Impact of High-Speed Passenger Trains on Freight Train Efficiency in Shared Railway Corridors

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TECHNICAL SUMMARY

Title

Impact of High-Speed Passenger Trains on Freight Train Efficiency in Shared Railway Corridors

Introduction

In the United States, freight rail demand had doubled from 0.9 trillion ton-miles in 1980 to 1.8 trillion ton-miles in 2007, and railroad carriers reached a 39.5% market penetration in 2007[1]. As intercity passenger rail is widely recognized as an energy-efficient, environmentally-friendly, and safe mode, the development of high-speed passenger rail holds the promise to mitigate highway congestion, achieve sustainable development, and reduce foreign oil dependency. To achieve a cost-effective investment to the HSR systems, a mixed traffic system (i.e., heterogeneous passenger and freight trains sharing the same railroad tracks that are privately owned) is highly likely to be implemented in the U.S. However, the introduction of a high priority passenger train (typically with higher speed) will induce both primary delays (due to operational uncertainties) and secondary or "knock-on" delays (due to meet, pass, and overtake for train conflicts, and delay propagations) to the existing freight trains (typically with lower speed). Resolution of the conflicts between passenger and freight trains is extremely essential for the future deployment of an HSR system. This highlights the need for an integrated, systems-level framework that incorporates cutting edge train control technologies and advanced analytical and simulation based modeling techniques for decision making and policy analysis. In particular, it is a pressing need to understand the complex interactions between high-speed passenger trains and freight trains in shared railway corridors. This project has developed a series of decision support tools that can help evaluate the impact of high-speed passenger trains on freight corridor capacity, e.g., by answering the following fundamental questions:

- How does the introduction of high-speed passenger trains affect the railroad freight carrying capacity?
- How is this impact dependent of various design factors (e.g., speeds, headways, and infrastructure design)?
- What policies will be suitable for public agencies and private sectors to support the development and deployment of the proposed high-speed passenger trains?

Findings

This research project addresses congestion chokepoints by considering congestion effects in railroad transportation network caused due to the impact of high-speed passenger trains on freight train.

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[1] Bureau of Transportation Statistics. National Transportation Statistics 2011. U.S. Department of Transportation, Washington D.C.

Advanced network analysis models, as a result of this work, will yield short-term (ready-to-use computer tools for practitioners) and long-term (new mathematical modeling approaches and design paradigms) impacts.

The research lays the foundation to address issues regarding both short-term and long-term passenger and freight transportation chokepoints. This research project brings systems-level perspectives and advanced train control technologies into the railway transportation context, integrated within theoretical models, optimization and simulation approach, policy analysis, and implementation framework. It also addresses the urgent national needs for the development of HSR plan.

Recommendations

The tasks under this project are the initial key step toward the creation of an advanced, integrated analytical and simulation framework for improving heterogeneous train traffic capacity in shared rail service corridors. This research provides a theoretical basis to address strategic, tactical, and operation level issues such as infrastructure investment, train timetabling plans, and train dispatching policies in such shared corridors. This project advances the state of the art in train delay estimation, train timetabling and dispatching, and complex system modeling.

The research efforts are the first few that considering the integration of different approaches in various analysis levels to estimate capacity impact and help to evaluate and determine train management policies and operational strategies (including speeds, headways, timetabling, dispatching, and control technologies) for HSR systems in shared railway corridors. Implementing this framework will provide important insights on policy analysis, corridor management strategy, railroad operational planning, and train control technology, for the on-going American National HSR Plan (including the Chicago-St. Louis HSR Project).

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CHAPTER 1. INTRODUCTION

1.1   *Background and Motivation*

United States (U.S.), freight rail demand has doubled from 0.9 trillion ton-miles in 1980, to 1.8 trillion ton-miles in 2007, and railroad carriers reached a 39.5% market penetration in 2007 (BTS, 2011). Meanwhile, intercity passenger rail is increasingly being recognized as an energy-efficient, environmentally-friendly, and safe mode of transport. Development of high-speed passenger rail can improve mobility, reduce highway congestion, contribute to sustainable development, and reduce foreign oil dependency. The U.S. has begun development of high-speed rail (HSR) service (White House, 2011). In many places the new systems use shared corridors in which freight and passenger trains with heterogeneous configurations and operating characteristics will use the same tracks. However, the introduction of higher speed, high priority, passenger trains causes both primary delays (due to uncertainties in running and dwell times) and secondary or "knock-on" delays (due to meet, pass, and overtake for train conflicts, and primary delay propagations) to freight trains (typically with lower speed) (Mattsson 2007). Resolution of the conflicts between passenger and freight trains is essential to successful development of HSR on shared corridors. This highlights the need for an integrated, systems-level framework that incorporates new train control technologies and advanced analytical and simulation based modeling techniques for decision-making and policy analysis.

Long-term freight demand is projected to increase 84% by 2035 (American Association of State Highway and Transportation Officials (AASHTO), 2007), and new passenger services are being proposed to operate over portions of the freight

infrastructure. These train types have different characteristics in terms of acceleration, braking, top speed, priority and on-time performance. Their unique characteristics place different demands on the freight infrastructure. Operating multiple train types on one line can introduce higher delays than operating a single train type (Dingler, Barkan, & Lai, 2009). Higher speed passenger trains in shared corridors introduce new challenges in managing the existing capacity of the railroad.

1.2 *Study Objectives*

This project is to understand the complex interactions between high-speed passenger trains and freight trains in on shared railway corridors. The objective of this project is to develop a decision support modeling framework that can help evaluate the impact of high-speed trains on railroad freight corridor capacity and draw technical and policy insights that will address key issues of the proposed US HSR plan. This decision support modeling framework includes three types of approaches: (1) analytical approach, (2) simulation approach, and (3) hybrid analytical-simulation approach. We conduct numerical analysis using the simulation and hybrid approaches to demonstrate the proposed decision support modeling framework for real-world applications.

1.3 *Organization of the Report*

The remainder of the report is organized as follows. Chapter 2 provides a literature review in railway capacity analysis on shared railroad corridors. Chapter 3 proposes analytical corridor capacity models for ideal shared double track corridors using a time-space diagram approach. In Chapter 4 impact of higher speed passenger trains to freight trains in shared double track networks is studied using simulation approaches. Two experiments are conducted and analyzed with various combinations of passenger and freight trains. Chapter 5 presents a hybrid analytical-simulation analysis of shared corridor capacity. Chapter 6 summarizes the research and its contributions, and provides future research directions.

CHAPTER 2. REVIEW OF CAPACITY ANALYSIS ON SHARED RAILROAD CORRIDORS

This chapter reviews existing shared railroad corridor capacity analysis studies using analytical, simulation, and hybrid approaches in the U.S. and Europe.

2.1   *Analytical Approach*

One of the first analytical models on shared railroad corridor capacity was developed by Frank (1966) by studying the delay levels along a single track corridor considering both directional and bidirectional scenarios. The Frank's model used one train running between two consecutive sidings (using manual blocking system) and a single average speed for each train to calculate the number of possible trains (theoretical capacity) on the given segment. Petersen (1974) expanded Frank's model by considering two different speeds, independent departure times, equal spacing between sidings, and constant delays between two trains. Higgins et al (1998) developed a model for urban rail networks to evaluate the delays of trains by considering different factors such as trains' schedule, track links, sidings, crossings, and the directional/bidirectional operation patterns throughout the network.

De Kort et al. (2003) analyzed the capacity of new corridors in 2003 by applying an optimization method and considering uncertainty of demand levels on the planned route. Ghoseiri et al. (2004) introduced a multi-objective train scheduling model of passenger trains along single and multiple tracks of rail network, based on minimizing the fuel consumption cost as well as minimizing the total passenger-time of trains. Burdett and Kozan (2006) developed analytical techniques and models to estimate the theoretical capacity of a corridor based on several criteria, such as mixed traffic, directional

operation pattern, crossings and intermediate signals along the track, length of the trains, and dwell time of trains at sidings or stations. Wendler (2007) used queuing theory and semi-Markov chains to provide a technique of predicting the waiting times of trains based on the arrival times, minimum headway of trains and the theory of blockings. Lai and Barkan (2009) introduced an enhanced technique of capacity evaluation tools based on the parametric modeling of capacity evaluation, which can evaluate the expansion scenarios of network by estimating the line capacity and investment costs, based on the future demand and available budget.

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

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

2.2   *Simulation Approach*

Simulation is an imitation of a system's operation which should be as close as possible to its real-world equivalent (Abril et al., 2007). In this approach, the process of simulation is repeated several times until an acceptable result is achieved by the software. The data needed for the simulation are similar to the analytical methods, but typically at a higher level of detail. The simulation practices in rail industry started in the early 1980s

through the development of models and techniques, such as dynamic programming and branch-and-bound as well as heuristic methods. Today, the simulation process utilizes computer tools to handle sophisticated computations and stochastic models in a faster and more efficient way. The simulation approaches use either general simulation tools, such as AweSim, Minitab, and Arena (Murali et al. 2009; Noble and Nemmers, 2007); or commercial railroad simulation software specifically designed for rail transportation, such as RTC, MultiRail, RAILSIM, OpenTrack, RailSys, and CMS (Abril et al., 2007; Khadem Sameni et al., 2011). The use of general simulation tools requires the user to develop all models, equations and constraints step by step (often manually). This requires more expertise, creativity and effort, but it can also offer more flexible and customization when it comes to results and outputs. The commercial railroad simulation tools offer an easier path toward development of different scenarios, in addition to providing a variety of outputs in a user-friendly way, but the core decision models and processes are not easily customizable or reviewable, which may reduce the flexibility of applying these tools.

The commercial railroad simulation software typically revolves around two key simulation components; 1) Train movement, and 2) Train dispatching. The first component uses railroad system component data provided as an input, such as track and infrastructure characteristics (curvature and grades), station and yard layout, signaling system, and rolling stock characteristics, to calculate the train speed along the track. Train dynamics are typically determined based on train resistance formulas, such as Davis equation, and train power / traction. The dispatching simulation component typically emulates (or attempts to emulate) the action of the dispatcher in traffic management, but in some cases, it can be also used as part of a traffic management software to help traffic dispatchers to manage and organize the daily train schedules (White, 2005).

According to Pachl (2002), the simulation method can also be divided into asynchronous and synchronous methods. Asynchronous simulation software is able to consider stochastically generated train paths within a timetable, following the scheduling rules and the train priorities. In synchronous simulation, the process of rail operations is

followed in real time sequences, and the results are expected to be closely aligned with real operations. In contrast to the asynchronous method, synchronous methods cannot directly simulate the scheduling, or develop a timetable, without use of additional computer tools and programs to create a timetable. The outputs of simulation software typically include several parameters such as delay, dwell time, waiting time, elapsed time (all travel time), transit time (time between scheduled stops), trains speed, and fuel consumption of trains (Abril et al., 2007; White, 2005).

Simulation analysis has also been used to analyze the delay caused by the interactions of unit trains and intermodal trains. Simulation techniques have also been used to study the interactions between passenger train speeds and bulk freight trains on single track (Sogin, 2011). The objective of this paper is to analyze the impact of adding passenger trains to double track freight railroad networks. We used simulation software called Rail Traffic Controller (RTC) to evaluate effects of homogeneous and heterogeneous operations (Wilson, 2011).

Delay, measured in minutes per 100 train miles, is the main output from the simulation analyses. Delay is defined as the difference between the simulated actual run time and the simulated minimum run time (MRT). The MRT is the fastest a particular train can traverse the network with no interfering traffic, slow-orders or other external factors that could cause the train to deviate from normal track speed. The delay includes time for meets and passes, and excludes time spent at scheduled stops. This metric provides insight into the capacity of a line. All delay values presented in this analysis refer to the performance of the trains on a line and not the maximum number of trains that can be operated on the line.

2.3   *Hybrid Approach*

In addition to the analytical and simulation approaches, a hybrid analytical-simulation approach can also be used to investigate the rail capacity. Parametric and heuristic modeling (in analytical approach) are more flexible when creating new aspects and rules for the analysis. On the other hand, updating the railroad component input data and criteria tends to be easier in the simulation approach, and the process of running the

new scenarios is generally faster, although simulation may place some limitations when adjusting the characteristics of signaling or operation rules. A hybrid simulation-analytical methodology takes advantage of both methodologies' techniques and benefits, and the process can be repeated until an acceptable set of outputs and alternatives is found. There are several ways to combine analytical and simulation tools. For instance, finding a basic and reasonable schedule of trains through simulation, followed by analytical schedule can be considered as one example of combined analytical-simulation approach. Another example would be application of a simplistic analytical model to provide the basic inputs, such as determining the type of signaling system, or developing train schedule, followed by more extensive and detailed analysis in commercial rail simulation tools.

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

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

adjust the simulation outputs to be more accurate, in addition to locating infrastructure bottlenecks which caused the capacity issues and delays (WDOT, 2006).

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

In research conducted through combined analytical-simulation approach, Medeossi et al applied stochastic approach on blocking times of trains to improve the timetable planning by using OpenTrack simulation software. They redefined timetable conflicts by considering a probability for each train conflict as a function of process-time variability. The method repeatedly simulated individual train runs on a given infrastructure model to show the occupation staircase of trains in different color spectrum while each color represents the probability of trains' conflict which should be resolved (Medeossi, 2011).

Pouryousef, et al, (2013) provides a brief synopsis of methods and tools to evaluate capacity and the level of service (LOS) of trains, but concentrates on introducing the hybrid approach, where commercial rail simulation software from U.S. and Europe are used together for the analysis. While the concept of capacity and the objective to maximize its utilization are global, the configuration differences between the European and the U.S. rail systems (such as the infrastructure ownership and the operations philosophy) lead to the use of different methodologies, techniques, and tools for capacity evaluation. Since the European simulation software is more equipped with timetable

management features, the results of optimized timetable, developed through it, is verified by the U.S. based simulation tool through the hybrid approach of capacity analysis to evaluate any challenge and benefit of conducting such approach through further investigation on the U.S. rail network. This differs from traditional analysis by taking advantage of the complementary features offered by each tool, since the results of one software is again validated in the other software and vice versa. A case study using a single-line rail corridor is presented to demonstrate the approach and a discussion on the outcomes and challenges of the analysis are included.

CHAPTER 3. ANALYTICAL CAPACITY ANALYSIS OF IDEAL SHARED DOUBLE TRACK CORRIDORS

Chapter 3 presents an analytical corridor capacity analysis for ideal shared double track corridors. In this Chapter, we discuss the ideal case of a railway corridor shared by freight trains and high-speed rail (HSR) passenger trains, where the stations are evenly distributed along the shared railway corridor and HSR passenger train headway is a constant. In Section 3.1, we present the corresponding capacity of freight trains during a given HSR passenger train headway, followed by delay analysis due to the introducing HSR passenger trains in Section 3.2. Section 3.3 presents a total cost function of freight sector for operating mixed train types in the ideal shared corridor.

3.1 *Capacity Analysis of Freight Trains*

The primary tool to conduct capacity analysis is the time-space diagram. According to the time-space diagram for one direction of an ideal double-track railway corridor shared by freight trains and HSR passenger trains in Figure 3.1, we can derive equations as in Eqs. (3.1-3.2)

$$H = \tau + (n-1)h + \tau' \tag{3.1}$$

$$\tau' + \frac{s}{V} = \frac{s}{v} + \tau \tag{3.2}$$

where,

h is the minimum headway of freight trains.

H is a given headway of HSR passenger trains.

h is the minimum headway of freight trains.

n is the maximum number of freight trains departing during H.

τ is the minimum safety waiting time for yielding.

τ' is the time between departure time of an HSR passenger train and the departure time of latest departed freight train.

v is the average speed of freight trains.

V is the average speed of HSR passenger trains.

s is the ideal distance between two successive train stations.
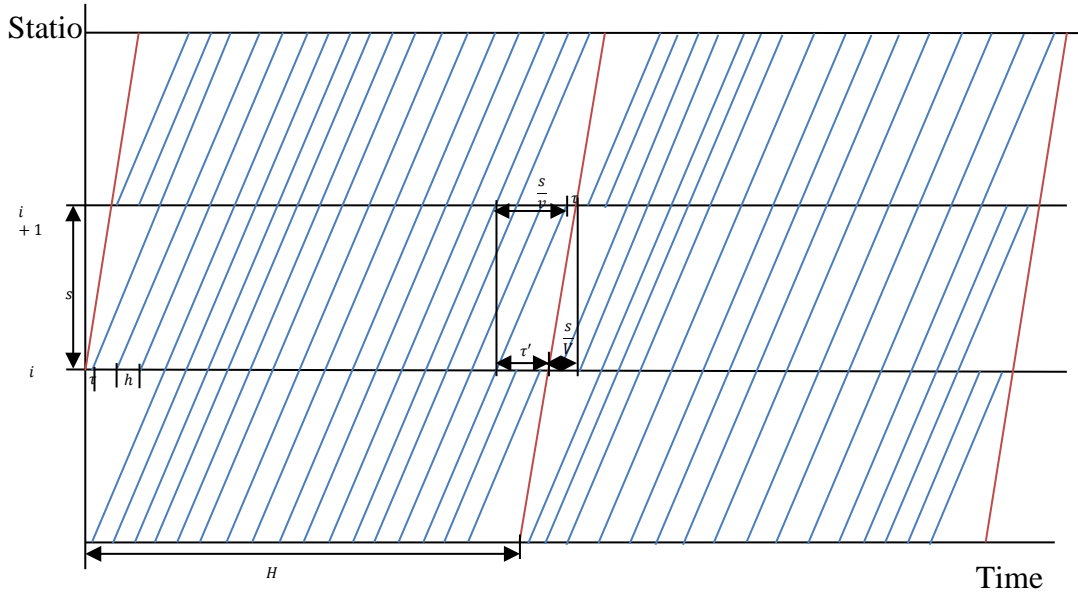
Figure 3.1. Time-Space Diagram for One Direction of an Ideal Double-Track Railway Corridor.

In light of Eqs. (3.1-3.2), we can further find the maximum number of freight trains departing from station i to station $i + 1$ during a given headway of HSR passenger trains as in Eq. (3.3).

$$n = \frac{H - 2\tau - \left(\frac{s}{v} - \frac{s}{V}\right)}{h} + 1 \tag{3.3}$$

Please note that we assume that H and τ' are larger than τ to allow multiple freight train arrivals and departures.

3.2   *Delay Function of Freight Trains*

According to the time-space diagram in Figure 3.1, the cumulative arrival and departure curves of one direction of an ideal double-track railway corridor is shown in Figure 3.2. The total delay of freight trains during a given HSR passenger train headway H is the area between the cumulative arrival and departure curves as in Figure 3.2, where $A(t)$ is the cumulative arrived freight trains at time t, and $D(t)$ is the cumulative departed freight trains at time t. A mathematical formulation can be derived as in Eq. (3.4).

$$delay(s, \tau, v, V, h, H) = \frac{\tau'}{h}(\tau' + 2\tau) \tag{3.4}$$

In light of Eq. (3.2), we can rewrite Eq. (3.4) as in Eq. (3.5).

$$delay(s, v, V, H; \tau, h) = \frac{\left(\frac{s}{v} - \frac{s}{V} + \tau\right)\left(\frac{s}{v} - \frac{s}{V} + 3\tau\right)}{h} \tag{3.5}$$
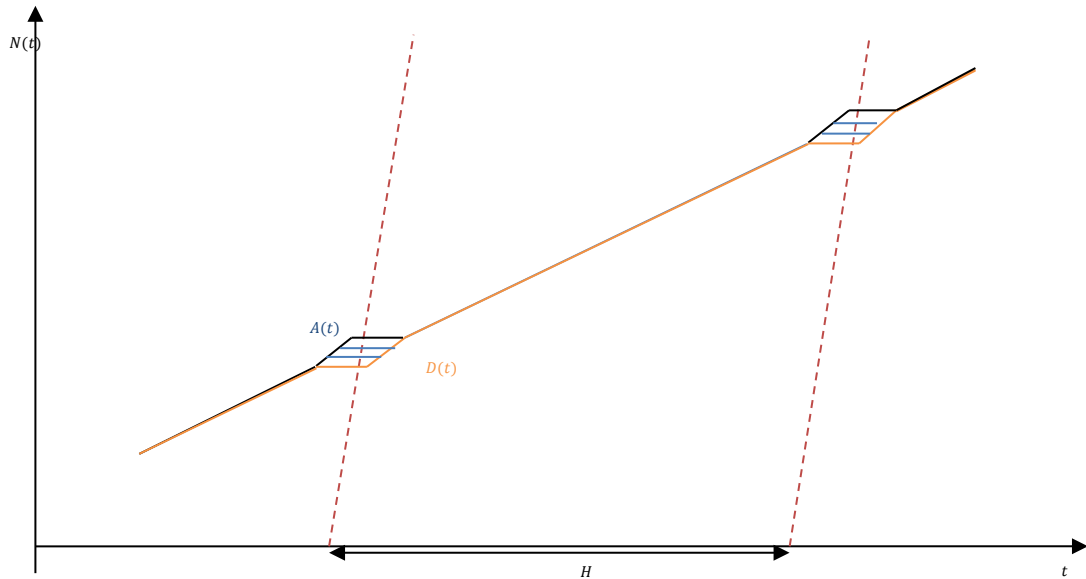

Figure 3.2. Cumulative Arrival and Departure Curves of One Direction of an Ideal Double-Track Railway Corridor.

3.3 *Total Cost Function of for the Freight Sector*

We assume that the minimum freight train headway h and minimum safety waiting time τ for yielding are given. Then, the total cost per mile per hour for investing and operating a shared railway corridor for a given HSR passenger train schedule and speed scenario can be formulated as in Eq. (3.6).

$$UC(s, v; V, H) = IC(s) + OC(v) + \alpha \cdot \frac{delay(s, v; V, H)}{s \cdot H} \tag{3.6}$$

where,

α is value of time.

$IC(s)$ is annualized infrastructure investment cost per mile per hour.

$OC(v)$ is train operation cost per mile per hour.

$UC(s, v; V, H)$ is the total cost per mile per hour.

We can solve an optimization problem to minimize Eq. (3.6) to find optimal ideal station space, s, and freight train speed, v, for a given HSR operational plan.

3.4 *Conclusion*

The proposed time-space diagram approach to analyzing capacity of freight trains on ideal double track shared corridors provides mathematical insights of designing new shared corridors for strategic corridor parameters such as average station space and expected freight train space for any given high-speed passenger train operational plans.

CHAPTER 4. SIMULATION ANALYSIS OF SHARED DOUBLE TRACK
NETWORKS

This Chapter uses simulation software to analyze the benefits of capacity expansion projects to help plan for increased railroad traffic of passenger trains to the freight railroad double track networks. Section 4.1 gives the background and Section 4.2 proposes the methodology of the simulation process. In Section 4.3 and 4.4, two experments have been conducts on shared double track networks. Section 4.5 analyzes the two experments. Section 4.6concludes this section.

4.1   *Background*

Double track lines can move more traffic than single track by removing the need for trains to start and stop at sidings to allow the other train to clear the bottleneck section. The largest component of delays for train interaction in single track is the meet delays at these sidings (Dingler, Koenig, & Sogin, 2010). Subsequently, double track lines should have very small meet delays. Because of these inherent efficiencies, double track lines can be utilized to run more trains at higher average speeds than single track configuration.

When speed differentials are present in double track configurations, there are two options to resolve the conflict when a fast train catches up to the slower train. The first option is to delay the fast train and slow it down to the speed of the slower train. Another option is to preserve the on time performance of the faster train by using the 2nd track for an overtake maneuver. There are two methods of accomplishing this maneuver. The first is to have the slow train use a crossover to transfer to the 2nd track and allow the fast train to pass at its track speed. The slow train will then take the next available crossover to return to the original track. Another approach is to have the faster train change its speed to that of the crossover speed and transfer to the 2nd track. The faster train can then pass the slower train and use the next downstream crossover to transfer back to the

original track. The latter option can cause more delays to the faster train but use the 2nd track for a shorter period of time. The consequence of the overtake maneuver is that the 2nd track is being utilized to pass trains to preserve on time performance instead of using the 2nd track to move trains in the opposite direction.

If there are large speed differentials between train types then there is a greater need for overtakes which consume capacity of train movements in the opposite direction. The assumption of whether or not to allow overtake maneuvers greatly influences the total number of trains per day that can be operated along the line. In a congested double track line, often a low priority train in the opposing direction stops before the crossover in order to let the overtake maneuver finish. This stopped train incurs the braking, accelerating and stopped delays. Alternatively in the no overtake scenario, the passenger train only has to slow down to a slower speed and then accelerate back to the track speed. The overtake decision indicates which trains will be delayed and the capacity of the line since there are greater delays with stopped trains than with trains that are travelling at a reduced speed. There could exist a fast enough train with such a high speed differential that the trailing delays of the fast train could equal the meet delay of the low priority slow train. Such a large speed differential would dictate the need for dedicated tracks. Additionally, these faster trains often have better operating characteristics in terms of braking and accelerating. This scenario is unlikely.

4.2   *Methodology*

The simulated route characteristics are shown Table 1. The route is simplified as much as possible to facilitate comparison of the effects of key variables regarding traffic composition, priority, and passenger train speed. The route is symmetrical to prevent any directional biases that could affect the average of an entire train group. Grade and curvature were eliminated from the model since these factors affect different train types differently. Freight trains are more sensitive to grade, while passenger trains are more restricted by degree of curvature (Pachl, 2002).

Table 1: Route Parameters Used In Simulation Model

Parameter	Value
Type	Double Track (1 O-D Pair)
Length	265 miles
Universal crossover spacing	15 miles
Siding length	7,920 feet
Traffic control system	2-Block, 3-Aspect ABS
Average signal spacing	2.0 miles

Individual trains vary in length, power, and weight. Each train in the simulation is based on the characteristics specified in Table 2. The freight train characteristics are based on the Cambridge Systematics National Rail Freight Infrastructure Capacity and Investment Study (2007) conducted for the Association of American Railroads (AAR) (Cambridge Systematics, 2007). Freight car tonnages and lengths were based on averages for each car type. The power-to-ton ratios were based on experience and information from the Transportation Research Board Workshop on Railroad Capacity and Corridor Planning (2002) (Workshop On Railroad Capacity and Corridor Planning, 2002). The unit freight trains were scheduled to depart ± 20 minutes from their scheduled departure time in a random-uniform-distribution.

The passenger train was based on the Amtrak Cascades service in the Pacific Northwest and the expected consist that was used in the planning of the 110 mph service between Madison and Milwaukee Wisconsin. The passenger train stops were spaced at 32.4 mile intervals based on the current Amtrak station spacing on routes in California, Illinois, Washington State, and Wisconsin (Coran, 2010). The speeds tested were 79 mph and 110 mph. Trains are limited to a maximum speed of 79 mph without advanced signaling and highway crossing technologies. Illinois and Michigan have proposed increase the track speed to 110 mph.

Table 2: Train Parameters for Simulation Model

	Unit Freight Train	Passenger Train
Locomotives	x3 SD70	x2 P42
No. of Cars	115 hopper cars	11 Articulated Talgo Cars
Length (ft.)	6,325	500
Weight (tons)	16,445	500
HP/TT	0.78	15.4
Max Speed (MPH)	50	79,110

Unique Characteristics	± 20 minutes departure time	32.4 miles between stops

Train starts were balanced between the east and west end of the network with all train starts spaced evenly. The headways for all trains were held constant throughout the simulation. At 64 trains per day, there are 32 eastbound and 32 westbound with a train departing each origination yard every 45 minutes. Each simulation includes the performance of all the trains that operate within a 5-day period. Each particular traffic mix was repeated four times. Passenger trains were scheduled to start during daylight hours between 7:00 am and 8:00 pm. This process was repeated for different passenger speeds tested: 79 mph, and 110 mph.

The primary output from each simulation was the total delay for each train. This number was then normalized by the route length to determine delay minutes per 100 train miles. This metric was used to analyze the freight train performance because the track speed of the freight trains was held constant over all of the simulation models. An increase in passenger train speed increases the cost of a delay inducing event to the passenger trains. A 10 minute delay for a 79 mph train costs 13.2 miles of travel, and a 10 minute delay for a 110 mph train costa 18.3 miles of travel. Instead of delay per 100 train miles, passenger train performance is analyzed as the time to travel 100 miles (White, 2006).

There were two experiments conducted to examine the effects of train speed on freight traffic. The first experiment was designed to look at three factors: traffic composition, passenger train priority and maximum speed of passenger trains. The traffic level was held constant at 64 trains per day. The traffic composition starts with a homogenous freight line and then passenger trains replace a percentage of the freight trains to create a heterogeneous traffic composition. Eventually the line will transition to only homogeneous passenger traffic. There were 9 compositions studied. The traffic composition is measured by the heterogeneity level defined as the percentage of the total traffic that is freight trains.

Each traffic mix was analyzed under two scenarios where the passenger train was given high priority and where it had the same priority as a freight train. A high priority passenger train would require an overtake maneuver to pass a freight train while an equal priority passenger train would trail behind a freight train. The equal priority case can represent a lower bound on passenger train performance. A high priority passenger represents the upper bound on train performance. Freight railroads do give priority to passenger trains in their dispatching practices. Additionally, a minimum service agreement may be required to protect on time performance of passenger trains. In practice, the performance of the passenger train should be between these two bounds.

The second experiment was to analyze the impact of passenger trains to an existing freight network. Under this scenario the base traffic level was 40 freight trains per day. Increments of two roundtrip passenger trains were sequentially added to the base of 40 freight trains until the network reached a total of 68 trains per day. Experiment 2 considers the effect of compressed headways that are caused by additional passenger trains. Experiment 1 focuses more on traffic composition.

Both Experiments have a shared traffic mix of 40 freight and 24 passenger trains per day. This particular traffic mix will be analyzed in further depth.

The results presented here are not intended to represent absolute predictive measurements for a particular set of conditions. Rather, they are meant to illustrate comparative effects under different conditions.

4.3   *Experiment 1*

All the delays present in this experiment are solely due to the heterogeneity in train type. Under homogenous traffic of all passenger or all freight trains, there are no delays. There is no speed differential between trains to cause a delay event. Any delays that incurred in the simulation were related to the terminals.

The freight trains are delayed significantly in 110 mph passenger dominated lines as show in Figure 1. These trains often have to stop frequently in order to

allow for overtakes on the other track. Another source of delay is when a freight train has to wait to enter the mainline at a terminal in order to let the passenger train depart first. As the heterogeneity level increases, there are more freight trains present in the network and these types of delays decrease sharply. The degree of these delays is also dominated by the speed and priority of the faster trains. 79 mph passenger trains did not cause as much delays to the freight trains as the higher speed did. 79 mph passenger trains require fewer overtake maneuvers and also have an average speed closer to the freight trains. As the passenger trains stop at stations every 32.4 miles, the average speed between terminals decreases. Without any freight train interference, the 79 mph passenger trains average 65 mph.
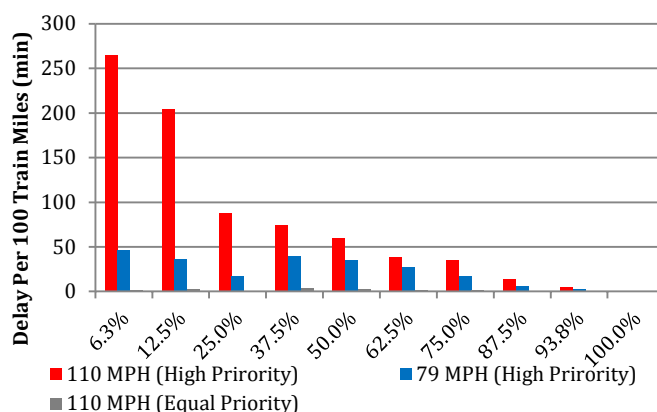

Figure 4.1. Induced freight train delays caused by speed differentials in train types

The travel time for passenger trains to cover 100 miles at various heterogeneity levels is shown in Figure 2. At 64 trains per day with no freight trains, passenger trains will not be delayed. The passenger trains maintain their minimum run times at 92.5 minutes per 100 miles with a track speed of 79 mph and 74.6 minutes per 100 miles with a track speed of 110 mph. Under heterogeneous conditions, passenger trains can catch up to a freight train and then experience trailing delays. These additional delays increase the time to travel 100 miles. The priority of the train can help mitigate this type of the delay. Figure 2 shows that high priority trains have faster travel times in heterogeneous traffic compositions than the equal priority condition, regardless of their speeds. The 110 mph high priority passenger trains are more sensitive to the

heterogeneity traffic level. In heterogeneous conditions, the 79 mph high priority passenger train maintains travel times close to its MRT.
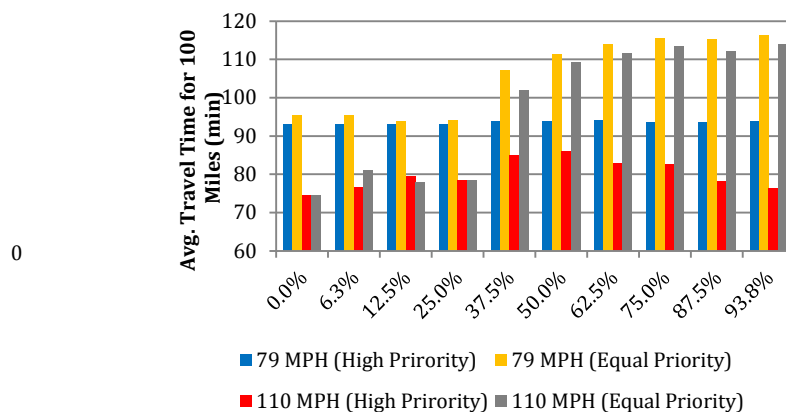

Figure 4.2. Induced passenger train delays caused by speed differentials in train types

Under the equal priority scenario, the passenger trains incur most of the delays within the network. The travel times can be maintained within heterogeneity levels of 13% and 25%. With heterogeneity levels within 38%-88% range, the MRT is not be maintained and these trains receive significantly higher delays. At the 50%-88% range, the travel of the 110 mph and 79 mph train is within 4 minutes per 100 train miles. In freight dominated lines with low priority passenger trains, the benefit of speed can be negated.

4.4   *Experiment 2*

The addition of passenger trains causes the median freight train delay to increase in an exponential manner. Another implication of running passenger trains on the freight network is the increase in the amount of additional variation in delay introduced to the freight network. Figure 3 and Figure 4 show the distribution of freight delay in 10% bands. The higher number of passenger trains operated, the higher the variation in the delay of the unit trains, and the more skewed the distribution is. The performance of the worst 10% of freight trains is particularly important because train crews can only be on duty for 12 hours before a relief crew must takeover. Higher variation results in more relief crews are needed. Variation in freight service also affects time sensitive goods,

connections at terminals, and customer satisfaction [3,10]. In both adding 79 mph and 110 mph trains to the base of 40 freight trains per day, the median delay of the freight trains increased. The 110 mph passenger trains added more delay and variability to the arrival times of the freight trains shown in Figure 4 than the 79 mph passenger trains as shown in Figure 3.
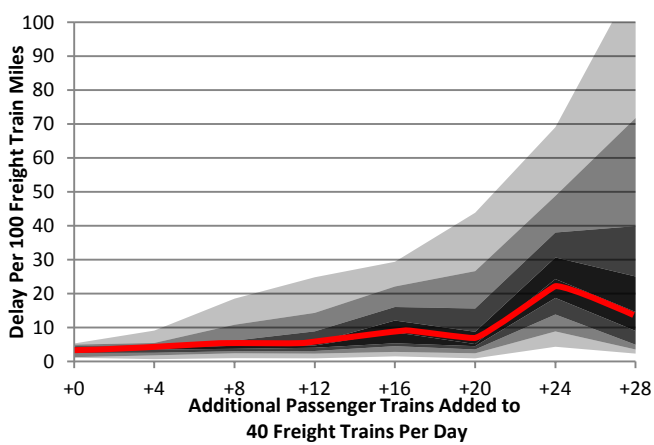

Figure 4.3. Distribution of freight delays when 79 mph passenger trains are added to a base of 24 freight trains
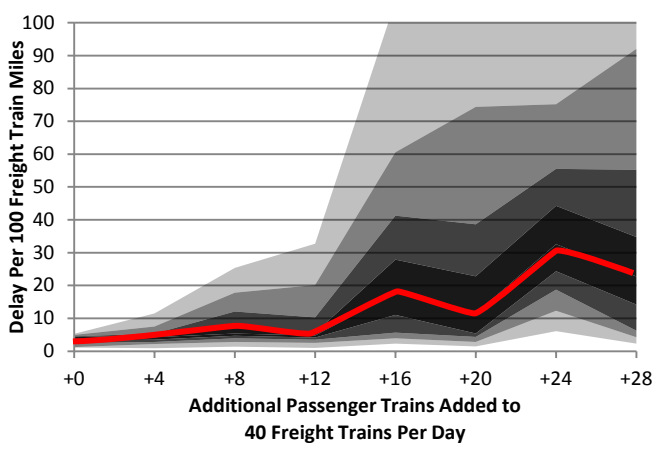

Figure 4.4. Distribution of freight delays when 110 mph passenger trains are added to a base of 24 freight trains

4.5   40 Freight Trains + 24 Passenger Trains

The subsequent analysis will focus on the mix that was present in both Experiment 1 and Experiment 2 where 24 passenger trains operate alongside 40 freight trains.

The distribution of delays to the freight trains is positively skewed to the right with 79 mph and 110 mph passenger train speeds as shown in Figure 5. The peak of the distribution is more pronounced under the 79 mph scenario than with the 110 mph scenario. The amount of data in the right tail of the distribution is higher in the 110 mph cases. The higher speed of the passenger train resulted in a shift in the cumulative frequency diagram as shown in Figure 6. Higher delays are more frequent with 110 mph service. The median value of delays caused by 110 mph service is 34% higher than 79 mph. The 95th percentile is also 40% higher with 110 mph interference than with 79 mph interference.
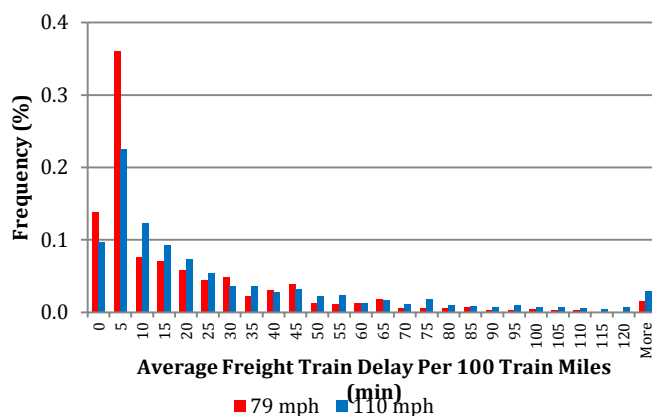

Figure 4.5. Freight train delay distribution with 79 mph & 110 mph passenger train interference
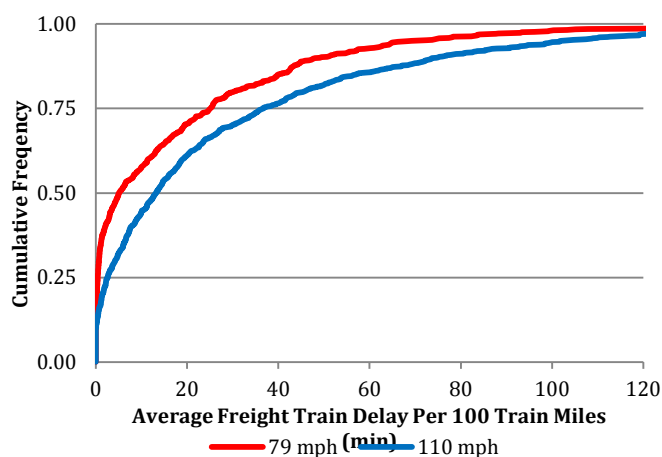
Figure 4.6. Cumulative distribution of freight train delays with 79 mph & 110 mph passenger train interference

Passenger run times to cover 100 miles in a high priority low capacity settings are mostly faster with 110 mph trains than with 79 mph trains as shown in Figure 7. The minimum run times are denoted by the 0th percentile and are 73.9 minutes (B) at 110 mph and 92.2 minutes (A) for 79 mph train speeds. A steep slope from the MRT point indicates better reliability. If the data within the 5th percentile and 95th percentile is considered likely to occur, than 90% of the travel times to travel 100 miles are within 62.9 minute for 110 mph track speed. At a 79 mph track speed, 90% of the data is within 22.3 minutes. The 79 mph passenger train speeds operates more consistently to the MRT than the 110 mph passenger trains. While 110 mph can offer faster travel times, the train suffers more time loss in a delay event and cause lower reliability.
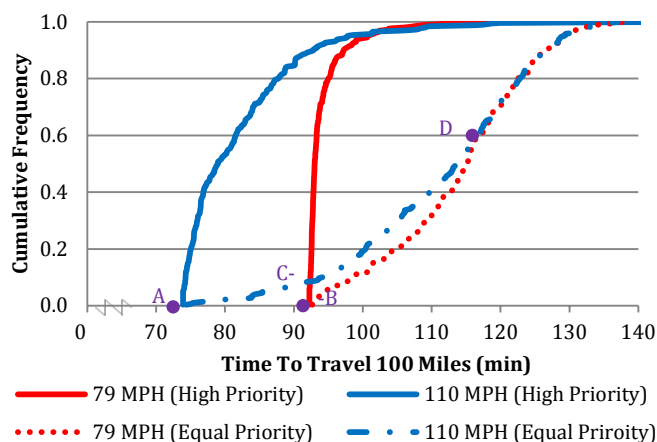
Figure 4.7. Cumulative frequency of travel times for passenger trains at various speeds and priority

When the element of priority between passenger trains and freight trains is removed, their performance decreases compared to when these trains operated at a higher priority. The best performing train are still similar to that of the best performing train (A&B) in the high priority scenario. However, when a fast train catches up to a slow train, a delay event occurs and causes the faster train to slow down. At the 10th percentile of the equal priority 110 mph case, the train performance has already deteriorated to the speed of a 79 high priority passenger train (C). At the 60th percentile, the distributions of the equal priority 79 mph and 110 mph trains converge (D). After this percentile, there are enough delay events to these worse performing trains that the benefit of operating at higher passenger train speed is negated.

The distribution of the worse performing 110 mph and 79 mph high priority trains are shown in Figure 8. The 110 mph distribution crosses the 79 mph distribution at the 97th percentile. After this point, there is an increased probability that there will be a slower travel time for a 110 mph train than with a 79 mph train. This is likely due to the additional disturbance to the freight trains that a high priority 110 mph train causes to the freight traffic.
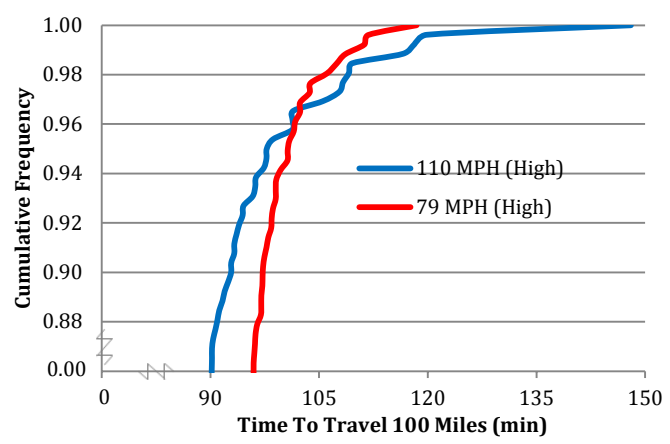
Figure 4.8. Cumulative distribution of the 10% worse performing Trains

4.6   *Conclusion*

Double track configurations can handle a significantly large amount of traffic under homogeneous conditions. Speed differentials in traffic introduce delays to the system and decrease the capacity of the line. Larger speed differentials cause larger delays and greater variability to the traffic on the line. Having a fast high priority train requires overtake maneuvers that uses capacity of the 2nd track. This overtake maneuver prevents the 2nd track from moving trains in the opposite direction. An equal priority scenario can move more trains through the network. The priority of the trains dictates which train types will receive the delays. Under the equal priority scenario there are less total delays.

CHAPTER 5. HYBRID ANALYTICAL-SIMULATION ANALYSIS OF SHARED CORRIDORS

The Chapter uses a case study to introduce a new hybrid approach for capacity analysis. Section 5.1 describes the methodology of the hybrid analytical-simulation approach. Section 5.2 gives the case studies. Section 5.3 concludes this section.

5.1   *Methodology*

The objective of the study was to incorporate the use of timetable management tools in the capacity analysis. The methodology included development of a new, hybrid analysis concept that takes advantage of the strengths of both timetable and non-timetable based software. The tools used in the study included RTC as the non-timetable based simulation tool and RailSys as the timetable-based tool. Figure 5.1 presents key features of each simulation package. RTC has the capability to use preferred departure times, the train dispatching simulation process, and its automatic train conflict resolution tools to develop the initial timetable (stringline), while RailSys can use its timetable compression technique that is based on UIC code 406 to improve and optimize the initial timetable of trains in order to provide more efficient capacity utilization.
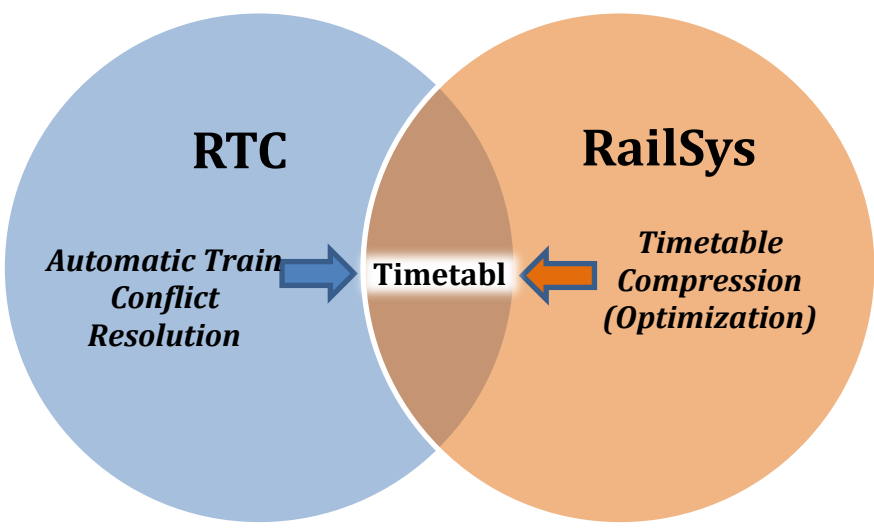
Figure 5.1. The main features of RTC and RailSys in terms of timetable development

The hybrid approach uses the timetable developed in the RTC as input for RailSys and attempts to improve the outcomes of original RTC simulation by adjusting the operational parameters inside RailSys (using timetable-compression technique). After adjustment, the improved timetable identified by RailSys, is imported as input to RTC to validate the results in the U.S. rail environment. (Figure 5.2)

Figure 5.2. Main outputs of each step in a "Hybrid Approach"

Figure 5.3 illustrates the hybrid simulation approach on step-by-step basis. Step 1 represents the development of the initial timetable using RTC. Step 2 improves the RTC's timetable by using RailSys compression techniques, and Step 3 validates the new timetable in the RTC.
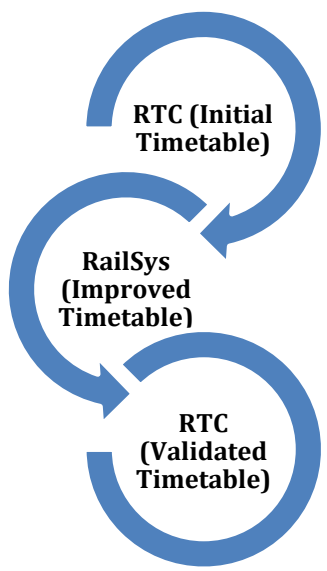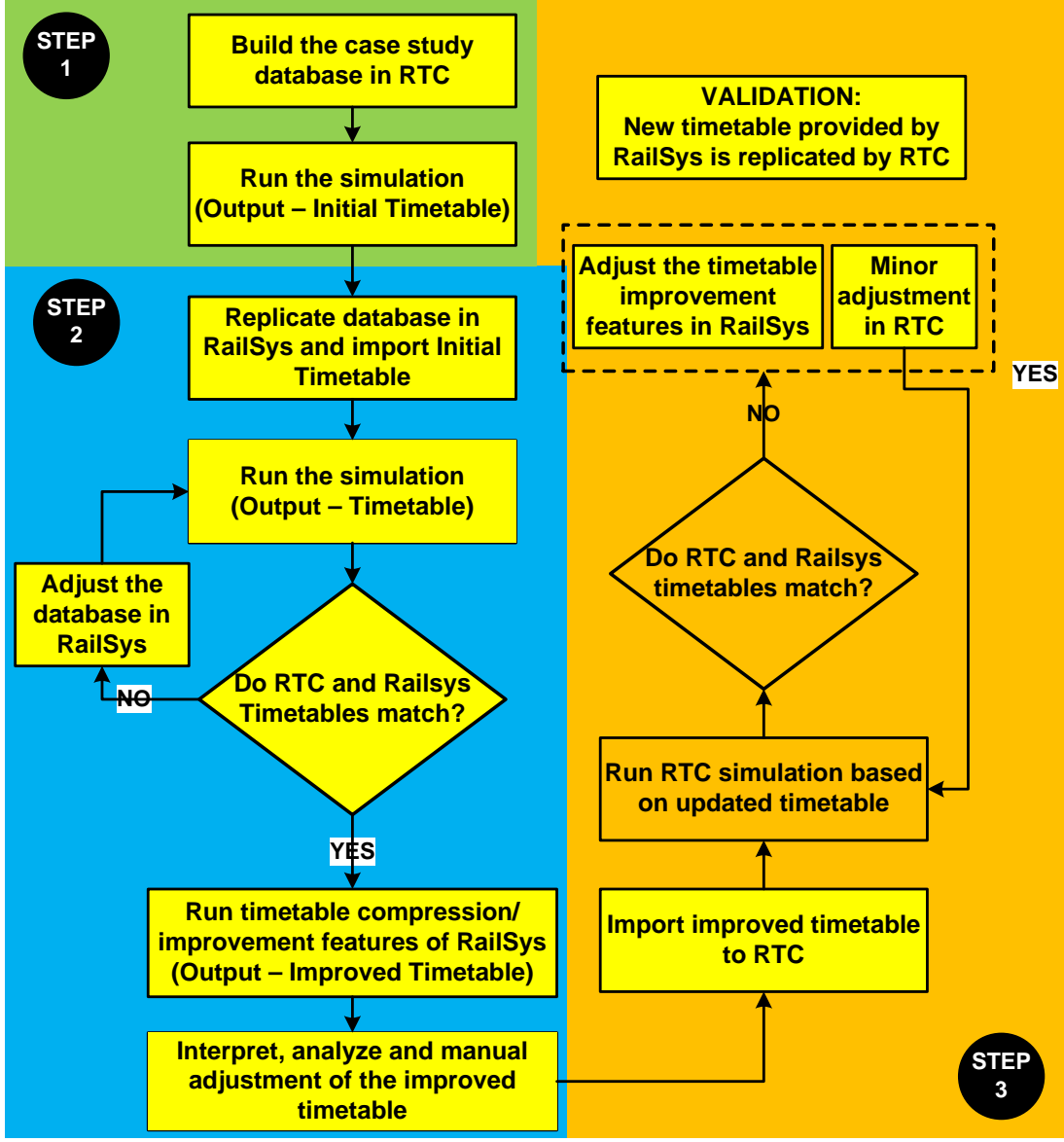

Figure 5.3. Flowchart of hybrid simulation (RTC-RailSys-RTC)

As presented in Figure 5.3, the hybrid approach requires conversion of the database from RTC to RailSys and checking that the key simulation outcomes match with each other. There are four categories in the database and the level of conversion criteria and difficulty vary. Table 1 provides a synopsis of the replication process and the challenges in making the respective database categories. The conversion of infrastructure and operation rules consists mainly of unit conversion (English to metric), but the conversion of train and signaling characteristics is a much more involved and challenging task and may require specific adjustments in individual parameters.

Table 1- Summary of database conversion from RTC to RailSys

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

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

5.2   *Case Studies*

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

The line is a 30 mile long single track segment with three sidings/yards for any meet/pass and stop purposes. (Figure 5) The vertical track profile and locations of the sidings were precisely derived from an existing corridor data, but the horizontal curves were not considered, as their impact on the train speed is not as significant as the grade, especially for speeds under 50 mph. Table 2 summarizes the infrastructure parameters for the case study.

Figure 5.4. A simple scheme of sidings and yard located along the case study

Table 2- Details of case study infrastructure

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

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

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

(such as power, weight, length, axle load, acceleration/ deceleration rate, resistance) were imposed and adjusted in the RailSys database as a new type of locomotive.

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

5.3   Conclusion

This paper has provided a brief introduction to the railway capacity, capacity analysis, and the use of commercial railway simulation software. The paper introduced a hybrid approach that attempts to improve level of service (LOS) criteria and capacity utilization through operational (scheduling) improvements. The method uses both timetable (RailSys) and non-timetable based software (Rail Traffic Controller (RTC)) for capacity analysis, by combining the strengths of each tool. The hybrid approach used for this research takes the output of RTC as input of RailSys and uses timetable compression technique offered by RailSys to improve the initial timetable. The improved results of RailSys are, again, considered as input in RTC, to validate the results of European capacity improvement technique in the U.S. rail environment. The approach was tested on a case study corridor and the results are promising. Ten minute maximum dwell time provided the best corridor capacity utilization, in addition to providing good level of service for the trains, in terms of delays, dwell times and number of stops. In that scenario, the unnecessary stops were reduced by 55%, delays reduced by 85%, and maximum dwell time was reduced from 60 minutes to 10, while the timetable duration

was increased by only 18% compared to the initial schedule. This emphasizes the trade-off between LOS criteria and capacity utilization levels, as if LOS is improved, the capacity utilization of existing services may be increased (especially when capacity utilization is over 70%); and vice versa.

The outcomes (validated in RTC) suggest that UIC 406 compression techniques have the potential to be successfully applied for the U.S. rail environment. However, it was also recognized that while the conversion of infrastructure and operation rules database between software was simple, the fact that RailSys is originally developed in Europe makes the procedure of developing North American rolling stock and signaling features relatively challenging in RailSys, as the default database and information use European characteristics rather than North American ones. The deviations between signaling and rolling stock characteristics of European and U.S. rail systems may also cause some minor differences between the results of simulation packages.

CHAPTER 6. CONCLUSIONS

This chapter summarizes the research, highlights its contributions, and proposes directions for future research.

6.1 *Summary*

This study has addressed two primary objectives:

1. Propose a series of decision support modeling frameworks by developing three new   capacity analysis approaches: analytical, simulation, and hybrid. These three capacity analysis approaches can be used in separately or in combination for various applications such as strategic policy design and operational plan evaluation.

2. Demonstrate real-world case studies using simulation and hybrid approaches. These case studies show that the proposed decision support modeling frameworks can be used to analyze the impact of high-speed passenger trains to freight trains on shared corridors. This helps address some of the most pressing needs faced by the current U.S. railroad industry.

6.2 *Future Research Directions*

The present research addressed the problem of impact of high-speed passenger trains to freight trains on shared corridors using three new proposed capacity analysis approaches for decision support. Future research can be conducted in a number of directions; some examples are listed as follows.

1. Develop a method to compare different approaches for shared corridor capacity analysis.
2. Develop analytical approach to analyze single track shared corridor capacity.
3. Develop approach to optimize infrastructure planning and operations, building upon the corridor capacity modules developed from this study.

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