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CAPACITY EVALUATION AND INFRASTRUCTURE PLANNING TECHNIQUES FOR OPERATION OF FREIGHT AND HIGHER-SPEED PASSENGER TRAINS ON SHARED RAILWAY CORRIDORS

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DISCLAIMER

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TECHNICAL SUMMARY

Title

Capacity Evaluation and Infrastructure Planning Techniques for Operation of Freight and Higher-Speed Passenger Trains on Shared Railway Corridors

(Dissertation title: Capacity Evaluation and Infrastructure Planning Techniques for Heterogeneous Railway Traffic under Structured, Flexible and Mixed Operations)

Introduction

A railway line has finite capacity to provide transportation of goods and people at an acceptable level of service. The capacity of a particular route segment to satisfy railway traffic demand is largely a function of the track infrastructure layout and traffic control system. The amount of railway capacity consumed by a given demand for freight and passenger transportation is primarily a function of three factors: the number of trains required to transport the demanded freight and passenger volumes; the level-of-service requirements of each type of train; and complex interactions between different types of trains arising from the operating plan over a particular route segment. While much previous research has documented the relationship between infrastructure, traffic control and train volume, understanding the relationships between operating plans, train-type interactions and train-type-specific levels of service is still a knowledge gap. This research explores these latter factors in more detail and develops new capacity evaluation and infrastructure planning techniques to account for their effects.

The objective of this study is to develop new railway capacity evaluation tools and infrastructure planning techniques to address infrastructure or operations planning challenges under different operating styles. Three main research questions will be answered during the development of these tools:

- What is the relationship between the operation style, variability of train priority and speed, and the capacity of a single-track line?
- Can the properties of this relationship be used to gain insights on where to conduct capacity expansion projects or operational changes?
- Can this relationship be used to better predict the distribution of train delay?

Approach and Methodology

The research in this document addresses several aspects of railroad capacity evaluation and infrastructure planning:

- Chapter 2 develops a capacity evaluation technique for calculating the maximum train throughput per day given the different level of service requirements specific to individual types of trains.
- Chapter 3 applies the capacity evaluation process developed in Chapter 2 is applied to compare four different infrastructure expansion strategies for low-density single-track lines under flexible operation.
- Chapter 4 develops an optimal siding location model that can identify the optimal number and location of passing siding projects as well as evaluate the performance of rail traffic under structured operations.
- Chapter 5 proposes a new capacity screening tool based on an analytical method for identifying appropriate infrastructure and operating solutions to increase capacity under mixed and flexible operations.
- Chapter 6 proposes a new parametric model to predict the train delay distribution on a single-track mainline with consideration of traffic heterogeneity. The research in this chapter first identifies new train delay indices based on the concept of traffic conflicts and then uses these indices to construct a parametric model of the train delay distribution.

Findings

The results of Chapter 2 suggest that for flexible operation, the optimal traffic mixture with the largest available capacity varies. Thus it is important to consider the current traffic mixture when evaluating the impact of plans to introduce additional traffic on a route.

In Chapter 3, it was found that since the interaction of trains under flexible operation varies significantly, a reliability test of the entire train delay distribution in addition to the traditional efficiency test of average train delay may be required to determine the optimal capacity expansion strategy.

Structured operation aims to follow the preplanned schedule strictly, thus the locations of traffic conflicts are more stable than with flexible operations. Under this scenario, determination of optimal number and locations of sidings is possible. An optimization model was developed to find the locations and number of sidings on a single-track line with sparse density of sidings. Using this model can help the planners improve train performance on pure passenger corridors, transit operations or corridors that are dominated by passenger trains and premium intermodal trains. However, this optimal siding location model is fragile to any potential departure or travel time randomness and is thus less applicable to mixed corridors where freight trains share track with passenger trains.

A capacity screening tool and a regression model were developed based on the concept of traffic conflict analysis for mixed operation. The concept of expected number of traffic conflicts was adopted to capture the impact of different degrees of operating flexibility. The capacity screening tool identifies points of capacity constraint based on the projected location of traffic conflicts. The train delay distribution model predicts train delay based on the number of conflicts a train expected to encounter during its trip. These two tools provide a new way to approach capacity planning on shared corridors with mixed or flexible operations.

Conclusions

To better understand and improve approaches to the current rail capacity problem in North America, this study considered the impact of operating style and LOS in addition to priority and speed variation on single-track lines. Techniques and tools were developed and tested to gain more comprehensive understanding of the influence of the operating style. There are several contributions worth mentioning. First, this study approached the capacity problem with different strategies based on operating styles. This helps improve the quality of operations and capacity planning on North America railroads. This study also conducted an application to connect the root cause approach to traffic conflict analysis with evaluation of train traffic heterogeneity and capacity. The tools developed on the basis of this concept provide an alternative to the simulation-based planning process in North America.

Recommendations

Future research should work to more completely validate the capacity screening tool and delay distribution models to demonstrate their applicability to a wide range of railroad infrastructure and operating scenarios. Upon validation they can be adopted by industry practitioners to more effectively analyze capacity and efficiently plan infrastructure. Improving the ability of railroads to perform at a consistent level of service while providing capacity for future traffic growth will increase the efficiency and reliability of transportation of goods and people. Additionally, researchers can benefit from the general relationships and procedures uncovered and developed in association with this work such as how the performance requirements of different train types govern the capacity of a rail line, the optimal siding location model, capacity screening tool and conflict-based model of the train delay distribution.

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Capacity Evaluation and Infrastructure Planning Techniques for Heterogeneous Railway Traffic under Structured, Flexible and Mixed Operations

BY

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PRELIMINARY REPORT

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Contents

1. INTRODUCTION

1.1 Purpose of the Study

The purpose of this research is to develop new capacity evaluation and infrastructure planning techniques that consider the impact of relationships between train operating plans, train characteristics and train-specific levels of service on line capacity.

1.2 Background and Current Problem

North American Railroads have an ongoing business incentive to properly match railway line capacity to traffic demand. While insufficient capacity reduces the level of service to railway customers, excess capacity, or poorly located capacity expansion projects, represent an inefficient use of railroad budget. The forecasted increase in future rail traffic, and corresponding changes in demand for railway capacity, will require railroads to make strategic decisions regarding the infrastructure and operational changes required to meet this demand. North American railroad operations and infrastructure planning are typically conducted based on practitioner experience combined with detailed simulations of train operations (Bronzini and Clarke, 1985). However, recent trends in rail traffic have resulted in operating conditions that fall outside the realm of historical experience and may lend themselves to different types of analytical capacity evaluation and optimization tools. These recent traffic trends include growth of freight rail traffic and expansion of passenger service on freight corridors, with a resulting increase in rail traffic heterogeneity and more precisely scheduled operations. These trends are compounded by the limited capacity of the single-track lines that comprise the majority of the North American rail network. Since these issues are highly relevant to the analytical capacity evaluation and optimization techniques developed through this research, they will be introduced in more detail in the following subsections.

1.2.1 Long-Term Growth of Traffic Volume

Although rail traffic volumes may fluctuate over the short-term, long-term the demand is expected to increase (HDR and Transit Safety Management, 2006; AAR, 2007; AAR 2015). In the US, freight rail traffic volumes steadily increased from 1990 to a peak in 2006 before declining during a period of economic recession (Figure 1.1). However, since 2009, the economic recovery has again spurred rapid increases in freight transportation demand and certain traffic metrics have reached new all-time highs (AAR, 2015). Daily average train-miles per mile of track is a more direct measure of train density across the rail network than other volume metrics such as carloads or ton-miles. The near doubling of train density on the network of Class I railroads between 1990 and 2014 (Figure 1.1) suggests that railroads are facing unprecedented demand for railway line capacity. The increase of traffic density is originated from both the long-term growth of traffic volume and the reduce of total length of tracks in the rail network.

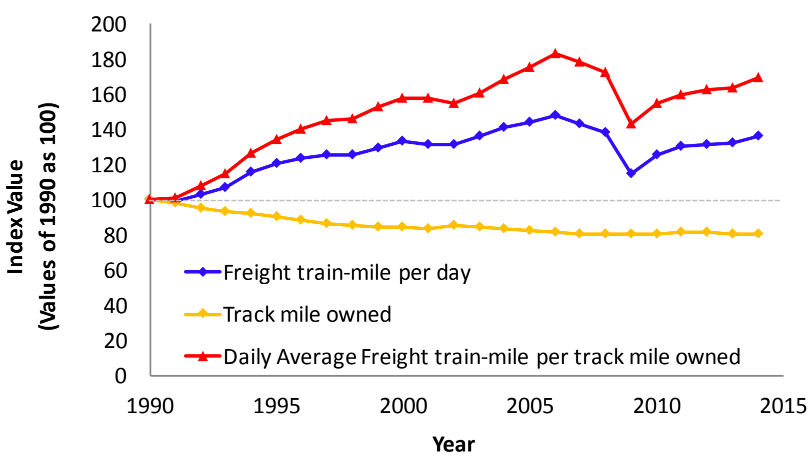


Figure 1.1. US Class I Railroads Traffic Volume and Density, and Track Mile Owned from 1990-2014 (AAR, 2015)

1.2.2 Traffic Heterogeneity

Dingler et al. (2009) defined the difference between the speed, priority, acceleration and braking characteristics of trains that serve the domestic intermodal, bulk freight and passenger rail markets as "traffic heterogeneity". They also used simulation to show that under the same number of trains per day, heterogeneous rail traffic consumes more capacity than homogeneous operations with a single train type, resulting in a lower level of service. Other studies support this conclusion (Carey, 1994; Huisman and Boucherie, 2001; Vromans et al., 2004; Vromans, 2005; Landex, 2008; Dingler et al., 2010; Dingler et al., 2013; Van den Berg and Verhoef, 2014).

There continues to be interest in expanding intercity passenger and commuter rail services, including increased train frequency and speeds on existing freight corridors (Bing et al., 2010, Martland, 2010). The introduction of additional passenger service on a freight corridor adds extra traffic heterogeneity to the rail operations, reducing the available time and space for operation of freight trains (Sogin et al., 2013a; Shih et al., 2015a) and overall mainline capacity (Sogin et al., 2013b; Sogin et al., 2013c; Shih et al., 2015a). A parametric model proposed by Krueger (1999) and a regression model presented by Gorman (2009) can model the performance of traffic with multiple train types. Lai et al. (2012) proposed a standard mechanism to evaluate the effect of heterogeneity by converting different types of trains into a standard unit.

The introduction of passenger and other premium freight services requires railroads to adopt operating styles that limit flexibility to stricter train schedules. Studies mentioned above only considered the impact of priority and speed variation, but not changes in the train operating flexibility (Figure 1.2). My proposed dissertation research will address the combined impact of schedule flexibility, operating style, priority and speed on train performance and line capacity. A more comprehensive definition of operation style and schedule flexibility will be introduced in the next subsection.

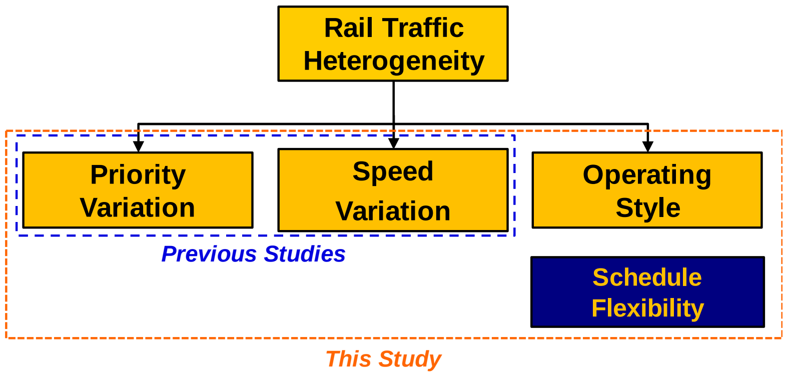


Figure 1.2. Factors Considered in the Previous and This Study

1.2.3 Operating Styles and Schedule Flexibility

In this dissertation, the schedule flexibility of a train is defined by the flexibility of its departure time and trip time flexibility (Figure 1.3). Departure time flexibility of a train is defined as the potential range of its departure time from an initial terminal, or the end of a particular route segment under study. Once a train departs, there will also be variability in its travel time to its final terminal, or the opposite end of the route segment. Trip time flexibility can also be described by the range in time-space path of a train. Departure and trip time flexibility have a direct relationship to schedule flexibility. Since higher schedule flexibility leads to higher uncertainty in train arrival time, it is inversely related to Level of Service (LOS) (Figure 1.4).

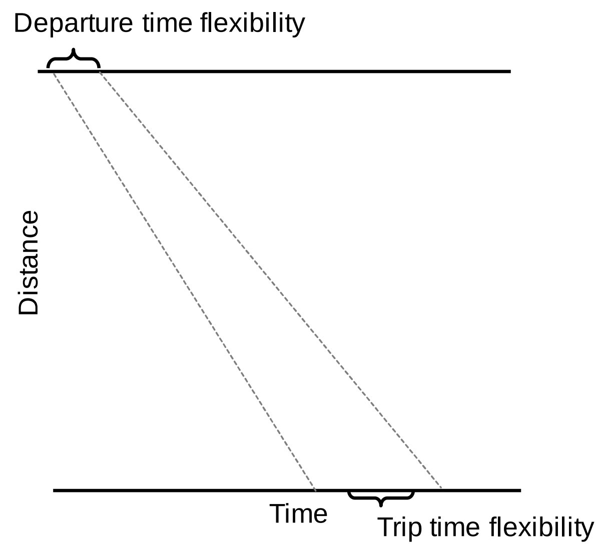


Figure 1.3. Departure and Trip Time Flexibility

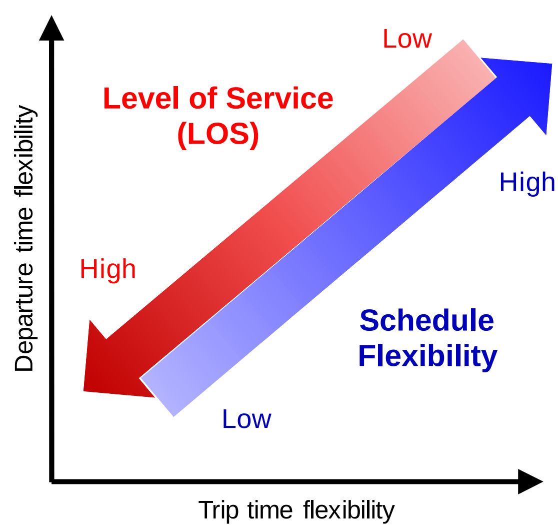


Figure 1.4. Relationship between Departure Time Flexibility, Trip Time Flexibility, Schedule Flexibility, and Level of Service (LOS)

Operating style refers to the variation in schedule flexibility observed across the individual trains operating on a mainline during a given period. Rail systems adopt different operating styles according to their customer requirements, business needs and objectives (Figure 1.5).

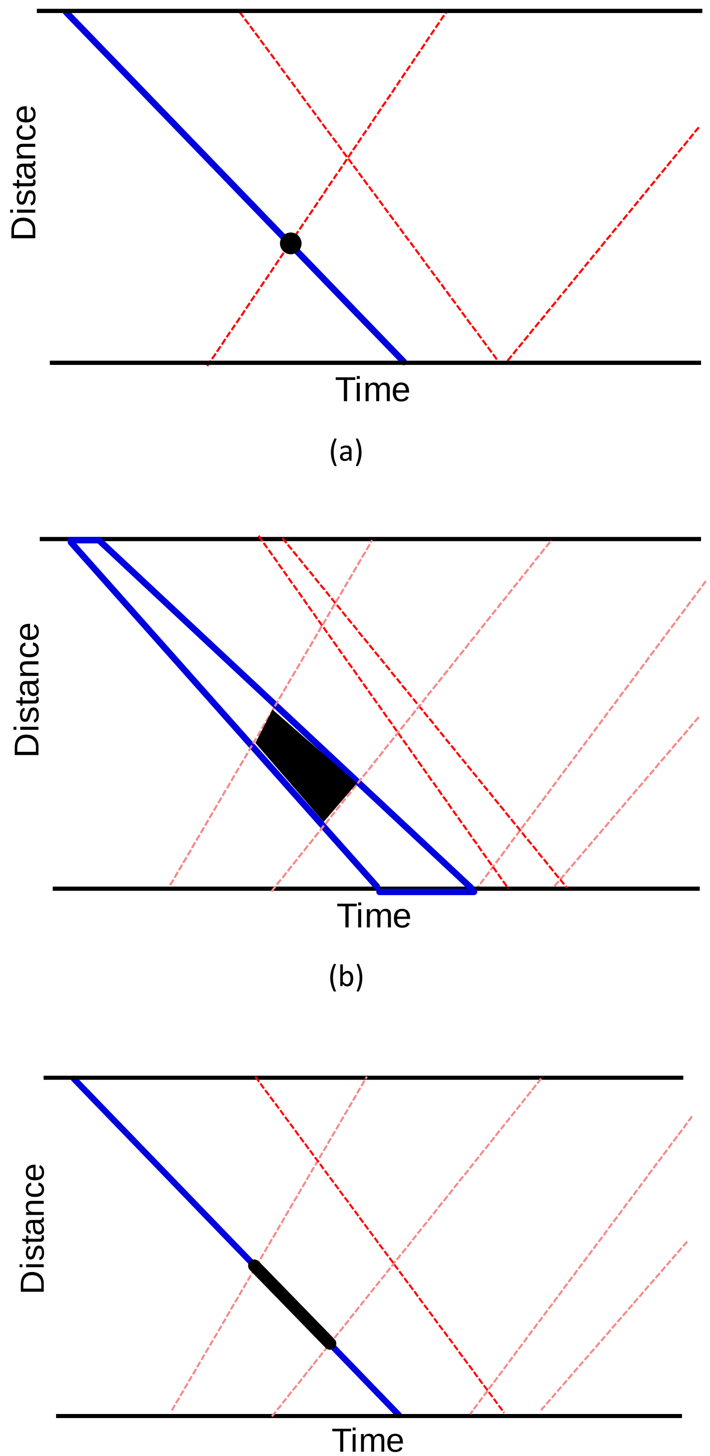


Figure 1.5. Examples of Different Railway Operating Styles (a) Structured Operation (b) Flexible Operation (c) Mixed Operation

For North American freight railroads, the business objectives of carload freight service require dispatchers to dynamically adjust predefined train plans. This flexibility is often used by the dispatchers to accommodate the train operation requirements caused by random disruption events such as mechanical failures, signal failures, temporary slow orders, insufficient crew or locomotive availability, train makeup requirements, or track inspection delays. As a consequence, predefined train operating plans in North America are relatively imprecise compared to other types of railway operations with a fixed timetable. North American freight train plans do not usually specify the locations and times for trains to meet or pass; but instead indicate only the approximate departure and arrival times of trains at yards and terminals. This operating style was named “improvised operation” by Martland (2010) and is termed “flexible operation” in this study.

The opposite operating style, where the operators carefully adhere to planned train paths, meet locations, dwell times and routes from origin to destination is termed “structured operation” (Martland, 2010). In general, passenger and transit systems try and follow a more structured operating style in North America although most of the operations involved a variety of unplanned events. Under structured operations in Europe, dispatchers often have little flexibility, and even their responses to schedule disruptions are usually prescribed by some emergency handling procedures or a pre-set rescheduled timetable (Norio et al., 2005; Luethi et al., 2007). Both of these operating styles are can be found on shared corridors in the US. On these routes, passenger trains attempt to follow structured operations and freight service follows flexible operations while sharing the same track. In this study I refer to the operating style on these corridors as “mixed operation”.

Operation style impacts train delay and line capacity. Each of the three time-distance diagrams in Figure 1.6 contains four train paths under a different operation style. The schedule flexibilities of each train follow the characteristics of the corresponding operation style. Focusing on the traffic conflicts encountered by the blue train path or band, the black dot (Figure 1.6a), area (Figure 1.6b), and line (Figure 1.6c) in the diagrams. They represent the different range of traffic conflicts in the time-distance space encountered by that train. As will be demonstrated in this research, the range of traffic conflicts influence train delay, and affects the appropriate locations for capacity expansion projects. The same single-track line could have different line capacities due to the variation of the range of traffic conflicts created by each operating style.

Dick and Mussanov (2016) examined the capacity impact of different operating styles by quantifying operational flexibility. They measured the effect of varying train departure randomness on train delay and level of service for a given traffic volume. Since the authors only examined homogeneous traffic, they did not consider the combined impact of train priority, speed variation and operating style.

A comparison between the operating style of passenger-dominant and freight-dominant systems and its relationship to capacity evaluation was elaborated on by Pouryousef et al. (2015). Capacity studies related to freight rail systems focused on simulating the random factors involved in their stochastic operation environment (Pouryousef et al. 2013). Passenger rail capacity studies emphasize the efficiency and robustness of the predefined schedules through optimization, and the strength of the emergency schedule to mitigate against disruption (Ekman, 2004; Norio et al. 2005; Pouryousef et al. 2013). However, neither of these two capacity study types can adequately address the current capacity problems on shared corridors with a mixed operating style. Optimization tools for structured operations cannot handle unscheduled freight trains. Simulation-based approaches for flexible operations may not meet specific passenger level-of-service and timetable requirements at intermediate stops.

The operating style on a corridor can also be connected to the length of infrastructure or operations planning period. Generally, for longer planning periods, there is increasing uncertainty in the specifics of future train plans. Methods, processes, and tools applicable for scenarios with a larger degree of randomness, or more flexible operation styles, can be used for longer-term planning. Similarly, tools developed for more structured operating styles are more appropriate for short-term planning. Understanding the effect of different operating styles on train delay and mainline capacity is another important characteristic that modern capacity analysis tools should consider. This study seeks to develop new tools and approaches to capacity evaluation that are better-suited to different operation styles found on North American railroads.

1.2.4 Single-track With insufficient Capacity

To minimize costs, railroads attempt to utilize their existing infrastructure as efficiently as possible. This implies that network capacity available for new traffic is always limited, especially on single-track lines with minimal track infrastructure due to their historically low traffic density. In some parts of North America, recent changes in energy markets and associated transportation of ethanol and crude oil have increased the traffic volume on many low-density, single-track lines. Infrastructure or operating solutions must be applied to these low-density lines to solve the congestion arising from increasing demand but limited capacity.

North American railroads have been investing in substantial infrastructure expansion and improvement projects over the past 15 to 20 years. Most of the projects were related to adding multiple main tracks to key segments of high-density rail corridors on their core network. Recently, railroads have shifted part of their capital investment plans to construct new passing sidings or upgrade signal systems on formerly low density, single-track lines with growing traffic. This dissertation will develop new tools for evaluating both passing siding and double-track projects on single-track lines.

1.3 Objective and Scope of the Study

The objective of this study is to develop new railway capacity evaluation tools and infrastructure planning techniques to address infrastructure or operations planning challenges under different operating styles. Three main research questions will be answered during the development of these tools:

- What is the relationship between the operation style, variability of train priority and speed, and the capacity of a single-track line?
- Can the properties of this relationship be used to gain insights on where to conduct capacity expansion projects or operational changes?
- Can this relationship be used to better predict the distribution of train delay?

According to Lai (2008), the existing capacity analysis tools can be categorized into four types: simulation (Petersen, 1982; Leilich, 1998; Salido et al., 2012; Stenstrom et al., 2013; Sipilä, 2015), optimization (Ahuja et al., 1993), analytical approaches (Parkinson and Fisher, 1996; Lindner, 2011; Salido et al., 2012), and parametric models (Mitra and Tolliver, 2010; Murali et al., 2010). Planning tools should be matched to capacity and infrastructure planning scenarios based on the properties of the infrastructure, traffic and operating styles. Several previous studies quantified fundamental relationships between infrastructure and traffic but did not systematically study operating style (Peterson and Tyler, 1987; Pawar, 2011; Lai et al., 2012). Consequently, this study aims to develop tools based on the demands of different operating styles. The types of tools appropriate for each operating style must have the ability to handle the amount of traffic heterogeneity and schedule flexibility associated with that operating style. The developed tools can help practitioners expedite the planning process and yield new knowledge of railway capacity relationships that will allow the railroads to maximize their operating efficiency.

1.4 Structure of Chapters

In the proposed dissertation structure (Figure 1.6), Chapter 1 will describe current railway capacity issues, review existing tools and their drawbacks, and summarize the overall research plan. A capacity evaluation technique is developed in Chapter 2. The developed technique built a regression model and then conducted a transformation process for calculating the maximum train throughput per day given the different level of service requirements specific to individual types of trains. The developed technique can be used to evaluate the additional capacity consumption arising from rail traffic heterogeneity. In Chapter 3, the capacity evaluation process developed in Chapter 2 is applied to compare four different infrastructure expansion strategies for low-density single-track lines under flexible operation. This chapter provides a general guideline for evaluating these types of capacity expansion projects.

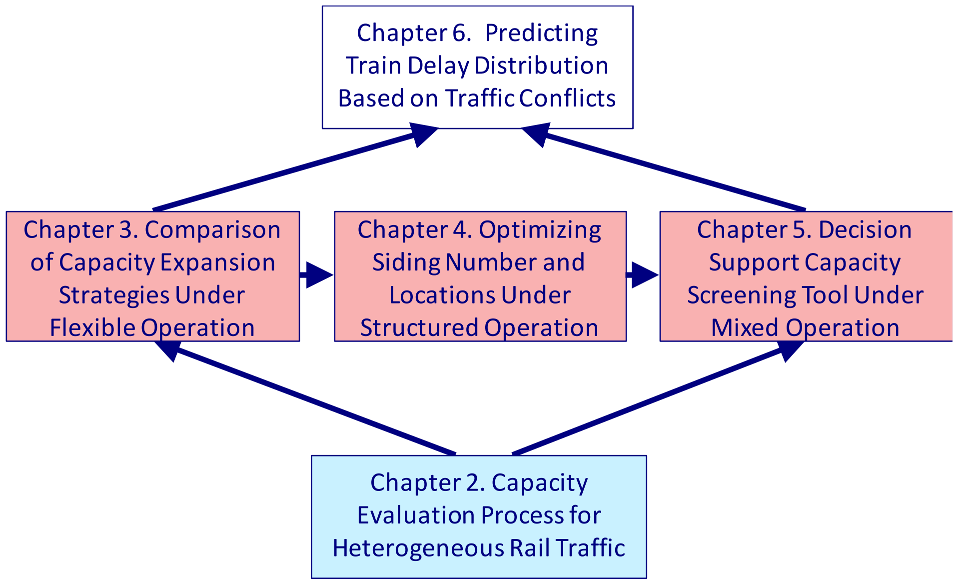


Figure 1.6. Structure of Dissertation and the Relationship between Chapters

The work in Chapter 2 and other simulation studies suggest that optimization approaches may be useful in selecting the locations of mainline projects to increase capacity. Thus, an optimal siding location model is developed in Chapter 4. The proposed model can identify the optimal number and location of passing siding projects as well as evaluate the performance of rail traffic under structured operations. This model can be used to determine the optimal infrastructure expansion plan for corridors dominated by passenger or premium-intermodal traffic that operates in a structured manner.

Since computational complexity limits the model proposed in Chapter 4 to structured operations, two tools are developed that use the concept of traffic conflicts to identify the location of capacity constraints on a mainline and predict train delay distributions under mixed operations. In Chapter 5 I propose a new analytical method for identifying appropriate infrastructure and operating solutions to increase capacity under mixed and flexible operations. In Chapter 6, a new parametric model is proposed to predict the train delay distribution on a single-track mainline with consideration of traffic heterogeneity. The research in this chapter first identifies new train delay indices based on the concept of traffic conflicts and then uses these indices to construct a parametric model of the train delay distribution. Chapter 7 will summarize conclusions and the directions for future study.

2. EVALUATING IMPACT OF TRAFFIC HETEROGENEITY AND LEVEL OF SERVICE ON CAPACITY

This chapter aims to develop a capacity evaluation process for mixed and flexible operation. This process can use either simulation or actual traffic data from a mainline segment of interest as inputs. The technique generates a relationship between line capacity (maximum possible throughput) and the variability of speed and priority according to a given level of service (LOS) requirement for each type of train on that line segment. Reducing traffic heterogeneity or relaxing LOS can increase line capacity (Figure 2.1) (Krueger, 1999; Mattsson, 2007; Abril et al. 2008). The area of the triangle defined by the three axes must remain constant for a fixed infrastructure arrangement. In scenario A, the degree of traffic heterogeneity and the LOS is higher than scenario B, resulting in the lower capacity for scenario A. Krueger (1999) tried to capture this relationship by using average traffic delay, heterogeneity-related factors, and the average LOS of traffic in his parametric capacity model. However, individual train types may have very different LOS requirements due to their differing business objectives (UIC, 2013). The process developed in this chapter improves upon previous methods by considering the impact of multiple train types, each with their own LOS requirements, on line capacity.

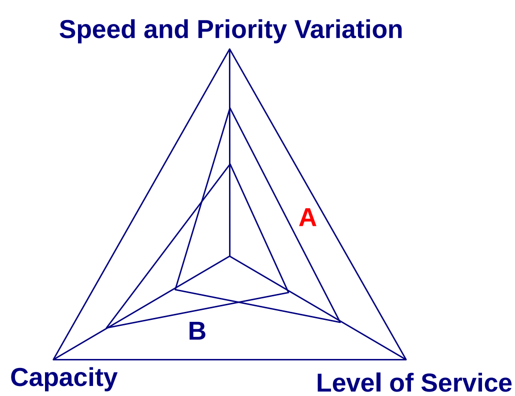


Figure 2.1. Example of the trade-off between line capacity, Speed and priority variation, and LOS

2.1. Overview of the Current Status

Currently, both parametric models and simulation models are used to evaluate the capacity of flexible operations on mainlines. Two parametric models frequently used by railroads and scholars in North American are the FRA parametric model (Prokopy and Rubin, 1975) and the Canadian National (CN) parametric model (Krueger, 1999). The models do not fully consider the current level of traffic heterogeneity, and the different operating styles and service quality requirements of different train types. Simulation models can account for the details of train operation randomness and traffic heterogeneity, but they require considerable time and effort to develop. Dingler et al. (2013) and Sogin et al. (2013a) investigated the impact of traffic heterogeneity on line capacity via simulation. They considered the interactions between two train types to understand the basic relationship between train delay and heterogeneity. However, the traffic mixture on most railway routes, and shared corridors in particular, usually contains more than two train types. Also, previous simulation studies only considered average train delay in their determination of capacity and thus do not directly apply to corridors where different train types have disparate LOS requirements. The capacity evaluation technique to be developed in this chapter is capable of considering the trade-off between line capacity, traffic heterogeneity and LOS for different train types under flexible operation.

2.2. Summary of Technical Approach and Research Results

The capacity process developed (Figure 2.2) requires index levels that depict traffic characteristics and train delay as an input. In this study, train delay inputs were obtained from the RTC simulation (Wilson, 2012) of a hypothetical rail line. Actual train delay data from lines with different traffic volumes and mixtures, or outputs of other simulation platforms could also be used by the process. A polynomial regression model was constructed to model the input train delay as a function of the number of trains of each train type operating over the route. A transformation process is then applied to the regression model to calculate line capacity as a function of the given traffic mixture and LOS for each train type.

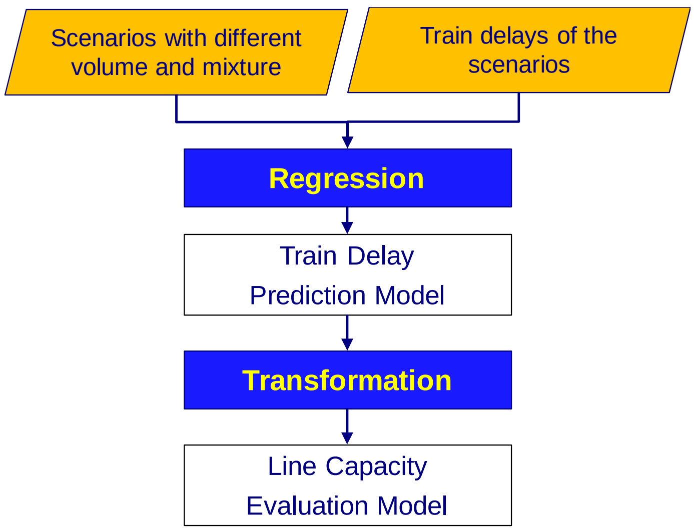


Figure 2.2. Flowchart of the capacity evaluation process

The transformation step in the process can be done graphically (Figure 2.3) or mathematically. The upper set of axes in Figure 2.3 displays the relationship between the average delay of intermodal trains and the freight traffic mixture (percent of unit train traffic in freight traffic, % Unit trains) for profiles of constant total traffic volume (ranging from 20 to 28 trains per day). By setting the maximum allowable average delay for intermodal trains to the LOS for intermodal traffic (D^{max}, 25 min in Figure 2.3), and intersecting this delay value with the profiles, the maximum traffic volumes that can be handled without violating the intermodal train LOS can be obtained for corresponding traffic mixtures. These points can be transferred to the lower set of axes and used to construct an intermodal capacity profile. This transformation process must be repeated for each train types, and the minimum of all the capacity profiles obtained is the final capacity profile. The values of this final profile represent the maximum throughput of trains for different freight traffic mixtures without violating the LOS of all train types.

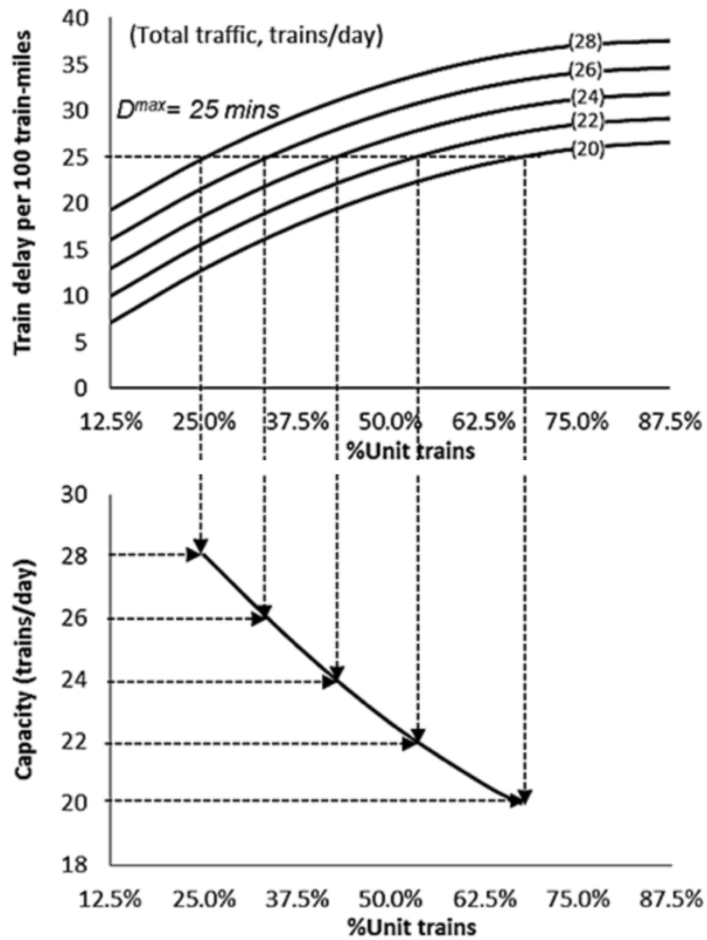


Figure 2.3. Geometrical Concept of the Transformation Process

Mathematically, a polynomial transformation process is applied to the regression model to generate an equation for the capacity profile of each train type. Since different train types may govern capacity for different traffic mixtures, the final capacity profile may not be a smooth function.

The potential of the capacity evaluation process for rail line capacity analysis was demonstrated through two case studies. First, the process was used to quantify the incremental impact of passenger trains on line capacity under different mixtures of freight traffic. This analysis also evaluated the relative impact of passenger trains on each type of freight train. For example, across a range of traffic mixtures, the addition of eight passenger trains has a differing effect on line capacity as defined by the LOS of each train types (Figure 2.4). The result implies that when assessing the ability of a line to accommodate additional traffic, not only is the existing volume of current traffic important, so is the traffic mixture.

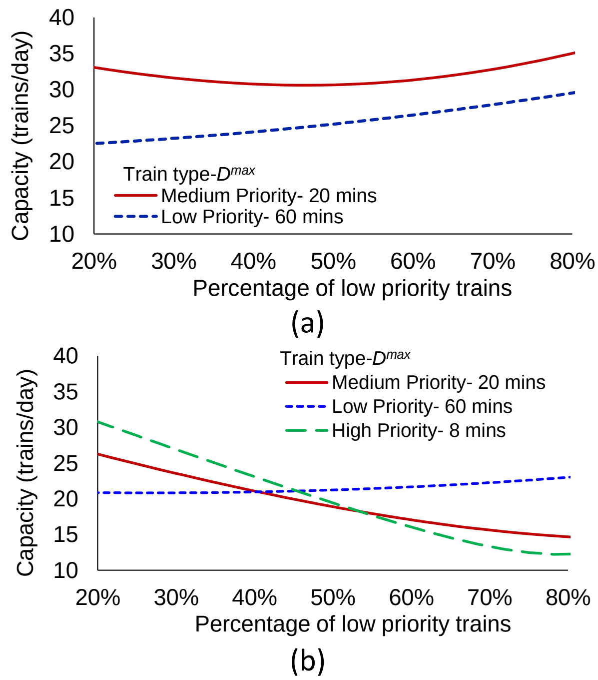


Figure 2.4. Final Capacity profile under the Scenarios with (a) Pure Freight Traffic and (b) Added Passenger Services

Since the LOS for each train type may vary between rail operators given different operational requirements or business objectives, the sensitivity of capacity consumption to changes in train-type LOS was examined. Capacity contour plots were used to illustrate that change in overall capacity consumption induced by a change in LOS for different combinations of traffic mixture and passenger service frequency (Figure 2.5). There is pattern evident (Figure 2.5) in which relaxing LOS (increasing maximum allowable delay) of a freight train type increases capacity. The result indicates that changes of LOS of a certain train type does not necessarily change line capacity. The change of line capacity under certain traffic mixtures is usually related to LOS of one or two train types only.

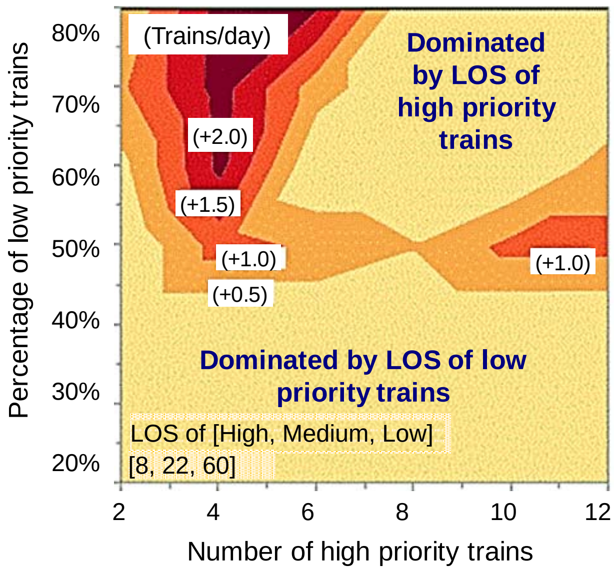


Figure 2.5. Capacity Contour Plot under the Scenarios with Relaxed (10% increase) LOS of Intermodal Trains

2.3. Intellectual Merit and Expected Impact

The research in this chapter evaluates and enable visualization the capacity interactions between more than two different train types under flexible operations. This study improves the general intellectual understanding of the impact of traffic heterogeneity on railway operations. The analysis of the impact of additional passenger trains suggests not only the volume of existing traffic related to the ability of a line to handle additional traffic, but the mixture of current freight traffic. The sensitivity analysis shows that relaxing LOS of a particular freight train type does not necessarily yield additional capacity. The capacity evaluation approach developed in this chapter provides a standardized method for practitioners to calculate the trade-off between line capacity, traffic heterogeneity and the train-specific LOS requirements under mixed operations.

2.4. Remaining Challenges and Goals

The research conducted for this chapter has been described in the journal paper "Impact of Passenger Train Capacity and Level of Service on Shared Rail Corridors with Multiple Types of Freight Trains" (Shih et al., 2015a). Since the research is essentially complete, the remaining effort is to write the dissertation chapter.

2.5. Plan for Completion and Success Criteria

The model developed in the study need to quantify the trade-off between the traffic heterogeneity, LOS, and line capacity in a numerical way. The case studies have to visualize that the relationship between variability of speed and priority, available line capacity and the LOS of each train type. If the mentioned points are displayed, they can be used by the rail sector practitioners as reference for their operational planning. They also provides an insight and a way to visualize on the fundamental interactions between the three important factors for the researchers to advance their knowledge.

3. COMPARING CAPACITY EXPANSION STRATEGIES FOR SINGLE-TRACK LINES UNDER FLEXIBLE OPERATION

As mentioned in the introduction section, business incentive has been keeping railways to properly match railway line capacity to traffic demand in North America. A poorly located capacity expansion projects increase only limited capacity which leads to inefficient use of railroad budget. Also, single-track lines provided less capacity than multiple-track lines thus is more likely to be the bottlenecks of a rail network. This chapter aims to suggest a general expansion strategy for increasing capacity of these single-track lines under flexible operations.

3.1 Overview of the Current Status

A number of previous studies have investigated the effectiveness of infrastructure improvements for increasing line capacity. European studies tend to focus on passenger rail corridors (Fransoo and Bertranda, 2000; Lindfeldt, 2007; Lindfeldt, 2009; Lindfeldt, 2012). There are also some studies more related to the freight rail corridors. Petersen et al. (1987) used simulation analysis to determine longer siding locations for improving the efficiency of passenger train operation on freight lines. An analytical model was proposed by Pawar (2011) to determine the appropriate length of long sidings for train meets. Both studies focused on only one specific type of capacity expansion alternative. Lindfeldt (2012a) used an analytical approach to find feasible strategies to increase capacity through incremental infrastructure projects. However, Lindfeldt (2012a) analyzed a particular real-world line with specific existing characteristics. Sogin et al. (2013a; 2013b) used simulation methods to study the relationship between the general length of second main track and train delay. Their study was more general but did not cover the transition from single-track lines with sparse sidings to single-track lines with dense sidings. Since single-track lines with sparse sidings are common in North America and have been the subject of recent and planned infrastructure investment, a study investigating vague capacity expansion strategies for these lines will enable better informed investment decisions.

3.2 Summary of Technical Approach and Research Results

Potential capacity expansion alternatives for single-track lines with sparse sidings were identified and an experimental design developed (Figure 3.1). Four potential capacity expansion alternatives for single-track lines with sparse sidings were chosen based on previous academic studies and industry suggestions. An experiment matrix of simulation scenarios is needed to develope a delay response surface of the line under all possible traffic volumes, mixtures, and infrastructure alternatives. Partial factorial design method was used to select a representative subset of simulations from a full factorial design to reduce the number of simulation runs required (Montgomery, 1984; Box and Soren, 1987). The delay response of this subset is similar to the original experiment but fewer scenarios need to be simulated. RTC software was used to simulate scenarios selected to define the delay response surface of the alternatives under a range of traffic volumes and mixtures. The results of these simulation scenarios were used to construct a regression model of the train delay response. As described in Chapter 2, the regression model was transformed into a capacity model to calculate the maximum throughput of each alternative.

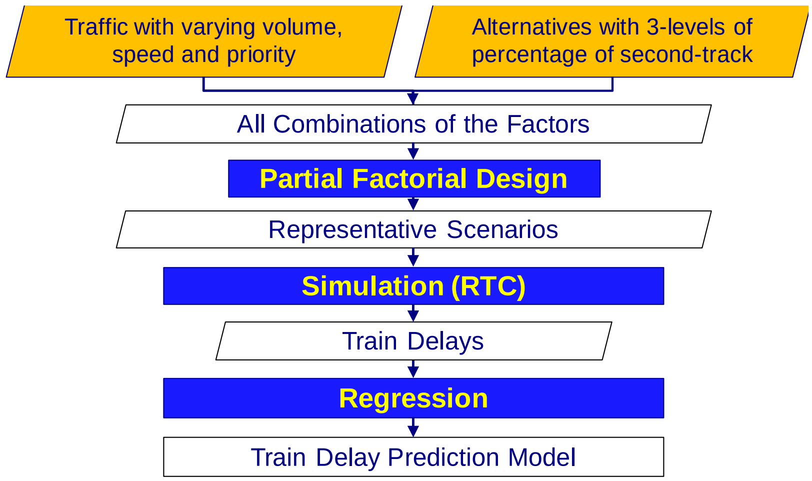


Figure 3.1. Flowchart of the Strategy Comparison Process

The capacity expansion alternatives evaluated are part of the larger transition process from a single-track line with sparse siding to a full two-main-track line (Figure 3.2). The dotted arrow lines indicate the transition process from single-track line with dense sidings to a full two-main-track line, previously studied by Sogin et al. (2013a) and Atanassov et al. (2014). The bold arrows are the focus of this study and the bold labels beside the orange arrows in Figure 3.2 indicate the alternatives evaluated in this study.

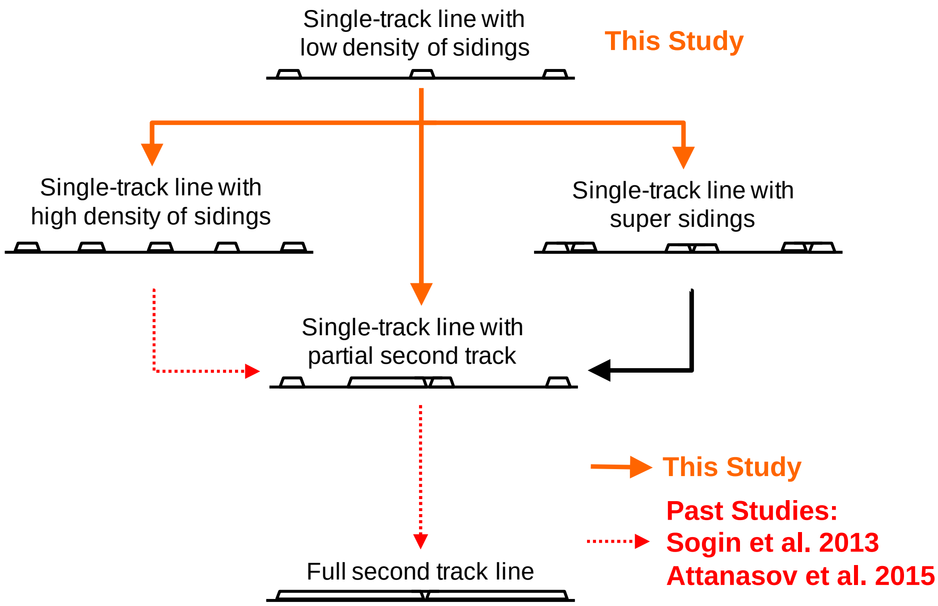


Figure 3.2. Flowchart of the Capacity Evaluation Process

Figure 3.3 illustrate an example for each alternative. Alternatives 1a and 1b both involve construction of new sidings between current passing siding locations to create a single-track line with dense siding spacing. The difference is that in Alternative 1a, construction of new sidings begins at the middle of the corridor and moves outward the ends. Based on the characteristics of the strategy, it is called as “center out”. Since Alternative 1b evenly distributes the location of new sidings along the corridor in each stage of construction, it is called as “spread evenly”. In Alternative 2 which called “second-track”, existing sidings are connected by additional second-track to form one continuous section of second-main-track. This approach is selected on the basis of past research by Lindfeldt (2012b) who found that continuous double-track sections were the most effective approach to increase capacity. In Alternative 3 “super sidings” are created by doubling the length of existing sidings and installing an intermediate universal crossover at the new midpoint. The “super sidings” are constructed by doubling the length of the original siding and installing an intermediate universal crossover at the midpoint of the new super siding. This strategy is used by some major North American railroads. For each alternative three scenarios with different length of installed second-track were constructed to represent the incremental process of capacity expansion. The unit used to quantify the length of second-track is the percent of second-track to total corridor length (ST). It is obtained by dividing the total length of sidings and double track by the corridor length and is used as an approximation of amount of total capital investment. Alternatives with the same value of ST are assumed to require the same capital investment. Each alternative is set to contain levels of ST (13%, 16%, 19%) to emulate the incremental infrastructure investment process.

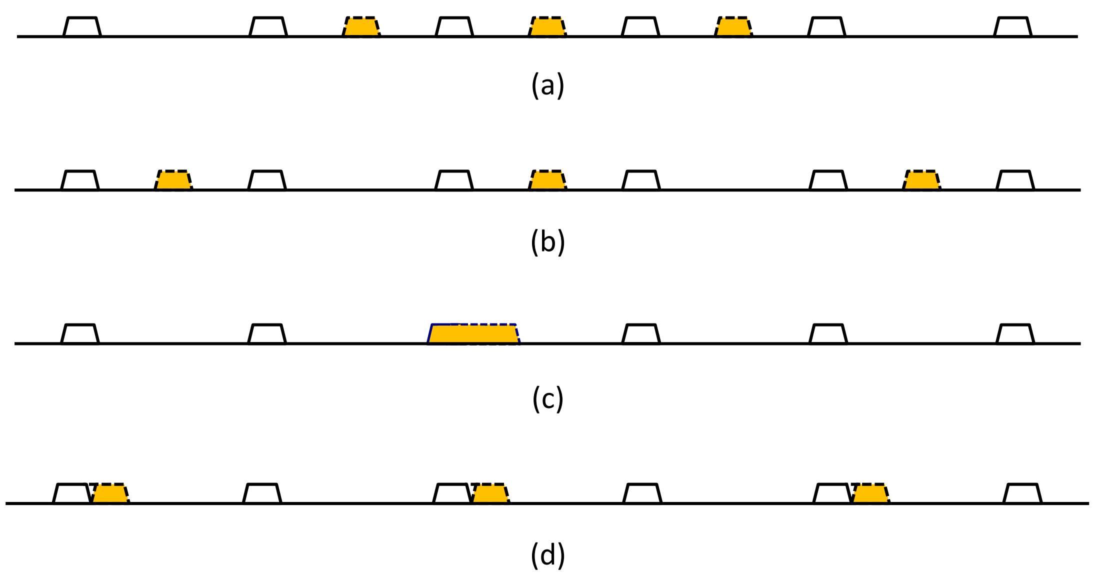


Figure 3.3. Capacity expansion alternative strategies for single-track lines with sparse sidings (a) 1a center out (b) 1b spread evenly, (c) 2 second-track (d) 3 super siding

To investigate the ability of each capacity- increase alternative, a hypothetical single-track line with 20-mile spacing between every pair of adjacent sidings was used as the base scenario for the simulation tests. Two different evaluations were conducted to evaluate the performance of each alternative under mixed traffic with passenger and unit freight trains. The first evaluation tested the efficiency of alternatives by comparing the average train delay of each alternative as an output of the developed train delay prediction model. The second evaluation tested the reliabilities of alternatives based on the train delay distribution data directly from the RTC. The efficiency of the alternatives (Figure 3.4) showed that Alternative 1a and b could be the potential candidates for implementation since they have the least of train delay throughout the incremental capacity expansion process. The sensitivity of alternatives suggested Alternative 1a as the best option since the delay distribution of 1a contains fewer high-delay trains than 1b (Figure 3.5). The results of the tests showed that Alternative 1a and 1b have an equivalent performance in terms of train delay. On the other hand, Alternative 1a is believed to be the best alternative among all the identified alternatives in terms of train delay distribution. This process can be adapted to evaluate a set of potential alternatives on a target mainline.

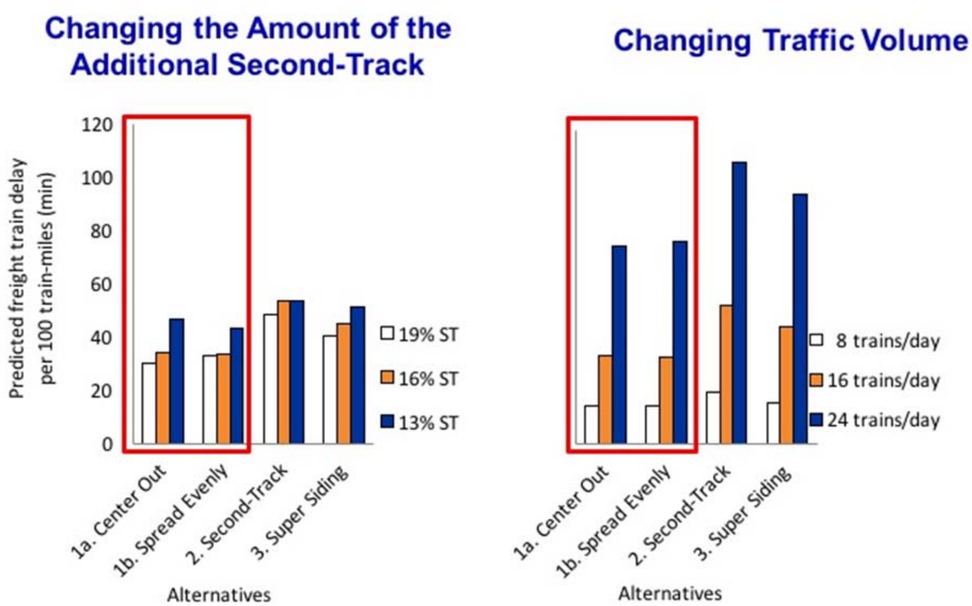


Figure 3.4. Result of the Efficiency Evaluation

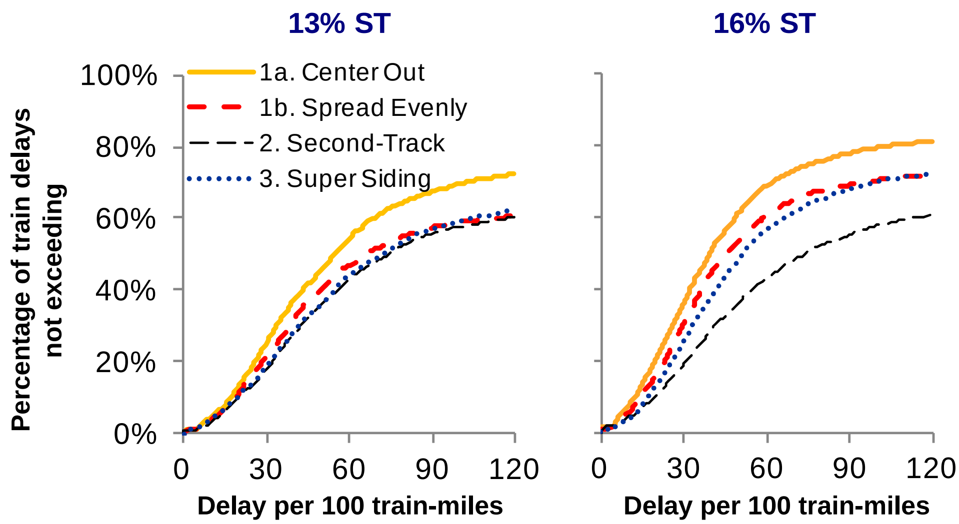


Figure 3.5. Output of the Reliability Evaluation

3.3 Intellectual Merit and Expected Impact

The results of this study indicated the relative effectiveness of the different capacity expansion alternatives, in which the alternative outward construction of additional passing sidings begins mid-corridor and moves outward. The case study displayed two potential tests to evaluate the efficiency and reliability of an infrastructure layout. This concept can be used by railroads to develop high-level siding expansion program plans on single-track lines experiencing congestion under mixed traffic and flexible operations. On the other hand, the trade-off between capital infrastructure investment and train delay cost can also be shown after converting the percent ST axis to construction cost. The results can also help practitioners and researchers understand the fundamental relationship between changes in infrastructure, traffic volume, heterogeneity, and traffic delay.

While the general guidelines presented here may be appropriate for high-level planning, they may be too general for mid-term capacity planning where simulation is used to capture sitespecific conditions. Also, general guidelines do not yield specific quantified benefits for return-on-investment calculations while simulation can provide measures of delay reduction. As alternatives to resource-intensive simulation, an optimization approach is formulated in Chapter 4 and a capacity screening approach is developed in Chapter 5 based on the concepts of White (2005) and Gorman (2009).

The approach used for reliability analysis in this study is still preliminary, it simply compared the delay distribution from the RTC simulations. Chapter 6 will develop an approach to better predict the distribution of train delay under different traffic volume and heterogeneity conditions without the need for simulation.

3.4 Remaining Challenges and Goals

This research was documented in the journal paper "Comparison of capacity expansion strategies for single-track railway lines with sparse sidings" (Shih et al., 2014a). The delay data of four alternatives have been obtained for the preliminary capacity tests conducted in the paper. The remaining effort is to write the dissertation chapter.

3.5 Plan for Completion and Success Criteria

The remaining work is expected to be done before the end of the spring 2016 semester. The developed comparison process should be capable to suggest an approach the railroads can follow for high-level siding project planning. Since the capital investments required for constructing siding projects are large, using the strategy suggested by this study can help maximize the return from the invested projects.

This study can be considered a success if the developed process can suggest a better capacity expansion strategy among some potential strategies for the reference of railroaders to do their capacity planning. Moreover, the reliability analysis addition to the efficiency test need to prove the robustness of the suggested solution to rail congestion problems addition to the efficiency of the solution.

4. OPTIMIZATION OF SIDING LOCATION FOR SINGLE-TRACK LINES UNDER STRUCTURED OPERATIONS

For single-track rail lines, having a proper allocation of passing siding locations can improve operational efficiency. Poor decisions on the allocation of siding locations leads to inefficiency and train delay. On the other hand, over or insufficient number of sidings leads to an imbalance of line capacity and demand. Railroad mainlines may be hundreds of miles long with an uneven distribution of siding locations, speed restrictions, and a heterogeneous traffic pattern with a varying number and timing of train departures each day. These complexities make it difficult to select the best locations for new passing sidings analytically. While simulation can consider these complexities, these models are data and resource intensive, making it difficult to consider all possible alternatives. Without considering every alternative, an optimal solution cannot be guaranteed. In this chapter, an optimization model will be developed to determine the number and locations of passing sidings on single-track lines with sparse sidings under the special case of structured operations.

4.1. Overview of the Current Status

Lai and Shih (2013) proposed a model to evaluate the strategic capacity planning problem with the consideration of demand fluctuation. However, this model did not suggest a detailed expansion plan for the mainline. Higgins et al. (1997) developed an optimization model to determine optimal siding locations at the mainline scale. However, the Higgins model is more theoretical than practical as it makes numerous simplifications in determining the number and locations of sidings. It does not include important factors such as siding capacity constraints, construction costs, or the existing pattern of passing sidings. In order to offer practical utility, a siding-placement optimization model should account for these factors as well as constraints due to bridges, grade crossings, tunnels, and narrow rights-of-way in urban areas.

This research aims to develop an optimal siding location model (OSLM) that considers infrastructure, construction cost, and traffic characteristics to determine the optimal number and location of passing sidings on a single-track route. Railroads can use this tool to both maximize the benefits from capacity projects, and improve the quality service provided to customers.

4.2. Summary of Technical Approach and Research Results

Traffic characteristics, track infrastructure properties, and operational parameters are used as inputs to the OSLM (Figure 4.1). On the basis of these input parameters, the optimization framework generates two types of output - train paths and an optimal siding location plan - that minimize the total of three cost categories: equivalent investment cost, meet and pass delay cost, and late departure cost.

Figure 4.1. Conceptual Diagram of OSLM

An optimization model for the siding planning problem needs to deal with the siding location and train dispatching problem at the same time. Consequently, a combination of capacity planning and train dispatching constraints are used as the basic structure of the model. The models developed in previous studies typically provided either an optimal siding plan for a fixed schedule or an optimal schedule for a fixed set of siding locations, but were incapable of solving the complete problem by optimizing both simultaneously. The OSLM is able to generate an optimal siding location plan and set of train paths to minimize total cost (including investment cost, delay cost, and late departure cost) without violating a set of practical constraints (e.g., train separation, construction cost and siding capacity).

The OSLM used the concept of integer programming and network modeling (Ahuja et al., 1993; Lai et al., 2010). It is similar to the scheduling or tactical planning models (Crainic et al., 1984). The following paragraphs present the formulation of the OSLM. Three different types of decision variables in OSLM are listed: time variables, infrastructure variables, and train dispatching variables.

Time variables indicate the arrival and departure time of trains at each node. The value of time variables can be used to construct the train paths.

D_i^q = departure time of train i at node q, $D_i^q \geq 0$

A_i^q = arrival time of train i at node q, $A_i^q \geq 0$

The infrastructure variables determine the need and location of additional sidings. An optimal siding plan can be obtained from the infrastructure variables.

d_p = positive variable, length of segment p, $d_p \geq 0$

z_c^q = equal to 1 if siding q exists on construction zone c, 0 otherwise, $z_c^q \in \{0,1\}$

Train dispatching variables are included in OSLM to ensure the headway between trains and avoid the potential conflicts between trains.

x_{ij}^p = equal to 1 if train i passing through segment p before train j, 0 otherwise, $x_{ij}^p \in \{0,1\}$

o_i^q = equal to 1 if train i stays on siding q to meet or pass another train during the dispatching period, 0 otherwise, $o_i^q \in \{0,1\}$

θ_{ij}^q = equal to 1 if and only if train i stays on siding q to meet or pass before train j stays on the same siding, 0 otherwise, $\theta_{ij}^q \in \{0,1\}$

Equation (4.1) is the objective function of OSLM. It aims to minimize the total cost during the planning horizon, defined by the summation of equivalent investment cost, meet and pass delay cost, and late departure cost. The equivalent weight for investment cost can be obtained by the method proposed by Lai and Barkan (2011). Since W^i is the delay cost for different types of trains, this objective function reflects the business objectives of North American railroads (Lovett et al., 2015).

Objective: $$Min\ \beta \sum_{c \in C} \sum_{q \in \eta^+} U^c z_c^q + \sum_{i \in N} \sum_{q \in \kappa} W^i (D_i^q - A_i^q) + \sum_{i \in N} \sum_{q \in \varepsilon_i} W^i (D_i^q - e^+{}_i) \tag{4.1}$$

This objective is subject to a set of constraints, including constraints on train dispatching, train schedule, siding capacity, construction cost, track configuration, and environmental characteristics. The constraints listed in equations (4.2) to (4.7) ensure the accuracy of the dispatching process. The basic principle is to ensure two adjacent trains at each node have a reasonable headway. Equations (4.2) and (4.4) maintain an appropriate headway between the departure times of any adjacent trains heading in the same direction, and equations (4.3) and (4.5) maintain a safe headway between the arrival times of any two adjacent trains. Equations (4.6) and (4.7) guarantee the headway between two adjacent trains in opposite directions.

$$M(1-x_{ij}^{p}) + D_j^q \geq D_i^q + h_{ij}^p + o_i^q \varsigma \qquad \forall (i,j) \in b^+,\ i \neq j,\ q \in \delta_p,\ p \in P \tag{4.2}$$

$$M(1-x_{ij}^{p}) + A_j^q \geq A_i^q + h_{ij}^p + o_i^q \varsigma \qquad \forall (i,j) \in b^+,\ i \neq j,\ q \in \delta_p,\ p \in P \tag{4.3}$$

$$Mx_{ij}^{p} + D_i^q \geq D_j^q + h_{ij}^p + o_i^q \varsigma \qquad \forall (i,j) \in b^+,\ i \neq j,\ q \in \delta_p,\ p \in P \tag{4.4}$$

$$Mx_{ij}^{p} + A_i^q \geq A_j^q + h_{ij}^p + o_i^q \varsigma \qquad \forall (i,j) \in b^+,\ i \neq j,\ q \in \delta_p,\ p \in P \tag{4.5}$$

$$M(1-x_{ij}^{p}) + D_j^q \geq A_i^q + h_{ij}^p + \varsigma \qquad \forall (i,j) \in b^+,\ i \neq j,\ q \in \delta_p,\ p \in P \tag{4.6}$$

$$Mx_{ij}^{p} + D_i^q \geq A_j^q + h_{ij}^p + \varsigma \qquad \forall (i,j) \in b^+,\ i \neq j,\ q \in \delta_p,\ p \in P \tag{4.7}$$

Equations (4.8) and (4.9) are train schedule constraints that consider the effect of traffic pattern and demand. Equation (4.8) forces trains depart from their origin within a given time range. Additionally, Equation (4.9) ensures that all passenger trains arrive at stations with an acceptable interval.

$$e_i^+ \leq D_i^q \leq e_i^- \qquad \forall i \in N,\ q \in \pi \tag{4.8}$$

$$\lambda_q^{i+} \leq A_i^q \leq \lambda_q^{i-} \qquad \forall i \in N,\ q \in \kappa \tag{4.9}$$

Equations (4.10) through (4.15) are siding capacity constraints. Equation (4.10) links the train dwelling variable o_q^i with the train meet and passing delay. Equations (4.11) and (4.12) identify the sequence of trains pass each siding. Equation (4.13) avoids two trains from occupying the same siding. This works together with equation (4.9), to maintain the stopping pattern of passenger trains. Equation (4.14) forbids a train from using a siding if the length of the train is longer than the siding itself. Equation (4.15) is the arrival time constraint, it also captures the extra travel time experienced by trains due to acceleration, deceleration, siding speed limit, and turnout switching time if a train take sidings. Equations (4.10) and (4.15) also work as a part of the schedule constraints as well. The notation τ_i^q in Equations (4.10) and (4.15) ensure the minimum dwell time for passenger trains at stations.

$$Mo_i^q \geq D_i^q - A_i^q - \tau_i^q \qquad \forall i \in N,\ q \in Q \tag{4.10}$$

$$\theta_{ij}^q \geq o_i^q + o_j^q + x_{ij}^p - 2 \qquad \forall i \in N,\ j \in N,\ i \neq j,\ q \in \delta_p,\ p \in P \tag{4.11}$$

$$3\theta_{ij}^q \leq o_i^q + o_j^q + x_{ij}^p \qquad \forall i \in N,\ j \in N,\ i \neq j,\ q \in \delta_p,\ p \in P \tag{4.12}$$

$$A_j^q \geq D_i^q + \varsigma + h_{ij}^p - M(1 - \theta_{ij}^q) \qquad \forall i \in N,\ j \in N,\ i \neq j,\ q \in \{\kappa \cap \delta_p\},\ p \in P \tag{4.13}$$

$$o_i^q \leq L_i^q \qquad \forall i \in N,\ q \in \kappa \tag{4.14}$$

$$D_i^q \geq A_i^q + o_i^q(f_i + t_i^q + \varsigma) + \tau_i^q \qquad \forall i \in N,\ q \in Q \tag{4.15}$$

The variation of siding construction cost is taken into account by Equation (4.16). It links the construction zone with the location of sidings to determine how much capital an additional siding requires in order to be implemented. This constraint can be neglected if the construction cost along the target mainline varies little

$$\sum_{c \in C} \sigma^{c-1} z_c^q - M(1 - \sum_{c \in C} z_c^q) \leq \sum_{r \in \{r \leq p\}} d_r \leq \sum_{c \in C} \sigma^c z_c^q + M(1 - \sum_{c \in C} z_c^q)$$

$$\forall q \in \{\kappa \cap \delta_p\},\ p \in P \tag{4.16}$$

The following constraints are the track configuration constraints. Equation (4.17) ensures minimum siding spacing is displayed. Equation (4.18), meanwhile, keeps the location of existing sidings. Equation (4.19) prevents trains from meeting or passing at a node without existing siding. Equation (4.20) ensures that a siding can only exist in a valid construction zone, while equation (4.21) ensures that the model selects all existing sidings.

$$d_p \geq g - M(1 - \sum_{c \in C} \sum_{q \in \psi^+} z_c^q) \qquad \forall p \in P \tag{4.17}$$

$$\sum_{r \in \{r \leq p\}} d_r = \varphi^q \qquad \forall q \in \{\eta^- \cap \delta_p\},\ p \in P \tag{4.18}$$

$$\sum_{i \in N} o_i^q \leq M \sum_{c \in C} z_c^q \qquad \forall q \in Q \tag{4.19}$$

$$\sum_{c \in C} z_c^q \leq 1 \qquad \forall q \in \eta^+ \tag{4.20}$$

$$\sum_{c \in C} z_c^q = 1 \qquad \forall q \in \eta^- \tag{4.21}$$

Equation (4.22) is the budget constraint and equation (4.23) ensures that OSLM completes the dispatching process within a given time period. Equation (4.24) sets the train running time between any two adjacent nodes as the average running time between the two points. The average running time can be obtained from simulations (Leilich, 1998) or analytical models (Chen and Harker, 1990; Higgins and Kozan, 1998).

$$\sum_{c \in C} \sum_{q \in \eta^+} U^c z_c^q \leq B \tag{4.22}$$

$$A_i^q \le E \qquad \forall i \in N,\ q \in k_i \tag{4.23}$$

$$A_i^q - D_i^s = d_p / v_M^i \qquad \forall i \in N,\ (q,s) \in \vartheta_p,\ p \in P \tag{4.24}$$

To demonstrate the function of OSLM, a hypothetical single-track line with a length of 105 miles and two usable intermediate passing sidings was considered with three train types. Passenger, intermodal and bulk unit trains are the types considered with their corresponding travel speed and delay cost. The train dispatching result demonstrates that the OSLM constraints provide reasonable train dispatching decisions (Figure 4.2). The optimal siding location plan (Figure 4.3) indicates the number and the locations of additional sidings.

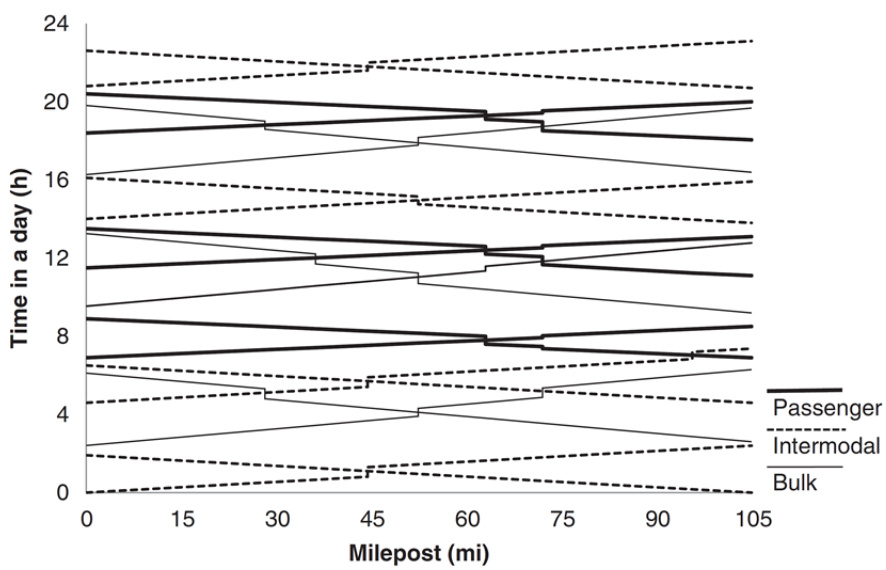


Figure 4.2. Example of Train Dispatching Result

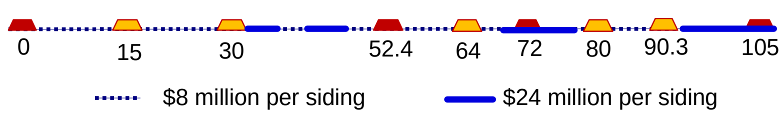


Figure 4.3. Example of Optimal Siding Location Plan

The OSLM solution can be compared to intuitive guidelines that suggest adding new passing sidings to a line at as evenly-spaced intervals as possible while, simultaneously avoiding areas of high construction cost. The comparison between the OSLM and the intuitive method suggests that OSLM was able to find a better (lower-cost) solution by placing the new siding closer to the middle of the route rather than the halfway point between milepost 0 and 52.4.

The basic OSLM formation has been expanded to consider variation in construction cost, variation in train speeds, and trains of different lengths that can only use certain long passing sidings on the route. To demonstrate the importance of variation in construction cost to the siding planning problem, OSLM has been applied to the same route with and without variations in siding cost. The difference between the scenarios shows the impact of variable construction cost to the total cost (Figure 4.4). The red numbers show the least total cost and indicate the optimal amount of investment. OSLM has also been extended to suggest both new passing siding construction and siding length extensions projects on routes where trains lengths are being increased (Shih et al., 2014b; Shih et al., 2015b), and determine the optimal siding locations on a mainline with significant speed variation (Shih et al., 2015b).

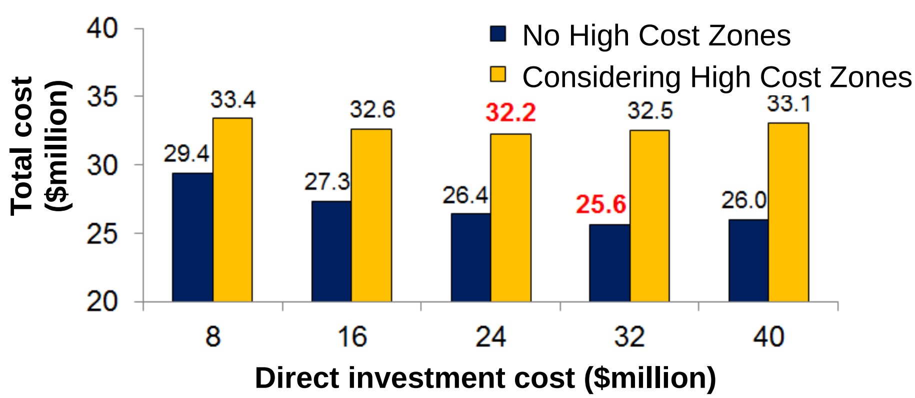


Figure 4.4. Comparison Between Scenarios With and Without High Cost Zones

4.3. Intellectual Merit and Expected Impact

The model provides an optimal siding location plan under structured operation used by mainline infrastructure planners. Using this model can help railroads maximize their return on investment and improve service quality. This model extends the work of Higgins (1997) model by introducing the practical engineering constraints. The basic model has also been successfully adapted to studies of train length and passing siding extensions. In this manner, OSLM can serve as an archetype for other researchers to use as a basis for developing modified forms to address other railway capacity and service design questions.

4.4. Remaining Challenges and Goals

Work completed on the OSLM was documented in the journal paper "Optimization of Siding Location for Single-Track Lines" (Shih et al., 2014b) and in two conference proceedings papers (Shih et al., 2015b; Shih et al., 2015c). The remaining effort is to write the dissertation chapter.

4.5. Plan for Completion and Success Criteria

The dissertation chapter can be finished before the end of spring 2017 semester. The study can be considered as a success if the developed model is capable of generating an optimal siding location plan based on the given budget, environmental parameters and the traffic characteristics. Also the result of the case study based on the developed model should be able to show the importance of considering the potential impact of variable construction cost on total cost. The case study should display that using this model can at give the planners an initial indication of where the optimal siding locations are without the need for simulation of a large number of alternatives, thus planners can then focus their simulation resources on the final engineering evaluation of a smaller subset of candidate capacity expansion projects.

5. A SCREENING APPROACH TO INDENTIFYING MAINLINE CAPACITY CONSTRAINTS UNDER FLEXIBLE HETEROGENOUS RAILWAY OPERATIONS

Over the past 15 years, the North American freight railroads have invested billions of dollars in infrastructure expansion and improvement projects to increase the capacity of key mainline routes. The locations of new passing siding and double-track projects on single-track lines are typically determined through a combination of simulation and engineering judgement of experienced practitioners. Simulation models, such as RTC, can compare the relative performance of the route under different infrastructure investment scenarios. However, constructing, running and analyzing the simulation model can be resource-intensive, particularly when there are many different possible combinations of investments to consider. Also, non-railroad practitioners such as commuter rail operators or State DOTs seeking to implement passenger service may not have all the data required to drive the simulation model. In the absence of data, or to reduce the number of scenarios that must be simulated in detail, engineering judgement is used to identify a small set of potential capacity expansion projects. A common practitioner approach is to conduct capacity expansion projects on longer, single-track segments to reduce the average length of gaps between passing sidings and double-track segments (Shih et al., 2014a). Another practitioner approach is to implement projects at the locations where train delay is accumulated (Williams, 2011). However, both of these intuitive methods may not always identify the critical bottleneck in a network and appropriate infrastructure investment under different operation styles.

While the optimal siding location model developed in the previous chapter is one approach to improve upon engineering judgment, the model is not tractable for mixed operations. To overcome this difficulty, this chapter proposes a screening approach to detecting the critical constraints on a mainline with flexible heterogeneous traffic. Like OSLM, it is anticipated that this methodology can be used to quickly identify a smaller subset of potential capacity expansion projects for further investigation with simulation tools, increasing the effectiveness of the railroad project planning process.

5.1. Overview of the Current Status

Several previous studies have attempted to develop general guidelines for optimal incremental capacity expansion strategies on single-track lines (Sogin et al., 2013a; Sogin et al., 2015). Shih et al. (2014a) suggested an incremental order to add sidings to single-track, freight rail lines with sparse siding density. Atanassov (2015a; 2015b) examined two incremental orders for double-tracking projects on single-track lines with variable sidings. The findings of these studies can be used as a general reference but may not present the optimal strategy for all infrastructure configurations, operating styles and traffic mixtures. Analytical approaches to project selection have also been developed, such as the siding location model in Chapter 4 and RailEval jointly-developed by Decisiontek and TEMS Inc (Decisiontek, 2014). A shortcoming of these analytical models is that they do not lend themselves to routes with mixed or flexible operations. Identifying locations where the greatest train delays accumulate as those requiring infrastructure expansion is another popular approach to the capacity planning process (Williams, 2011). However, this approach may only treat the symptom of train delay instead of the root cause of the congestion.

In an effort to improve on previous approaches and provide the capability to analyze flexible operations, the concept of quantifying train conflicts is used to develop a new screening approach for identifying capacity constraint locations on railroad mainlines.

5.2. Summary of Technical Approach and Research Results

White (2005) proposed the concept that using conflict locations for capacity analysis as a component of his "root cause analysis". In this chapter, this concept was adopted to develop a capacity screening tool which identify the expected locations of train conflicts on each zone of a single-track mainline as capacity constraints. It was used as the basic concept by capacity screening tool to identify capacity constraints. Alternately, using accumulated delay to identify capacity constraint is also a feasible option. An example comparing the analysis of traffic conflict or accumulated delay is displayed in Figure 5.1. The delay (Figure 5.1.a) and the conflict locations (Figure 5.1.b) are the capacity constraint of a mainline based on delay (Figure 5.1.a) or conflict analysis (Figure 5.1.b). Similar to the example, the capacity constraints identified by the two methods are usually different in other larger cases. This leads to two different methods of doing capacity planning, the zonal delay method based on delay analysis and the screening tool based on conflict analysis (Figure 5.2). The case study of this chapter will compare the capacity expansion plans and the performances of the plans as the outputs of the two methods.

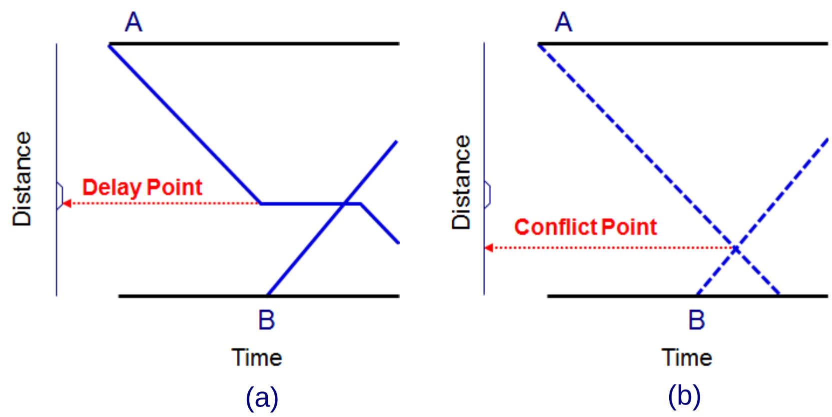


Figure 5.1. A Possible Scenario Which Biases the Identification of a Capacity Constraint Point (a) Accumulated Delay Analysis (b) Traffic Conflict Analysis

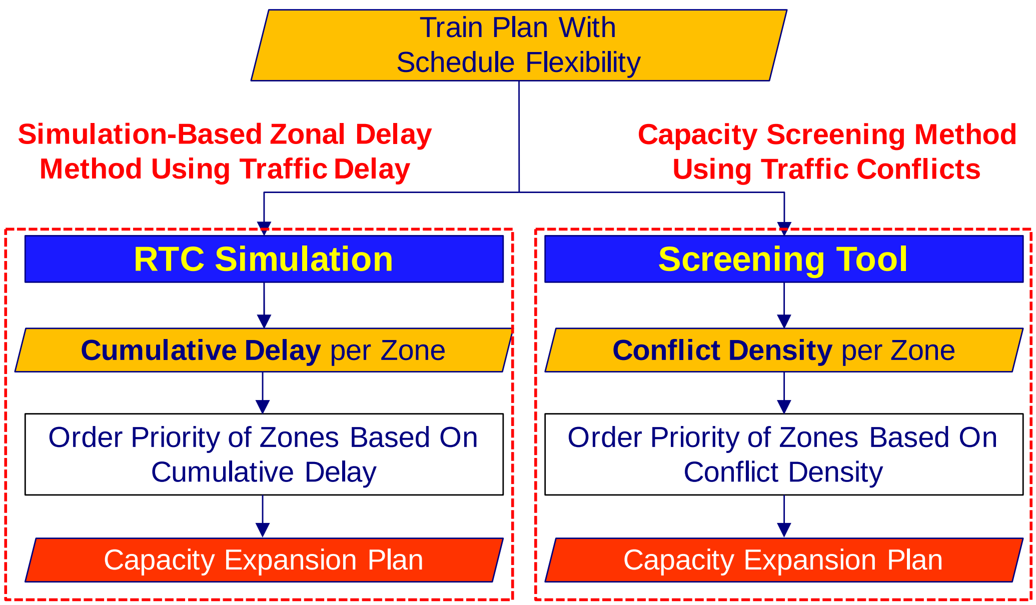


Figure 5.2 Two Methods Based on Delay and Conflict Analysis to Determine Capacity Expansion Plans

For mixed operations, the delay distribution for each train may not follow any existing parametric distributions. Thus it is not practical to develop a function for the conflict density using a direct mathematical approach. To overcome this, a process based on the Monte Carlo concept (Mooney, 1997) is adopted to build the framework for screening tool (Figure 5.3).

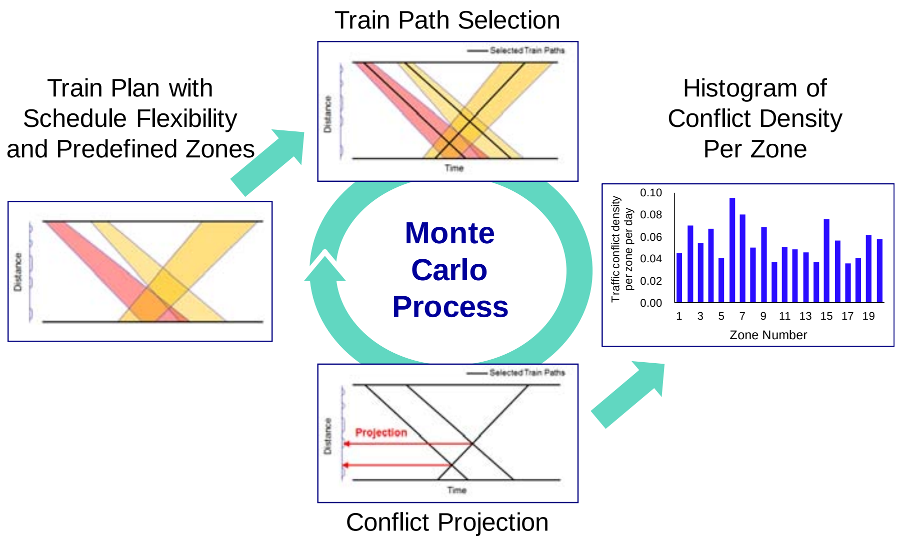
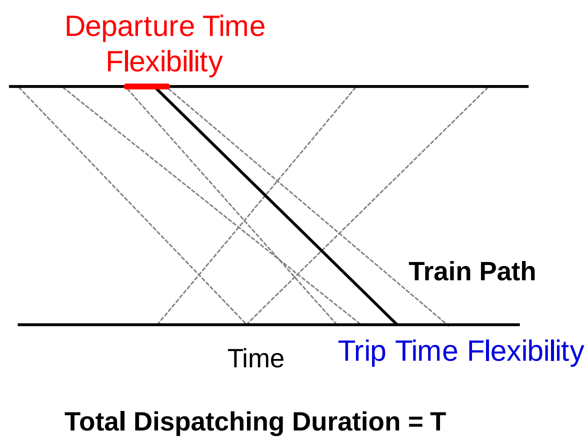
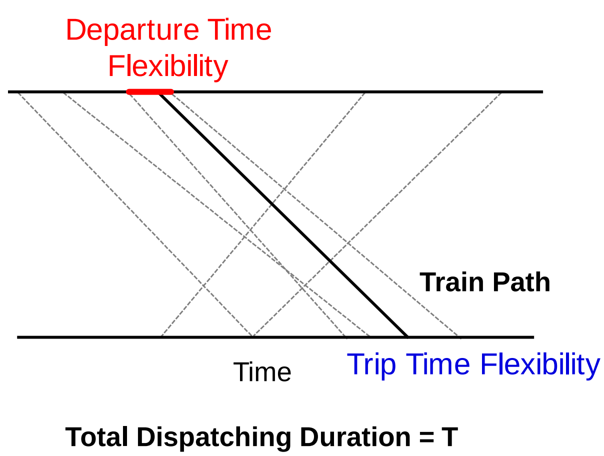


Figure 5.3. Flowchart of the Capacity Screening Tool

For each iteration, the train schedule generator creates a set of train paths (not bands) based on the given train departure and trip time flexibility. The conflicts of these train paths are used to reveal the original location of conflicts. The projection process calculates the expected number of conflicts along each zone of the mainline based on the set of generated train paths and the current infrastructure layout. This process is repeated for a different set of random train paths within each train band until the desired number of iterations has been reached. The final output is the mean number of the projected train conflicts in each zone on the mainline. Figure 5.4 illustrates the process. It shows three iterations of the screening tool on a simplified single-track line. For the initialization process, a pre-determined train plan with schedule flexibility needed is needed (Figure 5.4.a). As operations become structured and the width of each train path narrows, the locations of train conflicts become more certain. The conflict density distribution created by the capacity screening tool is likely to show a limited number of peaks that could be addressed by infrastructure expansion projects. In the special case of purely structured operations, analytical or optimization approaches can be used to determine the optimal locations for these projects, as discussed in Chapter 4. Another step of the initialization process is to divide, the target mainline into zones (Figure 5.4.b), just like the evenly divided mainline in the example. The zones can be defined randomly, or based on user's need, such as the location of potential capacity expansion projects. Three iterations were shown as an example of screening tool (Figure 5.4.c, Figure 5.4.d, Figure 5.4.e). The final output is the total projected conflicts. Since the train paths were generated randomly within each train band based on the stochastic properties of the train operation, taking the mean of the total projected conflicts is equivalent to calculating the expected number of traffic conflicts along the mainline.



(a)



(b)

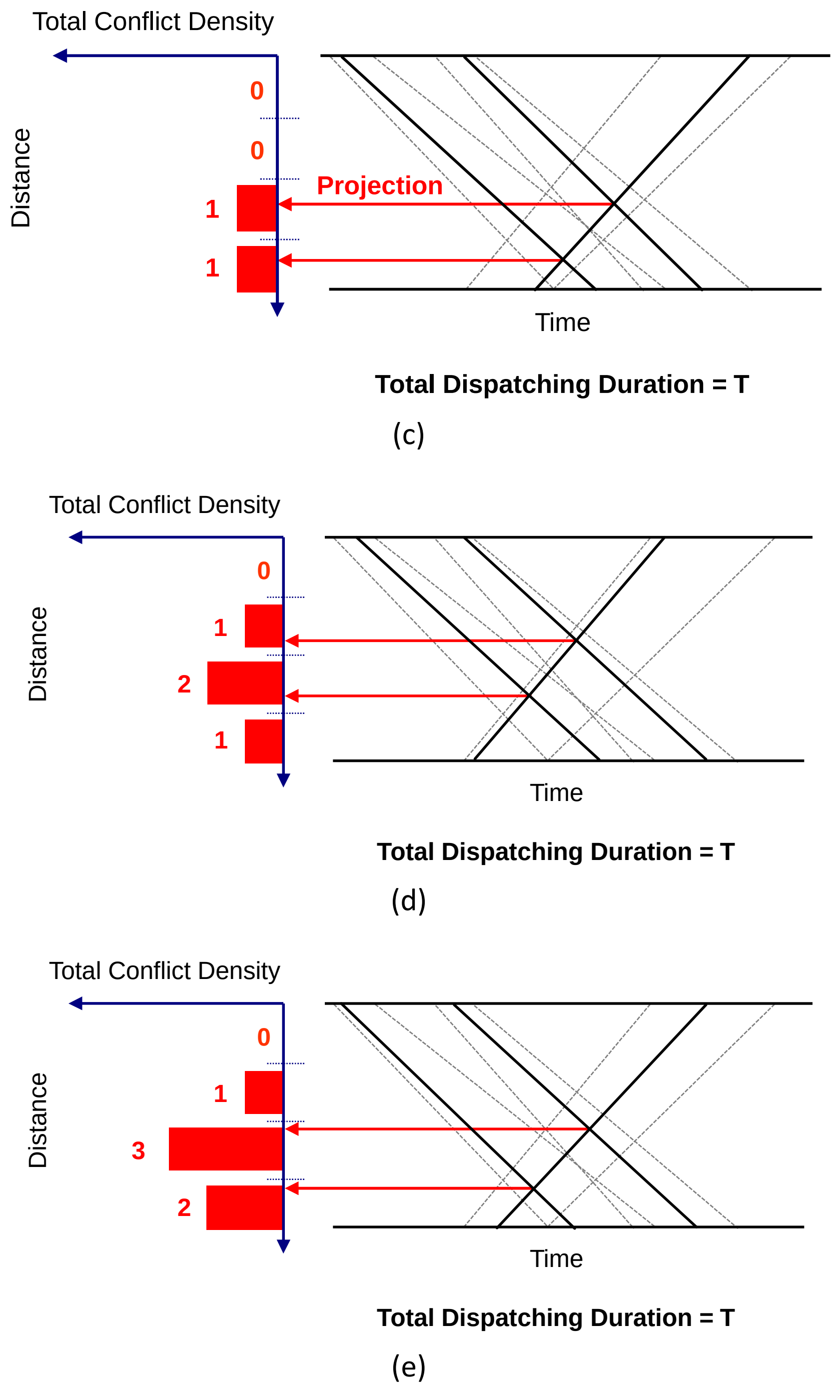


Figure 5.4. Example of the Two Initialization Steps and Three Iterations of the Screening Tool (a) Initialization of train plan with schedule flexibility (b) Dividing mainline into zones (c) First Iteration (d) Second Iteration (e) Third Iteration

A case study was conducted in which the performance of the zonal delay and screening tool methods were compared. Each method was used to determine capacity expansion plans for a hypothetical, single-track line. Their performances were then compared based on traffic delay. Each plan contains three construction periods with two siding projects constructed per period. This generates three infrastructure layouts with incremental number of sidings for each plan. The two sets of layouts generated by the methods were then constructed in RTC to access their performance. The result is shown in Figure 5.5 by train delays. The result indicates screening tool has an equivalent performance in terms of average train delay compared to the zonal delay method. However, the zonal delay methods require users to construct infrastructure in RTC, and, the simulation runs required by the zonal delay method are time consuming. Using the case study as an example, the screening tool took 15 minutes to generate a capacity expansion plan while the zonal delay method needed four hours. Using the screening tool can greatly reduce the computational effort required.

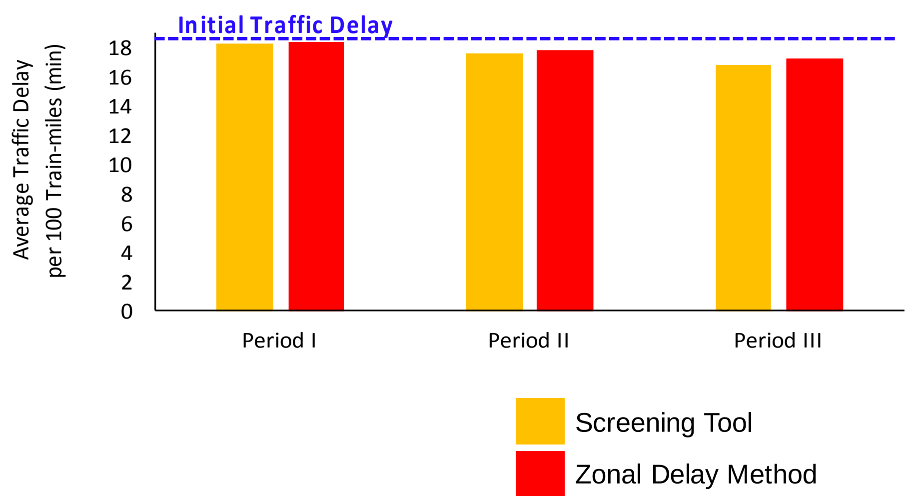


Figure 5.5. Performance of the Screening Tool and the Zonal Delay Method

5.3. Intellectual Merit and Expected Impact

For industry practitioners, it is anticipated that the capacity planning tool can be used to quickly identify a small subset of potentially effective infrastructure projects to improve operating efficiency that can then be subject to more detailed simulation and engineering analysis. The generated output can also help visualize the root cause of congestion and may be used to inform operational planning such as train rescheduling or track maintenance planning. This method provides a new approach for the research community considering the capacity planning problem. Also, most academic studies use optimization or simulation models to solve capacity planning problems. This method proposes an analytical method based on root cause analysis. The approach does not require the detail of simulation but can still consider the operational flexibility that is problematic for other analytical approaches. By considering fundamental delay mechanics arising from traffic heterogeneity and infrastructure, the approach should be able to generate appropriate solutions with less effort and computational time compared to optimization or simulation approaches.

5.4. Remaining Challenges and Goals

The capacity screening tool has been coded and the simulation scenarios used to validate the tool have been developed. A hypothetical single-track line with sparse sidings and variable siding spacing will be used to test the performance of the screening tool and zonal delay method relative to simulation. Their performance will be also compared with the performance of the best and worst capacity expansion plans (strategy) identified by Atanassov et al.(2015a). This help evaluates the effectiveness of the capacity screening tool comparing to the strategies found in the previous study. Double-track projects will be applied to the constraints identified by the two methods. Three traffic mixtures representing different operating styles will be simulated on the resulting infrastructure to test the performance between the delay method (determines the priority of projects based on the simulation output of the initial scenario), the iterative delay method (iterates the simulation after new projects are implemented), and the capacity screening tool. The result can help determine the types of operating styles where the infrastructure solutions identified by the capacity screening tool provide equivalent performance to simulation with less effort.

5.5. Plan for Completion and Success Criteria

This chapter has been developed into an unpublished paper, that includes all details of the study in this chapter and a partial validation result. The remaining work is to finish the validation case study, write the relevant sections of the paper and format the paper into the dissertation style. This process is expected to be finished during the spring semester 2017. This study can be considered as success if the case study shows that the screening tool has an equivalent performance compared to detailed simulations, but generates capacity expansion plans with reduced computational time. The developed tool can advance the state of art of capacity plaining on single-track mainlines under mixed operation.

6. A PARAMETRIC MODEL OF THE TRAIN DELAY DISTRIBUTION BASED ON MEET AND PASS CONFLICTS

Most analytical and parametric approaches to railway capacity focus on predicting average train delay (Burdett and Kozan, 2006; Mitra and Tolliver, 2010; Murali et al., 2010) not the performance of individual trains or their delay distribution. In practice, train delay varies around the average value according to some distribution and performance of particular trains may substantially deviate from the average. Using average values of train delay may lead to erroneous conclusions when, as described in Chapter 2, the level of service for certain types of particularly poor or well-performing trains controls the capacity of a railway line. In this chapter, I will develop a parametric model that estimates the distribution of train delay on single-track mainlines.

The parametric model of the train delay distribution is based on a new set of indices developed to measure both the amount of traffic and the degree of traffic heterogeneity present on the route under study. A quantile regression approach (Koenker and Bassett, 1978; Machado and Mata, 2001; Nielson and Rosholm, 2001) was used to build the model since the existing statistical distributions (such as Gaussian, Weibull, or Poisson) do not adequately represent the delay distribution of heterogeneous railway traffic. The model is coded in R (2015) and SAS (2016). The output of this model can be used to assess the impact of different attributes of heterogeneous traffic on the train delay distribution. Practitioners can use the developed model to improve the robustness of their infrastructure and operational strategies by making decisions on the basis of the entire train delay distribution and not just a single value of average train delay.

6.1 Overview of the Current Status

In Chapter 2 and 3 of this document, two studies related to rail traffic heterogeneity were conducted to investigate the fundamental behavior of rail traffic with multiple train types on single-track mainlines. The case studies also demonstrated a standardized capacity planning process. However, these approaches did not solve all of the problems of capacity assessment under heterogeneous traffic. The indices used for the studies in Chapter 2 and 3 can only describe the characteristics of traffic mixtures with up to three train types. Previous research has proposed indices to better quantify the characteristics of rail traffic with multiple train types (Chen and Harker, 1990; Kwon et al., 1995; Morlok and Riddle, 2001; Gorman, 2009; Lai et al., 2010; Landex, 2008; Bonsra and Harbolovic, 2012; Sogin et al. 2013a; Dingler et al. 2013). The indices proposed by other researchers are either empirical (such as the ratio of the maximum and minimum train speed in Krueger's study) or lack generality (the indices developed by Landex (2008) are only applicable to passenger rail systems under directional operation), and thus do not have a direct physical meaning that translates to train delay mechanisms. For example, the index representing the ratio of maximum and minimum train speed indicates the degree of speed heterogeneity but does not describe the specific speed heterogeneity mechanics leading to train delay. More generalized indices with direct linkages to the mechanics of train delay may better quantify rail traffic heterogeneity and the causal relationships leading to the distribution of train delay observed on a route.

Previous studies usually use "train types" as a measure of heterogeneity. However, since the requirements for individual trains within a train type can vary according to its specific business objective, general train types do not always correspond to the operational characteristics of an individual train. The proposed indices focus on quantifying the characteristics of each individual train and not general train types.

As stated above, previous models have generally considered average train delay but not the distribution. Since traffic heterogeneity has a disproportional impact on average train delay, it is plausible that it might also have a disproportional impact on train delay distribution. Increasing traffic heterogeneity may increase both the average train delay and its variance, decreasing both running-time performance and reliability. Previous analytical and parametric models for the average train delay value do not quantify this effect. It is anticipated that developing a parametric train delay distribution model based on generalized indices can reveal specific mechanics behind the line capacity effects of traffic heterogeneity. The model and associated knowledge can be used by industry practitioners to better serve railroads through improved infrastructure and operational decisions with a focus on the level-of-service reliability of all trains (not just the average).

6.2 Summary of Technical Approach and Research Results

The proposed parametric model was developed in two stages. In the first stage, appropriate heterogeneity indices were developed based on the number of potential traffic conflicts encountered by each train. In the second stage, the indices were used to construct a quantile regression model of the train delay distribution.

Train delay is usually related to traffic volume through delay-volume curves. A shortcoming of this approach is that it only considers the amount of traffic on the route under study and not the degree of traffic heterogeneity. The concept of using train conflicts (also referred to as traffic conflicts) to better predict train delay was formalized by Gorman (2009). He used historical data from ten single-track freight lines to test the relationship between train running time and various operating and infrastructure factors. Gorman found that traffic conflicts, represented by the number of meets, passes and overtakes, significantly affects train delay. However, Gorman did not connect his indices to traffic heterogeneity. This study seeks to determine if the traffic conflicts proposed by Gorman can be used to describe the relationship between the degree of traffic heterogeneity and the magnitude and distribution of train delay.

Various heterogeneous traffic scenarios were simulated with RTC in a preliminary study to investigate a relationship between the number of traffic conflicts and train delay on a representative shared corridor. Under these conditions, the expected number of traffic conflicts (calculated by counting the total traffic conflicts each train could encounter based on a process similar to the Monte Carlo process used in Chapter 5) is more closely correlated with train delay than the total traffic volume (Figure 6.1). Also, the number of expected traffic conflicts for a certain traffic volume is a function of both the traffic volume and the traffic mixture encountered at that traffic volume. This suggests that the number of traffic conflicts captures both the impact of traffic volume and heterogeneity and may be a better index for delay prediction than traffic volume alone.

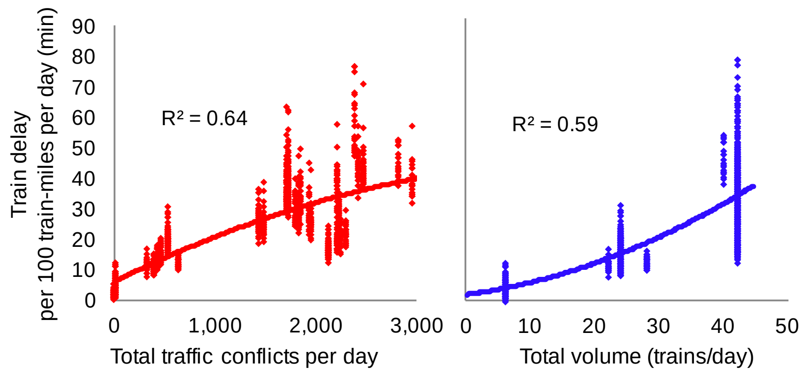


Figure 6.1. Relationship Between Traffic Conflicts, Traffic Volume, and the Average Train Delay per 100 Train-miles

As mentioned in the introduction, heterogeneity can arise from different combinations of speed variation, priority variation, and operating styles. Three indices were defined to reflect these attributes of heterogeneous rail traffic:

- Total Conflicts (TC) considers all of the potential conflicts a train could encounter during its trip. A larger number of traffic conflicts increases the difficulty of train dispatching. This index is also an analog to traffic volume since higher train volumes usually lead to more train conflicts. However, the calculation of TC did not count the potential number of additional conflicts due to trip time flexibility. Since trip time flexibility, train delay distribution in other terms, is the object to be predicted.
- Adjusted Train Priority (ATP) quantifies the actual priority of a train within the given traffic mixture on the route. ATP is calculated for a target train by the summation of inferior conflicts (target train has inferior priority relative to the conflicting train) and half of equal conflicts (target train has equal priority to the conflicting train). In previous studies, the assigned priority of a train was a static ordinal value based on its train type. The actual priority of a train should be a dynamic value since it varies with the traffic mixture. For example, the actual priority of an intermodal train within traffic composed

of 80% inferior trains should be higher than the relative priority of the same train within traffic composed of only 20% inferior trains. The physical interpretation of ATP as a delay mechanic is the percentage of conflicts that the target train will need to stop and wait for the other conflicting train to pass.

- Inferior Pass (IP) represents the impact of train speed heterogeneity on train conflicts and delay. When IP is low, there is a greater diversity in train speed and meets make up a smaller share of train conflicts. This is in comparison to cases where speed is homogeneous and all train conflicts are meets. IP calculates the expected number of inferior passes (target train has inferior priority to passing train). The physical meaning behind IP is the expected number of passes that will cause the target train to stop or encounter delay. Delays for passes are assumed to be the origin of extra delay caused by train speed heterogeneity.

With the three indices defined, the second step of the study is to apply a quantile regression approach to build the parametric model. The traditional way to model the train delay distribution is to use parametric statistics, such as the Gaussian distribution. Sogin et al. (2012) fit a Weibull distribution to the delay data from homogeneous unit train traffic. However, a preliminary test conducted for this study showed that a Weibull distribution or other common parametric distributions did not adequately model the delay distribution of a train in heterogeneous rail traffic. Consequently, a quantile regression approach will be used.

Quantile regression is a statistical method used by researchers in the area of macroeconomics to model the interaction between variables and output distributions (Arias et al., 2001). The quantile regression model creates multiple regression lines that each represent a quantile boundary (Figure 6.2). The 97.5 percentile line shows the best fit such that approximately 97.5 percent of the data points are below the line and 2.5 percent are above the line. In this case, the slope of the curve represents the sensitivity of the 97.5th percentile of train delay to the TC index defined above. Based on the quantile regression technique, the mentioned indices are used as possible variables to consider when building regression models to project train delay distributions.

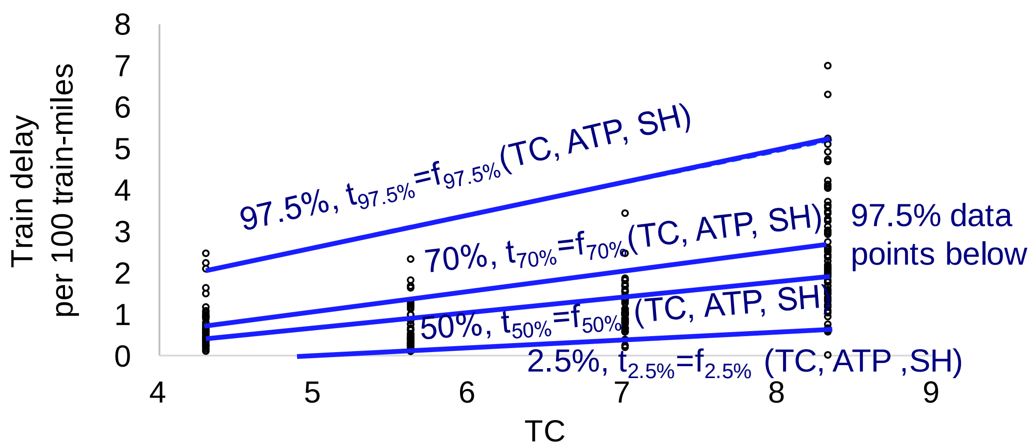


Figure 6.2. Example of a Quantile Line

The constructed model can be used to analyze the response of the train delay distribution to changes in traffic (as reflected by changes to the three heterogeneity indices). Also, the output of this model can help practitioners understand the impact of each heterogeneity index on the train delay distribution.

In the proposed case study, a comparison between the developed model and the CN parametric model will be conducted. The CN parametric model is one of the industry standard capacity models, and is thus an appropriate baseline for comparison. The outputs from the CN parametric and train delay distribution model will be visualized for comparison, just like the example shown in Figure 6.3. The predicted train path generated by the CN parametric model is a segmented line, but the output from train delay distribution model is a train band since it is capable to show the theoretical space of train path based on the predicted train delay distribution. This comparison can help understand the difference between the new and the old model. The other objective of the case study is to investigate the impact of train departure flexibility of a train at its original on total trip time. This result will be displayed by the graph shown in Figure 6.4, and also a graph to show the response of total trip time based on departure time.

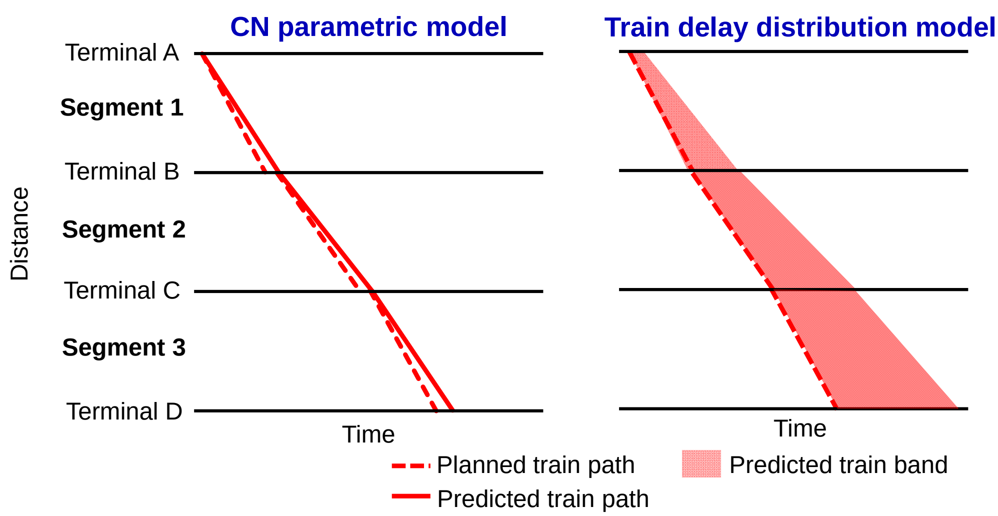


Figure 6.3. Visualization of Outputs of CN parametric and Train Delay Distribution Models

6.3 Intellectual Merit and Expected Impact

Railroad practitioners can use this model for different types of operations planning tasks. It can be used independently to assess a particular operating change, like the case study of this chapter, or combined with other models to improve their predictive ability. For example, combining the train delay distribution model with a rolling stock scheduling tool can increase the robustness of the equipment assignment plan. The delay distribution model may also be used as an input to the capacity screening tool developed in the previous chapter.

For an academic contribution, this study proposes many innovative ideas to advance the understanding of the mechanics of train delay on shared corridors. First, the study improves upon the concept of expected traffic conflicts as a predictor of train delay by defining three indices to quantify the attributes of heterogeneous rail traffic. The three indices can be used to predict the impact of each attribute on train delay individually or in combination, revealing how certain operating changes lead to specific delay-causing conflicts. This is also an application of the quantile regression technique in the field of rail capacity analysis. The application of the technique to this field improves the ability to predict the full train delay distribution and will likely be a springboard for further research by others in the future.

6.4 Remaining Challenges and Goals

The parametric model in this study has been constructed on the basis of the simulation output of a representative single-track line. The introduction, literature review and the methodology are complete. The remaining tasks are validation, the case study and documenting the result. The result of this case study will also be compared with a result from the CN parametric model to validate and potentially show the advantage of using this model.

6.5 Plan for Completion and Success Criteria

The case study is expected to be finished before the end of the spring 2017 semester. It is anticipated that the case study can be documented in journal paper and dissertation chapter format before early spring 2017. If the proposed case study does not adequately demonstrate the importance of this model for the train delay distribution, another case study related to heterogeneous train routing will be explored. The alternative study will compare the routing strategy suggested by the CN parametric model to the developed quantile regression model in order to show the advantage of full consideration of the train delay distribution compared to average train delay.

7. CONCLUSION

Recent changes in rail traffic patterns and volume in North America have increased the demand for network capacity. Freight transportation demand, boosted by the gradual economy recovery since 2009, and the continued interest in increasing the frequency of passenger rail service are responsible for the increase of traffic volume. This study expands industry understanding of traffic heterogeneity on current freight railroad operations.

On the other hand, single-track lines with sparse siding density are likely to be capacity constraints within the rail network since they supply less capacity than other mainlines. This dissertation developed techniques, tools and a model to assess the impact of traffic heterogeneity including operation style on train performance of single-track lines.

The capacity evaluation technique developed in Chapter 2 was used for measuring the extra capacity demand from the variation of priority, speed and LOS across multiple train types. The alternative comparison process was conducted to find a guideline for the capacity expansion planning of the single-track lines. These two tools are an initial step to understand the fundamental relationship between flexible operation and traffic performance. The results of Chapter 2 suggest that for flexible operation, the optimal traffic mixture with the largest available capacity varies. Thus it is important to consider the current traffic mixture when evaluating the impact of plans to introduce additional traffic on a route. In Chapter 3, it was found that since the interaction of trains under flexible operation varies significantly, a reliability test of the entire train delay distribution in addition to the traditional efficiency test of average train delay may be required to determine the optimal capacity expansion strategy.

Structured operation aims to follow the preplanned schedule strictly, thus the locations of traffic conflicts are more stable than with flexible operations. Under this scenario, determination of optimal number and locations of sidings is possible. An optimization model was developed to find the locations and number of sidings on a single-track line with sparse density of sidings. Using this model can help the planners improve train performance on pure passenger corridors, transit operations or corridors that are dominated by passenger trains and premium intermodal trains. However, this optimal siding location model is fragile to any potential departure or travel time randomness and is thus less applicable to mixed corridors where freight trains share track with passenger trains.

A capacity screening tool and a regression model were developed based on the concept of traffic conflict analysis for mixed operation. The concept of expected number of traffic conflicts was adopted to capture the impact of different degrees of operating flexibility. This concept was proposed by White (2005) and Gorman (2009) and this study tried to investigate and apply the concept in a more systematic way. The capacity screening tool identifies points of capacity constraint based on the projected location of traffic conflicts. The train delay distribution model predicts train delay based on the number of conflicts a train expected to encounter during its trip. These two tools provide a new way to approach capacity planning on shared corridors with mixed or flexible operations.

To better understand and improve approaches to the current rail capacity problem in North America, this dissertation study considered the impact of operating style and LOS in addition to priority and speed variation on single-track lines. Techniques and tools were developed and tested to gain more comprehensive understanding of the influence of the operating style. There are several contributions worth mentioning. First, this dissertation approached the capacity problem with different strategies based on operating styles. This helps improve the quality of operations and capacity planning on North America railroads. This dissertation also conducted an application to connect the root cause approach to traffic conflict analysis with evaluation of train traffic heterogeneity and capacity. The tools developed on the basis of this concept provide an alternative to the simulation-based planning process in North America. From the technical perspective, it used quantile regression in the field of rail capacity study. This technique provides a way for academia or industry to model the delay distribution of heterogeneous rail traffic. Overall, this dissertation advances the understanding of rail traffic heterogeneity while developing practical tools for the industry to improve their service quality and infrastructure planning.

8. ACKNOWLEDGEMENTS

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