Incremental Capacity in Transitioning from Double to Triple Track on Shared Freight and Commuter Rail Corridors in North America

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Abstract
North American railroads have invested in third main track infrastructure on key railway corridors with high traffic volumes, heterogeneous traffic composition, and high variability in speed between train types. High volumes of varied train types require extensive capability to meet opposing trains, pass or sort faster trains around slower trains, and accommodate temporal and directional peak periods. Often, this heterogeneity occurs on shared use corridors where slower freight trains use the same track infrastructure as faster, higher priority, and better-accelerating passenger trains. Via simulation, this study explores operations of shared use corridors with highly variable traffic types on three-main track infrastructure. Experiments were run with a variety of different operating parameters to find relationships between these factors and train delay, a key metric of operational performance and level of service for North American railroads. Studied factors include the speed differential between train types, station stop pattern for passenger trains, temporal and directional peaking of passenger train operations, percentage of third main track available, and continuous or distributed investment strategy for third main track construction.

Keywords
Commuter Rail, Capacity, Shared Corridor, Third Main Track, Passenger Rail

1 Introduction

The North American railroad network is projected to experience rising freight and passenger transportation demand in the coming decades, leading to increased congestion on many rail lines. Assuming homogeneity of train velocity and uniform acceleration and deceleration, the capacity of a rail corridor depends on the ability of the infrastructure to facilitate meets of trains in opposing directions and maintain minimum following headway. Introducing heterogeneity, or differences in train velocities, priorities or other performance characteristics, will decrease corridor capacity by creating sort or overtake conflicts where a faster train must be able to pass a slower train. Introducing passenger trains to a freight corridor and increasing desired passenger train frequency further strain rail corridor capacity. Operating disparate passenger and freight services on the same lines decreases the practical capacity of single track from 48 to 30 trains per day and double track from 100 to 75 trains per day (Cambridge Systematics (2007)). Handling in excess of 75 trains per day in a heterogeneous North American operating environment will require the addition of a third main track (3MT). The purpose of this study is to continue work by Atanassov and Dick (2015) and Atanassov, Dick, and Barkan (2014) and investigate the benefit of incremental investment of 3MT on representative freight and passenger shared use corridors. Via simulation of train operations on three-main track infrastructure, this study explores fundamental relationships between train-type speed differentials, passenger train station stop patterns, temporal and directional passenger traffic peaks, percentage of third main track available, continuous or distributed investment strategy for third main track construction, and train delay, a key metric of operational performance and level of service for North American railroads. The suggested relationships can be used by practitioners in high-level planning of rail corridors with dense heterogenous rail traffic and in screening initial alternatives for third-main-track construction projects to increase the capacity of these corridors.

2 Background and Overall Study Methodology

Much of the North American freight rail network is a single track with passing sidings (passing loops) or short sections of double track or Two Main Tracks (2MT). Using a quite limited amount of track infrastructure, this partial double track configuration efficiently resolves meets and a limited number of pass conflicts. In the United States, intercity passenger service on these corridors is often limited to one daily passenger train per direction. However, these limited number of passenger trains consume far more capacity than adding an additional pair of freight trains because their average velocity of nearly 50 MPH is approximately double the 32 to 40 KPH (20 to 25 MPH) average velocity of the freight trains sharing the same track infrastructure (Sogin et al. (2013)) (Shih et al. (2015)). Heterogeneity exists among freight trains as well. High-priority domestic intermodal trains with high horsepower-to-trailing-ton ratios and stricter schedules routinely need to pass slower bulk commodity unit trains and manifest freight trains with lower power-to-weight ratios and level-of-service requirements. Both of these scenarios correspond to an increase in pass conflicts (Dingler et al. (2010)).

When the need to wait at sidings for meets becomes the dominant driver of low average train velocity, it becomes necessary to invest in additional sidings or 2MT infrastructure. Previous research conducted by Lindfeldt (2012), Sogin et al. (2013) and Atanassov et al. (2014) revealed that for idealized single-track corridors with even siding spacing, double-track installation provided a linear reduction in train delay (a metric for capacity) for a wide range of freight traffic volumes (Atanassov and Dick (2015)). While eliminating meet conflicts, 2MT infrastructure does little to eliminate pass conflicts. Depending on the positioning of crossovers between tracks and assuming bi-directional signals on each track, it is possible to exchange meet capacity for pass capacity and facilitate an overtake by dispatching two trains in the same direction for a brief distance on both main tracks. A double-track configuration with uni-directional automatic block signals (i.e. signals only in one direction on each track with the "current" of traffic) would have little capability to facilitate train passes.

Renewed interest in expanded passenger rail service is also driving development of capacity to handle an increasing number of train pass conflicts. In the United States, ridership on regional and short-haul passenger trains increased by over 50 percent between 2002 and 2013 as various states developed new intercity passenger rail corridors and Amtrak set a new annual ridership record 10 out of 11 years. According to the US Department of Transportation report “Beyond Traffic 2045”, between 1997 and 2012, commuter rail ridership increased by 49 percent and eight new commuter rail systems have inaugurated service since 2004 (U.S. DOT, 2015). As investigated by Tobias et al.

(2010) in a case study, 2MT infrastructure will be unable to sustain expected 20-year passenger and freight traffic growth leading to an unacceptable overall decrease in train speeds, significant increase in delays, subpar on-time performance, and poor resiliency to disruptions. While well-suited to handle homogenous operations of freight or passenger trains with very high capacities at small headways, 2MT infrastructure is limited in its ability to support heterogeneous operations of varying train types and speeds due to the pass conflicts created.

To accommodate growth of varying passenger and freight traffic types, incremental investment in 2MT with passing sidings or 3MT infrastructure becomes critical. In particular, this will become increasingly important in urban areas within North America where freight, regional intercity passenger service and local commuter rail services typically use the same track infrastructure. Under these conditions, the capacity of full triple track with heterogeneous rail traffic is estimated as 133 trains per day (Cambridge Systematics, (2007)).

In addition to variability in velocity between train types, there are unique dispatching challenges related to both intercity and commuter passenger trains on shared-use corridors. As it is generally infeasible to provide station platform access to the center track within a 3MT right-of-way, often North American stations only have platforms on the outermost two tracks of 3MT, restricting how passenger trains stopping at these stations can utilize the track infrastructure. Commuter rail services often operate express trains skipping certain stations and local trains stopping at all stations on the route. With many trains being “short turns” starting at the terminal city but not running out the entire length of the line before returning to the central terminal, much of the demand for capacity and greatest conflict density is in the segments nearest to the main city terminal. Furthermore, the third main track can be used for the express trains and can be used bi-directionally to accommodate peak-period flows.

To investigate the response of operational performance and line capacity to the addition of new triple-track segments and different operating factors, this study tests route models of representative rail corridors with Rail Traffic Controller (RTC) simulation software. RTC is the industry-leading rail traffic simulation software in the United States, and is used by a wide range of public and private organizations, including most Class I railroads, Amtrak, and Bay Area Rapid Transit (BART) (Wilson (2016)). Design of experiments techniques are used to develop a series of simulation scenarios covering different combinations of factor levels of interest. Each scenario is simulated for 5 days of operation and replicated 8 times to provide 40 days of train operations data. In the simulation output is normalized into delay per 162 train km (100 train miles). Statistical analysis of the resulting train delay performance shows the sensitivity of the incremental benefit of sections of 3MT to the various operational factors under study.

Included in this study are two simulated networks. The first network is a more hypothetical case of a representative network designed to reveal fundamental relationships between different infrastructure and operating parameters. Corridor 1 is 386 km (240 miles) in length with shared use between unit coal freight trains and intercity passenger train operations. Variables in the experiment design include the total train volume, the number of freight trains and passenger trains (traffic composition), maximum allowable speed of the passenger trains, and the number of station stops made by the passenger trains.

The second network is more representative of actual triple-track operations in North America and is designed to investigate how these fundamental relationships apply in more complex settings. Corridor 2 is 121 km (75 miles) long and features a 80 km (50 mile) commuter network serving a major urban terminal located on one end of the network. Variables in the experiment design include the frequency of the commuter rail operation, express and local service changes, and changes to the number of freight trains.

On both networks, key operating and infrastructure factors are changed according to an experiment design to determine the impact on train delay. Each operational condition in the experiment design was run multiple times with the amount of 3MT being incrementally increased. The incremental third track construction was conducted in both a continuous and distributed order, adding another level to each experiment design. For the continuous methodology, 3MT was incrementally built in one continuous section. On Corridor 1, the 3MT continuous construction started at the center of the corridor and extended in both directions, increasing in 51 km (32 mile) increments. On Corridor 2, the 3MT continuous construction started at the urban commuter rail terminal located on the west end of the network and was extended eastward in 8 km (5 mile) increments. For both corridors, the distributed construction strategy for the 3MT placed it throughout the corridor to fill the largest gap in 3MT in existence at each stage.

3 Corridor 1 - Shared Use Freight and Intercity Passenger Rail

3.1 Experimental Design

Corridor 1 features a shared-use corridor hosting both unit coal freight trains and intercity passenger rail. A total of 504 unique simulation scenarios were conducted on RTC Version 70Q. The method of operation on the corridor is Centralized Traffic Control (CTC) with four-aspect route signalling. The studied variables and their respective values including network layout, percentages and location of available 3MT, traffic volume, passenger train speed, and passenger train stopping pattern are explained below.

Network Configuration

The Corridor 1 network is 386 km (240 miles) long with crossover interlockings allowing movement between the main tracks at 16-mile intervals (Figure 1). The interlockings are of a herringbone configuration allowing movement between all of the tracks. The West Yard and East Yard are freight terminals serving as the origin of east and westbound freight trains respectively. Passenger trains enter the network on main track on its east and west ends.

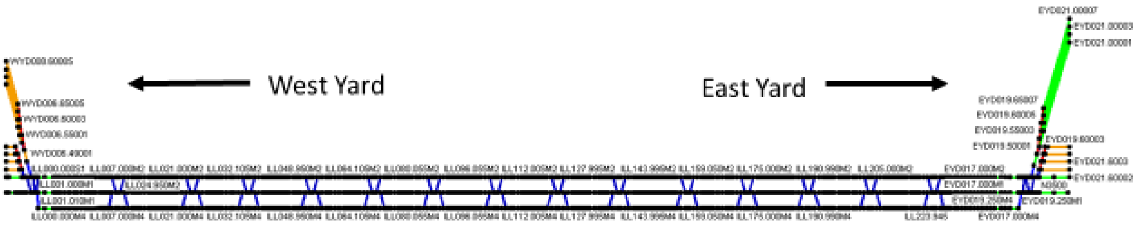

Figure 1: Corridor 1 Schematic

The entirety of the top and bottom main tracks remained in service throughout all experiments. Portions of the center main track between interlockings were incrementally taken out of service to simulate various proportions of 3MT available. The fifteen 26 km

(16 mile) segments of third main track were placed in service in nine increments, numbered 0 through 8 in both a distributed and continuous pattern ranging from 0% to 100% 3MT. For the distributed cases, 3MT segments were added to service following the methodology of Atanassov (2015) (Figure 2). The methodology looks to fill the largest gaps between segments of 3MT at each stage. For the continuous cases, 3MT was added starting first at the center segment (the eighth 25 km (16 mile) segment) and then building outward one 25 km (16 mile) segment in each direction for each successive stage. At any particular stage, the percentage of 3MT remains consistent for both the distributed and continuous cases.

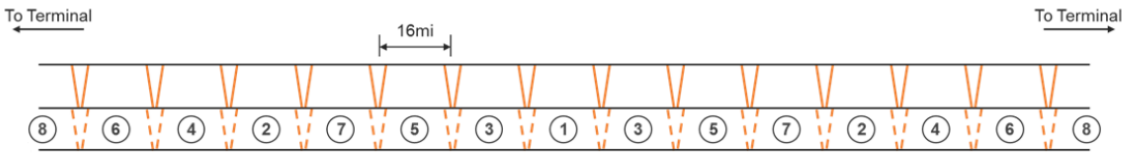

Figure 2: Order of Distributed 3MT Construction (Atanassov, 2015)

Station stops for passenger trains were restricted to the bottom track for eastbound trains and to the top track for westbound trains. Seven passenger stations were located across the network, spaced 48 km (30 miles) apart at mileposts 30, 60, 90, 120, 150, 180, and 210. The number of station stops each passenger train makes was varied to 0, 1, 3 or 7 across the experimental design matrix, and the minimum dwell for each station stop was 3 minutes. When only one station stop was made, this stop occurred at milepost 120. When increased to three station stops, the stations at mileposts 30 and 210 were added to the schedule. Lastly, trains with seven scheduled station stops stopped at all station stops listed above. Passenger trains were set to a higher priority than the freight trains. Speed of the freight trains was held constant at 97 KPH (60 MPH) consistent with FRA Class 3 track. Speed of the passenger trains was varied, set to either 97 KPH (60 MPH), 127 KPH (79 MPH), or 177 KPH (110 MPH).

Three train volumes and traffic compositions were considered: 52-12, 48-16, and 60-12 where the first two digits indicate the number of freight trains and the final two digits indicate the number of passenger trains. All trains operated on fully randomized schedules to more closely match flexible North American operating practices. The time each train entered the network each simulated day was randomly selected according to a uniform distribution over a 24-hour period, with a different random seed used for each replication of the same scenario in the experiment design.

Experiment Scenarios and Variables

The experiment design for Corridor 1 includes traffic volume (composition), passenger train speed, passenger train stops, percent 3MT and 3MT distribution (Table 1). Passenger train speed factor levels were selected to match common train speeds on shared passenger-freight corridors in North America. The 0%, 7%, 87%, and 100% values of 3MT available yielded an identical configuration for both the continuous and distributed patterns. The total experiment design included 504 unique scenarios. Each scenario was replicated with eight random seeds to reduce variance in the train delay output for statistical significance. Each replicate simulated five days of train operations with one day for warm up and one day for cool down.

Table 1: Corridor 1 Experiment Design Matrix

Variable, Units	Number of Levels	Levels
Traffic Volumes, Trains (#FRT-#PAX)	3	52-12, 48-16, 60-12
Passenger Train Speed, MPH	3	60, 79, 110
Passenger Train Station Stops	4	0, 1, 3, 7
Percentage 3MT, %	9	0, 7, 20, 33, 47, 60, 73, 87, 100
3MT Distribution Patterns	2	Continuous, Distributed

3.2 Results

Consistent with the finding of Atanassov (2015), an increase in the percentage of 3MT caused a linear reduction in train delay per 100 train-miles for both the distributed and continuous construction patterns Figure 3. Spread in train delay at each of the levels of percentage 3MT is due to variation of other experimental factors including traffic volume and composition, passenger train speed, and number of station stops. However, as the percentage of 3MT is increased, spread in train delay values decreases. At the 0%, 7%, 87%, and 100% levels, both the distributed and continuous strategies yield an identical infrastructure configuration and due to this have an identical delay profile at these points of investment. At the 20% and 33% 3MT, the distributed strategy has a slightly larger delay value across all cases and has slightly lower delay in the 47%, 60%, and 73% 3MT cases compared to continuous.

The incremental value of 3MT can be quantified by considering the slope of the train delay versus %3MT function for a given group of scenarios. The greater the magnitude of the linear regression line slope, in units of minutes of train delay saved per % 3MT, the greater the incremental return on investment for installation of 3MT (Figure 4). More negative values include green shading indicating a larger return on investment and a stronger case for 3MT. The rows are grouped into groups depicting traffic volume. Note that the first two groups, 48-16 and 52-12 have the same total traffic volume per day but with a higher proportion of passenger traffic in the former case. Each row group is organized in increasing number of scheduled station stops for passenger trains. Columns are grouped into "Continuous" and "Distributed" groups indicating the 3MT implementation strategy used. Within both column groups, the columns are ordered following increasing passenger train speed. The last column group "Delta" shows the relative difference in ROI between the "Continuous" and "Distributed" groups. A negative value indicates that the "Distributed" offers a better ROI on %3MT installed.

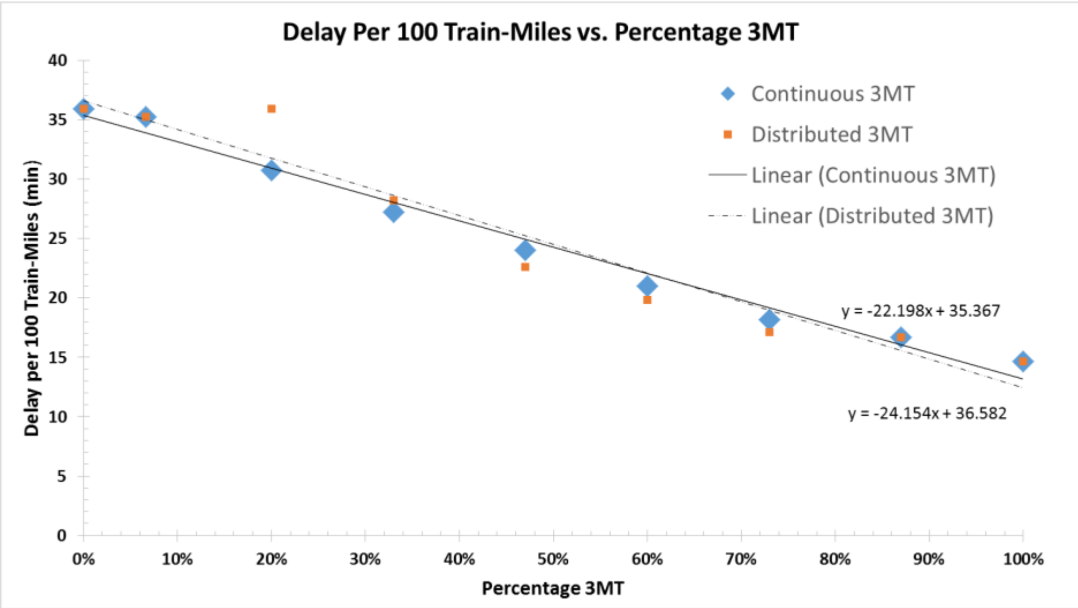

Figure 3: Delay Per 100 Train-Miles vs. Percentage 3MT

		Continuous			Distributed			Delta		
	PAX Speed	*60*	*79*	*110*	*60*	*79*	*110*			
48-16	Station Stops *0*	-0.14	-0.26	-0.26	-0.15	-0.26	-0.24	*-0.01*	0.00	0.02
	1	-0.15	-0.15	-0.30	-0.17	-0.15	-0.31	*-0.02*	0.01	-0.02
	3	-0.16	-0.23	-0.30	-0.18	-0.26	-0.32	*-0.03*	-0.02	-0.02
	7	-0.09	-0.32	-0.36	-0.14	-0.37	-0.44	*-0.04*	-0.05	-0.08
	PAX Speed	*60*	*79*	*110*	*60*	*79*	*110*			
52-12	Station Stops *0*	-0.13	-0.15	-0.24	-0.14	-0.16	-0.24	*-0.01*	-0.01	0.00
	1	-0.11	-0.25	-0.26	-0.13	-0.25	-0.29	*-0.02*	-0.01	-0.02
	3	-0.10	-0.18	-0.23	-0.12	-0.20	-0.24	*-0.03*	-0.02	-0.01
	7	-0.09	-0.20	-0.35	-0.15	-0.23	-0.41	*-0.06*	-0.03	-0.05
	PAX Speed	60	79	110	60	79	110			
60-12	Station Stops *0*	-0.16	-0.22	-0.26	-0.16	-0.20	-0.26	*0.00*	0.02	0.00
	1	-0.19	-0.31	-0.26	-0.19	-0.33	-0.25	*0.00*	-0.02	0.01
	3	-0.28	-0.24	-0.25	-0.30	-0.25	-0.32	*-0.02*	-0.02	-0.07
	7	-0.16	-0.32	-0.40	-0.21	-0.52	-0.40	*-0.04*	-0.19	0.00

Figure 4: ROI Matrix

From Figure 4, certain trends become evident. Within the "Delta" group, in nearly all cases, the "Distributed" strategy has a steeper or equal ROI slope compared to the "Continuous" strategy. While the 3MT strategies both start and end at the same infrastructure configuration and ROI, these results and those presented in Figure 3 indicate that at values of %3MT above ~40%, the distributed strategy yields a stronger ROI for delay reduction per %3MT installed than does continuous.

Overall, ROI magnitude increases with increasing traffic volume and speed of the passenger trains. As the number of station stops in the passenger schedule increases, this has the effect of locking in the route of the passenger trains. Because platforms are only located on the top and bottom tracks, and must be used by westbound and eastbound trains respectively, increasing the number of station stops decreases the ability of passenger trains to utilize the new main track for sort conflicts. As the number of station stops is increased as well as the passenger versus freight speed differential increases, the incremental benefit of the 3MT increases.

For the 177 KPH (110 MPH) case, the ROI values remain relatively the same regardless of the traffic case. The ROI is largely dependent upon the number of passenger trains and the number of scheduled station stops. ROI magnitude increases with an increasing number of passenger trains and station stops.

With general trends established, the next step is to look at conditional delay reduction for freight and passenger trains with the distributed 3MT strategy (Figure 5). Rows are grouped by traffic pattern and station stop as was done in Figure 4. The first column group, “All,” includes the overall corridor average delay identical to the second column group in Figure 4. The “Passenger” column group includes delay reduction data for only passenger trains while the “Freight” column group includes delay reduction data for only the freight trains. The “Delta (FRT/PAX)” column group shows the difference in ROI between the freight and passenger trains. A negative value indicates that the freight trains receive a greater reduction in delay per %3MT than do passenger trains.

		All			Passenger			Freight			Delta (FRT/PAX)		
	PAX Speed	60	79	110	60	79	110	60	79	110			
48-16	Station Stops 0	-0.15	-0.26	-0.24	-0.09	-0.12	-0.12	-0.17	-0.30	-0.27	-0.08	-0.18	-0.15
	1	-0.17	-0.15	-0.31	-0.08	-0.09	-0.16	-0.19	-0.17	-0.36	-0.11	-0.08	-0.20
	3	-0.18	-0.26	-0.32	-0.08	-0.12	-0.17	-0.22	-0.30	-0.37	-0.14	-0.19	-0.20
	7	-0.14	-0.37	-0.44	-0.05	-0.15	-0.20	-0.16	-0.44	-0.53	-0.11	-0.30	-0.33
	PAX Speed	60	79	110									
52-12	Station Stops 0	-0.14	-0.16	-0.24	-0.05	-0.07	-0.11	-0.16	-0.18	-0.27	-0.11	-0.12	-0.15
	1	-0.13	-0.25	-0.29	-0.07	-0.12	-0.17	-0.14	-0.28	-0.31	-0.07	-0.16	-0.15
	3	-0.12	-0.20	-0.24	-0.06	-0.11	-0.17	-0.14	-0.23	-0.26	-0.07	-0.12	-0.09
	7	-0.15	-0.23	-0.41	-0.05	-0.10	-0.23	-0.17	-0.26	-0.45	-0.12	-0.17	-0.21
	PAX Speed	60	79	110									
60-12	Station Stops 0	-0.16	-0.20	-0.26	-0.09	-0.10	-0.17	-0.18	-0.22	-0.28	-0.09	-0.12	-0.10
	1	-0.19	-0.33	-0.25	-0.13	-0.17	-0.19	-0.20	-0.36	-0.26	-0.08	-0.19	-0.07
	3	-0.30	-0.25	-0.32	-0.20	-0.14	-0.18	-0.32	-0.28	-0.34	-0.12	-0.13	-0.17
	7	-0.21	-0.52	-0.40	-0.08	-0.15	-0.33	-0.23	-0.59	-0.41	-0.15	-0.44	-0.08

Figure 5: Distributed 3MT - Passenger / Freight ROI Distribution

Overall, investing in 3MT has a higher delay reduction ROI for the freight trains than passenger trains. A possible explanation is that the passenger trains are dispatched with a higher priority value than the freight rains. As such, when a conflict between a passenger train and a freight train is encountered, the model gives preference to the passenger train at the expense of creating delay for the freight train. In theory, a homogeneous traffic mixture consisting exclusively of freight trains would have very low values of delay even without 3MT infrastructure. With 2MT, the trains would be able to meet at any location, and a lack of variation in train speeds and priority would eliminate sort or pass conflicts. The need for 3MT infrastructure to mitigate delay is due to the introduction of heterogeneous traffic. Hence additional 3MT will tend to benefit the lower-priority trains that would otherwise need to wait at 2MT bottleneck sections and accumulate delay.

While the trends of increasing ROI for increasing passenger speeds and station stops (at passenger speeds greater than 97 KPH (60 MPH)) for passenger trains follows the overall network trend, it is significantly less pronounced than for freight trains. As such, this study suggests that freight train delay reduction is the primary driver of ROI for installation of 3MT.

4 Corridor 2 - Shared Use Freight and Commuter Rail

4.1 Experimental Design

Corridor 2 is a shared-use corridor hosting both freight trains and commuter passenger trains. A total of 304 unique scenarios were simulated on RTC Version 70Q. The studied variables and their respective values including network layout, percentages and location of available 3MT, traffic volume with a “Light” and “Peak” commuter rail schedule and number of intermodal freight trains are described below. The “Light and “Peak” commuter rail schedules are representative of typical weekend and weekday operations respectively.

Network Configuration

The Corridor 2 network is 121 km (75 miles) long with crossover interlockings allowing movement between the main tracks on 8 km (5 mile) spacing (Figure 6). The method of operation is CTC with four-aspect route signalling. Maximum allowable speed is 127 KPH (79 MPH) for commuter trains and 97 KPH (60 MPH) for the intermodal freight trains, consistent with a FRA Class 4 route. The interlockings are of a herringbone configuration allowing movement between all of the main tracks. On the west end of the corridor is a commuter rail passenger terminal and a freight facility serving as an origin and destination for eastbound commuter trains and intermodal trains respectively.

The commuter corridor extends 80 km (50 miles) to the east with stations spaced every 8 km (5 miles), for a total of ten stations numbered in increasing order eastbound. East of the final station is the commuter rail layover facility where train sets are stored overnight prior to the beginning of each simulated day of operations. “All Stops” commuter trains make all station stops (1 through 10) over the entire commuter corridor. “Express” commuter pass stations 1, 2, 3, and 4 without stopping, and stop at stations 5, 6, 7, 8, 9, and 10. “Local” commuter trains stop at stations 1, 2, 3, 4, and 5 and then reverse direction and head back to the central terminal. Station stops for passenger trains are restricted to the bottom track for eastbound trains and to the top track for westbound trains.

No commuter trains operate east of the interlocking at Milepost 50 where the commuter rail layover facility connects to the main line. Eastbound intermodal freight trains operate all the way out to the east end of the corridor. Westbound freight trains originate at the east end of the corridor.

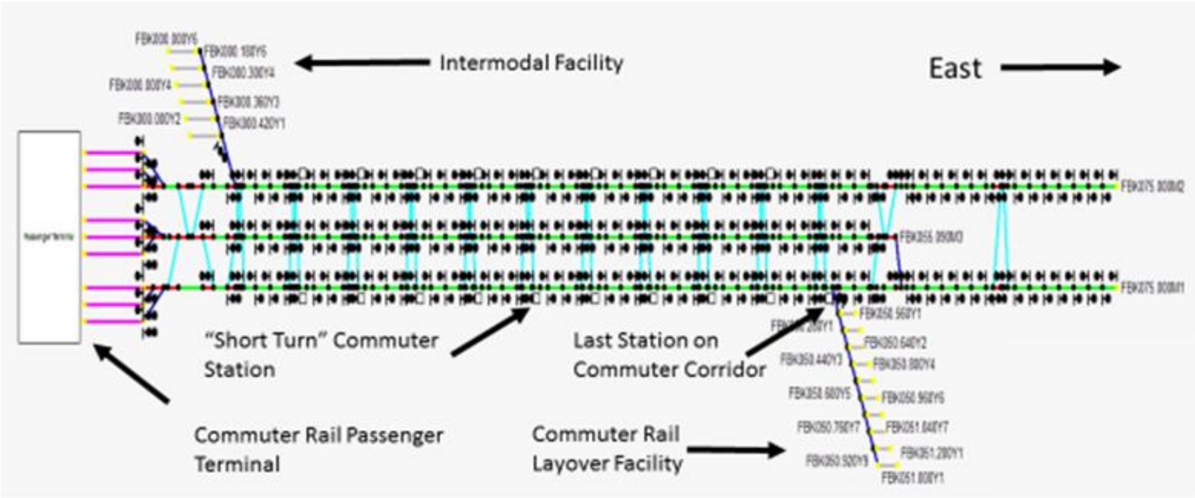

Figure 6: Corridor 2 Schematic

The entirety of the top and bottom main tracks remained in service throughout all scenarios. Portions of the center main track between interlockings were incrementally taken out of service to simulate various proportions of 3MT available.

The eleven 8 km (5 mile) segments of third main track were placed in service in five increments in both a distributed and continuous pattern ranging from 0% to 100% 3MT. For the distributed cases, 3MT segments were added to service filling the largest gap in 3MT at that stage. For the continuous cases, 3MT was added extending eastward from the passenger terminal. At any particular stage, the percentage of 3MT remains consistent for both the distributed and continuous cases.

All passenger trains consisted of one 3000 HP F40PH-2C locomotive and five bi-level commuter rail coaches. All commuter trains were linked to an equipment cycle using the linked equipment feature within RTC. Each train set is responsible for a subset of the trains included in the timetable and each train run in the subset must be completed before the next can begin. All movements are linked including non-revenue repositioning movements between the layover facility and Station 10 at the beginning and end of each equipment cycle. Using this methodology, RTC will account for secondary delay from late arriving trainsets at terminals in addition to the primary delay from line-of-road train conflicts. Between each run, there is a minimum 15-minute turn time when the crew changes the direction of the trainset. For westbound trains, the equipment turn occurs at the passenger terminal. For eastbound trains, the equipment turn occurs at station 5 or station 10 depending on the commuter train. Often, the dwell time to turn trains on the main line is a limiting factor in line of road dispatching on commuter railroads. Minimum dwell time for intermediate station stops is set to 1.5 minutes. At the passenger terminal, the model dispatches trains to any of the available station tracks.

The "Peak" commuter rail schedule is a typical weekday commuter rail operation with 5:00 AM to 9:00 AM and 3:00 PM to 7:00 PM designated as peak periods. Service is offered on 30-minute headways. For each headway period, an express train and local train is operated. During off-peak hours, "All Stops" trains are operated on one-hour headways. Throughout the entire day, the "Peak" commuter rail schedule includes 86 daily scheduled revenue commuter trains using ten sets of equipment. The "Light" commuter rail schedule simulates a typical weekend commuter rail operation. Service is offered on one-hour headways with "All Stops" trains. Throughout the entire day, 34 daily scheduled revenue commuter trains are operated using three sets of equipment.

Freight trains are operated on fully randomized schedules. The times freight trains will enter the network both eastbound and westbound are chosen at random according to a uniform distribution over a 24-hour period. The number of freight trains operated starts at zero and is increased to 36 in increments of two freight trains per day.

Experiment Scenarios and Variables

The experiment design matrix for Corridor 2 includes passenger train volumes operated on a "Light" or "Peak" volume schedule as defined in the previous section (Table 2). The number of freight trains varies from zero to 36 trains per day in increments of two. There are five levels of the percentage of 3MT available and two different implementation strategies, continuous and distributed. The total experimental design included 304 unique scenarios each replicated eight times with random seeds for statistical significance. Each simulation scenario included five days of operation with one day for warm up and one day for cool down.

Table 2: Corridor 1 Experimental Design Matrix

Variable, Units	Number of Levels	Levels
Passenger Train Volume	2	Light, Peak
Freight Train Volume, Trains	19	0, 2, 4, 8, 10, 12, 14, 16, 18, 20, 22, 24, 26, 28, 30, 32, 34, 36
Percentage 3MT, %	5	0, 27, 45, 63, 100
3MT Distribution Patterns	2	Continuous, Distributed

4.2 Results

Similar to the results of Corridor 1, and consistent with findings of Atanassov (2015), increasing percentage of available 3MT reduces train delay linearly (Figure 7). The figure includes both the continuous and distributed cases for experiments operated using the "Peak" commuter rail schedule. Points from the "Light" experiment were not included as many utilize the corridor far below capacity. Each point on the graph is the average of all experiments at each considered level of %3MT available for both construction strategies. There is significant spread in the delay values for the different train volume experiments for each percentage of 3MT. However, for both construction strategies, the number of points averaged to make each point on the graph and respective traffic volumes are identical.

At values of 0% and 100%, the distributed and continuous strategies are identical and thus have the same delay value. However, at intermediate points, the continuous strategy has lower delay values than distributed. However, the drop in delay is still approximately linear until the 63% level, well after the 45% level. At 45%, the 3MT has been constructed as far as Station 5, where all of the "short turn" trains terminate and return to the central terminal. There is little further delay savings beyond the 63% 3MT level.

For each family of cases, defined as operating the same traffic volume on varying percentages of 3MT, the slope of the line indicates a savings in delay per %3MT installed. The more negative the slope, the greater the delay savings return on investment of installing 3MT (Figure 8). The first three column groups represent the light commuter rail schedule. The second three column groups represent the peak commuter rail schedule. Within each column group, the two column sub-groups show delay savings for the continuous and distributed strategies. The third column sub-group, labelled “Delta” indicates the difference in delay savings ROI between these two strategies. A negative value indicates the continuous strategy outperforms distributed and has a stronger ROI. Within each column sub-group, the three individual columns divide the data by train type with the first including all trains on the network, the second including only the commuter trains, and the third including only the freight trains. The rows indicate the number of freight trains operating on the network.

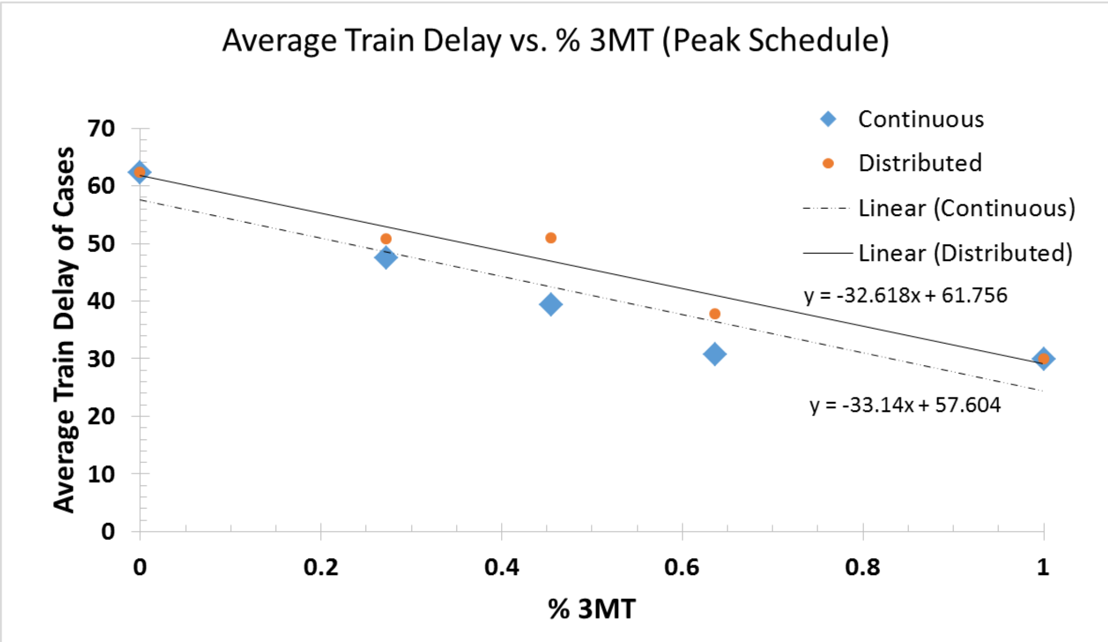

Figure 7: Average Delay vs. % 3MT

	Light Commuter Schedule									Peak Commuter Schedule								
	Continuous			Distributed			Delta			Continuous			Distributed			Delta		
Number of Freight Trains	All	Pax	Frt	All	Pax	Frt	All	Pax	Frt	All	Pax	Frt	All	Pax	Frt	All	Pax	Frt
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	-0.02	-0.01	-0.26	-0.02	-0.01	-0.19	0.00	0.00	-0.07	-0.03	-0.02	-0.34	-0.03	-0.02	-0.37	0.00	0.00	0.03
4	-0.04	-0.01	-0.26	-0.03	-0.01	-0.19	-0.01	0.00	-0.07	-0.08	-0.06	-0.57	-0.08	-0.05	-0.63	0.00	0.00	0.06
6	-0.06	-0.02	-0.28	-0.05	-0.02	-0.20	-0.01	0.00	-0.08	-0.16	-0.13	-0.58	-0.15	-0.12	-0.61	-0.01	-0.01	0.03
8	-0.07	-0.03	-0.25	-0.05	-0.02	-0.19	-0.02	0.00	-0.07	-0.13	-0.10	-0.43	-0.12	-0.09	-0.46	-0.01	-0.01	0.03
10	-0.08	-0.03	-0.25	-0.06	-0.03	-0.18	-0.02	-0.01	-0.07	-0.22	-0.18	-0.59	-0.20	-0.16	-0.57	-0.02	-0.02	-0.02
12	-0.09	-0.05	-0.23	-0.07	-0.04	-0.15	-0.03	-0.01	-0.08	-0.14	-0.09	-0.54	-0.16	-0.10	-0.65	0.02	0.01	0.12
14	-0.16	-0.05	-0.42	-0.13	-0.04	-0.33	-0.03	-0.01	-0.09	-0.22	-0.14	-0.82	-0.24	-0.14	-0.93	0.02	0.01	0.11
16	-0.18	-0.06	-0.46	-0.14	-0.05	-0.35	-0.04	-0.01	-0.12	-0.24	-0.12	-0.93	-0.21	-0.08	-1.00	-0.03	-0.04	0.07
18	-0.18	-0.05	-0.42	-0.12	-0.04	-0.27	-0.06	-0.01	-0.15	-0.33	-0.21	-0.99	-0.29	-0.14	-1.09	-0.05	-0.08	0.11
20	-0.17	-0.05	-0.37	-0.10	-0.04	-0.21	-0.06	-0.01	-0.16	-0.40	-0.23	-1.26	-0.38	-0.17	-1.45	-0.02	-0.06	0.19
22	-0.23	-0.04	-0.54	-0.16	-0.02	-0.38	-0.07	-0.02	-0.15	-0.40	-0.26	-1.00	-0.40	-0.21	-1.26	0.00	-0.05	0.27
24	-0.25	-0.05	-0.55	-0.19	-0.05	-0.40	-0.06	0.00	-0.15	-0.32	-0.21	-0.78	-0.32	-0.14	-1.06	0.00	-0.07	0.28
26	-0.27	-0.05	-0.57	-0.21	-0.04	-0.43	-0.06	-0.01	-0.13	-0.43	-0.23	-1.21	-0.47	-0.21	-1.48	0.04	-0.02	0.27
28	-0.28	-0.07	-0.55	-0.22	-0.06	-0.41	-0.07	-0.01	-0.14	-0.43	-0.23	-1.21	-0.47	-0.21	-1.48	0.04	-0.02	0.27
30	-0.38	-0.07	-0.74	-0.27	-0.06	-0.52	-0.11	-0.01	-0.21	-0.49	-0.30	-1.11	-0.41	-0.13	-1.34	-0.07	-0.16	0.22
32	-0.38	-0.09	-0.71	-0.27	-0.07	-0.49	-0.11	-0.01	-0.22	-0.67	-0.38	-1.54	-0.71	-0.32	-1.91	0.04	-0.07	0.37
34	-0.48	-0.09	-0.89	-0.35	-0.06	-0.65	-0.13	-0.03	-0.24	-0.72	-0.38	-1.71	-0.66	-0.17	-2.08	-0.06	-0.21	0.38
36	-0.53	-0.11	-0.95	-0.42	-0.08	-0.75	-0.11	-0.03	-0.20	-0.88	-0.31	-2.44	-0.89	-0.15	-2.88	0.01	-0.15	0.44

Figure 8: 3MT Delay Savings ROI Slope Values

In all cases, increasing the number of freight trains operated increases the delay savings ROI. Also, the “Peak” schedule with more commuter trains operated, has higher savings ROI values. For both schedule frequencies, while the ROI grows for both the commuter and freight trains as the number of freight trains increases, ROI grows much more rapidly for the freight trains. This is because the commuter trains are scheduled and have higher priority values; without interference from freight trains there is little delay for the commuter trains. When freight trains, attempting to enter the network at random times chosen by the model in each random seed, are added and come into conflict with the commuter trains, the majority of the delay accrues to the freight train. As 3MT infrastructure becomes available, freight trains will experience more delay reduction as they had the highest delay values initially.

For the “Light” schedule, there is a very small trend of better ROI values with increasing number of freight trains. Nearly all of this savings occurs on the freight trains specifically; passenger trains have nearly identical savings for both strategies. However, for the “Peak” schedule, the “Continuous” strategy has either identical or slightly superior return overall. Also, the two train types benefit differently from each of the different strategies: with continuous, passenger trains see a slight reduction in delay per percentage of 3MT constructed while freight sees greater benefit with the distributed strategy. Given the small lengths of the 3MT segments, it is likely that when the first 3MT sections are built in the distributed strategy, the segments are utilized as though they were passing sidings. The train can be stopped incrementally throughout the route, so the dispatcher can keep the freights moving by committing to shorter routes than they would in the continuous case. Having short, distributed sections of 3MT allows the model to commit to shorter routes for freight trains when it otherwise would be unable to commit to any route.

The marginal cost of adding a freight train to the corridor is linear as well (Figure 9). At any point, the slope of the line is an indication of the marginal cost of adding an additional freight train to the route in terms of the additional delay minutes per 162 train km (100 train miles) added. Note that both lines have Y-intercept values near zero which is to be expected. Both the “Light and “Peak” schedules were designed so that the commuter trains do not have conflicts with each other even on 2MT infrastructure. When a “peak” commuter service is being operated, the marginal cost of adding an additional freight train is higher.

The marginal delay of adding an additional freight train as a function of %3MT shows a sensitivity to the amount of track infrastructure available (Figure 10). All of the points are regression slopes, following the sample methodology shown in Figure 9. The marginal cost is shown for all trains in the network as well as for commuter and freight trains. Data shown is from the continuous 3MT distribution strategy. Overall, marginal cost tends to decrease linearly as the percentage of 3MT is increased. For the commuter trains, the marginal cost remains relatively constant. For the freight trains, the highest marginal costs are incurred when there is little 3MT available. As more 3MT is available, the decline in marginal cost tends to slow for freight trains. Increasing the commuter volume from “light” to “peak,” all of the marginal costs curves are shifted upwards, and the variation in the freight marginal cost increases as well.

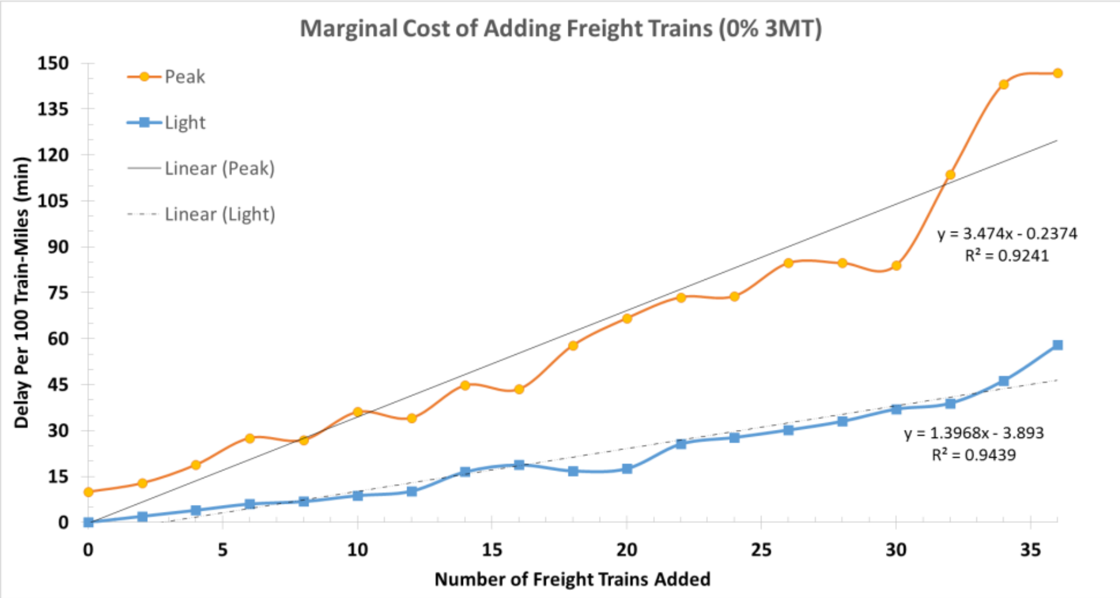

Figure 9: Marginal Cost of Adding Freight Trains (0% 3MT)

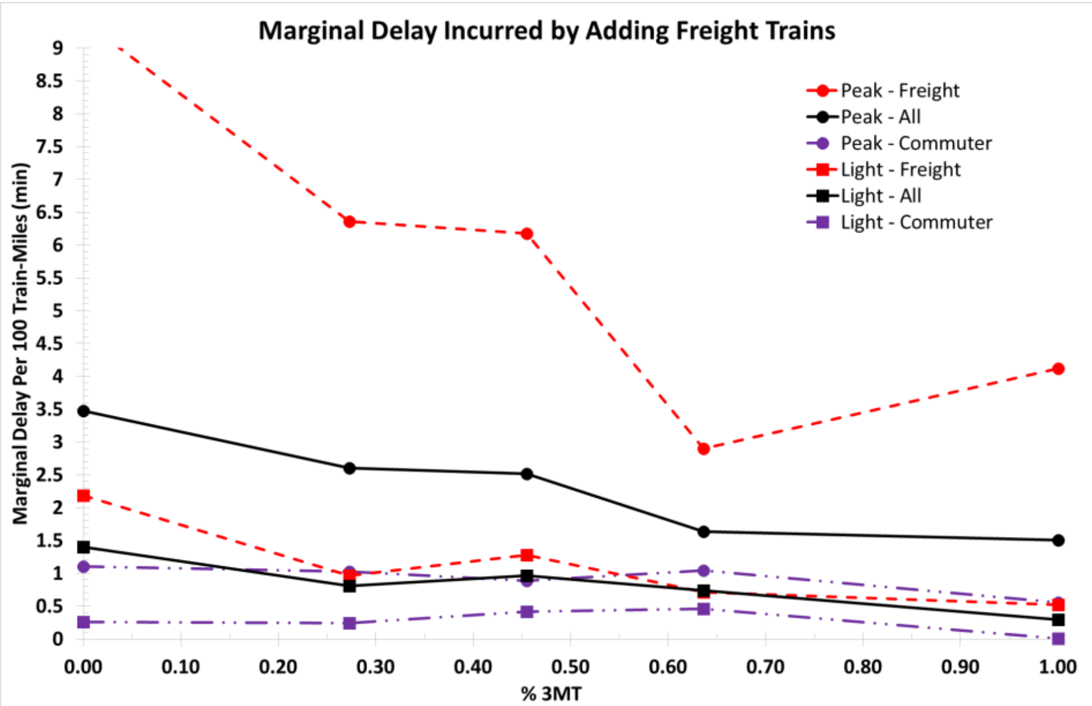

Figure 10: Marginal Delay Incurred by Adding Freight Trains

5 Conclusions

The two corridors examined in this study suggest that some of the experimental design factors have a consistent effect across all 3MT corridors regardless of layout and traffic composition whereas others are dependent on the local conditions of the corridor. Consistent with previous research, an increase in %3MT causes a linear reduction in train delay. However, the optimality of either the "continuous" or "distributed" 3MT construction strategies depends on the corridor and the trains considered. For Corridor 1, small amounts of 3MT were far more effective when continuous; however, as a greater percentage of the corridor became 3MT (>30%), it was more effective to have it distributed in sections. On Corridor 2, the continuous strategy had lower values of train delay and a stronger ROI slope than did distributed at intermediate quantities of 3MT. While overall, Corridor 2 performed better using the "Continuous" strategy, the "Distributed" strategy resulted in moderately better delay savings for freight trains specifically when the "Peak" commuter rail service level was operated. The relationship that stronger delay reduction at low percentages of 3MT could be achieved through the continuous strategy was the same in both cases even though the continuous strategies differed conceptually. On Corridor 1, the continuous 3MT was built near the center of the corridor; on Corridor 2, the continuous 3MT started at the central passenger terminal and extended eastward.

For both groups of experiments, stronger ROI slopes were observed at higher traffic volumes as the corridor neared capacity. In the unscheduled operation of Corridor 1, where both passenger trains and freight trains were unscheduled, there was a higher marginal cost of adding additional passenger trains compared to freight trains. On Corridor 2, where the passenger trains were scheduled, freight trains had a higher marginal cost.

Experiments on Corridor 1 indicated that increasing the passenger train speed and relative heterogeneity compared to freight trains increased the investment ROI slope for 3MT. Furthermore, once significant heterogeneity had been introduced at the 177 KPH (110 MPH) passenger speeds, the ROI was comparable irrespective of the traffic volume. An increase in the number of passenger stops corresponded to an increase in ROI particularly when speeds were highly heterogeneous.

Experiments on Corridor 2 indicated that the marginal cost in terms of corridor train delay of adding additional freight trains to the corridor is linear. However, the experiments included in this study were within capacity of the corridor. It is expected that further significant increases in the number of freight trains being operated, beyond 36 trains per day and to network capacity, would ultimately result in an exponential delay cost for additional volume.

Lastly, results from both corridors show that most of the delay savings provided by 3MT primarily accrue to freight trains. Without 3MT, the freight trains experience the majority of the delay on a shared-use corridor irrespective of whether the surrounding passenger trains are operating on an unstructured or structured plan. As a passenger train is given a higher priority, the resolution of a conflict will give priority to the passenger train at the expense of delay to the freight train.

Acknowledgements

This research was supported by the Association of American Railroads (AAR) and the National University Rail Center (NURail) a US DOT-OST Tier 1 University Transportation Center. The lead author was also supported by the CN Research Fellowship in Railroad Engineering. The authors would like thank Eric Wilson of Berkeley Simulation Software, LLC for the provision of Rail Traffic Controller (RTC).

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