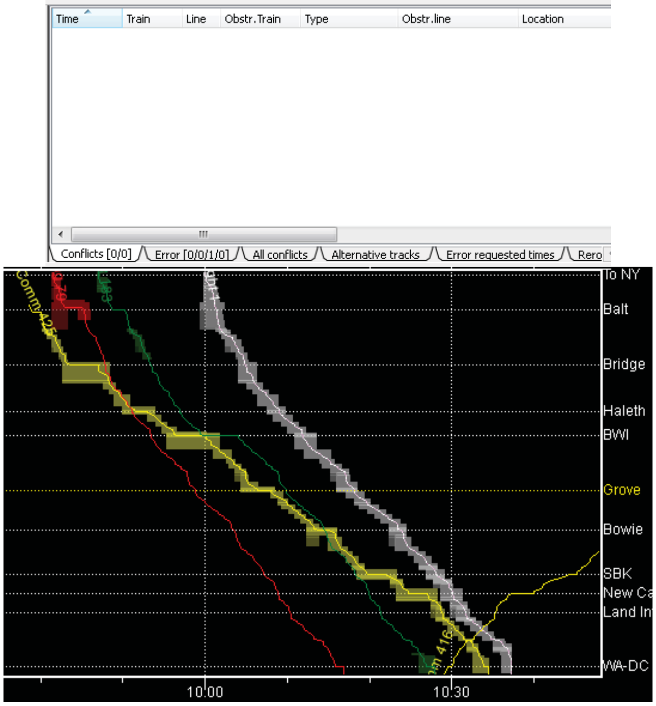


Figure 3-6- The resolution in RailSys by adjusting the departure time of freight train to 10 am and rerouting other trains in some segments of corridor

3-6-2- Scenario 2: Timetable Compression Technique

As discussed before, one of the techniques of improving capacity utilization and level of service used in Europe is timetable compression. RailSys uses a compression technique (UIC 406) to optimize a feasible timetable and to improve the capacity utilization levels. There are several factors which should be defined prior to the capacity optimization (timetable compression), such as:

- Overtaking option in the sidings
- Maximum dwell time of trains in the sidings
- Using initial timetable as input data
- The compression technique (Austrian method, OBB, or German method, DB)
- Timetable duration (the portion of timetable which is planned to be optimized)
- Directional or bidirectional operations

- The route option (The tracks or platforms numbers which are going to be used in the analysis)

In this research, we applied the compression procedure of RailSys to the current timetable and considered overtaking option in maximum two stations based on OBB compression algorithm. DB algorithm wasn’t used in this study, as it considers one of the trains as a “dummy” train for the purpose of the compression technique, causing the number of simulated trains to deviate from RTC results. Other major differences between OBB and DB methods are related to the way occupation time of trains along the corridor is calculated, as well as the criteria and steps of compressing the first and last trains of the service within the compression period. Figure 0-1 presents the final results of compressed timetable by using UIC 406 compression approach. Railsys organized routing of train operations in directional manner with southbound trains using the first track and northbound trains the second track and used maximum of two minutes dwell time in sidings/yards. After timetable compression, the homogeneity indicator of operations (an index showing the similarity between trains speed and characteristics) was approximately 97.4% and 97.8%, respectively for southbound and northbound directions. This reveals that the trains operating in the study scenario had high level of homogeneity, making their operational characteristics consistent with each other and easier to reach higher levels of capacity utilization (the percentage of capacity consumption out of available capacity for each line). The utilization after compression was estimated as 13.2% and 12.5% for respective directions, which is fairly low for homogeneous train operations. However, these values should be used cautiously, as they may change significantly, once all 141 trains are considered in the next phase of analysis.

Railsys provides the compressed timetables (Figure 3-7) separately for each track/route and direction of operations, since European operations of multi-track corridors are typically directionally oriented. It is not possible to automatically combine both compressed timetables in a single stringline diagram in RailSys, except for single track operations.

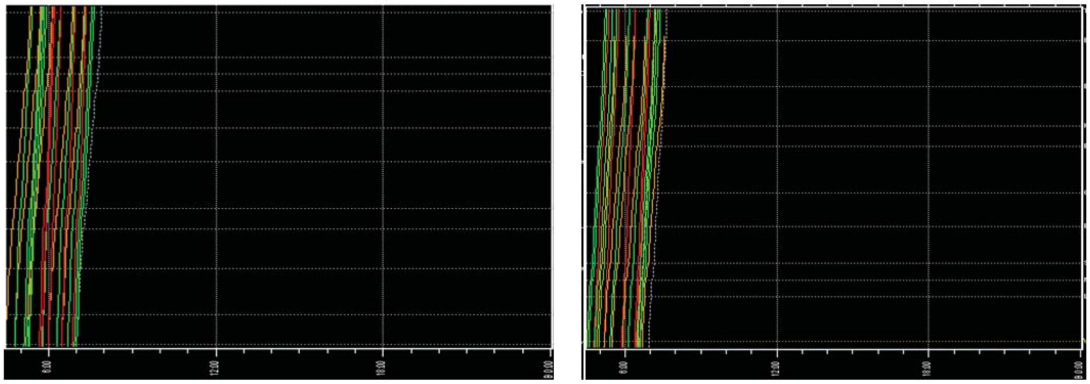


Figure 3-7- Compressed stringline of trains in both directions, 4 am -12 am (Left: Southbound, Right: Northbound)

In addition to directional considerations, several other observations were made during the application of compression technique:

- The order of trains in the optimized timetables of RailSys was exactly the same as defined in the input timetable, but the optimized arrival/departure times were different. It was not clear whether RailSys optimization technique used the preferred departure times from input timetable.
- The maximum dwell time at stations considered by RailSys was the same for all trains and at all stations, while it might be variable in real practices. Consideration of an individual dwell time for each train or each station might improve the outcomes of timetable compression technique.
- In addition to compressing the existing timetable, new trains that possess the same or different operational characteristics (speed, stop patterns, type of trains,

etc.) can be introduced in between the existing trains. Figure 3-8 shows new trains that could run along southbound direction of the case study, considering the existing train schedules. According to RailSys, there is, theoretically, an option of running 353 new trains during the 19.5 hours of operations until 96.5% of capacity utilization indicator (traffic saturation factor) is reached.

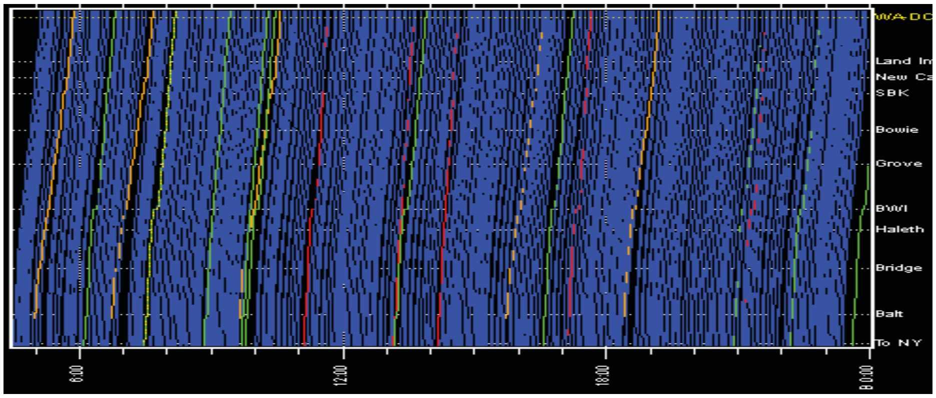


Figure 3-8- 353 new trains (shown in blue lines) literally inserted within the existing schedule of trains along southbound direction of case study

3-7- Conclusions and Next Steps of Research

This paper introduced two commercial railway simulation tools available in the market for evaluating the capacity levels and train operations. Rail Traffic Controller (RTC) is non-timetable based simulation software, typically used predominantly for improvised operation philosophy conditions (the dominant operations approach in the U.S. rail environment). On the other hand, RailSys, is a timetable-based simulation software commonly used in Europe which includes infrastructure data management, timetable construction/slot management, track possession planning, and simulation features.

To compare the similarities and differences of RTC and RailSys software, a short segment of the Northeast Corridor (NEC) between Baltimore and Washington, DC was selected as a shared-use corridor case study and applied in both simulation packages. The comparison of the simulation procedure and outcomes led to the following observations and conclusions:

1. Both RTC and RailSys software are powerful tools for operations simulation, but the procedure and steps of developing the operations rules and dispatching system for improvised operation philosophy with no predefined schedule (preferred departure times only as input) is easier to implement in RTC. RTC can dispatch a predefined schedule of trains, but specific timetable management should be conducted manually by the user, as necessary.
2. RailSys requires more steps and details when developing the network and original timetables, but also possesses more versatile features and tools for identifying train conflicts and rerouting trains when considering new trains or improving existing timetable. RTC suggests reroutes as a function of its dispatching capability, if tracks are not assigned or if alternate nodes are allowed. In RailSys, rerouting should be set up by the user, based on the assistance provided by the timetable and network graphical and tabular features.
3. Solutions to train conflicts in RTC are automatically suggested and tested during the RTC simulation. They can then be manually hardcoded into the schedule and used iteratively in new simulation runs, until the schedule is optimized. The train conflicts in Railsys must be manually resolved, but there are several features and graphical and tabular tools provided by the Railsys to assist the user in gradually resolving the conflict.
4. Since RailSys is originally developed in Europe, the procedure of developing North American rolling stock and signaling features is relatively challenging in

RailSys, as default database and information use European characteristics rather than North American ones.

5. Several factors should be defined in the capacity optimization tools of RailSys but overtaking scenario, the selected route, directional and bidirectional operations, the amount of dwell time and the algorithm used for timetable compression (OBB vs. DB pattern) seem to impact the final results of the optimized timetable the most.

6. RailSys timetable compression technique maintains the order of trains through the optimized timetable option (as defined in the input timetable), but it doesn’t keep the preferred departure times. RailSys can also impose new trains within the current trains schedule, but it only considers one direction of operations, instead of both directions.

7. The timetable compression technique of RailSys may not be an ideal solution for double and multi-track operations in the U.S., as the outcome of compressed timetables in both directions can’t be automatically combined to a single diagram. The separate presentation of the compressed timetable is especially challenging at station exit and entrance sections if there is an option of using crossovers or bi-directional operations.

The next step of the research is to evaluate the use of timetable management modeling approaches, such as timetable compression techniques to improve the train timetable, capacity utilization, of a given case study in the U.S. shared-use corridor. The main objective of next step of research will be to identify the key modeling parameters for operational management techniques and how they can be implemented using current simulation tools and features. It will also expand the use of hybrid approach by returning the compressed timetable to RTC for validation process.

3-8- Acknowledgments

The authors are grateful for the assistance provided by Amtrak, including respective information and database of NEC provided for this academic research. Special thanks for the assistance and feedback received from Davis Dure. The authors would also like to thank Eric Wilson (Berkeley Simulation Software, LLC), Sonja Perkuhn (RMCon), and Gabriele Löber (RMCon) for providing academic licenses to simulation packages, RTC and Railsys respectively, and for their great support for the research team at Michigan Tech.

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CHAPTER 4

4. Capacity Evaluation of Directional and Non-directional Operational Scenarios along a Multiple-Track U.S. Corridor [8]

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4-1- Abstract

Railroad corridors with two or more continuous tracks can be operated in two approaches: directional or non-directional, and the selected approach affects the overall capacity of the corridor in terms of average speed, train delay and track occupancy. This research used a U.S. multiple-track corridor (Baltimore-Washington, D.C.) as a case study to investigate the effects of non-directional/directional approaches on train performance. Three scenarios were considered as "Initial" schedule that used a database obtained from the Amtrak on 2012 non-directional train operations, "Scenario 1" which allowed for rerouting of trains while maintaining the schedule, and "Scenario 2" which allowed both rerouting and rescheduling to provide a fully directional operation pattern. The results indicated that the number of trains with non-directional pattern was reduced in "Scenario 1", while average train speeds increased and total train delay was maintained. Under "Scenario 2", the average train speed was improved, but the total delay of trains and the average level of occupancy of Track #2 increased due to the fact that more traffic converged to a specific track. However all trains in "Scenario 2" operated in a directional pattern, leaving Tracks # 3 and 4 open for new operations. Overall, the research suggests that operational modifications, including a shift to directional train operations through rerouting, rescheduling, or combined rerouting/rescheduling efforts are worth exploring for improved corridor performance. The next steps in the research will examine a new rescheduling/rerouting optimization model for the U.S.

environment to optimize single, double and multiple-track corridors under both directional and non-directional operation patterns.

4-2- Introduction

Almost 80% of the U.S. rail network has a single track with intermediate sidings [73]. In shared use passenger and freight corridors with double-track or multiple-track sections, the additional tracks can significantly increase the corridor capacity, although the operational efficiency (utilization) of the corridor is also affected by different operational philosophies and dispatching principles.

There are two main operational approaches along double or multiple-track corridors: “Directional” and “Non-directional” (or bidirectional). In directional operations one or more of the tracks are designated for one direction of train traffic and the other tracks are designated for traffic operating in the other direction, removing any conflict between the opposing train movements. In non-directional, or bi-directional operations, train traffic is not directionally separated between different tracks, but crossovers along the corridor are used to allow for train movements from one set of tracks to another as deemed necessary by the train dispatcher. Most of the double tracks in the U.S. are operated in a non-directional pattern, while in Europe a directional operation pattern is commonly used. Although non-directional double-tracks give more flexibility for scheduling in double track corridor, a non-directional pattern offers a lower utilization of capacity when compared with directional operations [1, 9].

This paper describes research work that used simulation technique to evaluate directional and non-directional scenarios and their impacts on the capacity utilization and service quality of trains on a segment of a multi-track U.S. corridor (Baltimore-Washington, D.C., along Northeast Corridor). The first part of the paper provides a brief literature review of past studies that have investigated directional and non-directional operations and introduces the research methodology and simulation tools used in the research. The second part introduces the Baltimore-Washington, D.C. corridor case study, including the simulation inputs, and the third part provides an overview of the case study results and a discussion of the various factors that affects the capacity and level of service. It also introduces a normalized speed-delay parameter which was developed to evaluate the tradeoff between speed and delay in the capacity analysis. Finally, the conclusions and future steps in the research are briefly summarized.

It should be noted that the research uses the Baltimore-Washington, D.C. segment of the Northeast Corridor (NEC) as a stand-alone segment of infrastructure and does not examine continuation of routes on either end. The objective of the research was not to evaluate or recommend any changes to current NEC operations, but rather to take advantage of actual infrastructure and train operation data to understand the impact of different operation philosophies along a multiple-track corridor (non-directional/directional pattern) in self-contained context. Since the case study did not consider the movement of trains beyond the study limits, none of the suggested modifications are implementable without further study that evaluates the impacts and challenges over the entire length of the corridor.

4-3- Research Background, Methodology and Tools

4-3-1- Research Background

There are several methodologies and tools available to analyze the capacity of any rail corridor. Typically, methodologies can be classified in three approaches: analytical, simulation and combined (analytical-simulation). Analytical and simulation approaches are more common in the research literature than the combined approach [12, 32-35] and simulation tools are regularly used by the rail industry at various levels of operations planning. Details on different capacity methods and tools are covered by Pouryousef, et al. (2013) [73].

The non-directional pattern is a common operational philosophy in the U.S., as it provides more flexibility for train operations and scheduling on shared-use corridors [1, 4]. When evaluating the effects of directional/non-directional operations on capacity and level of service, several parameters that are typically considered would include:

- Train speed
- Train delay
- Track occupancy level
- Access to platforms at stations (sidings)
- Train service requirements (e.g. stop pattern, preferred departure time, etc.)

Past research to evaluate the impact of directional/non-directional operations for the parameters is limited. Tolliver (2010) briefly discussed the impact of directional/non-directional operation philosophy on capacity utilization and pointed out that directional pattern can typically provide up to 25% more capacity in comparison to the non-directional approach [9]. In other research, Nei and Hansen evaluated the train operations and track occupancy at rail stations based on estimated running times. They used actual data collected in both directions between two major stations of existing corridor in Netherlands. They emphasized improvements of the timetable and feasibility of arrival and departure times as the main tools to improve the capacity [76]. In a thesis, Schlechte (2012) discussed railway track allocation models and algorithms that use operational research techniques, as well as simulation packages including OpenTrack and RailSys. He developed a model to identify any train conflict which may occur in non-directional operation pattern and evaluated different techniques and approaches of track allocation through different scenarios of bi-directional operation. Based on the results, he could develop optimized timetable of trains without schedule conflicts [77].

4-3-2- Research Methodology

The goal of this research was to use a multiple track rail corridor as a case study to evaluate the impact of directional/non-directional operations. The data used for the research was 2012 Rail Traffic Controller (RTC) database for the Baltimore-Washington, D.C. corridor, provided by Amtrak, which included infrastructure, operations rules, train characteristics and signaling systems. The database was replicated for the directional/non-directional rescheduling and rerouting modeling and analysis in another simulation package (RailSys) that offers more extensive timetable management features. RailSys, developed by Rail Management Consultants GmbH (RMCon) in Germany, is an operation management software package that includes infrastructure data management, timetable construction/slot management, track possession planning, and simulation features. It has been in the market since 2000 and it is one of the most common “timetable-based” and “synchronous” simulation software used in Europe. RailSys uses the UIC code 406 technique for capacity analysis and timetable optimization [43, 44]. Although RailSys was used in this study, other similar software exist, explained by Pouryousef and Lautala (2013) [30], Pachl (2002) [34], and White (2005) [24]. A more detailed description of the replication and validation process between RTC and RailSys can be found in a paper by Pouryousef and Lautala. [31].

In addition to RailSys, several spreadsheets were developed in MS Excel to analyze train speeds and delays for directional/non-directional patterns, to perform scheduling/re-routing analysis, and to calculate track occupancy levels based on the results extracted from RailSys.

There are several approaches and methodologies to reschedule trains depending on the acceptable level of flexibility when modifying routing and schedules and what level of service and constrains are enforced on each train (such as demand, origin/destination departure times, etc.). The method presented in this paper evaluated the capacity improvement between the current or “Initial” operations and two alternative rerouting/rescheduling scenarios, as described below.

- **Current (Initial) schedule of trains:** The original train schedules received from Amtrak and replicated in RailSys was used as the “Initial” scenario.
- **Scenario 1- Rerouting only:** Trains could be rerouted (as much as possible) to reduce the use of crossovers, while maintaining all train schedules (departure/arrival times) and stop patterns the same as in the original schedule. This scenario addressed situations where there is no

flexibility in train schedules, but alternative routings may improve train performance along the corridor.

- **Scenario 2- Directional operations:** Both train routing and arrival/departure times could be adjusted with an objective to obtain a fully directional operation pattern for all trains. However, the stop patterns were maintained the same as in the initial plan and trains could only be rescheduled within certain deviation from the initial time (e.g. 15 minutes sooner or later), as explained later in the paper.

Figure 4-1 presents the research steps in the process. The same research steps were used for both Scenarios 1 and 2, but the rescheduling in Scenario 2 built on the results of Scenario 1 to provide more integrity between the scenarios for easier comparison.

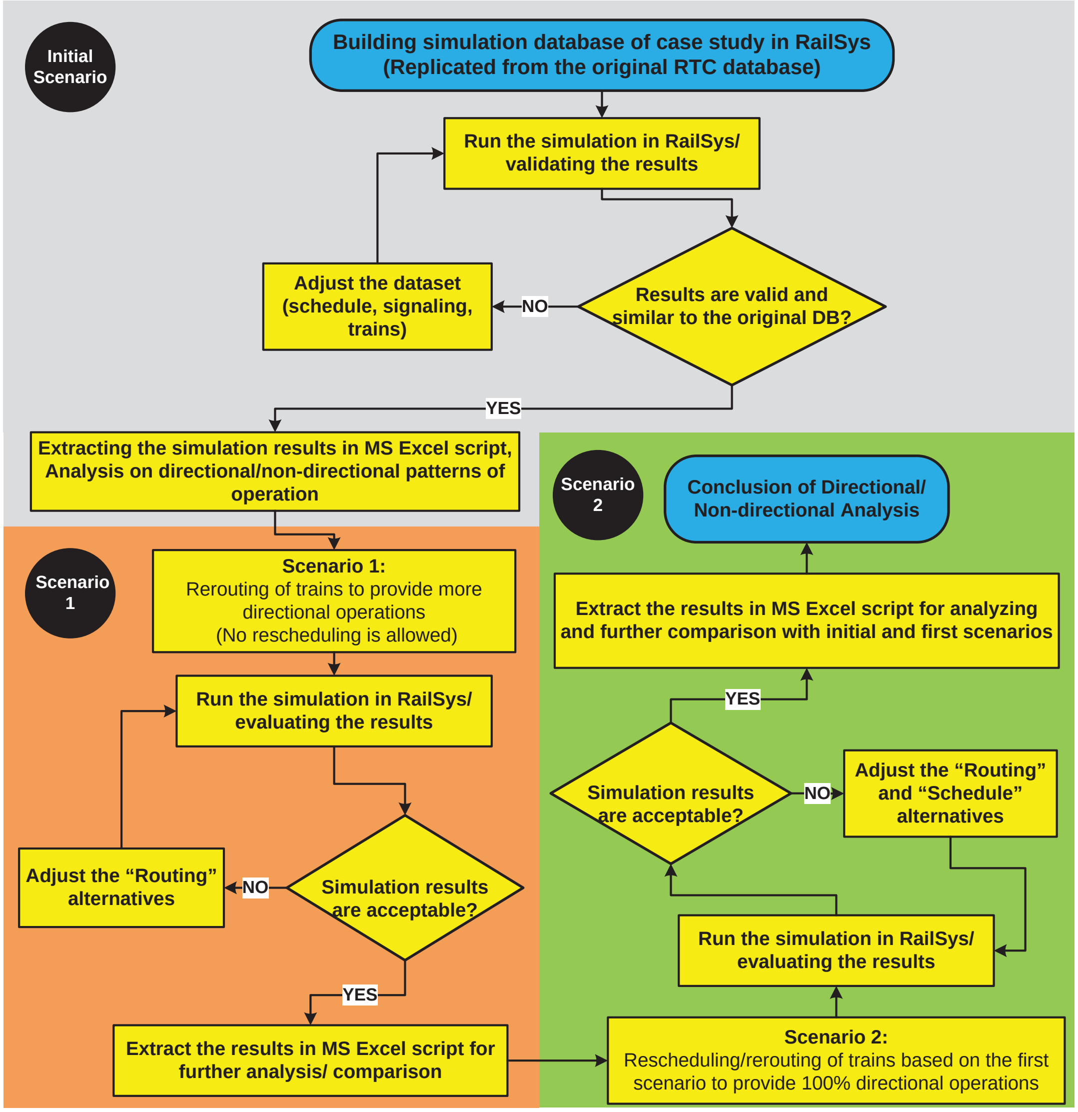

Figure 4-1- Research methodology and steps to compare directional/non-directional operation scenarios

4-4- Baltimore- Washington, D.C. Case Study

The case study selected for the research was a 40.6 mile segment of the Northeast Corridor (NEC) between Baltimore and Washington, D.C. The selected segment is one of the most congested and complicated corridors in the U.S. rail network, in terms of:

- Number of tracks along the corridor (sections with triple and quadruple tracks)
- Number of trains per day,
- Diversity of train types,
- Inclusion of the high speed train service (Acela Express), and
- Complexity of signaling systems (both wayside and cab signaling systems)

The research used the complete infrastructure database (tracks, sidings, crossovers and signaling systems) and included all existing passenger trains running on the segment (136 daily trains in both directions) in the analysis.

4-4-1- Infrastructure and Routing Characteristics

The infrastructure contains 33.94 miles of triple track, 5.18 miles of quadruple and 1.48 miles of double track rail, as presented in Table 4-1 and Figure 4-2. Table 4-1 provides additional corridor details and Figure 4-2 presents the track schematic, including the track numbers, crossovers and intermediate stations/ platforms along the corridor.

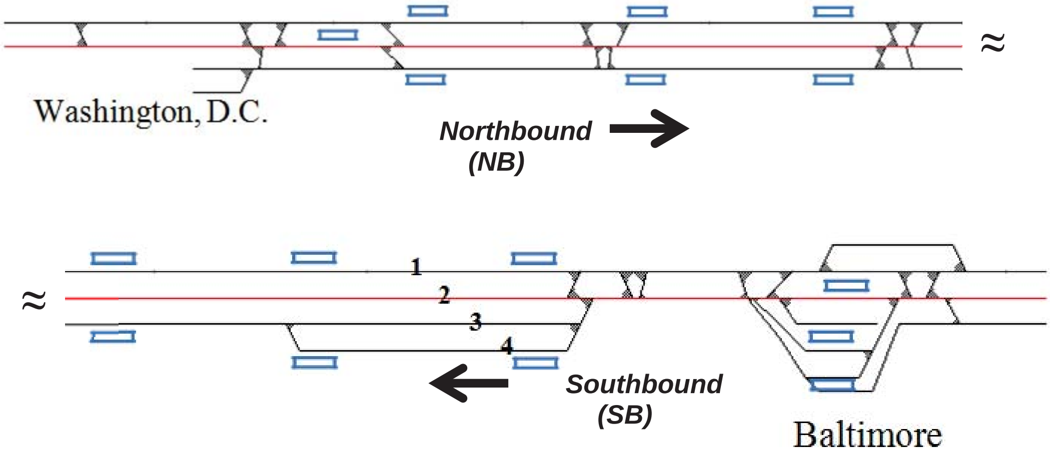

Figure 4-2- Case study infrastructure between Washington, D.C. - Baltimore

Table 4-1- Details of case study infrastructure

Corridor Length	40.6 miles
Sidings/yards	2 main yards + 7 station platforms
Max. vertical grade	2.12%
Curvature	0.01 - 7.27 degrees
Length of double track	1.48 miles
Length of triple track	33.94 miles
Length of quadruple track	5.18 miles
Turnout #s	# 32.5, # 15 (one crossover)

As shown in Figure 4-2, most intermediate station platforms can only be accessed from specific tracks, with the exception of the Baltimore station. Platform arrangements in Washington, D.C. station were not considered in the simulation. The lack of access to platforms from certain tracks limits train operations, especially in Northbound direction (from Washington, D.C. to Baltimore), as trains with passenger boarding/disembarking activities must use Tracks #3 or #4. This also increases the need for the use of crossovers in the vicinity of stations to access those tracks.

In current operations, trains use 28 different routes in the corridor (total for both directions), 16 of which are used for northbound direction and 12 for the southbound operations. Nine routes (out of 28) do not use crossovers while the remaining 19 do. Figure 4-3 shows four example routes used by northbound (NB) and southbound (SB) trains.

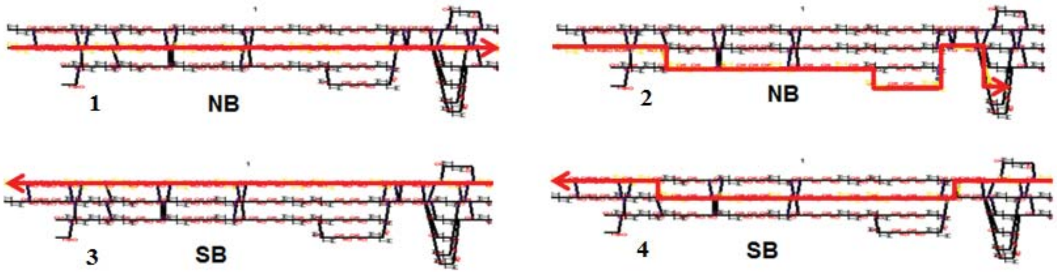

Figure 4-3- Four examples of routes (1: directional NB, 2: non-directional NB, 3: directional SB, 4: non-directional SB)

4-4-2- Signaling Characteristics

The signaling system includes a wayside system, and a cab signaling system. These two systems have been integrated and work in unison to improve the capacity and safety levels of the corridor. All trains running through NEC are required to be equipped with working cab signals and in the case of failure of the cab signals, the dispatcher grants permission for movement in the absolute block between each interlocking, with a reduced, 79 mph speed limit.

4-4-3- Rolling Stock Characteristics

All types of passenger trains operating on the corridor have been included in the case study; Long-distance passenger, Commuter, Regional Amtrak, and High Speed trains (Acela). There is no freight traffic on the segment under investigation. The characteristics of each train type have been closely derived from the actual configurations of current rail services along the corridor. Since the type and configuration of pre-programmed locomotives differ between RTC and RailSys database, some of the main characteristics of locomotives (such as power, weight, length, axle load, acceleration/ deceleration rate, and resistance) were adjusted in the RailSys input to provide train performance similar to the original database. The main characteristics of rolling stock used in the case study are presented in Table 4-2.

Table 4-2- Main features of case study's trains

Train	Daily trains (pairs)	# of cars	Trailing weight (ton)	Trailing length (feet)
Acela	32	6	378	649
Long-distance Amtrak	14	9	450	816
Regional Amtrak	34	7	385	744
Commuter	56	5	175	483

4-4-4- Operation Rules

There are several operation rules for simulation, including the train priority, speed limits, stopping patterns, and preferred time and order of train departures. The priority by train type in diminishing order is Acela, Commuter, Regional, and Long-distance trains. The predefined arrival/departure times and preferred priority of trains were replicated in RailSys simulation database for all trains. The maximum speed of Acela trains was 137 mph, but their actual speed was calculated by the software based on the track profile and speed restrictions, such as at crossovers. Intercity passenger trains were limited to 110 mph and commuter trains to 90 mph maximum speeds. The initial speed of all trains from Washington, D.C. toward Baltimore (Northbound direction) was 30 mph when they reached the track segment starting the simulation process. For the southbound direction, the initial speed of trains had to be maintained at 30 mph for approximately 1.2 miles after entering the simulated segment, due to the technical requirements at “Baltimore-Bridge”. Trains had various intermediate stops, but all trains stopped at Baltimore and Washington, D.C. Some Acela trains had no intermediate stops in the case study segment.

4-5- Simulation Results

The following sections provide results of the simulation and related parameter analysis for the three simulation scenarios which included “Initial” (current) Scenario: based on current train operations, “Scenario 1”: Rerouting only, and “Scenario 2”: Rerouting/rescheduling (directional operations). In the analysis, “directional pattern” is defined as any train that moves through the corridor without changing tracks, and “non-directional” pattern as any train that uses turnouts/cross-overs to change tracks at some point along the corridor, except within Baltimore and Washington, D.C. stations.

4-5-1- Outcomes of Initial Run

The database provided by Amtrak was used to develop train performance and level of service parameters for the current condition (“Initial Schedule”). As presented in

Figure 4-4 almost 70% of the Acela trains operate in a directional pattern while the other trains are more evenly divided between directional/non-directional operations. Overall, southbound trains use more directional patterns than northbound trains due to the lack of platform access from Track #2 at most intermediate stations.

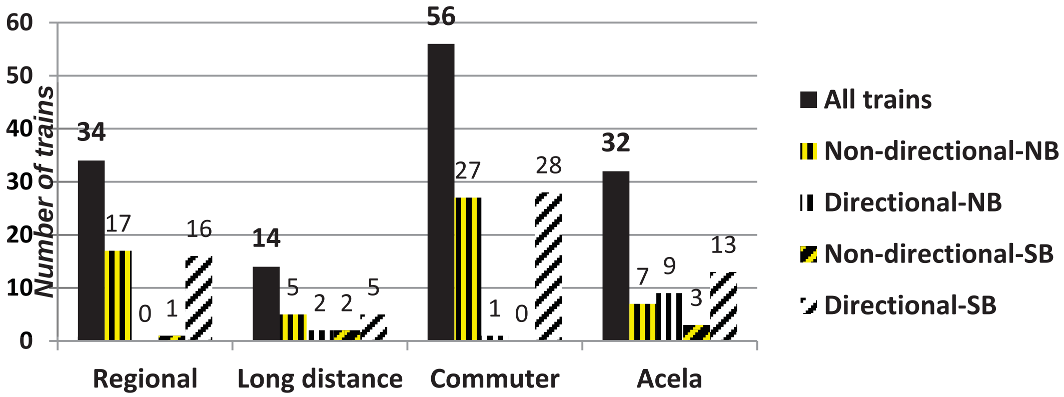

Figure 4-4- Breakdown of trains by type with directional/non-directional operating pattern

The running times that include train acceleration/deceleration, but exclude dwell/waiting time at stations were individually collected from the RailSys reports and used to calculate average speed for each train type. Figure 4-5 summarizes the average speed of all train types grouped by the direction of operation (NB and SB) and whether they used a directional or non-directional pattern. The overall average speed of all trains in NB direction (more non-directional trains) was 67.9 mph compared to 72.8 mph for SB direction. According to the vertical profile of tracks derived from original simulation database, the average ascending grades were approximately equal in both NB and SB directions and therefore should not have significant effect on the average speeds. However, it was recognized that majority of trains that used directional approach had higher average speed. Especially the speed gap between directional/non-directional operational patterns for Acela and Commuter trains in NB direction was significant, 23.5 and 15.2 mph, respectively. Based on the routing analysis, it was concluded that the main reason for the large gap in operational speeds was the use of crossovers (particularly for Acela trains).

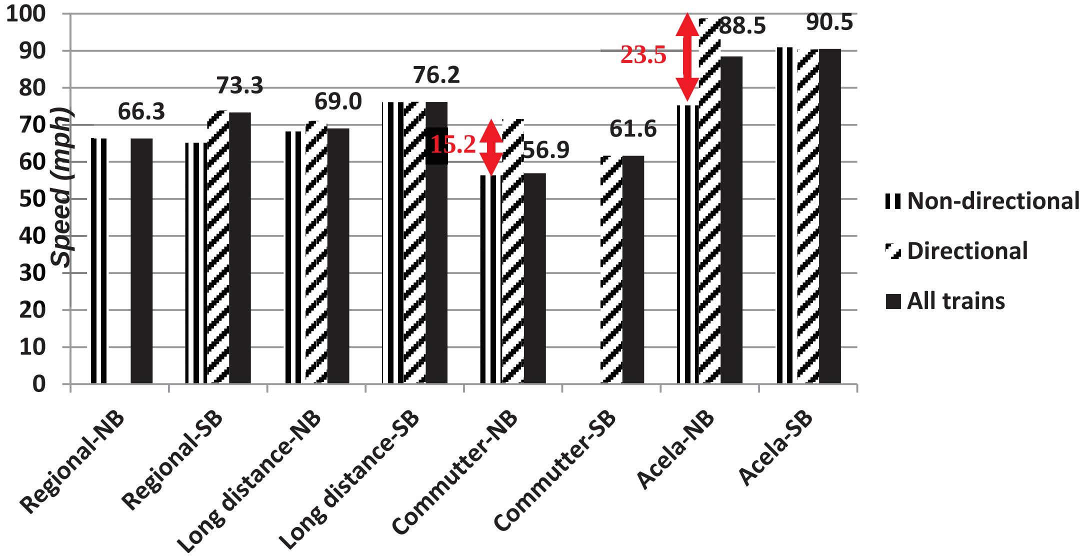

Figure 4-5- Average speed of NB/SB trains with directional/non-directional operational pattern

Train delay was also analyzed for the initial schedule. According to the simulation results (Figure 4-6), NB trains have higher total delays than SB trains. However, it cannot be concluded that trains with non-directional pattern are more likely to have higher delays, as the concept of delay is more related to the risk of schedule disturbance and corridor congestion level than the physical conditions of infrastructure or routing alternatives.

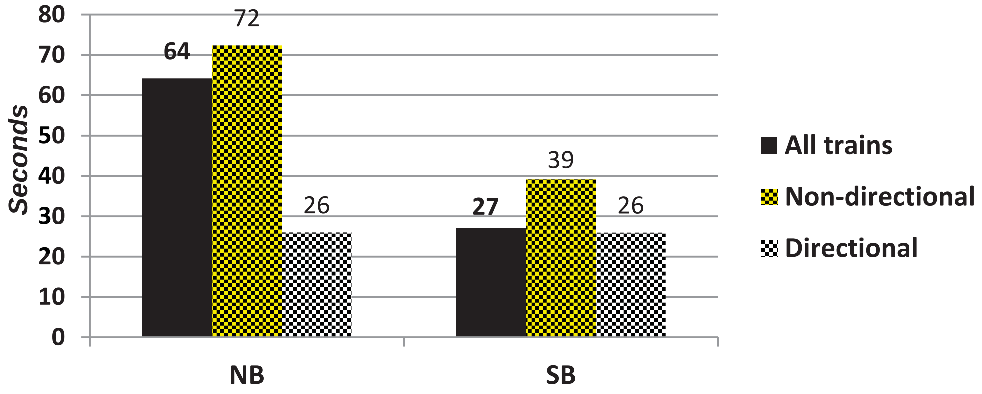

Figure 4-6- Delay analysis for NB/SB trains (Average delay per train)

4-5-2- Outcomes of Scenario 1-Rerouting Only

As explained before, Scenario 1 concentrated on rerouting, so higher portion of trains operate on directional pattern while maintaining the original train departure/arrival times. This scenario could be applied in situations, where a single entity wants to make changes on a multi-agency corridor without affecting the other service providers or rail authorities. The rerouting scenario differs from the current situation by requiring that all tracks in the intermediate stations have access to a platform (assuming existence of new island platforms between Tracks #2 and #3).

In the rerouting scenario, 47 trains (out of 63 trains with non-directional pattern in initial schedule) were rerouted to reduce the trains with non-directional operation pattern. 37 of rerouted trains were directional (59% of all non-directional trains in previous scenario). After rerouting, all but one train that used Track #4 in "Initial schedule" were diverted to either Track #2 or track #3, opening up capacity for Track #4. The new routing option slightly increased the average speed of trains, especially for NB (1.8 mph increase from Initial scenario). The total train delay remained approximately the same as in the Initial scenario, even though there was more traffic on Tracks #1 and #2. Figure 4-7 shows an example schedule of rerouted trains. The changed routing of one train is also shown as an example on the left side of the figure.

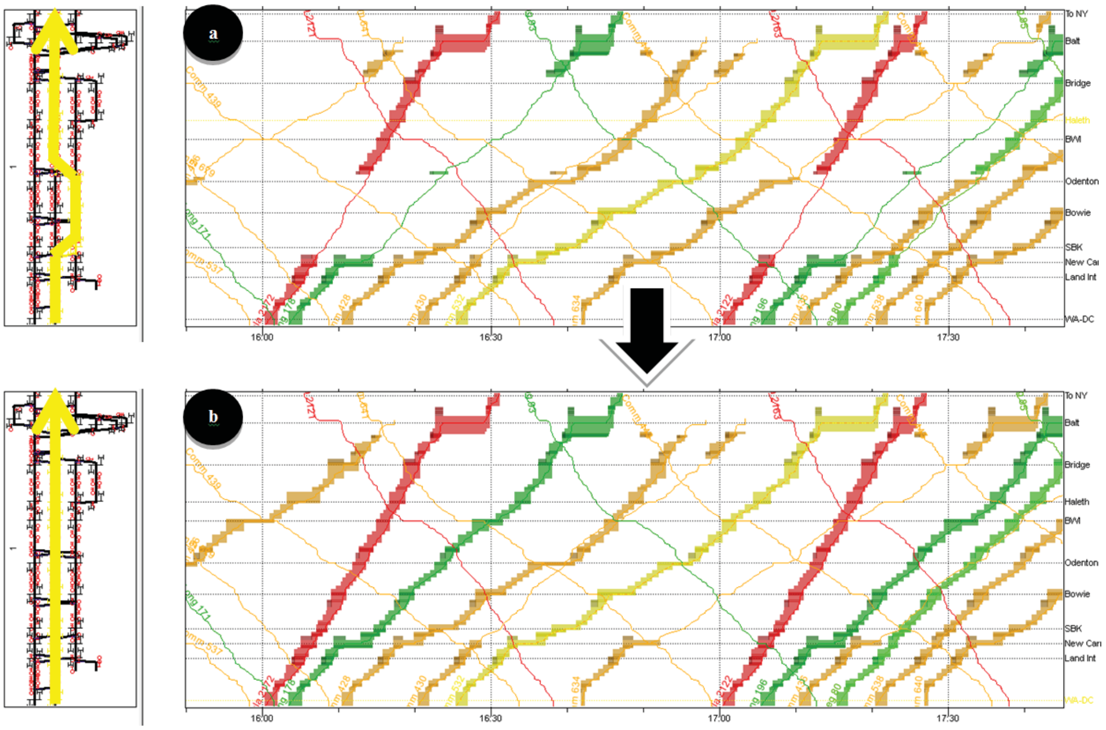

Figure 4-7- Snapshot of the "Initial" schedule (a) and modified schedule after rerouting (Scenario 1) (b). Different types of trains in NB direction are separated by colors and highlighted trains use the same track(s) with the example train (left)

4-5-3- Outcomes of Scenario 2- Rerouting and Rescheduling

Allowing rescheduling of trains provided more routing alternatives. There are different approaches to reroute and reschedule trains, but in this study, the rescheduling was limited based on a specific maximum time deviation (±X minutes) from the initial requested departure time. Acela trains had maximum time deviation of ±15 minutes, and Commuter, Long distance/Regional trains ±40 and ±60 minutes, respectively. All stop patterns and dwell times were maintained the same as in the Initial schedule. After rescheduling, the average difference between new departure times and initial departure times was eight minutes, with standard deviation of seven minutes.

After rerouting and rescheduling, all trains moved in directional pattern with Northbound trains using Track #2 and Southbound trains using Track #1. Since trains no longer used Track #3 or #4 they would be open to new services (Especially Track #3 because it is approximately laid out along the entire corridor). Figure 4-8 demonstrates an example stringline after rerouting and rescheduling. In this example, seven NB trains were rescheduled, three NB trains simultaneously rerouted/rescheduled, and one SB train was rerouted to provide fully directional operation pattern. For instance, Train #80 was rescheduled to depart approximately 19 minutes earlier than in the Initial schedule, while Train #634 was rerouted and rescheduled to depart 35 minutes later than the initial schedule. As shown in Figure 4-8, all NB trains (highlighted) used Track #2.

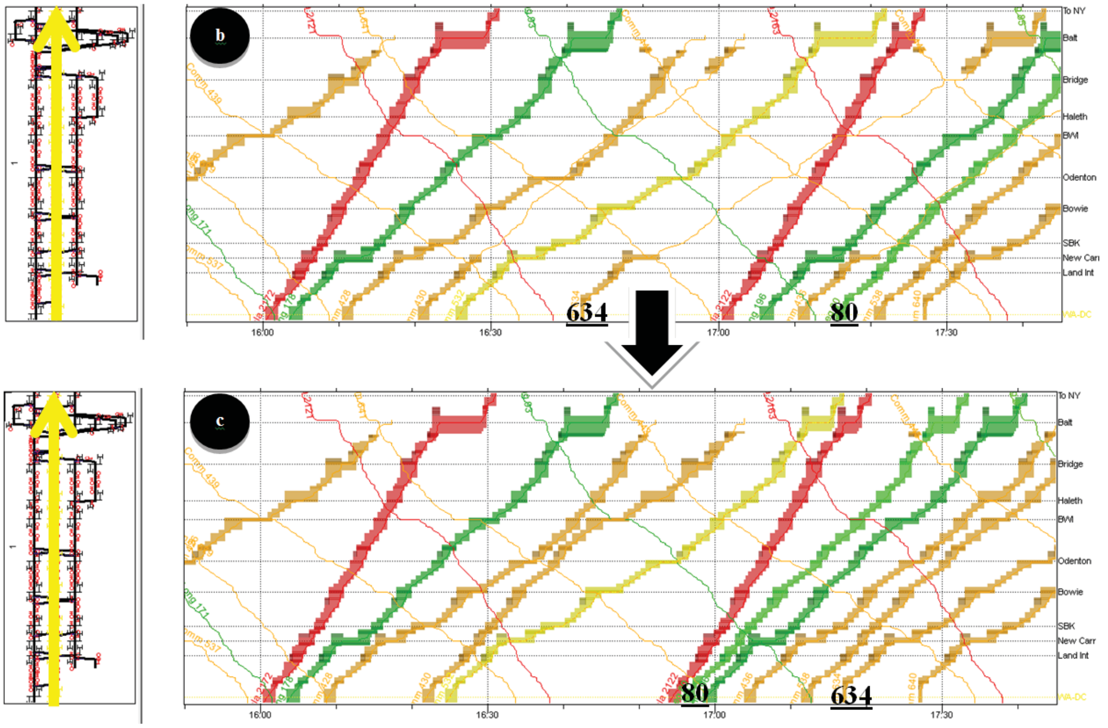

Figure 4-8- Snapshot of the "Scenario1" (b) and "Scenario 2" after rerouting/rescheduling (c) to provide fully directional operations. Different types of trains in NB direction are separated by colors and highlighted trains use the same track(s) with the example train (left)

The average speed of trains increased, especially for NB direction (2.9 mph increase from the Initial schedule). However, there was approximately 13% increase in average delay of trains, as more trains were operating on Tracks #1 and #2, resulting in higher risk for traffic congestion.

4-6- Discussion of Results

A detailed analysis was conducted between the Initial scenario and the final results of Scenario 2 (fully directional operations) to identify the effects of rerouting/

rescheduling on various parameters, such as the total number of trains rerouted / rescheduled, and changes in train speeds and delays. The following sections discuss the results of the analysis.

4-6-1- Number of Rescheduled/Rerouted Trains

The number of trains rerouted and/or rescheduled to achieve directional operations is important, as minimizing the number of changes would facilitate the potential implementation. Figure 4-9 breaks down the number of trains that were either rerouted, rescheduled, or both. Overall, 46% of all trains (NB and SB combined) maintained their initial routing and schedule, most of them in SB category. 27% of trains were rerouted, 6% rescheduled, and 21% (mainly NB trains) simultaneously rerouted/rescheduled.

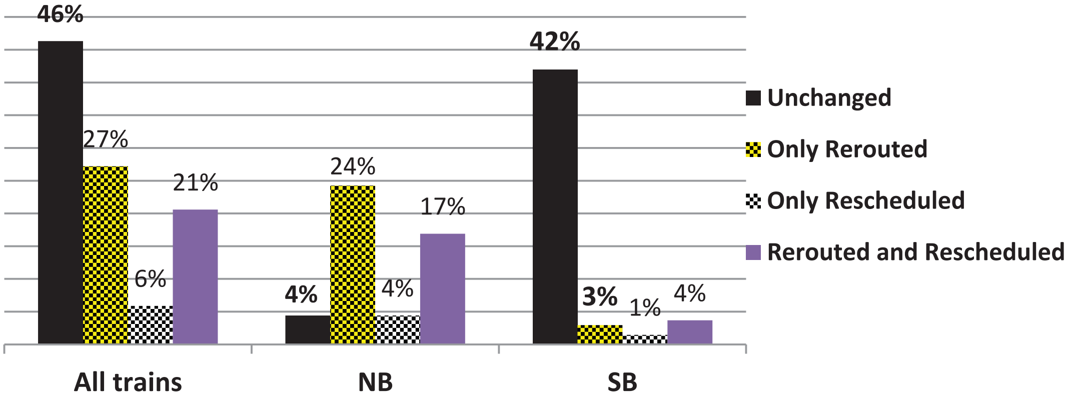

Figure 4-9- Summary of rerouting and rescheduling changes to provide a fully directional operation

4-6-2- Effects of Rerouting/Rescheduling to Corridor Performance

The effects of rerouting/rescheduling on train performance were calculated and are presented in Table 4-3. The performance was divided to two main categories for analysis: **"Speed-Delay ",** and **"Track Occupancy level".**

Table 4-3- Effects of Different Scenarios on Key Parameters

Evaluation Criteria			**Initial Schedule**	**Scenario1- Rerouting**	**Scenario2- Rescheduling/rerouting**
Speed & Delay	Total delay of all Trains		103.5 min	103.7 min	117.4 min
	Avg delay per train		45.6 sec	45.7 sec	51.8 sec
	Longest delay of a train		180 sec	180 sec	161 sec
	Avg speed of all trains		70.4 mph	71.3 mph	71.9 mph
	Sum of “Speed-Delay” normalized parameters		81.20	81.95	84.95
Track Occupancy Level	Avg Occupancy level of tracks per day (%)	Track #1	10.5%	12.2%	10.8%
		Track #2	6.6%	9.8%	11.6%
		Track #3	5.7%	3.5%	0.0%
		Track #4	7.0%	0.3%	0.0%
	Max. Occupancy level of tracks per hour (%)	Track #1	50.7%	50.7%	50.7%
		Track #2	36.9%	44.6%	45.5%
		Track #3	34.4%	34.4%	0.0%
		Track #4	19.2%	8.5%	0.0%

4-6-3- Speed-Delay Analysis

The results suggest that moving from non-directional to directional operations has potential to increase speeds, but it also makes the corridor more susceptible for train delays (see Abril, 2007) [33]. As shown in Table 4-3, the **"Average speed of all**

trains" was slightly higher in Scenario 2 than the Initial schedule due to the eliminated use of crossovers. **"Total delay of all trains"** had increased in Scenario 2 (directional approach) in comparison to the Scenario 1 and Initial scenario, due to the fact that under this scenario more trains were moving on Track #1 and Track #2, increasing the risk of traffic saturation (congestion) on those tracks. However, there was no significant difference in **"Average delay per train"** between the scenarios and the **"Longest train delay"** had decreased in Scenario 2 (directional approach) due to the train rescheduling.

A new combined parameter, defined here as **“Speed-Delay” normalized parameter**, was introduced to evaluate the tradeoff between increased speeds and delays. “Normalization” is a common mathematical term in Operation Research (OR) and statistics when two, or several parameters with different dimensions (units), such as speed and delay (mph and minute) are converted into a dimensionless (unit-less) parameters to make them comparable [78]. In this research, the value of average speed and total delay of each individual train was normalized into a dimensionless value between “0 and 1” and the delay value was deducted from the speed value. An increase in “SD” parameter indicates an improved performance and a summation of all “speed-delay” values can be used to compare the performances of each scenario.

Equations to calculate the "SD" parameter were defined as:

$$SD = \sum_{i} (\alpha . S_i^{'} - \beta . D_i^{'})$$

$$S_i^{'} = \frac{S_i}{S_{max}}$$

$$D_i^{'} = \frac{D_i}{D_{max}}$$

SD : "Speed – Delay" Parameter of all trains under the same scenario

$S_i^{'}$: Normalized speed of train i $\quad 0 \le S_i^{'} \le 1$

$D_i^{'}$: Normalized delay of train i $\quad 0 \le D_i^{'} \le 1$

S_i : Average speed of train i

S_{max} : Maximum speed of all trains under the scenario

D_i : Total delay of train i

D_{max} : Maximum delay of all trains under the scenario

α : Weighted Coefficient of Speed

β : Weighted Coefficient of Delay

i : Individual train

The calculation of "SD" parameter used **equally weighted coefficients for both speed and delay parameters.** The results show that both Scenario 1 and 2 provide higher values, suggesting that they can provide better performance in terms of delay and speed than the Initial schedule. However, the value of "SD" is slightly higher for Scenario 2 with fully directional operation pattern than Scenario 1 with non-directional operation pattern.

4-6-4- Track Occupancy Level

Track occupancy level comparison between different scenarios reveals that the directional approach (Scenario 2) occupies only Tracks #1 and #2. The **"Average**

occupancy level” of these tracks (the percentage of a given track occupied within 24-hour period) has increased only slightly from the Initial schedule. The **“Maximum occupancy level” (**the highest hourly percentage of a given track occupied by the trains) was maintained for Track #1, while it had slightly increased for Track #2 (45.5% vs. 36.9%), mainly due to increased number of trains using Track #2. Since the two remaining main Tracks (#3 and #4) have no traffic under the directional approach (scenario 2), they can be allocated for new traffic.

There is no clear methodology to quantify how much additional capacity has been provided through Scenarios 1 and 2 as practical capacity depends on train types, preferred schedules and dispatching patterns of new services. While quantifying the capacity available to new traffic is difficult, it can be concluded that a directional approach (Scenario 2) has opened up capacity on Tracks #3 and #4, while only slightly increasing the occupancy levels of Tracks #1 and #2. For example, Track #3 used to have average daily utilization of 5.7% and maximum hourly utilization of 34.4% during busiest hour, but after all traffic was rerouted, its capacity utilization is zero.

In summary, it can be concluded that all capacity evaluation parameters used in the study improved under directional approach of operation (Scenario 2-rescheduling/rerouting) except delay status of trains and the occupancy level of Track #2. However, the results are only applicable, if both Tracks #1 and #2 have access to platforms at the intermediate stations (either side or island platform).

4-7- Summary and Conclusions

This research used a U.S. multiple-track corridor (Baltimore- Washington, D.C.) as a case study to investigate the effects of non-directional/directional operation pattern on train performance. The study explain three scenarios; an “Initial” schedule that utilized a database obtained from Amtrak for 2012 train operations, “Scenario 1” which allowed for rerouting of trains while maintaining the schedule, and “Scenario 2” which allowed both rerouting and rescheduling to achieve a fully directional operating pattern.

The simulation results indicated that 27% of trains were rerouted, 6% were rescheduled and 21% rescheduled and rerouted in “Scenario 2” when compared to the “Initial” schedule. The number of trains with non-directional pattern was reduced in “Scenario 1”, while average train speeds were increased and total train delay was maintained the same. Under “Scenario 2”, average train speed was improved, but the total delay of trains and the average level of occupancy of Track #2 were increased due to the fact that more traffic was converged to the specific track. However, under Scenario 2”, all trains were operating in directional pattern, leaving Tracks # 3 and 4 open for new operations. A new “Speed-Delay normalized parameter” (SD) was introduced to evaluate the tradeoff between increased speeds and train delays. Both Scenario 1 and 2 produced a higher SD parameter value, thus suggesting an overall better speed vs. delay performance.

While the implementation of a directional approach in this multiple-track case study would require the addition of a side or island platform at intermediate stations to provide platform access for rerouted trains, it might be an attractive alternative to address corridor congestion instead of construction of additional track infrastructure. In larger perspective, the research validates some of the perceived capacity benefits of directional operations and suggests that increasing the number of directional trains through rerouting, rescheduling, or combined rerouting/rescheduling efforts is worth analyzing when searching for alternatives toward improved corridor performance.

4-8- Further Steps of Research

The research objective was to investigate the potential to improve the capacity of an existing multi-track corridor in the U.S. by moving to directional operation pattern. Although all multiple-track corridors are different, the analytical and simulation processes are repeatable. Part of the research was to use the results in the development of an optimization model for the U.S. rail environment. The current simulation software in the U.S. offers limited tools for automated timetable optimization and European software presents challenges when applied in the U.S. operational environment. The authors have taken the first steps toward an analytical model that could be used in conjunction with the existing simulation tools to perform the optimization of the train timetable of single, double and multiple-track corridors under both directional and non-directional operation patterns.

4-9- Acknowledgments

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CHAPTER 5

5. Development of Hybrid Optimization of Train Schedules (HOTS) Model for Railway Corridors [9]

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5-1- Abstract

From a capacity perspective, an efficient utilization of a railway corridor has two main objectives; 1) avoidance of conflicts between different trains and 2) maximization of the number of trains through a corridor within a given timeframe. Various commercial simulation and timetable management tools can be used to evaluate and improve the operations of a corridor, but many of them offer limited tools to either achieve train conflict resolution, automate timetable improvement, or address different types of corridor configurations. This paper introduces a new model called "Hybrid Optimization of Train Schedules" (HOTS), which can be used to complement a commercial rail simulation model (or timetable management tool) in the development of a "Conflict-Free" and "Compressed Timetable" of trains for the corridor under investigation. The HOTS model is applicable to various corridor configurations, including single, double and multiple track corridors using both directional and non-directional (bi-directional) operations patterns. This paper presents the justification behind model development, its components, formulation, parameters and variables. The model performance in solving train conflicts and performing timetable compression was tested under various single track and multiple track case studies and validated in established commercial capacity software. The test scenarios and related outcomes are summarized. The model performed well in each tested scenario, and provided comparable results (either improved or obtained the same results) to the commercial software.

Keywords: Railway Optimization, Train Scheduling, Railway Capacity, Hybrid Optimization, Timetable Compression Technique

5-2- Introduction

The concept of railway capacity and the objective to maximize its utilization are similar everywhere, although there are configuration differences between the rail systems, such as the infrastructure ownership and the operations philosophy. These differences may lead to the use of different methodologies, techniques, and tools for capacity evaluation [73]. There are two general approaches to improve the capacity in a rail corridor, either by applying new capital infrastructure investment or by improving the operation of the rail services. Techniques to evaluate the potential improvements of railway operation include modeling and optimization through the commercial timetable management and rail simulation tools [32]. The majority of past capacity analysis work in the U.S. has concentrated on the infrastructure improvements, while potential benefits of operational changes are commonly conducted in European practices; typically in the form of rescheduling and timetable (TT) management methods [13]. As the U.S. continues to develop higher speed passenger services with similar characteristics to those in European shared-use lines, (e.g. Northeast corridor and accelerated Michigan passenger services) some of the differences may diminish and common methods and tools used for operational capacity should be considered.

Timetable management, such as train scheduling, rescheduling, and a particular type of rescheduling, called timetable compression, are common techniques to improve the timetables with an objective to increase capacity and allow for additional trains along a given corridor. Rescheduling can be applied for any corridor type, but it is especially applicable for the shared-used corridors with a significant number of intercity and commuter passenger trains, as these trains need to follow regular timetables on daily basis. Common objective for rescheduling is to evaluate the potential capacity for future traffic or to develop a higher quality of service for the existing traffic. There are several timetable tools and rail simulation packages that can be used for rescheduling, but the available features vary from tool to tool, and timetable management techniques (e.g. timetable compression) or optimization models for rescheduling and timetable improvement are limited in most of them. This is especially true in tools that target the U.S. rail environment which is structured around non-timetable based operating principles [73].

This paper begins with a brief synopsis of the literature review on the scheduling and timetable management techniques in the rail industry, but its main objective is an introduction of a new stand-alone rescheduling optimization model called **“Hybrid Optimization of Train Schedules” (HOTS),** which can be used with any simulation/ timetable management tools for rescheduling and timetable compression. The HOTS model can be applied to any type of rail infrastructure (single, double and multiple-track corridors), under both directional and non-directional operational patterns. It can provide a “Conflict-Free” and compressed schedule based on the initial timetable and user-defined parameters. This paper describes the HOTS model, including its purpose, model concept and application steps, mathematical formulation, and model benefits/limitations. Two case studies, each with several scenarios, are used to test different applications and capabilities of HOTS model in either improving or maintaining the results obtained from commercial software. Finally, a summary and conclusions of the research are presented as well as a review of some future research topics.

5-3- Literature Review

Train scheduling\timetable management has been practiced for decades. Ever since the rail transportation industry was established in early 19th century, train movements have been coordinated through operating rules and time schedules to provide logical progression of trains along rail corridors and to avoid conflicting movements between trains. Today, an application of computerized timetable management tools and simulation techniques can help rail planners and dispatchers to be more productive in train scheduling and operation management [4]. Typically, the approaches that evaluate trains' operational features are done either analytically or through simulation, but a combined approach that uses both analysis methods is also used [1, 5, 6].

5-3-1- Analytical-based Applications

The analytical approach uses several steps of data processing through mathematical equations (or algebraic expressions) to determine the best feasible solution for the problem (timetable management and train scheduling optimization) [7]. Several analytical and optimization models and techniques have been developed, mostly by academic researchers. Two of the first analytical models were developed by Amit and Goldfarb in 1971 and Szpigel in 1973. A train scheduling problem can be developed as a linear programming (LP) model, but a mixed integer programing

(MIP) model is a more common approach, since the number of trains or time periods should be considered in the model as integer values. Examples of MIP models include Kraay et al, 1991, [8] and Carey and Lockwood, 1995 [9]. More information on optimization models and techniques of train scheduling can be found from a paper by Ghoseiri, et al, 2004 [10].

The following is a review of some of the most important and recently developed optimization models for train scheduling and timetable management in a chronological order. The review briefly explains the structure of the models/application, the approach for solving the models and study conclusions, and their relevancy to scheduling, rescheduling or timetable compression applications. Higgins, et al, [11], developed an optimization model of train scheduling for single track corridors based on each train's earliest departure time from the origin and planned arrival time to the designation. Directional traffic was used for any double track segments and the model took into account scheduled stops and headways. The model variables were defined as optimum departure and arrival times of each train from each station and the objective was to minimize the train delay at destination, as well as the train operating costs.

Carey and Carville, [12], developed a train scheduling and platforming[10] optimization model for busy/complex train stations to ensure no conflicts exist between trains. They used a heuristic method and defined an eight-step algorithm of track/platform assignment for each train to find the best option of platforming. The objective of model was to minimize the deviation from the desired platforms/tracks as

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[10] Assignment of a train to a particular platform at a given station

well as minimizing the deviation from the desired headway, turnaround time, and dwell time of each train.

Ghoseiri, et al, 2004 [10], introduced a multi-objective train scheduling model of passenger trains along single and multiple track corridors to minimize the fuel consumption and optimize the total time that passengers spent in a train. Burdett and Kozan, 2006 [13], developed analytical techniques and models to estimate the theoretical capacity of a line based on several criteria, such as traffic mix, directional operation pattern, location of crossings (crossovers, junctions, sidings) and intermediate signals, length of the trains, and dwell time of trains at sidings or stations. Lindner, 2011 [14], reviewed the applicability of timetable compression technique (UIC approach), to evaluate the line and station capacity on certain examples and scenarios, and concluded that UIC code 406 is a good methodology for evaluating the main line capacity, but it may encounter some difficulties when evaluating node (station) capacity. Corman et al, [15], conducted a study in 2011 to develop an innovative approach of optimizing a multi-class rescheduling problem. The problem focused on train scheduling of multiple priority classes in several steps, using branch-and-bound algorithm. In another study conducted by Canca, et al, 2014 [16], a nonlinear integer programming model was used for timetable development to adjust the arrival/departure times of trains based on a dynamic behavior of demand. The developed timetable could be used for computations by customers and operators to evaluate the train service quality.

As briefly reviewed in this section, numerous analytical and optimization models and techniques have been developed to address the rescheduling and timetable management features, depending on which aspects and what parameters of rescheduling problem were addressed by the model. For instance, Higgins et al, [11], focused on the arrival/departure and dwell times of trains in the stations, but they didn’t look into the details of station tracks and platforming aspects; whereas Carey and Carville, [12], specifically focused on the station’s platforming and track assignment features. As result, each station can be defined in Higgins’ model as a single node, while in Carey and Carville’s model, station should be explicitly identified with details of its tracks and platforms. Differences in model objectives also make the structure and network topology of these two models quite different, even though they both are considered analytical models for train scheduling problem.

5-3-2- Simulation-based Applications

The simulation methods utilize either general simulation tools or commercial railway simulation software specifically designed for rail transportation. The commercial railway simulation software can be divided into two major categories: **Non-timetable and Timetable based** [7, 17]. The non-timetable based simulations are typically used by railways which are operated based on an unstructured operation pattern without an initial timetable, such as the majority of the U.S. rail network. The timetable based software is commonly used under structured operation philosophy which is prevalent in Europe. There are numerous software available in each category, but in this paper Rail Traffic Controller (RTC) and RailSys represent non-timetable and timetable based simulation packages, respectively. More information on these two types of simulation and related software is provided by the authors in a paper published as part of the Transportation Research Board (TRB) 2013 Annual Meeting proceeding [1].

Several academic and industrial studies have recently been conducted using commercial simulation tools to evaluate rail operations and capacity features. Sogin, et al, [18], used RTC in University of Illinois at Urbana-Champaign to analyze the delay status of freight trains on double-track case studies. Sogin applied various speed scenarios and passenger/freight train volumes and concluded that running faster passenger trains on a double track corridor can reduce the total capacity of corridor and increase the overall delay. On the other hand, an equal priority scenario for all types of trains can reduce the overall delay. Another research by Sogin, et al, [19], used RTC simulation and delay analysis to compare train performance on single and double track corridors. In the study, Sogin developed and tested alternative scenarios by changing traffic volume, passenger train speed and heterogeneity level of freight and passenger trains and concluded that increasing passenger train speed can reduce the travel time, but it may also reduce the reliability of trains. Sogin, et al. took advantage of automatically train conflict resolution and randomization features of RTC, mainly to analyze the delay and speed metrics of different scenarios developed as part of the research. Train scheduling and timetable management aspects (e.g. rescheduling and timetable compression technique) were not included in the studies.

The timetable-based simulation research has concentrated on Europe. The Swedish National Rail Administration (Banverket) carried out a research project in 2005 to evaluate the application of the UIC capacity methodology (timetable compression) for the Swedish rail network. RailSys software was used for the simulations. The research confirmed the validity of the UIC's approach for Swedish rail network, but the team also concluded that buffer times are necessary for service recovery and without them, service punctuality can be significantly degraded due to increased capacity consumption [20]. In another study, Schlechte, et al [5], used another European rail simulation software (OpenTrack) to obtain microscopic level results of simulated runs, and then converted the results to macroscopic level for further timetable development/improvement by an analytical algorithm. The improved timetable was returned to the simulation for further analysis. Gille & Siefer [21], used RailSys in a 3-step application to analyze the capacity improvement of a case study that included obtaining maximum level of track occupancy, running the simulation to determine the service quality, and adjusting the maximum level of track occupancy. Goverde, et al [22], applied ROMA simulation package on Dutch railway corridors to analyze various signaling and traffic conditions. The analysis included timetable compression for unscheduled (disturbed) traffic conditions and Monte Carlo simulation technique was used for the analysis. In summary, many different timetable-based simulation tools are used in Europe and most include the train scheduling and timetable management features.

In addition to the timetable and non-timetable based simulation approaches, a new “Web-based Screening Tool for Shared-Use Rail Corridors” was developed in the U.S. by Brod and Metcalf, [23], to perform a preliminary feasibility screening on proposed shared-use rail corridor projects. The outcomes can be used to identify projects that should be investigated further by applying more detailed analytical/simulation tools. The concept behind the tool is based on a simplified simulation technique which does not provide optimization features, or complex simulation algorithms. The tool requires development of basic levels of infrastructure, rolling stock and operation rules (trains schedule) of the given corridor, and a conflict identifier within the tool can help the user to determine where a siding or yard extension is needed to resolve a conflict between existing and future train services along the corridor.

5-3-3- Timetable Compression Technique

Timetable compression technique is a particular way of rescheduling for timetable/capacity utilization improvement and can be completed through both analytical and simulation approaches. The method readjusts the operational characteristics of train service and is especially applicable for corridors with pre-scheduled timetables of all daily trains (structured operation pattern). A majority of European techniques and tools rely at least partially on timetable compression methodology, the UIC's standard for evaluating and improving the capacity (UIC leaflet 406) which is also based on the timetable compression technique [3, 20, 24-26].

In the UIC approach, the pre-scheduled timetable is modified by rescheduling trains to follow each other as closely as possible. Changes in the infrastructure or rolling stock specifications are not allowed during the process, and neither is modification of the travel times, crossing and/or station locations, or commercial stops. Potential new slots on the timetable which are generated through compaction (compression) can be dedicated for additional train service or for maintenance activities [7]. The basic steps of UIC methodology are presented in Figure 5-1.

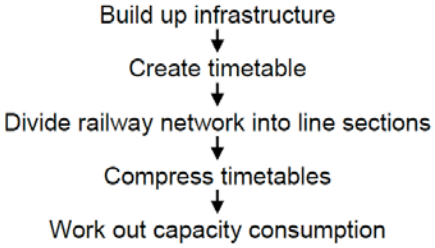

Figure 5-1- Main steps of timetable compression by UIC 406 method [13]

Figure 5-2 provides an example of the timetable compression technique where a timetable along a corridor with quadruple tracks (Scenario a) is first modified by compressing the timetable (Scenario b) and then further improved by rescheduling (optimizing) the train order (Scenario c). As demonstrated in the figure, the third scenario provides a higher level of theoretical capacity in comparison to the scenarios a, and b [3].

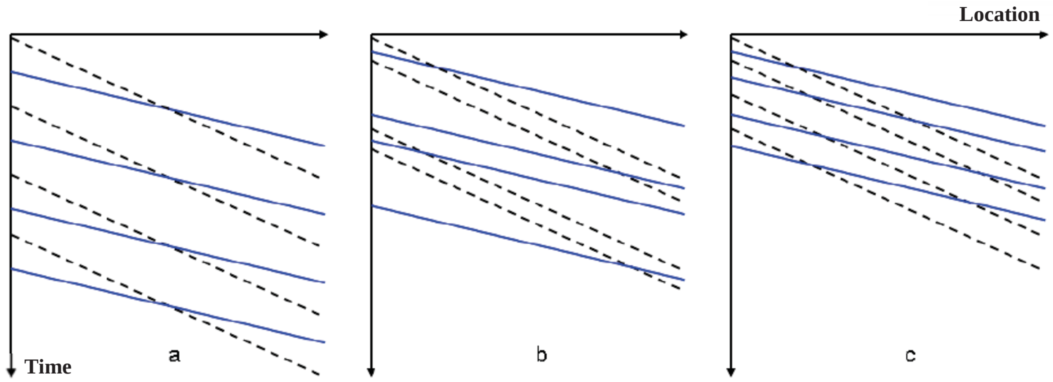

Figure 5-2 - Actual timetable for a quadruple-track corridor (a) compressed timetable with train order maintained (b) compressed timetable with optimized train order (c) (Note: chart layout follows typical European presentation and solid and dot lines represent different types of trains) [13]

5-3-3-1- Two Approaches for Rescheduling/Compressing Timetable

Typically, there are two approaches of rescheduling and compressing a timetable. **“Same-Order”** approach maintains the train order based on the initially requested departure times, but the train order when arriving may differ from the initial schedule due to the compression and potential adjustments in stop patterns. **“Order-Free” (shuffle)** departs trains based on defined user preferences (such as earliest possible departure times of trains). Train order may be changed in both departure and arrival locations.

Simulation and timetable management tools equipped with timetable compression techniques usually follow one of the two above mentioned approaches of rescheduling/compression. The UIC compression technique is typically developed based on “Same-Order” approach, including the timetable compression technique available in RailSys [27].

5-4- Overview of HOTS Model

5-4-1- Problem Statement

According to the previous studies conducted by the authors [1, 28, 29], and as discussed in the literature review, no simulation/ timetable management tool was identified that could address and develop train schedules with 1) automatic train conflict resolution and 2) automatic timetable compression features. Many of the past studies used either non-timetable based or timetable based simulation software. A more detailed review and testing of two of the most common tools (RTC and RailSys) revealed that neither of them can address both challenges automatically. A paper by Pouryousef and Lautala [28] presented a hybrid approach where RTC was first used to perform automatic train conflict resolution and initial timetable creation, and Railsys was then used to improve the timetable through automatic compression technique. While this method provided good results, it was extremely time-consuming, as it required constructing and matching databases in each simulation package. In another study, conducted by Pouryousef and Lautala [29], an existing multiple-track corridor in the U.S. was used to develop a compressed schedule of trains, but due to the non-directional operations pattern, the European simulation package (RailSys) could not provide an automatic compressed timetable.

The authors believe that a combination of automatic train conflict resolution and timetable compression methods have the potential to facilitate and maximize the utilization of the shared-use corridors under development in the U.S. and thus reduce the need for new infrastructure development. This warrants the development of a more robust solution to address the above-mentioned limitations of currently available tools, further summarized as:

a) Many of the existing simulation tools are not equipped with automatic train conflict resolution and timetable rescheduling/compression tools.
b) Simulation/ timetable tools equipped with optimization and rescheduling features are typically only valid for either single track or double (multiple) track corridors under directional operation patterns. As result, they cannot be easily applied to double/multiple track corridors in the U.S., most of which use non-directional operation pattern. For more information, see Pouryousef and Lautala [29].)
c) There is no timetable compression model for the U.S. rail environment, such as the European models derived from UIC timetable compression technique.

The Hybrid Optimization of Train Schedules (HOTS) model, developed as part of this research, is a new analytical standalone model based on the timetable compression technique that can address the limitations mentioned above by:

- Providing a rescheduling/timetable compression model which can be applied as an additional tool for any simulation/ timetable management packages to provide a “Conflict-Free” train schedules. (in response to limitation “a”)
- Developing an optimization model which can be applied for different types of rail case studies including single, double, and multiple-track, and directional and non-directional operation patterns. (in response to limitation “b”)
- Developing a timetable compression technique for the U.S. rail environment as well as other regions (in response to limitation “c”)
- Allowing more flexibility for the planner for rescheduling and/or rerouting trains under different scenarios.

5-4-2- Conceptual Design and Methodology of HOTS Model

The HOTS model is designed as a standalone analytical model that works together with any simulation/ timetable management tool. The objective is to provide more flexible/optimized results of rescheduling/train compression based on various criteria. Rescheduling is the key criteria, and it is based on user defined flexibility of each train’s departure times and dwell times at each stop point. In addition, the model can reschedule different trains based on a new routing scenario, as defined in the model, instead of using the current routes of given trains in the simulation package. The model outcomes can be used to update the requested departure and dwell times, and new train routes (if changed) in the simulation software to perform further analysis and calculations, or to simply verify the results.

The HOTS model operation (Figure 5-3) is a cyclical process to improve (reschedule/compress) the timetable that includes:

1- Extracting the initial (requested) timetable from a simulation or timetable management tool (A)
2- Developing the respective datasets in a tabular format, based on outputs from simulation/ timetable management tools and user-defined criteria (such as min/max. flexibility of departure and dwell times, and train routing) (B)
3- Running the optimization part of the HOTS model to identify the optimal departure and dwell times based on the defined parameters. This requires an optimization software, such as Cplex (by IBM), Gurobi (by Gurobi Optimization), LINGO (by LINDO Systems INC), etc. (C)
4- Updating the departure and dwell times, as well as the new routings if they were changed by the user in the tabular datasheets (D)
5- Validating the new departure, dwell times and new routes (if changed by the user during optimization) in simulation/ timetable management tools and performing further analysis, as desired (A)

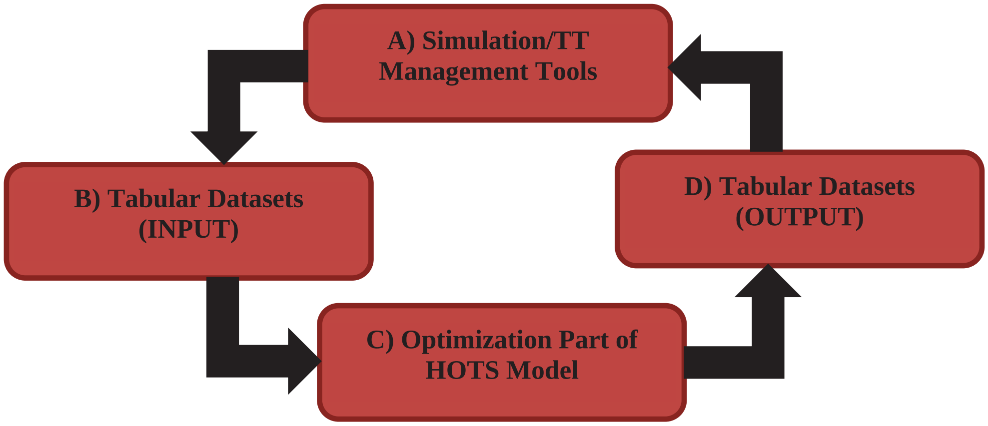

Figure 5-3- Main Steps of HOTS Model Operation

A more detailed flowchart of HOTS operational steps and activities performed is depicted in Figure 5-4.

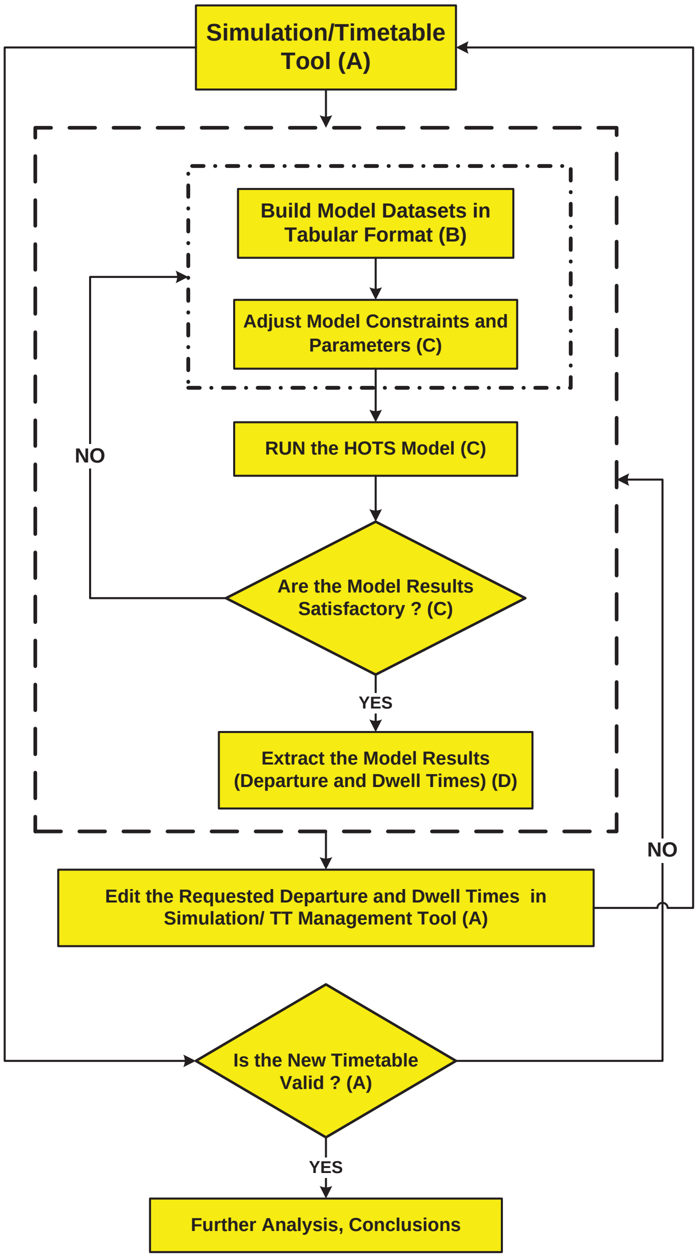

Figure 5-4- Flowchart of HOTS Model Operation

The HOTS model input is a combination of user-defined inputs and data extracted from a simulation/ timetable management tool. Figure 5-5 demonstrates the main inputs, categorized between data sources, optimization objectives and outputs.

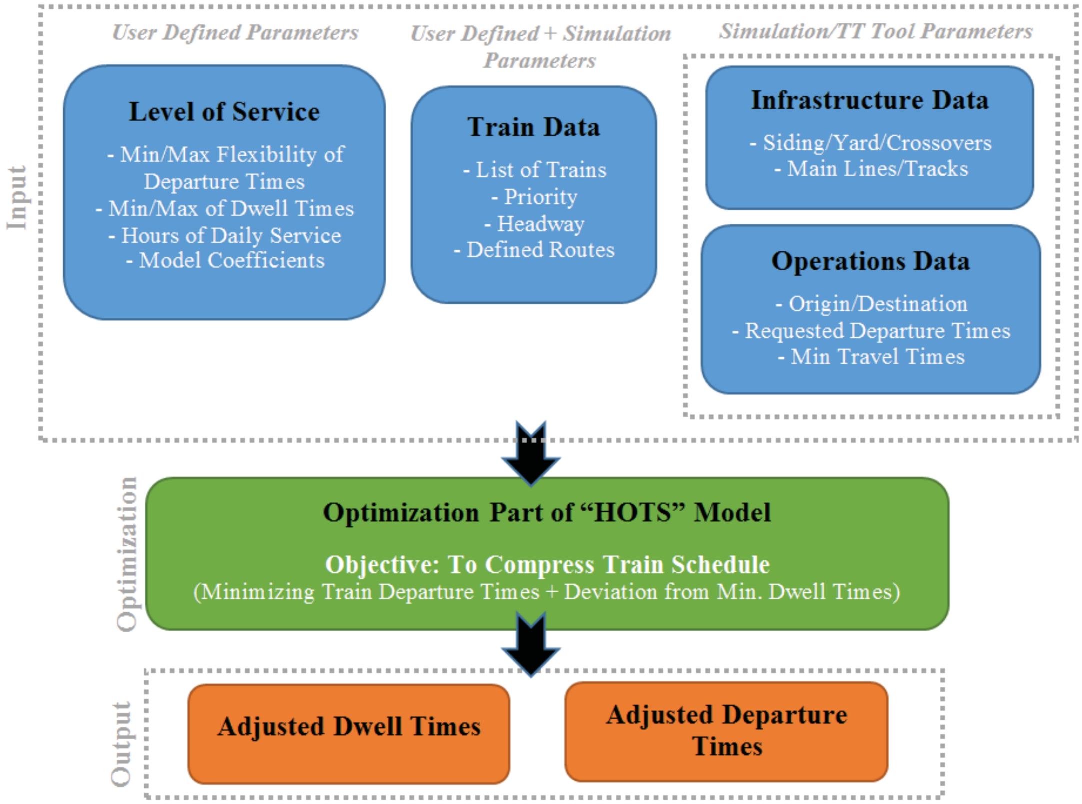

Figure 5-5- HOTS Model Input Categories and Sources and the Model Outputs/Objective

Two categories of model input, “Infrastructure data” and “Operations data”, are extracted from simulation/ timetable management tools. The “Level of service” (LOS) parameters are defined by the user and can be adjusted (calibrated) in the model, as necessary. “Train data” is developed jointly from simulation/ timetable management information and user preferences.

All model inputs (parameters) are used by the “Optimization Part of HOTS Model” with an objective of “To Compress Train Schedules”, or more specifically, “To minimize trains departure times + minimize the deviation between adjusted dwell times and respective minimum values”. The two main model outputs (variables) are; “Adjusted dwell times”, and “Adjusted departure times”.

5-4-3- Optimization Part of the HOTS Model

Optimization models have typically four main components:

- Model data and parameters (Inputs)
- Model decision variables (Outputs)
- Model objective
- Model constraints (Limitations and expectations)

The optimization part of the HOTS model (Component “C” in Figure 5-3) is a multi-objective problem formulated as a Mixed Integer Linear Programming (MILP) model. The mathematical structure of optimization part of the HOTS model is described in the following sections.

5-4-3-1- Model Parameters and Variables

The HOTS model data and parameters (Input) obtained from a simulation/ timetable management tool or defined by user, and variables (Output) generated by the model are summarized in Table 5-1.

Table 5-1- List of optimization parameters and variables of the HOTS Model

Parame	Description
T	Set of all trains "t" (or "p") $\forall t, p \in T$
R_t	Priority of train "t" $R_t \in \{1,2,3,..\}$ (Should be determined based on the importance of the train service quality and schedule of trains. The higher the priority of train, the higher value of R_t)
$H(T_t)$	A minimum headway of train "t" (departure headway) before dispatching another train on the same track. (min or sec)
SH	Maximum duration of timetable (converted to minutes or seconds) $SH > 0$
S	Set of stop locations "i" (e.g. station, siding, yard, crossover) $\forall i \in S$
α_1, α_2	Weighting coefficients of dwell (α_1) and departure times (α_2) $\alpha_1, \alpha_2 > 0$
O_t	The origin of each train "t" $\forall O_t \in S$, $\forall t \in T$
D_t	The destination of each train "t" $\forall D_t \in S$, $\forall t \in T$
U_t	Direction of train "t" $\begin{cases} 1 \;\; if \;\; O_t < D_t & (Eastbound \;\; or\, Northbound) \\ -1 \;\; if \;\; O_t > D_t & (Westbound \;\; or\, Southbound) \end{cases}$
DT_t^i	Requested departure time (daily clock time) of train "t" from stop point "i" (min or sec) $\forall i \in S$, $\forall t \in T$
$F1DT_t^i$	Maximum deviation (flexibility) of departing train "t" before the requested time from stop point (station) "i" (min or sec) $\forall i \in S$, $\forall t \in T$
$F2DT_t^i$	Maximum deviation (flexibility) of departing train "t" after the requested time from stop point (station) "i" (min or sec) $\forall i \in S$, $\forall t \in T$
LW_t^i	Minimum dwell time of train "t" at stop point "i". (min or sec) $\forall i \in S$, $\forall t \in T$
UW_t^i	Maximum dwell time of train "t" at stop point "i". (min or sec) $\forall i \in S$, $\forall t \in T$
TR_t^{ij}	Travel time of train "t" on allocated route between each two consecutive stop points "i-j" (min or sec) $\forall i, j \in S$, $\|i - j\| = 1$ $\forall t \in T$
MR_t^{ij}	Matrix of assigned routes (Track number) of each train between two consecutive stop points "i-j" (based on existing patterns from simulation tool or defined by user) $\forall i, j \in S$, $\|i - j\| = 1$ $\forall t \in T$
XDT_t^i	Adjusted departure times of train "t" from each stop point "i" (min or sec) **(VARIABLE)**
XW_t^i	Adjusted dwell time of train "t" at each stop point "i" (min or sec) **(VARIABLE)**

5-4-3-2- Model Objective

The HOTS model is formulated as a multi-objective problem that attempts to minimize two separate values, departure times and deviation of dwell times. The model tries to compress the train schedules as much as possible by allowing flexible dwell times of trains for meet-pass and stop purposes and by departing trains as early as possible, based on the defined priority, allowed flexibilities, and requested departure times. The priority level is defined by user, but in general higher priority trains are expected to be departed earlier and they may have lower dwell time flexibility than the trains with lower priority.

The objective function is presented in equation (EQ. 1). In this equation, α_1 and α_2 factors are coefficient parameters that determine the importance of dwell times versus departure times, respectively. As the value of dwell time deviation (part “1” of the function) is much smaller than the value of train departure times (part “2”), the user should consider the difference in scaling of these two parameters and can adjust the weighting between departure and dwell times by applying α_1 and α_2 in the objective. When α_1 is a large number (for example 500) and α_2 is small (for example 1), more weight is placed on making dwell times shorter. If α_1 and α_2 are assumed equal in value (for example 1), trains are expected to depart as early as possible, even if some trains may encounter longer stops to provide meet-pass option for faster/higher priority trains.

$$\mathit{Objective}:\ \mathit{MIN}\quad \alpha_1 \times \sum_t \sum_i \overbrace{(XW_t^i - LW_t^i)}^{1} \times R_t + \alpha_2 \times \sum_t \sum_i \overbrace{XDT_t^i}^{2} \times R_t \qquad (EQ.1)$$

5-4-3-3- Model Constraints

The HOTS model has several constraints which can be applied to both “Same-Order” and “Order-Free” rescheduling/compression approaches. The following sections provide a detailed description of the model constraints in each approach.

5-4-3-3-1- Model Constraints under “Same-Order” Approach

Equations 2 through 11 present the constraints for the “Same-Order” rescheduling.

$$\overbrace{XDT_t^i}^{1} \geq \overbrace{DT_t^i - F1DT_t^i}^{2} \qquad \forall t \in T \quad , \forall i \in S$$

(EQ. 2)

(EQ. 2) Departure time of each train from each stop point (part “1” of equation) should be no less than the earliest possible departure time allowed for the given train (part “2” of equation).

$$\overbrace{XDT_t^i}^{1} \leq \overbrace{DT_t^i + F2DT_t^i}^{2} \qquad \forall t \in T \quad , \forall i \in S$$

(EQ. 3)

(EQ. 3) Departure time of each train from each stop point/station (1) should be no greater than the latest possible departure time allowed for the given train (2).

$$\overbrace{LW_t^i}^{2} \leq \overbrace{XW_t^i}^{1} \leq \overbrace{UW_t^i}^{3} \qquad \forall\ t \in T \quad , \forall\ i \in S$$

(EQ. 4)

(EQ. 4) The dwell time of each train suggested by model (1) should be between minimum (2) and maximum dwell time (3) allowed at each stop point/station.

$$\overbrace{XDT_t^d - XDT_t^o}^{1} = \overbrace{\sum_j \sum_i TR_t^{ij}}^{2} + \overbrace{\sum_j XW_t^j}^{3} \qquad \forall t \in T \;, \forall i, j \in S \;, \; |i-j| = 1 \;, \; d \in D_t \,, \; o \in O_t \qquad \text{(EQ. 5)}$$

(EQ. 5) Total travel time of each train (1) should be equal to the sum of each individual route travel times between origin/destination (2) + sum of all dwell times in the stop points/stations (3).

$$\overbrace{XDT_t^j}^{1} = \overbrace{XDT_t^i}^{2} + \overbrace{TR_t^{ij}}^{3} + \overbrace{XW_t^j}^{4} \qquad \forall\, t \in T \;, \; \forall\, i, j \in S \;, \; |i-j| = 1 \qquad \text{(EQ.6)}$$

(EQ. 6) Train departure time from each stop point/station (1) should be equal to the departure time of previous stop point/station (2) + travel time of previous section of route (3) + dwell time of current stop point/station (4).

$$\begin{gathered} \overbrace{XDT_t^i - XDT_p^i}^{2} \geq \overbrace{H(T_p) + H(T_t) + (TR_p^{ij} - TR_t^{ij})}^{1} \\ If \; \underbrace{(U_t \times U_p = 1)}_{3} \; AND \; \underbrace{(DT_t^i > DT_p^i)}_{4} \; AND \; \underbrace{(TR_p^{ij} \geq TR_t^{ij})}_{5} \; AND \; \underbrace{(MR_p^{ij} = MR_t^{ij})}_{6} \\ , \forall t, p \in T \;\;, t \neq p \;\;, \forall i, j \in S \;\;, \; |i-j| = 1 \end{gathered} \qquad \text{(EQ. 7)}$$

$$\overbrace{XDT_t^i - XDT_p^i}^{2} \geq \overbrace{H(T_p)}^{1} \qquad If\ \overbrace{(U_t \times U_p = 1)}^{3}\ AND\ \overbrace{(DT_t^i > DT_p^i)}^{4}$$
$$AND\ \underbrace{(TR_p^{ij} < TR_t^{ij})}_{5}\ AND\ \underbrace{(MR_p^{ij} = MR_t^{ij})}_{6} \quad \forall t, p \in T\ , t \neq p\ , \forall i, j \in S\ ,\ |i-j| = 1$$

(EQ. 8)

(EQ. 7&8) There should be a minimum headway or buffer time (1) between departure times of two consecutive trains (2) in the same direction (3) based on the requested departure times (4), speed gap between trains (5), and defined train routes (6). EQ. 7 and EQ. 8 differ in the order of slower and faster trains. EQ. 7 represents the scenarios where faster train is following a slower one. Therefore, EQ. 7 has an extra expression which represents an additional buffer time, calculated based on the minimum headway of the faster train and the speed gap between the trains.

$$\overbrace{XDT_t^i}^{1} \geq \overbrace{XDT_p^j + TR_p^{ji}}^{2} + \overbrace{H(T_p)}^{3} \qquad If\ \overbrace{(U_t \times U_p = -1)}^{4}\ AND\ \overbrace{(DT_t^i \geq DT_p^j)}^{5}$$
$$AND\ \underbrace{(MR_p^{ji} = MR_t^{ij})}_{6}, \quad \forall t, p \in T\ ,\ t \neq p\ , \forall i, j \in S\ ,\ |i-j| = 1$$

(EQ. 9)

(EQ. 9) No train can depart (1) until the previous train in opposite direction has arrived to the given station (2) + minimum headway between these two trains (3). This depends on the operation direction of trains (4), requested departure times (5), and defined train routes (6).

$$\overbrace{XDT_t^d - XDT_p^o}^{1} \leq \overbrace{SH}^{2} \qquad \forall\, t, p \in T \quad , \; d \in D_t \, , \; o \in O_t$$

(EQ. 10)

(EQ. 10) Timetable duration (1) should be equal/less than maximum service hours defined by user (2).

$$XDT_t^i \geq 0 \;\; , \; XDT_t^i \in \text{integer} \quad , \; XW_t^i \geq 0 \;\; , \;\; XW_t^i \in \text{integer} \qquad \text{(EQ. 11)}$$

(EQ. 11) Adjusted departure times and dwell times suggested by model (variables) are positive integer values. If the travel times and min/max dwell times of trains are considered in the model as integer values, then the model is forced to also generate the variables (departure and dwell times) with integer values due to the structure of EQ.5 and EQ.6. In such situation, the model variables can be defined as real values (instead of integers) and the model will be changed from Mixed Integer Linear Programing (MILP) to only Linear Programing (LP). As result of such change, the LP model will be solved much faster with more reliability to find the optimum solution. The authors use the above mentioned approach (LP model) to solve the respective case studies.

5-4-3-3-2- Model Constraints under "Order-Free" Approach

In the "Order-Free" approach of the HOTS model, trains depart based on the earliest possible departure times, as determined based on allowed flexibility parameter (F1DT in the model). All variables, parameters and constraints of the "Order Free" approach are the same as the "Same-Order" approach, except constraints presented in EQ. 7, EQ. 8 and EQ. 9. The modified equations used in "Order-Free" approach are presented below.

$$XDT_t^i \geq XDT_p^i + H(T_p) + H(T_t) + (TR_p^{ij} - TR_t^{ij})$$
$$If\ (U_t \times U_p = 1)\ AND\ (DT_t^i - F1DT_t^i > DT_p^i - F1DT_p^i)\ AND\ (TR_p^{ij} \geq TR_t^{ij})\ AND$$
$$(MR_p^{ij} = MR_t^{ij})\ ,\forall t, p \in T \quad ,t \neq p\ ,\ \forall i, j \in S \quad ,\ |i - j| = 1$$

(EQ. 7-a)

$$XDT_t^i \geq XDT_p^i + H(T_p) \qquad If\ (U_t \times U_p = 1)\ AND$$
$$(DT_t^i - F1DT_t^i > DT_p^i - F1DT_p^i)\ AND\ (TR_p^{ij} < TR_t^{ij})\ AND\ (MR_p^{ij} = MR_t^{ij})$$
$$\forall t, p \in T \quad ,t \neq p\ ,\ \forall i, j \in S \quad ,\ |i - j| = 1$$

(EQ. 8-a)

$$XDT_t^i \geq XDT_p^j + H(T_p) + TR_p^{ji}$$
$$If\ (U_t \times U_p = -1)\ AND\ (DT_t^i - F1DT_t^i \geq DT_p^j - F1DT_p^j)\ AND\ (MR_p^{ji} = MR_t^{ij}),$$
$$\forall t, p \in T\ ,\ t \neq p\ ,\forall i, j \in S\ ,\ |i - j| = 1$$

(EQ. 9-a)

The updated equations are similar to the original equations, but the flexibility of early departure times (F1DT) is incorporated in the equation to identify the train that is more likely to depart earlier. $(DT_t^i - F1DT_t^i > DT_p^i - F1DT_p^i)$

The ability to modify the order of trains may allow higher compression level, although the new schedule may also face a station capacity shortage, if too many trains try to pass or stop at the same time in a given station with limited capacity.

5-4-4- Model Benefits\Advantages

Based on the structure of the HOTS model, it is expected that the following hypotheses can be achieved by the model. The performance of the model against these hypotheses was tested by applying HOTS model on several different case study scenarios. The outcomes are discussed in the next sections of the paper.

1- Ability to reschedule and compress the timetable of different train types on single, double and multiple track corridors under both directional and non-directional operation patterns.
2- Ability to provide a "Conflict-Free" train schedules, even if the initially requested schedule has serious conflicts between trains.
3- Ability to reschedule trains (the output of model) by assigning new train routing scenarios (input of model) for double and multiple track corridors.
4- The model can be applied for both "Same-Order" and "Order-Free" scheduling approaches based on the user preference.

5-4-5- Model Considerations\Limitations

When using the HOTS model, certain limitations should be considered, such as:

1- Each stop point/station is considered as one single node in the model. Since trains cannot be assigned to various station tracks, the HOTS model may provide more conservative departure and arrival times at stations. A more detailed simulation of track usage at stations can be conducted in the simulation/ timetable management tools during the validation process. If any train is too long for available tracks at a station, the train should not be allowed to stop, making minimum and maximum dwell time of such train "zero" at the given station.
2- Unlike more detailed simulation models, the HOTS model does not evaluate the station capacity. Thus, there might be a risk of allowing a train arrival at a station, even if all tracks are already occupied, especially if the "Order-Free" approach and broad range of departure flexibility (F1DT) are allowed. For instance, a given station may have only two tracks for arrival and departure, but HOTS may schedule three trains to either stop or pass through the station at the same time. Such capacity shortages should become evident during the validation process in simulation/ timetable management tools, which can then be used to update the HOTS model results (rerun the model) and force some

trains to depart later. The rest of the schedule (after the occurrence of capacity shortage) will be automatically updated by the model, while the schedule of train movements prior to the station capacity event remains unchanged.

3- The model is very sensitive to the requested departure times, flexibility parameters of departure times (F1DT and F2DT) and the minimum and maximum dwell times of trains. Reducing the value (flexibility) of these parameters may prevent the optimization part of HOTS model from finding a feasible solution for all trains. Increased flexibility (higher values) would be required to allow the solver software to find the best answer for all trains.

4- Due to the fact that acceleration and deceleration times of trains are not considered in the model; there might be small deviations between departure times suggested by the HOTS model and departure times provided by the simulation package (depending on the type of trains). To improve accuracy, it might be necessary to slightly update the suggested train schedules after implementing the results in a simulation/timetable management tools. To minimize variation between the HOTS model and implemented schedule by simulation packages, it is important to use proper train types and characteristics when determining minimum headways in the HOTS model.

5-5- Testing HOTS Model in Different Applications

Based on the hypothesis, several applications of rescheduling and timetable improvement can be carried out by the HOTS model. The following sections use single and multiple track case studies to examine the HOTS model performance on different applications and scenarios.

A comparison between the initial schedule of each case study scenario and the HOTS model results was used to test the capabilities of HOTS model in improving the schedule. As mentioned earlier, the databases for all scenarios were developed in Microsoft Excel and LINGO 14 was used as the optimization Solver.

5-5-1- Single Track Case Study

A single track test case study was a rail line in the U.S. that is currently used for excursion passenger trains. The modeled track infrastructure mimicked the existing infrastructure, but more complicated train and signal parameters were developed for the case study. The case study includes a 30-mile long single track segment with two sidings and a yard for meet/pass and stop purposes. Four types of trains were considered in the case study; intercity passenger (4 daily pairs or eastbound/westbound), commuter (2 daily pairs), merchandise freight (2 daily pairs) and intermodal freight trains (3 daily pairs). There were no planned stops for any trains, but trains were allowed to stop at the sidings/yard due to the meet-pass concept. There were no predefined arrival/departure timetables in the case study, although some preferred departure times were defined for each scenario. Table 5-2 summarizes the case study parameters.

Table 5-2- Details of case study infrastructure

Segment Length	30 miles, single track
Sidings/yards	2 sidings + 1 yard
Trains	11 (east) + 11 (west)
Traffic type	Mixed traffic (passenger, commuter, freight, intermodal)

The case study was initially developed in two simulation packages (RTC and RailSys) to test a Hybrid simulation method for timetable improvement. Detailed description of the study can be found in a paper by Pouryousef and Lautala [28]. For HOTS testing, three main scenarios were developed:

- **Scenario 1-1:** Using the HOTS model to Improve an initial timetable with serious conflicts
- **Scenario 1-2:** Using the HOTS model to improve an initial "Conflict-Free" timetable (developed by RTC) and to evaluate the station capacity limitation of HOTS model
- **Scenario 1-3:** Using compressed timetables developed by RailSys and HOTS model to compare their compression techniques

5-5-1-1- Scenario 1-1: Initial Timetable with Conflict

The purpose of this scenario was to investigate the capabilities of the HOTS model to transform an initial timetable with several schedule conflicts (developed intentionally) into a "Conflict-Free" schedule. Table 5-3 summarizes the user-defined parameters of the HOTS model in Scenario 1-1. All parameters of each train category, such as F2DT flexibility parameter (the most latest possible departure time) were considered equal through all stations.

Table 5-3- Details of defined parameters for the HOTS model to solve scenario 1-1 (timetable with conflicts)

Criteria	Passenger	Commuter	Intermodal	Freight
Min. allowed dwell time (min)	0	0	0	0
Max. allowed dwell time (min)	10	5	20	60
F1DT[1] (min)	0	90	90	60
F2DT[2] (min)	240	240	240	240
Headway (min)	2	2	2	2
Priority of train	3	4	2	1

[1]: The earliest possible departure time of trains

[2]: The latest possible departure time of trains

After running the model in LINGO Solver, the adjusted departure and dwell times of improved timetable were generated by LINGO (using a PC, Intel Core 2 Due, 2GB

RAM) in less than four seconds for both “Same-Order” and “Order-Free” approaches, but in separate model runs [11]. The output from LINGO was converted to the “hh:mm” format in Excel sheets for validation in RailSys. Figure 5-6 presents the initial timetable obtained from RailSys for Scenario 1-1 (top), and the HOTS model results for both “Same-Order” and “Order Free” approaches, (middle and bottom, respectively), as validated by RailSys. More than 25 serious initial timetable schedule conflicts were resolved in both “Same-Order” and “Order Free” approaches by providing appropriate meet-pass stop patterns for trains at the stations.

All trains of “Same-Order” approach were departed based on the initial order of dispatching, while trains of “Order-Free” approach were allowed to deviate from original patterns. For instance, in “Same-Order” approach all commuter (orange), intermodal (dark blue) and freight trains (blue) were departed after the first passenger train (yellow) with F1DT equal to zero, although they could have been departed earlier. However, in “Order-Free” approach, passenger trains were moved after two commuter trains. The F1DT parameter was assumed as zero for the passenger train, while commuter, intermodal and freight trains were allowed to be departed up to 90 minutes earlier than the initial schedule with no dependency on the passenger train schedule. The duration of timetable in the “Order-Free” approach is shorter than “Same-Order” pattern (approx. 30 minutes), but more stops were also proposed by the model. The test confirmed that HOTS model was able to automatically improve the initial timetable of Scenario 1-1 with over 25 serious schedule conflicts, and develop a “Conflict-Free” schedule with both “Same-Order” and “Order-Free” approaches.

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[11] 4114 constraints, 7984 non-zero parameters, and 220 variables

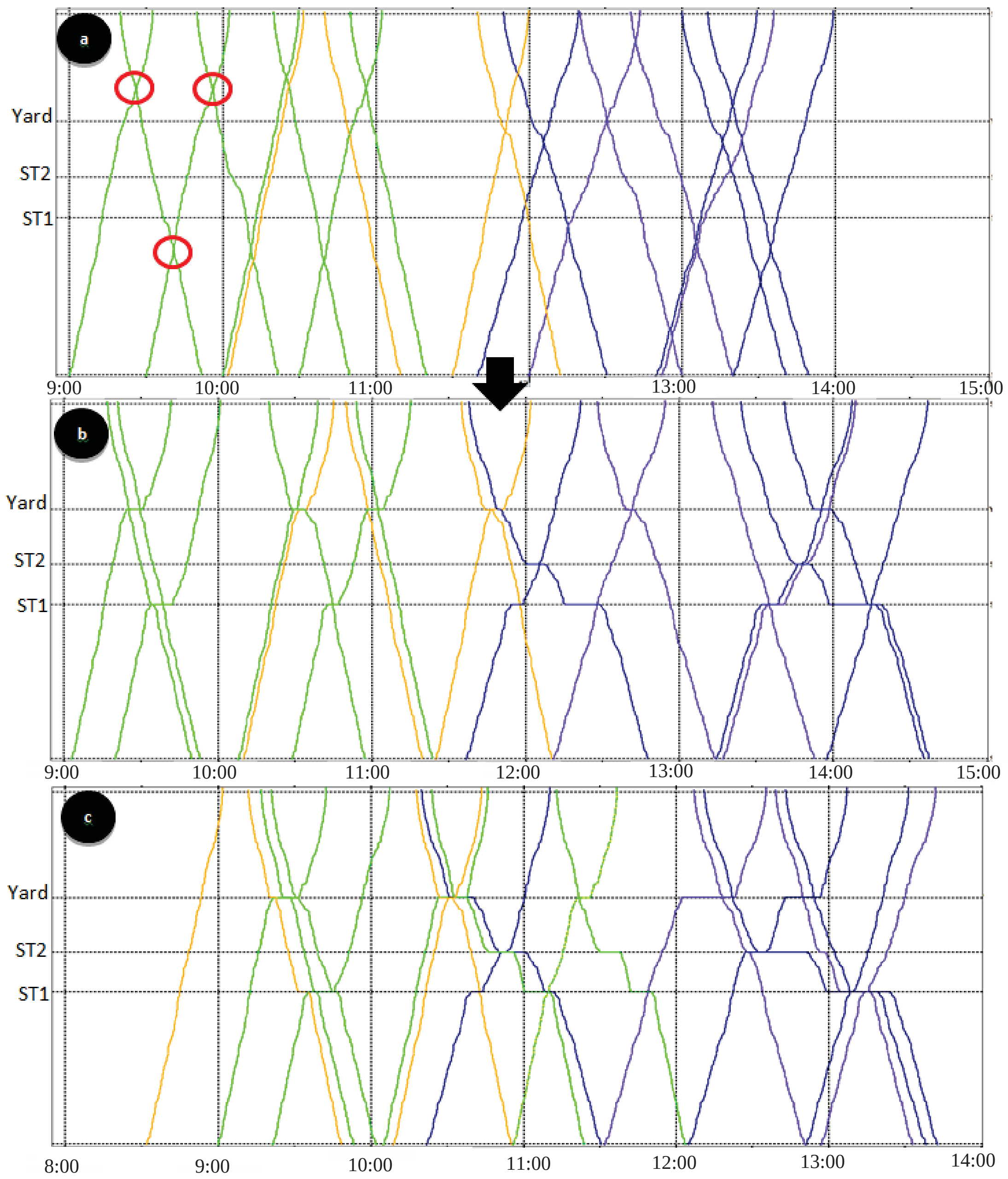

Figure 5-6- The initial timetable (a) with several schedule conflicts (three of them marked as example), improved timetables after the HOTS optimization: "Same-Order" approach (b), "Order-Free" approach (c)

5-5-1-2- Scenario 1-2: Initial Timetable of RTC with No Conflict

The purpose of this scenario was to evaluate the capabilities of the HOTS model to compress an initial timetable with no schedule conflict, but with poor quality of service (e.g. long waiting time at some stations). The initial timetable with serious conflicts (presented in Scenario 1-1, Figure 5-6-top) was simulated in RTC to resolve the conflicts. No manual improvements were attempted to improve the schedule. RTC has ability to automatically resolve the conflicts of any requested timetable, but in some cases the outcomes of the simulated timetable are later manually improved by expert users. [28, 30] The same steps of developing the datasets and running the HOTS model as in Scenario 1-1 were conducted for this scenario, but only for the "Same-Order" approach. Table 5-4 summarizes the user-defined parameters of the HOTS model used in Scenario 1-2.

Table 5-4- Details of defined parameters for the HOTS model to solve Scenario 1-2 (RTC timetable with no conflict)

Criteria	Passenger	Commuter	Intermodal	Freight
Min. dwell time (min)	0	0	0	0
Max. dwell time (min)	10	10	30	30
F1DT[1] (min)	60	60	180	180
F2DT[2] (min)	240	300	300	300
Headway (min)	2	2	2	2
Priority of train	3	4	2	1

[1]: The earliest possible departure time of trains

[2]: The latest possible departure time of trains

Figure 5-7 presents the results of the initial timetable developed by RTC (top) and the improved timetable by the HOTS model in the middle.[12] The HOTS model could compress the timetable by approximately one hour and improve maximum dwell times (from 61 to 30 minutes) and total dwell times (from 271 to 168 minutes) of trains at stations.

To evaluate the station capacity limitations of the HOTS model, it was assumed that station “ST2” could receive only two trains at the same time. As highlighted in Figure 5-7 (middle), three trains either pass or stop at “ST2” around 9:30 am which exceeds the capacity of the station. The capacity issue was solved by departing the third train (train “A”) after train “B”, and modified input was used to rerun the HOTS model and update the timetable. Figure 5-7 (bottom) presents the second round of the HOTS model results with changes on the stop patterns of trains “A”, and “C” highlighted. The capacity shortage at station “ST2” was resolved in the second round, while stop patterns and departure orders were maintained for all other trains. The overall duration of timetable was increased by approximately 20 minutes, since trains “A”, “C” and all trains after “C” were departed 20 minutes later to address the station capacity shortage.

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[12] : NOTE: The RTC stringline presented in this scenario is replicated and shown in RailSys simulation package to allow for graphical comparison between different scenarios.

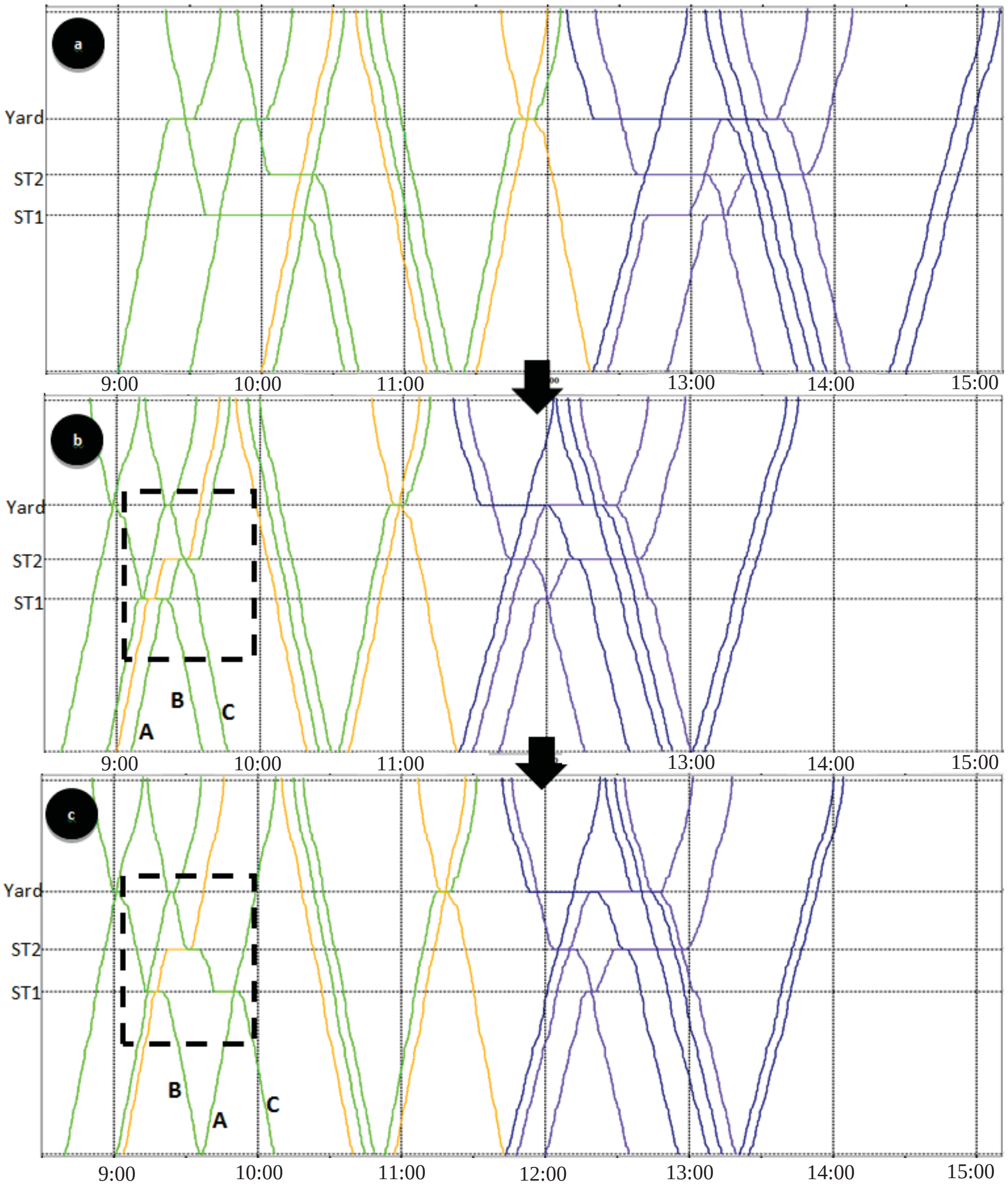

Figure 5-7- The initial timetable developed in RTC with no manual improvement (a) was improved using "Same-Order" approach of the HOTS model (b) and then it was readjusted by running the HOTS model for the second time to address the assumed station capacity limits in ST2 siding (c)

Table 5-5 provides a comparison of results after the HOTS model application. According to Table 5-5, the HOTS model could reduce the total and max dwell times while decreasing the duration of the timetable (better capacity utilization).

Table 5-5- Comparison between initial and improved timetable developed by the HOTS model in Scenario 1-2 of single track case study (Same-Order approach)

Criteria		**Scenario 1-2**	
		Initial TT	**Improved by HOTS[1]**
LOS	**Number of stops**	14	19
	Min. dwell time	0’	0’
	Max. dwell time	61’	30’
	Total dwell times	271’	166’
Capacity	**TT duration**	6h 10’	5h 25’
	TT Compression Level	-	45’
		-	12%

[1]: After addressing the station capacity issue

5-5-1-3- Scenario 1-3: Comparing the Results of RailSys and HOTS Compression Techniques

The purpose of this scenario was to perform parallel timetable compression by HOTS model and RailSys and compare the results. The timetable compressed by both RailSys and HOTS model was the same initial conflict-free timetable which presented in previous scenario (Figure 5-7- top). This timetable was automatically improved by UIC compression technique of RailSys, according to the defined criteria (max. dwell time: 10 min, overtaking allowed at station and DB compression algorithm). More details on compression steps and results can be found in a paper by Pouryousef and Lautala [28].

The same exercise was repeated in HOTS model assuming the same max dwell time of 10 minutes, although the compression technique structure for stop patterns and departure flexibility parameters are different in HOTS and RailSys. Table 5-6 summarizes the user-defined parameters of the HOTS model used in Scenario 1-3.

Table 5-6- Details of defined parameters for HOTS model to solve Scenario 1-3

Criteria	Passenger	Commuter	Intermodal	Freight
Min. allowed dwell time (min)	0	0	0	0
Max. allowed dwell time(min)	10	10	10	10
F1DT[1] (min)	180[3]	180[3]	180[3]	180[3]
F2DT[2] (min)	240	300	300	300
Headway (min)	2	2	2	2
Priority of train	3	4	2	1

[1]: The earliest possible departure time of trains

[2]: The latest possible departure time of trains

[3]: Excluding the origin station

The initial timetable (Figure 5-8-a) and the results of improved timetable developed by RailSys and the “Same-Order” approach of HOTS model (Figure 5-8-b and c) reveal the difference in train movement patterns between the improved timetables by HOTS and RailSys. Table 5-7 compares the outcomes of RailSys and HOTS improvements. HOTS model was able to provide approximately 36 minutes shorter timetable duration (better capacity utilization) than RailSys, but the number of stops was slightly increased (11 vs. 9). Also the results show that while both HOTS model and RailSys could significantly improve the LOS parameters in comparison to the initial timetable, the duration of timetabled developed by both compression models was slightly increased, mainly due to the sizable reduction in maximum dwell time from 61’ to 10’.

Table 5-7- Comparison between initial and improved timetable developed by RailSys and HOTS model in Scenario 1-3 of single track case study (Same-Order approach)

Criteria		**Scenario 1-3**		
		Initial TT	**Improved by RailSys**	**Improved by HOTS**
LOS	**Number of stops**	14	9	11
	Min. dwell time	0’	0’	0’
	Max. dwell time	61’	10’	10’
	Total dwell times	271’	80’	66’
Capacity	**TT duration**	6h 10’	7h 04’	6h 28’
	TT Compression Level	-	-	36’
			-	8%

The research team also developed another comparison between the compression techniques of RailSys and HOTS model by considering the output of the improved timetable by RailSys (Figure 5-8-b) as the initial timetable of HOTS model and by evaluating whether HOTS could further improve the timetable. HOTS used the same maximum 10 minutes dwell time. After running the HOTS model, it was concluded that the results were almost identical with the initial timetable (RailSys output) in all aspects of analysis including the number of stops, stop pattern, total dwell times, and timetable duration.

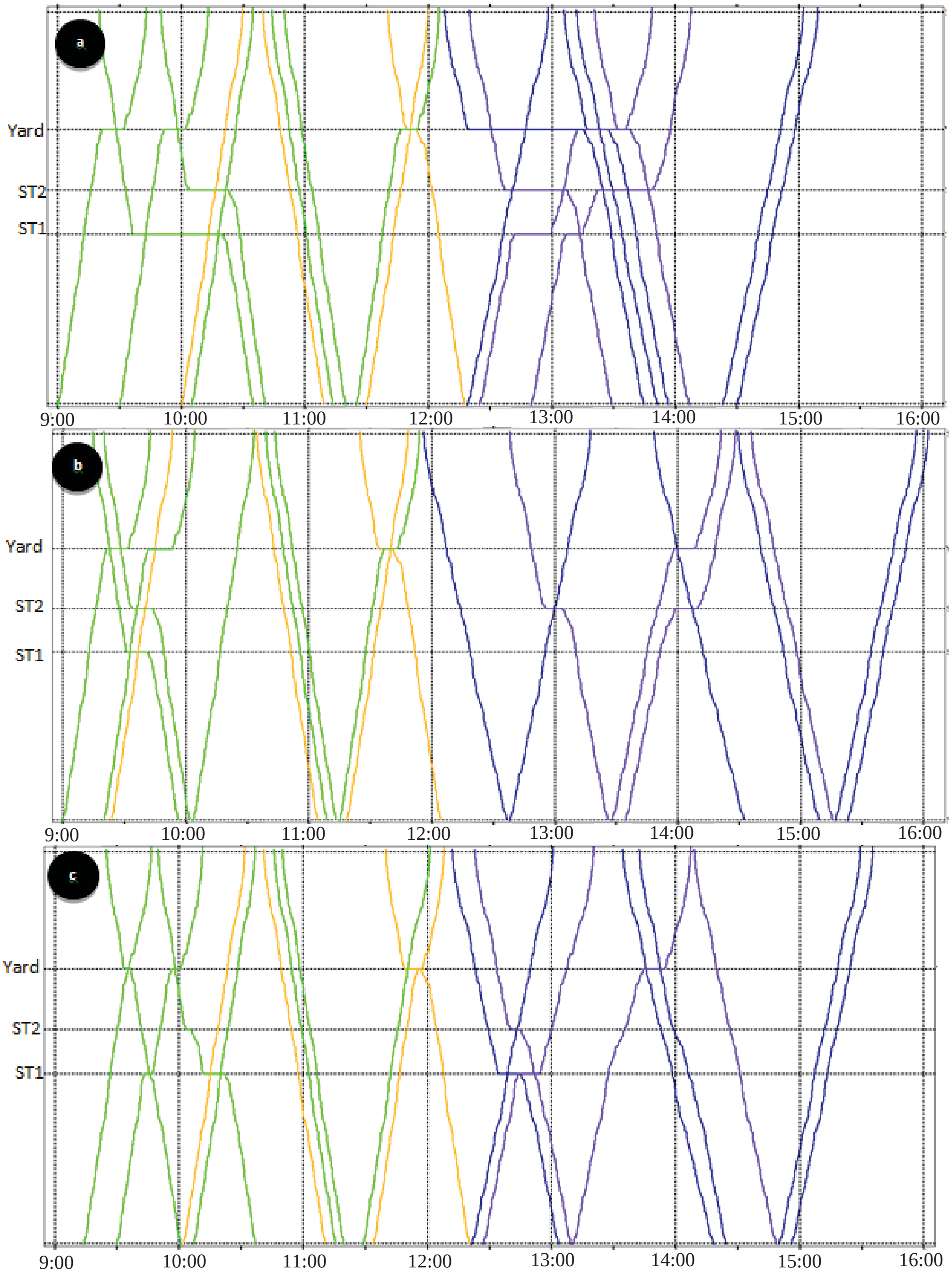

Figure 5-8- The initial timetable (a) was improved by RailSys (b), in comparison to the output developed by HOTS model (c) with shorter timetable duration

5-5-1-4- Summary of the HOTS Model Results for Single Track Case Study

Several scenarios were successfully implemented in the HOTS model to test the hypotheses on a single track case study. Based on the test:

- The HOTS model could transform an initial schedule with serious train conflicts to a “Conflict-Free” compressed schedule with both “Same-Order” and “Order-Free” rescheduling approaches. (Scenario 1-1)
- The HOTS model was able to improve and compress an initial conflict-free timetable developed by RTC. (Scenario 1-2), after manual adjustments were made to address station capacity limitations.
- RailSys and HOTS model provide similar compression results, even though techniques utilized are different. HOTS model could not further compress an already compressed timetable by RailSys. (Scenario 1-3)

5-5-2- Multiple-Track Case Study

A segment of North-East Corridor (NEC) between Washington, D.C. and Baltimore was used to evaluate the HOTS model in double and multiple-track situation. The case study is a 40.6 mile long multiple-track segment with several stop points and crossovers, and it is currently operated based on non-directional operation philosophy where trains use all tracks in both directions as necessary. A track schematic of the case study infrastructure, including the main track, platforms, switches and crossovers is presented in Figure 5-9.

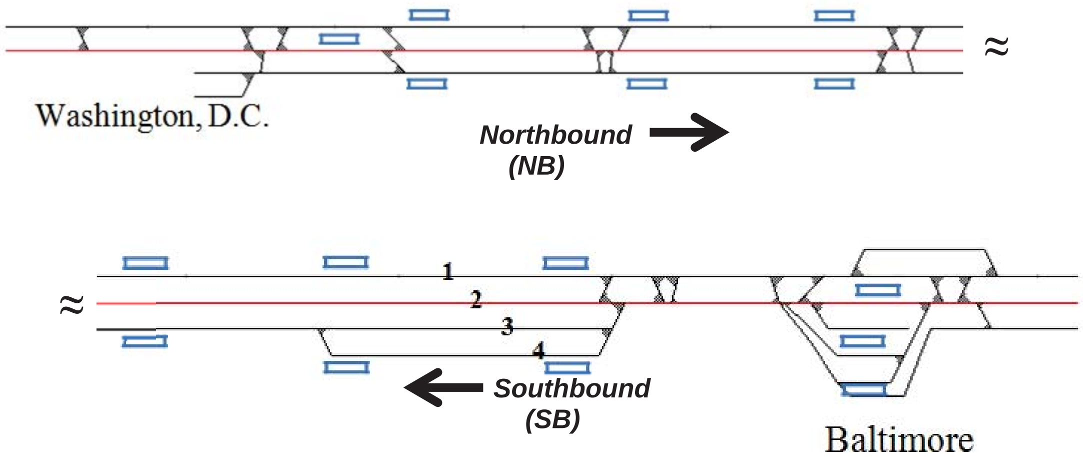

Figure 5-9- Case study infrastructure between Washington, D.C. – Baltimore including the tracks, platforms, and crossovers along the corridor

The segment is one of the most congested and complicated corridors in the U.S. rail network. Four types of trains (total of 136 trains) are in operation along the corridor, consisting of Acela Express (16 daily pairs), commuter (28 daily pairs), long-distance Amtrak (7 daily pairs) and regional Amtrak trains (17 daily pairs). Since trains are operated under non-directional operation pattern, trains regularly switch between tracks via crossovers, creating a total of 28 different route configurations for the case study. Table 5-8 presents a summary of the case study's characteristics.

Table 5-8- Details of multiple-track case study (Baltimore- Washington, D.C.)

Corridor Length	40.60 miles
Length of double track	1.48 miles
Length of triple track	33.94 miles
Length of quadruple track	5.18 miles
Sidings/yards	2 main yards + 8 station/crossover
Number of trains	68 (North) + 68 (South)
Operation pattern	Non-directional
Number of different routes	28 routes

RTC database that included infrastructure, signaling, rolling stock and operation characteristics was received from Amtrak and later replicated in RailSys for further analysis and comparison. More details of earlier corridor analysis can be found in a paper by Pouryousef and Lautala [29].

Two main scenarios were developed to test the HOTS model application in a multiple-track case study. The scenarios included:

- **Scenario 2-1:** timetable compression of the initial ("Conflict-Free") timetable of NEC through rescheduling
- **Scenario 2-2:** Further rescheduling of Scenario 2-1 after rerouting a single train.

It should be noted that the research uses the Baltimore-Washington, D.C. segment of the Northeast Corridor (NEC) as a stand-alone segment of infrastructure and does not examine continuation of routes on either end. The objective of the research was not to evaluate or recommend any changes to current NEC operations, but rather to take advantage of actual infrastructure and train operation data to understand the impact of different operation philosophies along a multiple-track corridor (non-directional/directional pattern) in self-contained context. Since the case study did not consider the movement of trains beyond the study limits, none of the suggested modifications are implementable without further study that evaluates the impacts and challenges over the entire length of the corridor.

5-5-2-1- Scenario 2-1: Timetable Compression of Initial Schedule

The purpose of this scenario was to evaluate whether the HOTS model is capable of rescheduling an initial timetable in a multiple-track case study with several non-directional routing patterns. It was assumed that Acela and Commuter trains could be departed up to 30 minutes earlier, while regional and long-distance trains could be departed up to 90 minutes earlier in the **"Same-Order"** rescheduling approach. Stop pattern and minimum requested dwell time of trains were maintained identical with initial timetable. Table 5-9 presents main parameters of HOTS model defined for this scenario. Flexibility parameters of the HOTS model (F1DT and F2DT) were assumed to be the same for each train category at all stations.

Table 5-9- Details of defined parameters for the HOTS model to solve Scenario 2-1

Criteria	Acela	Commuter	Long-distance	Regional
Min. allowed dwell time[1] (min)	1	1	1	1
Max. allowed dwell time[2] (min)	2	2	2	2
F1DT[3] (min)[4]	30	30	90	90
F2DT[5] (min)	30	30	90	90
Headway (min)	2	3	3	3
Priority of train	4	2	1	1

1: One minute minimum dwell time for planned stop points, otherwise zero
2: Two minute maximum dwell time for planned stop points, otherwise zero
3: The earliest possible departure time of trains
4: For the first train of the day, F1DT was assumed as zero (maintaining the same initial schedule)
5: The latest possible departure time of trains

The results of improved timetable (Same-Order approach) were generated by LINGO in less than one minute[13]. The same validation process as in the single track case study was conducted in RailSys. A two hour segment of the initial timetable before rescheduling is presented in Figure 5-10 (top) and the rescheduled timetable obtained from the HOTS model (bottom). Since Acela trains had higher priority, the model attempted to first reschedule them as early as possible (up to 30 minutes earlier), and then other trains were rescheduled to follow Acela trains while maintaining their initial order. Selected trains are identified in Figure 5-10 to demonstrate the train order and the level of timetable compression.

Overall, the HOTS model was able to compress the initial timetable by 48 minutes (based on “Same-Order” approach), while maintaining the initial departure order, routings, stop patterns, and minimum dwell times of all trains.

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[13] : 231,579 constraints, 460,300 non-zero parameters, and 2,720 variables

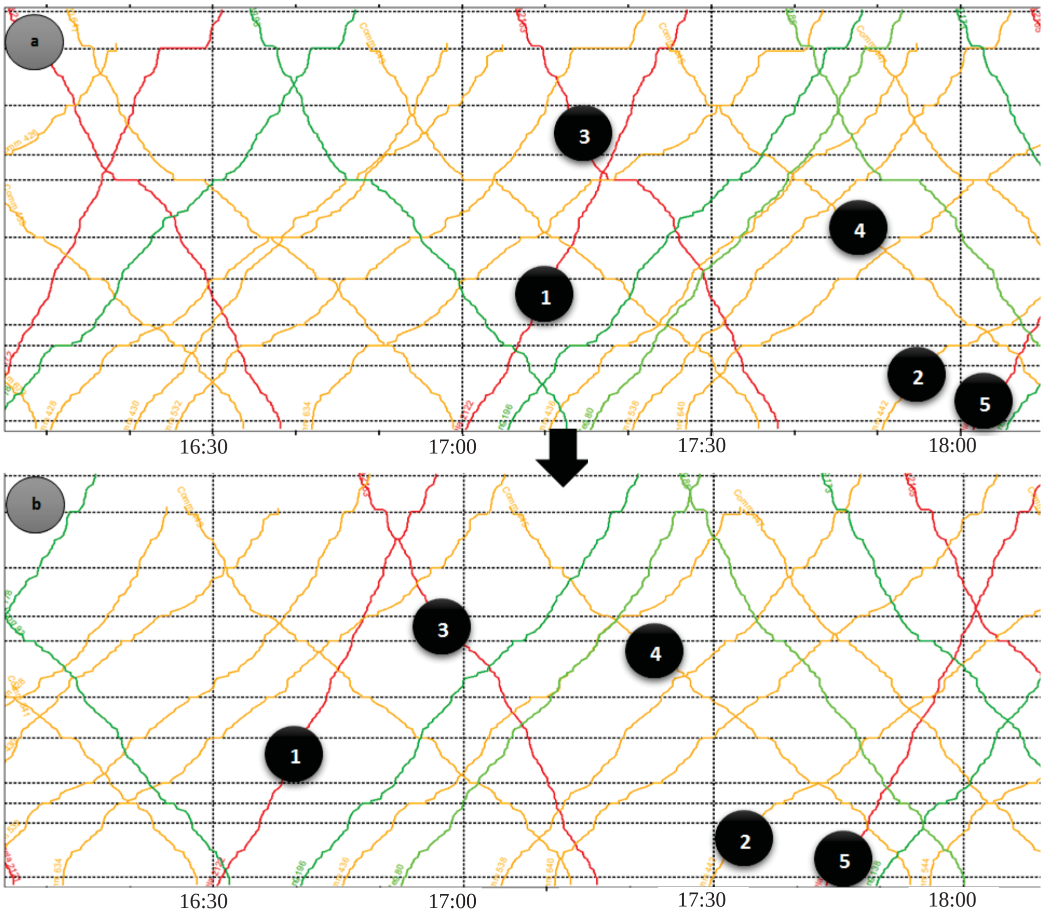

Figure 5-10- Initial (a) and rescheduled timetable (b) of NEC corridor based on "Same-Order" approach (Some of the trains are labeled in both figures for comparing the results before and after rescheduling)

5-5-2-2- Scenario 2-2: Rescheduling Trains Based on New Routing

The purpose of this scenario was to examine the capability of the HOTS model to reschedule an initial schedule while allowing new routing for a given train (or several trains), to provide a new conflict-free schedule. Train rerouting is a common practice on double and multiple track corridors, but introducing a new route to a given train(s) may also cause challenges and schedule conflicts with other trains, making rerouting a complex and laborious process. Train #2 was randomly selected from the improved timetable (Figure 5-10-bottom) for rerouting to the same route as Train #5. As shown in Figure 5-11, if both trains maintain their current schedule, there will be a conflict in Odenton station (highlighted on the figure) since there is no available track for meet-pass at this station. The situation was resolved by defining a new route and higher departure flexibility for Train #2. The rest of the parameters were considered the same as previously defined in the Scenario 2-1. The HOTS model was able to provide a "Conflict-Free" timetable considering the new route for Train #2, while the schedule before Train #2 remained unchanged. (Figure 5-11-bottom). This removed conflicting operations between Train #2 and Train #5. In addition to these two trains, six other trains (all departing after Train #2) were rescheduled by the model. The overall duration of timetable was maintained as the same as in Scenario 2-1.

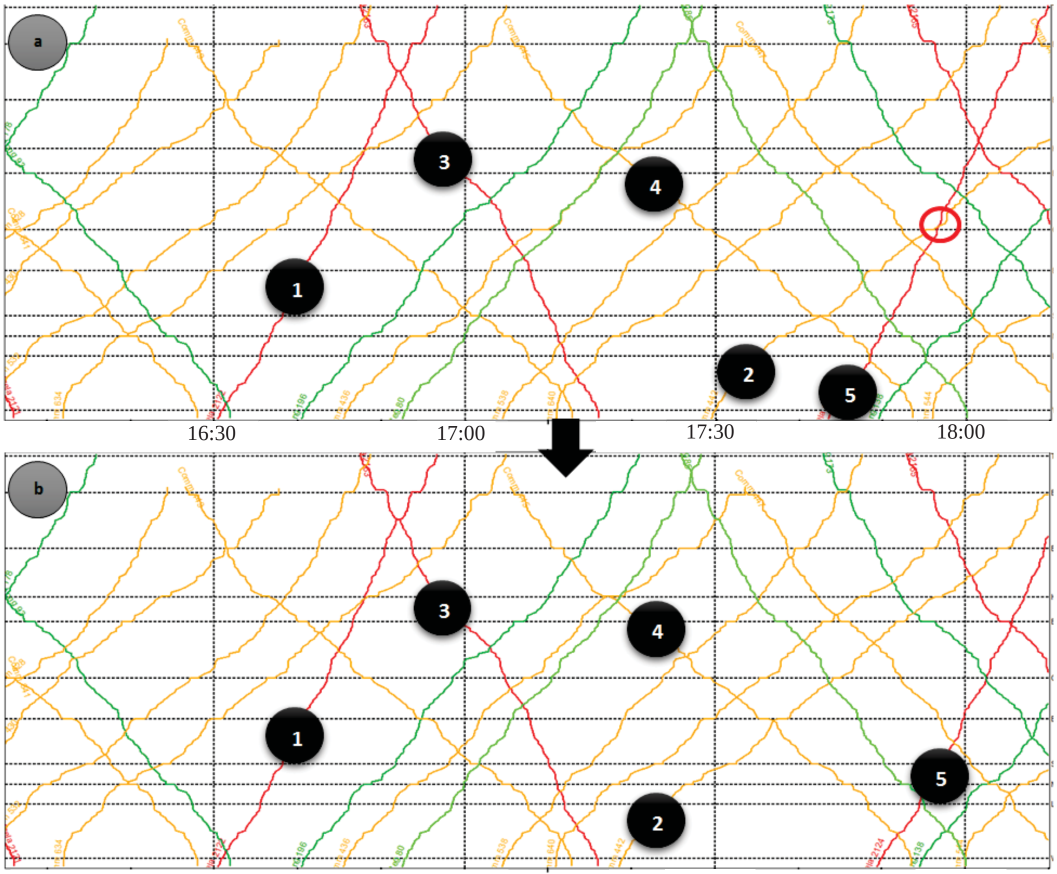

Figure 5-11- TT developed in Scenario 2-1 (a) was rescheduled by the HOTS model to address the new route defined for Train #2 (b)

5-5-3- Summary of the HOTS Model Results for Multiple-Track Case Study

Two multiple-track case study scenarios, rescheduling a multiple-track corridor and rescheduling trains after assigning a new route to a given train were successfully completed by the HOTS model for the NEC corridor. In the first scenario, the HOTS model was able to develop a “Conflict-Free” compressed schedule (Same-Order approach) with non-directional operation pattern, while maintaining the same routings and stop patterns of trains, but allowing the early/late departure flexibility parameters for trains (F1DT and F2DT). HOTS model compressed the timetable by 48 minutes from the initial schedule. In the second scenario, a given train was moved to a new route. The new route was defined in the HOTS model, and the new schedule was developed based on the necessary changes on the given train's parameters, but the rest of the HOTS model parameters remained unchanged from Scenario 2-1. Six other trains affected by the rerouting were rescheduled as part of the process, but the total duration of updated timetable remained unchanged. The outcome of the second scenario demonstrates the ability of the HOTS model to provide a "Conflict-Free" and compressed schedule when new routes for the trains are assigned.

Table 5-10 compares some of the operational and capacity related criteria between the initial and developed timetables (based on "Same-Order" approach) in the multiple-track case study. As presented in Table 5-10, the HOTS model could either improve or at least maintain the same characteristics of the initial timetable. While only the "Same-Order" approach was used, the HOTS model could also be used to reschedule the initial timetable of NEC corridor based on the "Order-Free" rescheduling approach, but different flexibility parameters of train departure and dwell times would be required.

Table 5-10- Comparison between initial timetable and rescheduled timetable developed by the HOTS model in different scenarios of NEC as multiple-track case study (Same-Order rescheduling approach)

Criteria		Initial TT of NEC	Rescheduled by HOTS (Scenario 2-1)	Rescheduled by HOTS Based on New Route (Scenario 2-2)
LOS	**Number of stops[1]**	402	402	402
	Min. dwell time[2]	1’	1’	1’
	Max. dwell time[2]	3’	2’	2’
	Total dwell times[1]	557’	405’	405’
Capacity	**TT duration**	23h 46’	22h 58’	22h 58’
	TT Compression Level	-	48’	48’
		-	3.3%	3.3%

[1]: *Excluding the origin and destination*

[2]: *Only for planned stop points, otherwise zero*

5-6- Summary and Conclusions

Rescheduling, and a particular a type of rescheduling called “timetable compression technique”, is one of the main methods to improve operational characteristics of a rail corridor. While there are several timetable tools and rail simulation packages with operational management capabilities available in the rail industry, the features vary from tool to tool, and timetable management techniques (e.g. timetable compression) or optimization models for rescheduling and timetable improvement are limited, especially in tools that target the U.S. rail environment with more non-timetable based operating principles.

A new standalone analytical model called “Hybrid Optimization of Train Schedules” (HOTS) was introduced in this paper. HOTS can work in conjunction with any commercial rail simulation software and it can reschedule an initial timetable (with or without conflict) to provide a “Conflict-Free” timetable. HOTS includes an optimization model which receives some of the main rescheduling parameters from the simulation/ timetable management tool outputs, in addition to user-defined parameters. The model outcomes can be used to update the requested departure and dwell times for validation in the simulation software, or to perform further analysis and calculations based on the new optimized results.

There are several applications in which the HOTS model can be used to improve the initial timetable, including:

- Rescheduling an initial timetable (with or without conflict) to provide a “Conflict-Free” timetable based on defined criteria
- Rescheduling trains on any type of rail corridor, including single, double and multiple track corridors under both directional and non-directional operation patterns
- Analyzing different stop patterns, flexibility of trains to be departed earlier or later, and min/max dwell times for selected trains to evaluate the level of service and capacity utilization under new scenarios
- Compressing the initial timetable to provide more capacity (shorter timetable duration of existing trains) for additional trains
- Rescheduling trains based on assigning new routing scenarios to the selected trains for double and multiple track corridors.
- Rescheduling trains by either maintaining the same order of initial departure times before improvement (“Same-Order” approach), or by shuffling trains based on the new earliest departure times (“Order-Free” approach)

Two case studies, both with several scenarios were demonstrated and analyzed in the paper to examine the different capabilities and hypotheses of the HOTS model (mentioned above), especially for the U.S. rail environment which is different from the European rail corridors (e.g. non-directional operation vs. directional operation approach). According to the results of scenarios/application tested in the paper, the

HOTS model could either improve or maintain the same criteria of an initial timetable as summarized below:

- Resolving the schedule conflicts of an initial timetable, in both “Same-Order” and “Order Free” rescheduling applications (Scenario 1-1)
- Compressing a “Conflict-Free” timetable (Scenario 1-2)
- Comparison between the compression techniques of HOTS model and RailSys. (Scenario 1-3)
- Compressing the initial schedule of a multiple-track corridor with non-directional operation pattern (NEC), while maintaining the routings and stop patterns of trains. (Scenario 2-1)
- Providing a “Conflict-Free” and compressed schedule of a multiple-track corridor (NEC), based on defining a new route for the trains. (Scenario 2-2)

5-7- Future Research

Although the HOTS model was capable of rescheduling/compressing timetables for different scenarios and applications, several limitations have been identified in the current version. The model structure cannot take into account the station capacity limits, requiring a second iteration of the model with manual adjustments. Incorporation of a station capacity constraint would make the model more user-friendly and allow it to reach the final solution with a single run. Another solution could be using the actual track/switch arrangements at stations, by updating station topology from a node-based approach to a link-based approach. Some of the constraints of the existing HOTS model should be consequently adjusted in an expanded version of the HOTS model to address respective changes needed for the link-based approach of stations.

The optimization part of the HOTS model has been developed based on minimizing the departure times as well as deviation of train dwell times, which forces the train schedules to be compressed as early as possible. In practice, there might be a preference to reschedule some selected trains to be departed as early as possible, while for others (e.g. freight trains) the dispatcher might prefer a late departure. This would provide more capacity in the middle of the timetable, instead of compressing all trains to the left side of timetable. An expanded version of the HOTS model that uses a dual-objective algorithm for minimizing the departure time of some selected trains while maximizing others (as late departure as possible), could be developed to expand the alternatives for analysis.

5-8- Acknowledgments

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CHAPTER 6

6- Conclusions and Future Research

This research investigated different methodologies, techniques and tools for railway capacity evaluation. More specifically, the research used an approach where case studies were developed within the U.S. and European railway simulation packages to study timetable management techniques. Based on the knowledge, a standalone analytical model, “Hybrid Optimization of Train Schedules” (HOTS), was developed that works with any simulation/ timetable management tools and uses initial timetable and user-defined criteria to develop a “Conflict-Free” and compressed timetable of trains.

The following sections provide conclusions of the research:

- The review of previous studies and papers revealed no single definition of railroad capacity. Rather, the definition varies based on the techniques and objectives of the specific study. The capacity analysis approaches and methodologies can be classified in several ways, but are most commonly divided into analytical and simulation methods. A third “combined” approach that takes advantage of both analytical and simulation methods, was also identified in the research.
- Past European rail capacity studies are more unified in terms of capacity concepts and techniques, while the U.S. studies use a variety of methods, tools and objectives. The majority of studies in both continents use either simulation, or combined simulation-analytical approach, but due to the significant differences between principle traffic type (passenger vs. freight), operating philosophy (structured vs. non-structured) and network characteristics of these two rail systems, European studies tend to use timetable-based simulation tools (e.g. RailSys) when compared to the non-timetable based tools (e.g. RTC) commonly used on the U.S. rail network. It was also found that validation of

studies against actual operations was rarely completed, or was limited to comparisons with base model.

- Several conclusions were made on the operation of current simulations software investigated as part of the project:
    - Non-timetable and timetable based tools offer different capabilities designed to match the type of operations analyzed. The timetable-based simulation tools are typically equipped with timetable management features (e.g. timetable compression technique), while non-timetable-based simulation packages concentrate on automatically resolving train conflicts.
    - It was concluded that the timetable compression technique of RailSys can be applied on any single-track corridor, but it is only valid for double/multiple track corridors if trains are operated under a directional operation pattern.
    - The outcomes of automatic timetable compression technique of RailSys (and perhaps any other simulation package), should be double checked for any further improvement opportunities by manual adjustments.
    - OpenTrack offers automated alternative routing options for trains. Similar to RTC, it is also capable of automatically resolve the train conflicts, although the respective parameters and criteria of resolving the conflict differ from RTC.

- The following conclusions were derived as part of the development of “Hybrid Optimization of Train Schedules” (HOTS) model:
    - The outcomes of a new hybrid simulation approach that utilized current non-timetable (RTC) and timetable based (RailSys) tools suggest that UIC 406 compression techniques have the potential to be successfully applied for the single track corridors in the U.S. rail environment. However, the procedure of replicating databases in two simulation software is time-consuming and the challenges in conversion of rolling stock and signaling

features may cause some minor differences in results. These issues limit the potential for a wider research application.

- Operational modifications, including a shift to directional train operations through rerouting, rescheduling, or combined rerouting/rescheduling efforts can offer increased capacity utilization on multiple-track corridor, but it is difficult to quantify the benefits of increased average speed of trains versus the disadvantages of increased train delays. A new “Speed-Delay normalized parameter” (SD) was introduced in the study to provide a method to investigate the tradeoff between changes in train speeds and train delays.
- The HOTS model condenses different capabilities currently offered either by non-timetable based, or timetable based software into a single analytical model. The capabilities of HOTS include:
  - Rescheduling an initial timetable (with or without conflict) to provide a “Conflict-Free” timetable based on defined criteria
  - Applicability to all rail corridors including single, double and multiple track corridors under both directional and non-directional operation pattern
  - Ability to use different stop patterns, flexibility of departing trains, and min/max dwell times for selected trains to investigate the level of service and capacity utilization on new scenarios
  - Ability of the model to work in conjunction with any commercial rail simulation and timetable management tools
  - Compression of the initial timetable (shorter timetable duration of existing trains) to provide more capacity for new trains
  - Rescheduling of trains based on new routing scenarios of selected trains on double and multiple track corridors.
  - Rescheduling of trains by either maintaining the same order of departures (“Same-Order” approach), or by allowing changes in train

order based on the new earliest departure times (“Order-Free” approach)

- In testing, the HOTS model was successful in either improving the capacity and/or service quality, or at least maintaining the initial capacity level and service conditions on single and multiple-track case studies.

6-2- Future Research Opportunities

Limited research has been conducted on using operational management techniques to improve the capacity and level of service of shared-use corridors in the U.S. The research presented in this dissertation has provided same initial steps to close the research gap, but there are numerous other topics that could be addressed in the future research. Some of the most critical needs related to the key topics of this research (capacity evaluation, train scheduling, and operations) include:

1: Long-term planning of the shared-use corridors:

What is the optimal train mix and dispatching approaches to maximize a shared-use corridor capacity? For instance, how would the capacity of a shared corridor be affected by a conversion from the currently operated heavy freight trains with slow speeds to shorter freight trains that possess similar train performance with passenger trains?

Would shared-use corridors in the U.S. rail environment benefit from a shift to structured operation philosophy where all trains have predefined and detailed daily schedules? If yes, how should operations philosophy be changed to maintain/improve the level of service of all passenger and freight trains under structured scenario?

2: Balance between capacity and level of service (LOS) metrics: How to determine the ideal balance between the capacity utilization (number of trains per day) and the level of service metrics (total and maximum dwell time, delay, number of meet-pass stops), so the most adequate service is provided for different operational mixes on shared corridors?

3: Operation patterns of multiple-track corridors: What would the criteria be to determine, if a multiple-track corridor could benefit from a shift to directional operation pattern through rescheduling/rerouting? Is the loss of operational flexibility caused by the shift adequately compensated by the advances in train speeds and capacity utilization, or should some of the trains maintain non-directional operations?

4: Dynamic planning and real-time rescheduling: Which features and tools of a given rail simulator or a scheduling model should be considered during real-time rescheduling and rerouting practices, in case of service interruption, maintenance activities, and emergency situations, to help dispatchers for making a quick and reliable decision to recover the schedule?

5: Urban rail transit rescheduling practices: The current research focused on the intercity rail operations and did not investigate on any application of urban rail transit practices, regarding rescheduling and timetable development. Therefore, it would be an interesting future research to explore differences and similarities between urban/rail transit (e.g., heavy rail rapid transit, light rail transit, commuter services), and intercity rail services in terms of rescheduling and timetable development models and tools. For instance, what parameters of timetable development and rescheduling might be more important and sensitive in only one of these systems, and what parameters are equally valid and essential in both systems?

Although the HOTS model was capable in rescheduling/compressing timetables for different test scenarios, future research and development is necessary to address the current model limitations. Some of the major recommendations for future HOTS development include:

- The current structure of HOTS model does not consider station capacity limits, so a second iteration may be needed to resolve potential station capacity shortage. Incorporating a station capacity constraint into the model would make the model more accurate and user-friendly, and remove the need for second iteration. Another solution for this issue would be updating station topology in the HOTS model database from node-based approach to the link-based approach that represents actual track/switch arrangements at stations.
- The optimization part of the HOTS model has been developed to force the trains to depart as early as possible. However, in practice, the dispatcher may prefer to consider selected trains, such as freight trains, to be departed as late as possible (compression to the right side of timetable). It would be beneficial to develop an expanded version of the HOTS model that uses a dual-objective algorithm for minimizing the departure time of selected trains (dispatch as early as possible) while the objective for the remaining trains will be to maximize the departure times (dispatch as late as possible).
- The current database structure and input of HOTS model relies on Excel spreadsheets. A graphic interface would improve the user-friendliness of database development.
- The current structure of the HOTS model has been built based on deterministic scheduling approach, while freight rail services (or even may follow more stochastic modeling approach where initial departure times and dwell times are considered under probabilistic functions. An extension of HOTS model, or a new model, with stochastic functions, has potential to benefit freight rail services with no predefined/detailed schedule.

HOTS model was tested only on limited applications as part of the research, but there are numerous potential future opportunities. Since the HOTS model includes a variety of scheduling parameters (flexible factors to be customized based on user preferences), it is beneficial to apply HOTS model through further research opportunities related to the rescheduling and timetable development practices, as identified earlier in the chapter.

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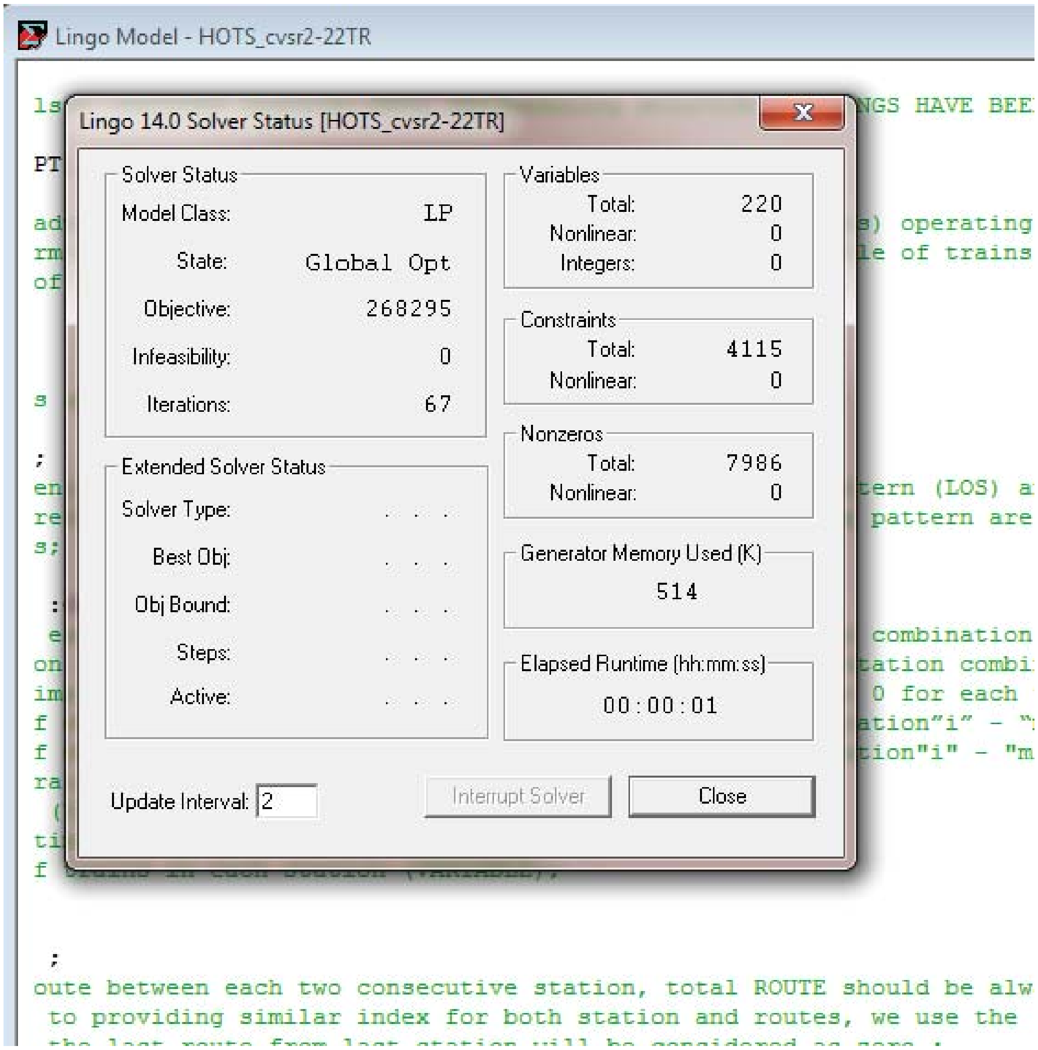
APPENDIX

Appendix

I: Screenshots of Lingo Results- HOTS Model



Solver Status
Model Class: LP
State: Global Opt
Objective: 268295
Infeasibility: 0
Iterations: 67

Extended Solver Status
Solver Type: . . .
Best Obj: . . .
Obj Bound: . . .
Steps: . . .
Active: . . .

Variables
Total: 220
Nonlinear: 0
Integers: 0

Constraints
Total: 4115
Nonlinear: 0

Nonzeros
Total: 7986
Nonlinear: 0

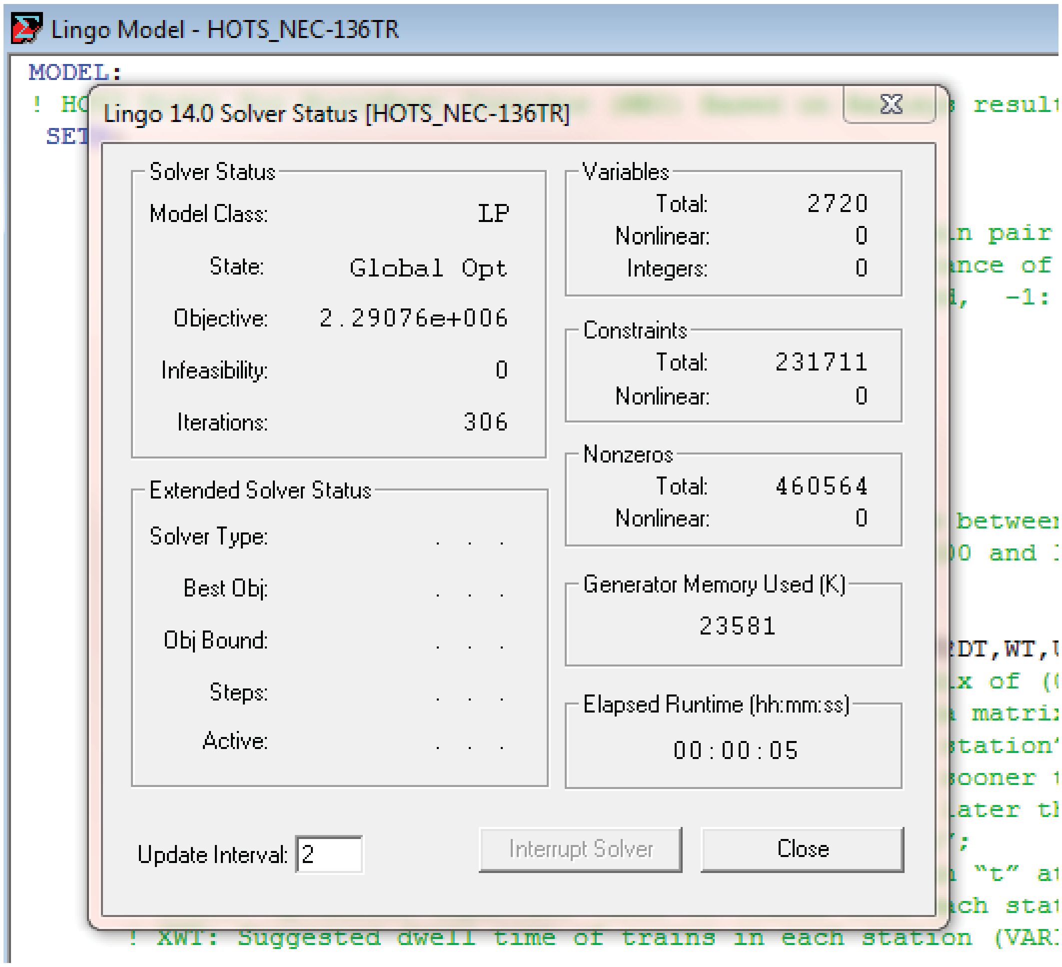
Generator Memory Used (K)
514

Elapsed Runtime (hh:mm:ss)
00:00:01

Update Interval: 2

```
oute between each two consecutive station, total ROUTE should be alw
 to providing similar index for both station and routes, we use the
```

Figure A-1- Snapshot of the optimum solution found by Lingo after solving the single-track case study based on HOTS model (Scenario 1-3 in Chapter 5)



Lingo Model - HOTS_NEC-136TR

```
MODEL:
! HO                                                    s result
  SET
                                                        in pair
                                                        ance of
                                                        1,   -1:
                                                        between
                                                        00 and 1
                                                        DT,WT,U
                                                        x of ((
                                                        a matri
                                                        station'
                                                        sooner t
                                                        later th
                                                        ;
                                                        n "t" at
                                                        ach stat
     ! XWT: Suggested dwell time of trains in each station (VAR
```

Lingo 14.0 Solver Status [HOTS_NEC-136TR]

Solver Status

Model Class: LP

State: Global Opt

Objective: 2.29076e+006

Infeasibility: 0

Iterations: 306

Extended Solver Status

Solver Type:

Best Obj:

Obj Bound:

Steps:

Active:

Variables

Total: 2720

Nonlinear: 0

Integers: 0

Constraints

Total: 231711

Nonlinear: 0

Nonzeros

Total: 460564

Nonlinear: 0

Generator Memory Used (K)

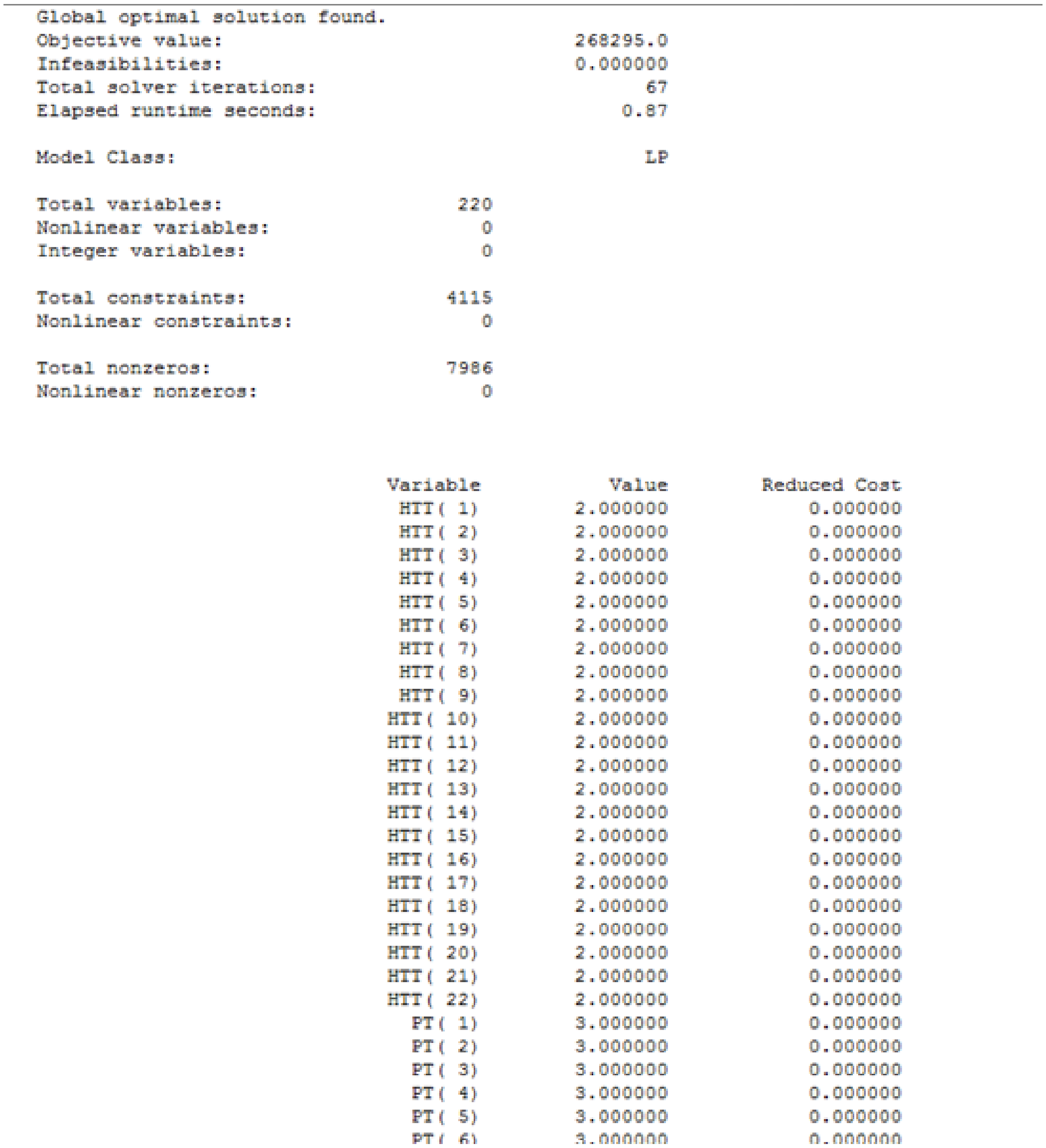
23581

Elapsed Runtime (hh:mm:ss)

00:00:05

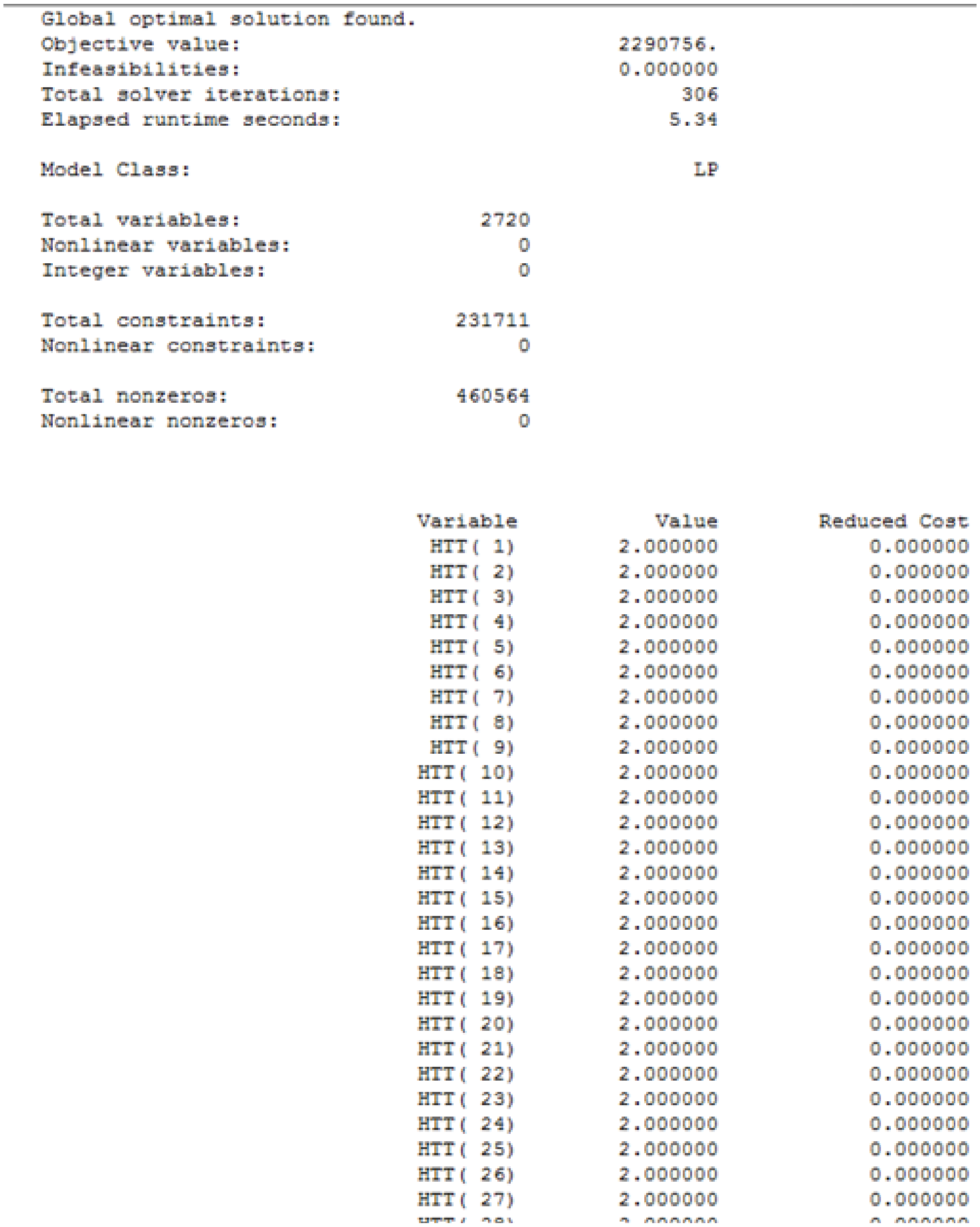
Update Interval: 2

Figure A-2- Snapshot of the optimum solution found by Lingo after solving the multiple-track case study based on HOTS model (Scenario 2-1 in Chapter 5)



```
Global optimal solution found.
Objective value:                              268295.0
Infeasibilities:                              0.000000
Total solver iterations:                            67
Elapsed runtime seconds:                          0.87

Model Class:                                        LP

Total variables:                    220
Nonlinear variables:                  0
Integer variables:                    0

Total constraints:                 4115
Nonlinear constraints:                0

Total nonzeros:                    7986
Nonlinear nonzeros:                   0


                              Variable           Value        Reduced Cost
                               HTT( 1)        2.000000            0.000000
                               HTT( 2)        2.000000            0.000000
                               HTT( 3)        2.000000            0.000000
                               HTT( 4)        2.000000            0.000000
                               HTT( 5)        2.000000            0.000000
                               HTT( 6)        2.000000            0.000000
                               HTT( 7)        2.000000            0.000000
                               HTT( 8)        2.000000            0.000000
                               HTT( 9)        2.000000            0.000000
                              HTT( 10)        2.000000            0.000000
                              HTT( 11)        2.000000            0.000000
                              HTT( 12)        2.000000            0.000000
                              HTT( 13)        2.000000            0.000000
                              HTT( 14)        2.000000            0.000000
                              HTT( 15)        2.000000            0.000000
                              HTT( 16)        2.000000            0.000000
                              HTT( 17)        2.000000            0.000000
                              HTT( 18)        2.000000            0.000000
                              HTT( 19)        2.000000            0.000000
                              HTT( 20)        2.000000            0.000000
                              HTT( 21)        2.000000            0.000000
                              HTT( 22)        2.000000            0.000000
                                PT( 1)        3.000000            0.000000
                                PT( 2)        3.000000            0.000000
                                PT( 3)        3.000000            0.000000
                                PT( 4)        3.000000            0.000000
                                PT( 5)        3.000000            0.000000
                                PT( 6)        3.000000            0.000000
```

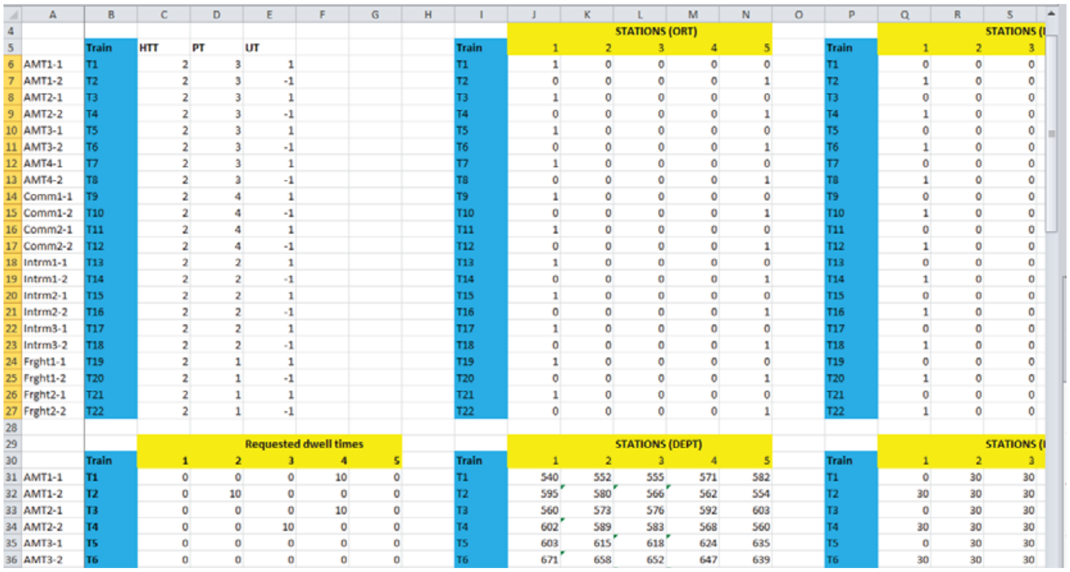
Figure A-3- Snapshot of the results of Lingo Software after solving the single-track case study based on HOTS model (Scenario 1-3 in Chapter 5)



```
Global optimal solution found.
Objective value:                              2290756.
Infeasibilities:                              0.000000
Total solver iterations:                           306
Elapsed runtime seconds:                          5.34

Model Class:                                        LP

Total variables:                   2720
Nonlinear variables:                  0
Integer variables:                    0

Total constraints:               231711
Nonlinear constraints:                0

Total nonzeros:                  460564
Nonlinear nonzeros:                   0



                                Variable           Value        Reduced Cost
                                 HTT( 1)        2.000000            0.000000
                                 HTT( 2)        2.000000            0.000000
                                 HTT( 3)        2.000000            0.000000
                                 HTT( 4)        2.000000            0.000000
                                 HTT( 5)        2.000000            0.000000
                                 HTT( 6)        2.000000            0.000000
                                 HTT( 7)        2.000000            0.000000
                                 HTT( 8)        2.000000            0.000000
                                 HTT( 9)        2.000000            0.000000
                                HTT( 10)        2.000000            0.000000
                                HTT( 11)        2.000000            0.000000
                                HTT( 12)        2.000000            0.000000
                                HTT( 13)        2.000000            0.000000
                                HTT( 14)        2.000000            0.000000
                                HTT( 15)        2.000000            0.000000
                                HTT( 16)        2.000000            0.000000
                                HTT( 17)        2.000000            0.000000
                                HTT( 18)        2.000000            0.000000
                                HTT( 19)        2.000000            0.000000
                                HTT( 20)        2.000000            0.000000
                                HTT( 21)        2.000000            0.000000
                                HTT( 22)        2.000000            0.000000
                                HTT( 23)        2.000000            0.000000
                                HTT( 24)        2.000000            0.000000
                                HTT( 25)        2.000000            0.000000
                                HTT( 26)        2.000000            0.000000
                                HTT( 27)        2.000000            0.000000
```

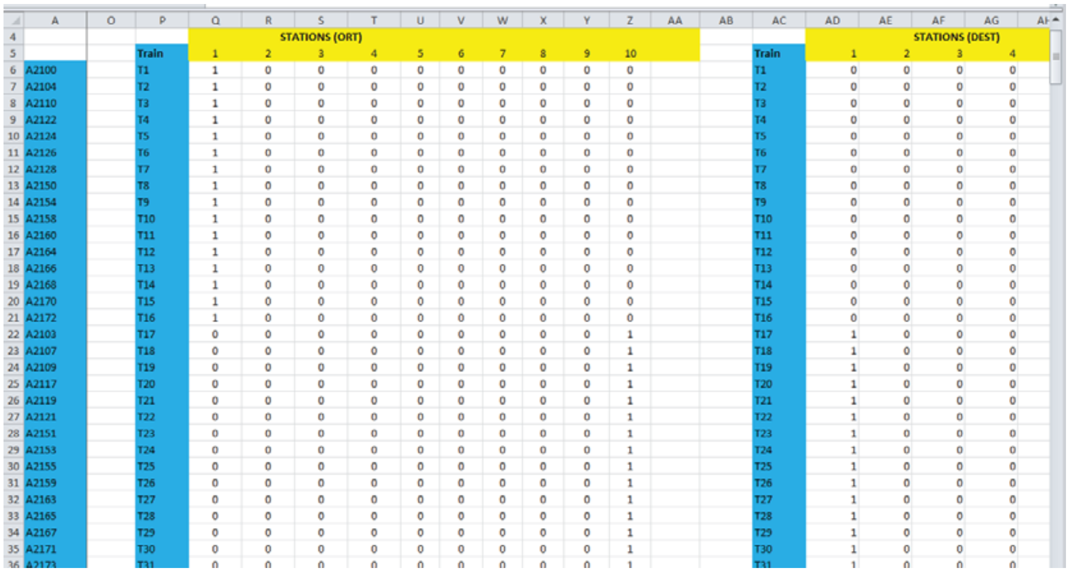
Figure A-4- Snapshot of the results of Lingo Software after solving the multiple-track case study based on HOTS model (Scenario 2-1 in Chapter 5)

II: Screenshots of Datasets Developed through the Case Studies of HOTS Model



	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S
4										STATIONS (ORT)							STATIONS (		
5		Train	HTT	PT	UT				Train	1	2	3	4	5		Train	1	2	3
6	AMT1-1	T1	2	3	1				T1	1	0	0	0	0		T1	0	0	0
7	AMT1-2	T2	2	3	-1				T2	0	0	0	0	1		T2	1	0	0
8	AMT2-1	T3	2	3	1				T3	1	0	0	0	0		T3	0	0	0
9	AMT2-2	T4	2	3	-1				T4	0	0	0	0	1		T4	1	0	0
10	AMT3-1	T5	2	3	1				T5	1	0	0	0	0		T5	0	0	0
11	AMT3-2	T6	2	3	-1				T6	0	0	0	0	1		T6	1	0	0
12	AMT4-1	T7	2	3	1				T7	1	0	0	0	0		T7	0	0	0
13	AMT4-2	T8	2	3	-1				T8	0	0	0	0	1		T8	1	0	0
14	Comm1-1	T9	2	4	1				T9	1	0	0	0	0		T9	0	0	0
15	Comm1-2	T10	2	4	-1				T10	0	0	0	0	1		T10	1	0	0
16	Comm2-1	T11	2	4	1				T11	1	0	0	0	0		T11	0	0	0
17	Comm2-2	T12	2	4	-1				T12	0	0	0	0	1		T12	1	0	0
18	Intrm1-1	T13	2	2	1				T13	1	0	0	0	0		T13	0	0	0
19	Intrm1-2	T14	2	2	-1				T14	0	0	0	0	1		T14	1	0	0
20	Intrm2-1	T15	2	2	1				T15	1	0	0	0	0		T15	0	0	0
21	Intrm2-2	T16	2	2	-1				T16	0	0	0	0	1		T16	1	0	0
22	Intrm3-1	T17	2	2	1				T17	1	0	0	0	0		T17	0	0	0
23	Intrm3-2	T18	2	2	-1				T18	0	0	0	0	1		T18	1	0	0
24	Frght1-1	T19	2	1	1				T19	1	0	0	0	0		T19	0	0	0
25	Frght1-2	T20	2	1	-1				T20	0	0	0	0	1		T20	1	0	0
26	Frght2-1	T21	2	1	1				T21	1	0	0	0	0		T21	0	0	0
27	Frght2-2	T22	2	1	-1				T22	0	0	0	0	1		T22	1	0	0
28																			
29			Requested dwell times							STATIONS (DEPT)							STATIONS (		
30		Train	1	2	3	4	5		Train	1	2	3	4	5		Train	1	2	3
31	AMT1-1	T1	0	0	0	10	0		T1	540	552	555	571	582		T1	0	30	30
32	AMT1-2	T2	0	10	0	0	0		T2	595	580	566	562	554		T2	30	30	30
33	AMT2-1	T3	0	0	0	10	0		T3	560	573	576	592	603		T3	0	30	30
34	AMT2-2	T4	0	0	10	0	0		T4	602	589	583	568	560		T4	30	30	30
35	AMT3-1	T5	0	0	0	0	0		T5	603	615	618	624	635		T5	0	30	30
36	AMT3-2	T6	0	0	0	0	0		T6	671	658	652	647	639		T6	30	30	30

Figure A-5- Snapshot of the Excel dataset developed for single-track case study through HOTS model (Scenario 1-3 in Chapter 5)



	A	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA	AB	AC	AD	AE	AF	AG
4				STATIONS (ORT)													STATIONS (DEST)			
5			Train	1	2	3	4	5	6	7	8	9	10			Train	1	2	3	4
6	A2100		T1	1	0	0	0	0	0	0	0	0	0			T1	0	0	0	0
7	A2104		T2	1	0	0	0	0	0	0	0	0	0			T2	0	0	0	0
8	A2110		T3	1	0	0	0	0	0	0	0	0	0			T3	0	0	0	0
9	A2122		T4	1	0	0	0	0	0	0	0	0	0			T4	0	0	0	0
10	A2124		T5	1	0	0	0	0	0	0	0	0	0			T5	0	0	0	0
11	A2126		T6	1	0	0	0	0	0	0	0	0	0			T6	0	0	0	0
12	A2128		T7	1	0	0	0	0	0	0	0	0	0			T7	0	0	0	0
13	A2150		T8	1	0	0	0	0	0	0	0	0	0			T8	0	0	0	0
14	A2154		T9	1	0	0	0	0	0	0	0	0	0			T9	0	0	0	0
15	A2158		T10	1	0	0	0	0	0	0	0	0	0			T10	0	0	0	0
16	A2160		T11	1	0	0	0	0	0	0	0	0	0			T11	0	0	0	0
17	A2164		T12	1	0	0	0	0	0	0	0	0	0			T12	0	0	0	0
18	A2166		T13	1	0	0	0	0	0	0	0	0	0			T13	0	0	0	0
19	A2168		T14	1	0	0	0	0	0	0	0	0	0			T14	0	0	0	0
20	A2170		T15	1	0	0	0	0	0	0	0	0	0			T15	0	0	0	0
21	A2172		T16	1	0	0	0	0	0	0	0	0	0			T16	0	0	0	0
22	A2103		T17	0	0	0	0	0	0	0	0	0	1			T17	1	0	0	0
23	A2107		T18	0	0	0	0	0	0	0	0	0	1			T18	1	0	0	0
24	A2109		T19	0	0	0	0	0	0	0	0	0	1			T19	1	0	0	0
25	A2117		T20	0	0	0	0	0	0	0	0	0	1			T20	1	0	0	0
26	A2119		T21	0	0	0	0	0	0	0	0	0	1			T21	1	0	0	0
27	A2121		T22	0	0	0	0	0	0	0	0	0	1			T22	1	0	0	0
28	A2151		T23	0	0	0	0	0	0	0	0	0	1			T23	1	0	0	0
29	A2153		T24	0	0	0	0	0	0	0	0	0	1			T24	1	0	0	0
30	A2155		T25	0	0	0	0	0	0	0	0	0	1			T25	1	0	0	0
31	A2159		T26	0	0	0	0	0	0	0	0	0	1			T26	1	0	0	0
32	A2163		T27	0	0	0	0	0	0	0	0	0	1			T27	1	0	0	0
33	A2165		T28	0	0	0	0	0	0	0	0	0	1			T28	1	0	0	0
34	A2167		T29	0	0	0	0	0	0	0	0	0	1			T29	1	0	0	0
35	A2171		T30	0	0	0	0	0	0	0	0	0	1			T30	1	0	0	0
36	A2173		T31	0	0	0	0	0	0	0	0	0	1			T31	1	0	0	0

Figure A-6- Snapshot of the Excel dataset developed for multiple-track case study through HOTS model (Scenario 2-1 in Chapter 5)