Using Advanced PTC with Moving Blocks to Improve the Operational Feasibility of Short Trains on Single-Track Rail Corridors

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ABSTRACT

Rail transportation can achieve excellent economies of scale related to labor, fuel, infrastructure, and equipment. To magnify these inherent efficiencies, many U.S. Class I railroads have traditionally focused on increasing average train lengths. However, railroads may soon leverage investments in Positive Train Control (PTC) communications network infrastructure to implement "advanced PTC" systems with moving blocks. Advanced PTC could also enable single-person crews or driverless trains, reducing the labor incentive for long trains. Compared to long trains, shorter trains can facilitate more direct trains that bypass intermediate classification yards and/or more frequent train departures between origin-destination pairs, expediting the movement of railcars and yielding potentially significant time and cost savings. Conversely, operating the same number of railcars in shorter trains increases the total number of trains traversing a given rail line, increasing congestion and delay. To investigate the effects of a short-train operating strategy on rail corridor performance, Rail Traffic Controller software is used to simulate varying combinations of long and short trains operating on representative single-track rail corridors under fixed or moving block control systems. Comparing delay performance reveals that, for a fixed traffic demand, increases in delay are likely when converting existing long trains into more frequent shorter trains. However, moving blocks can be used to partially mitigate these performance impacts. Considering the ability of shorter trains to reduce yard and terminal dwell time, advanced PTC with moving blocks can improve the overall net benefits of shorter trains, enabling faster railcar transit times and higher quality service for shippers.

INTRODUCTION

A fundamental reason enabling low-cost, high-efficiency freight transportation by rail is the ability of trains to haul many carloads with a small number of locomotives and crew. Operating a train incurs certain fixed costs that do not depend on train length. Labor costs are one of the largest components of total operating cost *(1)* and a significant fixed cost, providing a strong economic incentive to increase train lengths. With the widespread implementation of business strategies incorporating Precision Scheduled Railroading (PSR) and its focus on asset utilization and cost control, several Class I railroads are pursuing ever longer trains *(2, 3, 4).*

From a capacity standpoint, incrementally lengthening trains allows more railcars to be transported without operating additional trains on a corridor. However, long trains spend more time traversing speed restrictions and impose higher individual meet delays on opposing traffic *(5, 6).* In mountainous territory, mid-train remote-controlled distributed power locomotives enable longer trains while minimizing related increases in damaging lateral forces imparted on the track *(7)*. From a safety perspective, statistical analysis of derailments on U.S. Class I railroads from 2006 to 2015 suggests dispatching a fixed number of railcars in fewer, longer trains can decrease the expected number of derailments *(8)*. Increasing train length can also increase fuel efficiency, partly because aerodynamic drag is greatest at the front of a train; but other factors such as speed and train weight have a greater effect on fuel efficiency *(9)*.

Operational safety issues associated with longer trains, such as crew fatigue, braking reliability, and lengthened blockages of highway-rail grade crossings, have drawn U.S. federal government attention *(4)*. For train crews, long trains can have more challenging train handling characteristics and require crewmembers to walk greater distances to perform work actions. At yards, long trains with a greater number of blocks are more complicated to assemble and prepare for departure, decreasing yard efficiency *(10)*. From a competitive standpoint, operating long trains reinforces railroad cost advantages but runs counter to many shippers' preferences for faster, more reliable transit times. In coming years, autonomous trucks will significantly reduce truck costs, presenting a competitive challenge to railroad modal share *(11)*. Operating shorter trains may be one effective response for railroads to compete on service and cost. Subsequent introductory sections expand on these justifications for short trains, leading to the specific research questions examined by this study.

Short Trains

The cost-service trade-offs associated with train length have been debated since at least the 1950s, when train crews typically consisted of five people *(12)*. Studies in the 1970s emphasized balancing the cost incentive for long, slow trains against the revenue incentive of higher service quality provided by short, fast, and frequent manifest and intermodal freight trains *(13, 14, 15)*. Manifest freight traffic, where individual carloads are transported on multiple trains using a hub-and-spoke network topology, remains a significant freight rail market *(16)*. A key metric of carload service quality is average railcar transit time, or the total amount of time elapsed between origin and destination. Connections between trains at classification yards are a major source of delay and transit time variability, directly impacting the performance of railway mainlines through an integrated network efficiency cycle *(17)*. When multiple connections with a given reliability are made in succession (i.e. via connecting hubs), end-to-end reliability is lower than that of any individual connection, with implications for railcar scheduling across a manifest train network *(18)*.

Operating shorter, simpler trains can have direct yard benefits. Simulations have shown that for a given level of service, a classification yard can process more outbound trains if each train is composed of fewer blocks of railcars *(10)*. Assembling a greater number of single-block trains can significantly improve the percent of trains that depart on time according to the train plan. By carrying smaller batches of railcars more frequently, short trains can spread inbound and outbound railcar volumes throughout the day, avoiding traffic peaks that strain yard capacity.

At a network level, short trains enable two operating strategies to address yard reliability: increasing frequency of train departures between yards; and running more direct trains bypassing intermediate yards. Increasing train departure frequency from, for example, one every 24 hours to one every 12 hours decreases average railcar transit time but comes with diminishing returns as headways become smaller *(19)*. Increasing the number of direct connections from origin to destination allows railcars to bypass intermediate yards, eliminating connection time and associated uncertainty. A past study found implementing direct connections to be more effective than increasing frequencies, but both strategies only achieved modest average transit time reductions without a significant increase in cost *(20)*. However, this conclusion did not consider railcar transit time variability in detail, which is often of greater importance to shippers managing inventory costs *(21)*. Transit time reliability requirements differ by freight market segment, significantly affecting mode choice decisions *(22)*. By decreasing batch sizes, short trains can help railroads tailor service to different market segment demands and maximize overall revenue.

Transporting a given number of railcars in shorter trains increases the number of trains and conflicts on a rail corridor, decreasing fluidity and increasing congestion delay *(23)*. On North American heavy haul railroads, this effect is exacerbated by rail traffic exhibiting a high level of heterogeneity in train characteristics such as maximum speeds, dispatching priorities, and power-to-weight ratios. A mixture of train types, particularly when there is a minority of trains with significantly poorer acceleration characteristics and lower priorities, suffers from more delay than a comparable number of homogenous trains *(24, 25)*. Therefore, obtaining net service benefits from a short trains operating strategy involves a distinct trade-off between yard benefits and mainline delay disbenefits. The primary focus of this study is understanding the mainline portion of this trade-off.

Advanced Train Control Systems

By December 2020, the North American rail industry expects to implement Positive Train Control (PTC), a safety-focused overlay on existing fixed-block train control systems capable of automatically enforcing train movement authorities *(26, 27)*. With PTC implementation, railroads have an opportunity to leverage sunk investments in digital communications systems, network infrastructure, and train positioning technology to introduce “advanced PTC” systems incorporating moving blocks and/or driverless trains.

Existing signalized train control systems maintain train separation by dividing mainlines into a series of fixed control blocks, each regulated by wayside signals displaying block occupancy information to approaching train crews. Since fixed blocks are set for the braking characteristics of a design train, the control system has limited flexibility to accommodate trains with significantly different braking parameters. In contrast, moving blocks customize train movement authority to a train’s length and absolute braking distance. Using real-time train location, movement authority boundaries constantly update to define a “moving block” protecting the train as it travels along the mainline *(28)*. Moving blocks decrease minimum train distance headways and can significantly increase line capacity relative to fixed block systems *(29, 30)*. By reducing the fixed capacity cost of dispatching a train, moving blocks can mitigate the capacity disbenefits of operating shorter trains.

Besides capacity benefits, advanced train control systems could support single-person crews or driverless trains *(31)*. Advanced PTC or similar technologies could enable a remote operator to control multiple long-haul trains from a centralized location, a concept tested in Germany and France in 2019 *(32, 33)*. Coupled with the safety benefits of systems like PTC, single-person crews or remote-controlled trains could be supported by roaming conductors who travel by highway vehicle and perform work events for multiple trains *(34)*. Fully autonomous trains began operating on iron ore lines in Western Australia in 2019 *(35)*, with autonomous trains under development in North America and France *(36, 37)*. By cutting fixed labor costs, driverless trains enabled by advanced PTC promise to dramatically change the economics of train length, boosting the attractiveness of operating shorter trains *(38)*. One major hurdle is that freight train crew size is a highly contentious issue, with labor unions, states, and local officials advocating for federal regulations requiring a minimum of two-person crews *(39)*. However, by enabling railroads to provide a higher quality of service, short trains may promote overall traffic and revenue growth that potentially benefits both railroads and labor.

OBJECTIVE AND PREVIOUS RESEARCH

Research Questions

This study seeks to address the following specific research questions:

- What are the quantified mainline capacity and line performance impacts of operating a given number of railcars in shorter, more frequent trains?
- Can mid-siding crossovers and/or advanced train control systems incorporating moving blocks effectively mitigate the capacity impacts of operating shorter, more frequent trains?

Previous Research

To answer the research questions, this study examines mainline corridors operating with different combinations of long and short trains under fixed and moving block control systems. Operating both short and long trains introduces train length heterogeneity to a mainline corridor. Previous studies on the capacity impacts of train heterogeneity have focused on factors such as speed, priority, and power-to-weight ratio differences among traffic operating under conventional fixed block control systems *(40, 41, 42, 43, 44)*. Lai et al. drew from the highway domain to develop a metric to compare the capacity impacts of different train types for a given level of traffic *(45)*. While these works indirectly evaluated the effect of train length in the context of the average consists for different train types, the fundamental capacity impacts of train length heterogeneity were not explicitly investigated.

Several studies used Rail Traffic Controller Simulation software to quantify the capacity effects of train heterogeneity. Dingler et al. simulated varying combinations of bulk and intermodal trains operating on a heavy-haul rail corridor, finding that differences in train priority and acceleration performance were the principal factors reducing relative capacity *(25)*. Conducting a cost-benefit analysis on alternatives to reduce delays from train type heterogeneity, Dingler et al. also determined that one of three strategies performed best depending on the specific traffic mix and volume: no change, equalizing priorities, or adding sidings *(46)*. Increasing power-to-weight ratio and adding second track had fewer delay reduction benefits compared to the incremental costs. Dick et al. examined the siding infrastructure necessary to manage traffic flows consisting of different combinations of “short” trains and “long” trains exceeding the length of existing sidings *(47)*. Simulations were run under 3-aspect fixed blocks only and found that for a given track infrastructure, operating more railcars in long trains results in lower average train delay.

Investigating advanced train control systems, Dick et al. examined the relative capacity benefits of moving blocks in the North American freight railway context by comparing simulated operations under fixed and moving block control systems across various combinations of traffic volume, traffic composition, and percent second main track *(29)*. Scenarios with moving blocks exhibited consistently lower average train delay than those with fixed block signals. Diaz de Rivera et al. simulated operating intermodal or unit trains in fleets, finding that combining train fleeting and moving blocks can reduce delay relative to cases with just one of the two components present *(48)*. This study builds on previous research by using simulation methods to investigate the train delay disbenefits of operating more frequent, shorter trains, and the potential mitigation effects of moving blocks and modified track layouts.

METHODOLOGY

Rail Traffic Controller

This study primarily uses Rail Traffic Controller (RTC) simulation software to investigate the research questions. RTC is a railway corridor simulation software used by most passenger and Class I freight railways, consultants, and rail capacity researchers in North America *(49)*. RTC simulates mainline operations by emulating decisions made by train dispatchers to resolve conflicts according to North American train control systems and operating practices. General RTC model inputs include track layout, signaling, train plan, train characteristics, and train priority. RTC can simulate operations under both fixed and moving block control systems. To fully capture the characteristics of moving blocks, the frequency of train performance calculations was set at an aggressive interval of 25 feet to obtain more fine-grained results than typically used for RTC. To promote passes between trains with differing operating speeds, and to make full use of the available track infrastructure, operator handling was set to be aggressive with an overall objective of increasing average train speed.

Study Parameters and Experiment Design

Simulation experiments considered a flat, tangent, 152-mile single-track mainline with 2-mile passing sidings every 10 miles, intended to be representative of a typical North American Class I freight rail corridor. For scenarios with a fixed-block control system, the block length was set at two miles. Total demand across the freight-only study corridor was 5,184 railcars per day, divided between “short” and “long” manifest and intermodal trains (**Table 1**). Train length was set such that each siding can accommodate either one long train or two short trains. The number of railcars and locomotives on a short train is exactly half of those on a long train to maintain a constant power-to-weight ratio and enable direct conversions from long to short trains. Manifest and intermodal trains were chosen for their ubiquity on the North American freight rail network and their synergies with short train benefits. Intermodal trains are generally faster and higher priority with a higher power-to-weight ratio, introducing train type heterogeneity. The train plan dispatched trains evenly throughout the day with an even directional split, regularly alternating train types and lengths. All trains traversed the entire corridor without planned stops.

TABLE 1 Train parameters and characteristics

	“Short” Train		**“Long” Train**	
Parameter	**Manifest**	**Intermodal**	**Manifest**	**Intermodal**
Locomotive Power (hp)	4,380	4,380	4,380	4,380
Locomotives per Train	2	2	4	4
Number of Railcars	72	72	144	144
Train Length (feet)	4,610	4,610	9,220	9,220
Train Weight (tons)	10,720	8,340	21,440	16,680
Hp per Ton	0.82	1.05	0.82	1.05
Maximum Operating Speed (mph)	40	60	40	60
Initial RTC Priority Assignment	3,000	6,000	3,000	6,000

North American freight railways generally do not operate to strict timetables *(50, 51)*. Instead, trains have some amount of schedule flexibility where a train may be dispatched earlier or later than planned, depending on factors such as crew and equipment availability or network and yard congestion. The amount of schedule flexibility defines the period around the planned train departure time over which trains randomly depart. For this experiment, 60 minutes of schedule flexibility was incorporated in all scenarios. For example, if a train was planned to depart at 9:00am, the actual departure time varied between 8:00am and 10:00am according to a random uniform distribution.

The experiment design includes four variable factors: train length heterogeneity, train type heterogeneity, train control system, and percent of sidings with mid-siding crossovers. Each factor was simulated over a range of values or "levels" (**Table 2**) in a full-factorial design. To capture train length heterogeneity, the total number of railcars per day was fixed while the total number of trains per day varied according to how the railcars were distributed between long and short trains. 0, 33, 67, or 100 percent of railcars traveled on short trains, with the remainder traveling on long trains. Two combinations of train types were tested: the *Carload* case consisting only of manifest trains and the *Mixed* case with 50 percent manifest and 50 percent intermodal trains.

TABLE 2 Primary experiment design factor levels

Factor	Levels	Level Specification
Train Length Heterogeneity (Percent of Railcars on Short Trains)	4	0, 33, 67, 100
Train Type Heterogeneity	2	*Carload*:100% Manifest, 0% Intermodal *Mixed*: 50% Manifest, 50% Intermodal
Train Control System	2	3-Aspect Signals with Fixed Blocks (3A) Advanced PTC with Moving Blocks (MB)
Track Layout (Percent of Sidings with Mid-Siding Crossovers)	3	0, 50, 100

The latter two factors in the experiment design test strategies to mitigate the anticipated mainline capacity disbenefit of operating a greater number of short trains. Two train control systems are included: 3-aspect signals with fixed blocks and advanced PTC with moving blocks. Moving blocks tend to increase capacity and mitigate heterogeneity between trains and therefore are hypothesized to produce a lower average train delay. Three track layouts are also tested: one with conventional sidings (**Figure 1a**) and two with different numbers of mid-siding crossovers (**Figure 1b**). Mid-siding crossovers provide flexibility by allowing short trains to enter sidings later or exit sidings earlier. They also allow two short trains in opposing directions to occupy the same siding simultaneously. This flexibility may mitigate the effect of increased complexity of train conflicts that comes with train length and type heterogeneity. While not as effective as adding additional sidings, extending sidings into "super sidings" with mid-siding crossovers has been shown to improve delay performance *(52)*.

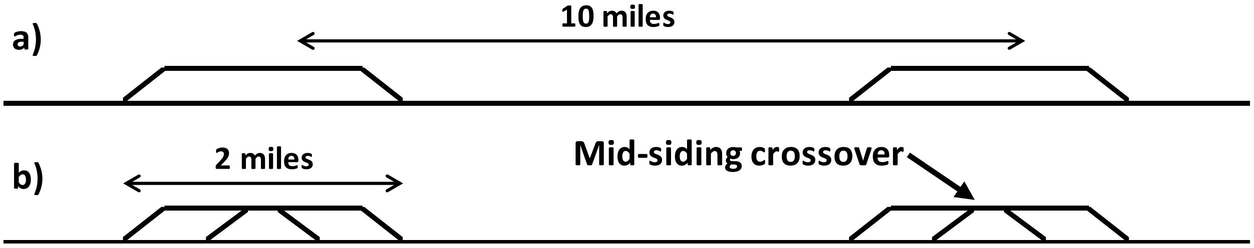

FIGURE 1 Experiment track layout with 2-mile passing sidings every 10 miles featuring a) a conventional layout and b) mid-siding crossovers.

Analysis

Train delay is the primary operational performance metric output from each RTC simulation run. Following typical North American practice, RTC calculates train delay as the difference between the actual running time for a given train, and its minimum running time operating at maximum authorized speeds without any train conflicts or other impedances. The actual running time includes the time a train is in motion, delays departing the origin terminal, and any delays incurred from train meets, passes, and other conflicts regardless of if the conflict is planned or not. Average train delay can be used to estimate capacity, with several Class I railroads viewing average train delay of 60 minutes per 100 train-miles as indicative of a line operating at capacity.

To account for schedule flexibility, each scenario in the experiment design is replicated 30 times with unique simulation seeds. Each replicate consisted of one single-day schedule repeated for three days, including one warm-up day and one cool-down day. Average train delay per 100 train-miles was calculated across all replicates for each scenario. When RTC determined a particular seed was infeasible, that replicate was omitted from the average results. Finally, 95 percent (α=0.05) confidence intervals were calculated to represent the variation in the results across replicates.

RESULTS

Average train delay values and 95-percent confidence intervals for each operating scenario were determined from RTC simulation outputs and grouped by number of long and short trains. Values of train delay are considered significantly different if their respective confidence intervals do not overlap. Higher train delay is indicative of a more congested, poorer-performing scenario.

For the *Carload* traffic mix, increasing the proportion of railcars on short trains leads to increases in the total number of trains, causing an increase in average train delay (**Figure 2a**). Adding mid-siding crossovers does not have a significant effect on average train delay for both 3-aspect fixed blocks and moving blocks, in part because the traffic mix is homogenous with respect to train type heterogeneity. Since all trains have the same maximum operating speeds, priorities, and train handling, train conflicts are less complex and do not benefit from the flexibility provided by mid-siding crossovers. As the percent of railcars on short trains increases, the performance of each control system diverges, with moving blocks better able to mitigate the performance impact of adding more trains to the corridor. However, even when all railcars travel on short trains and the number of trains doubles (from 36 long trains to 72 short trains), average train delay for all cases remains below 60 minutes per 100 train-miles.

For *Mixed* train traffic, the effect of train priority, speed, and handling heterogeneity has a substantial negative impact on delay performance of the corridor compared to the *Carload* results (**Figure 2b**). When 100 percent of railcars travel on short trains, all scenarios exceed 60 minutes of average train delay per 100 train-miles, indicating generally poor performance with highly congested conditions where the specific differences in delay values do not provide useful comparisons. The effectiveness of adding mid-siding crossovers is dependent on the number of railcars traveling on short trains. Since long trains are too long to take advantage of mid-siding crossovers, mid-siding crossovers have no effect in the baseline case with only long trains. When 67 percent of railcars are dispatched in short trains, going from 0 to 100 percent of sidings with mid-siding crossovers produces slight delay benefits under both 3-aspect fixed blocks and moving blocks. Under moving blocks, installing crossovers on only 50 percent of sidings yields the same delay benefits as building crossovers on every siding, suggesting that only installing crossovers on certain highly utilized sidings may be an effective delay reduction strategy when combined with moving blocks. Such a strategy may be more economically feasible than installing crossovers on every siding given the substantial capital and operating costs associated with special trackwork.

Approaching 100 percent of railcars traveling on short trains, the *Mixed* delay curves separate further, with greater benefits from moving blocks and mid-siding crossovers. With moving blocks and 100

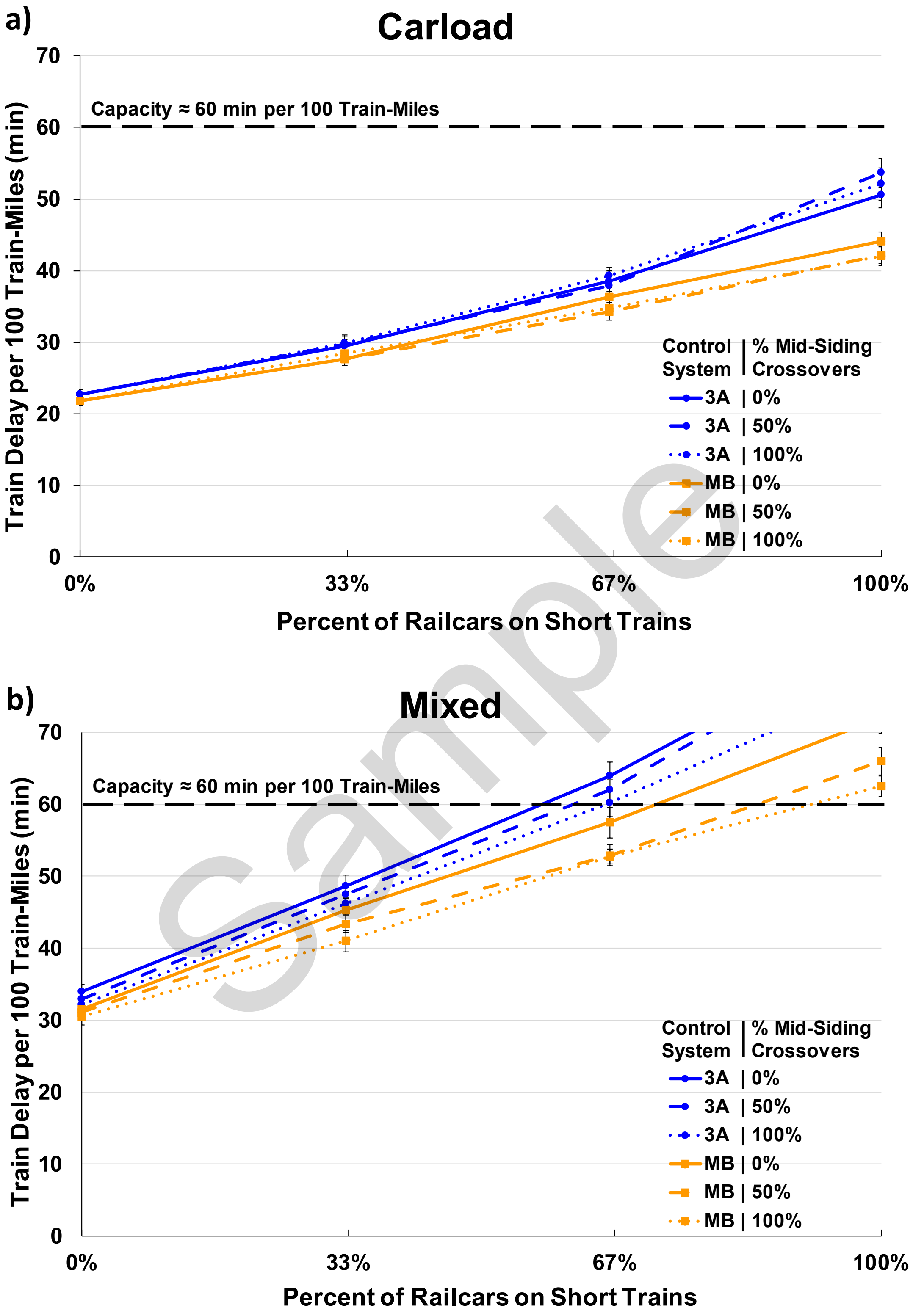

FIGURE 2 Average train delay per combination of control system and percent mid-siding crossovers for (a) *Carload* and (b) *Mixed* traffic mixes as a function of percent of railcars on short trains.

percent mid-siding crossovers, corridor performance is improved such that it is only slightly above the 60-minute capacity line, a much more tolerable operating condition. For mid-siding crossovers to be effective, there must be a significant number of short trains operating along the corridor as well as train type heterogeneity creating more complicated train conflicts. Similarly, moving blocks are most effective at minimizing average train delay when there is a high degree of train length and train type heterogeneity, as observed with the *Mixed* results.

As a mainline corridor approaches capacity, there is an increasing incremental delay penalty associated with operating additional trains (*25)*. Therefore, the mainline delay penalty of splitting existing trains into an equivalent number of shorter trains is increased. To further investigate this concept, additional RTC simulations were run with the *Carload* traffic mix, 0 percent mid-siding crossovers, 3-aspect fixed blocks and moving blocks, and a total transportation demand of 2,592 railcars per day (half the baseline demand, or 18 long trains per day), representing a single-track line operating well below capacity. For the same percentages of railcars on short trains, average train delay values can be compared against the equivalent baseline *Carload* results (**Figure 3**). With 5,184 railcars per day, when shifting from 0 to 100 percent of railcars on short trains, average train delay more than doubles for both control systems. With half the railcar volume, the increase is much smaller, and the delay penalty of short trains decreases. At 2,592 railcars per day, there is no significant difference between the 3-aspect fixed block and moving block results. The primary capacity benefit of moving blocks is reducing minimum train separation, which is less of an issue when traffic volume is low. These results indicate that short trains can have less critical mainline delay disbenefits on existing rail corridors with fixed block signals when initial traffic volume is significantly below capacity.

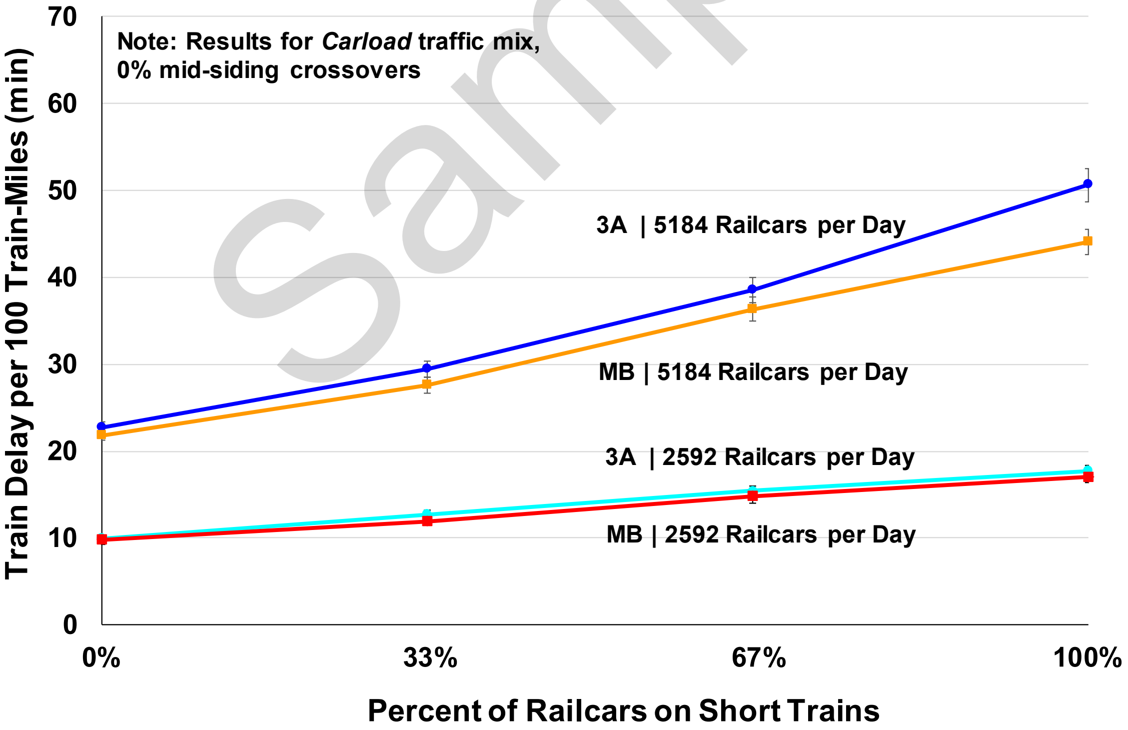

FIGURE 3 Average train delay per combination of control system and transportation demand for *Carload* traffic mix as a function of percent of railcars on short trains.

CONCLUSIONS

To operate a train, certain expenses such as the cost of labor are incurred regardless of train length. Therefore, current freight railway economies of scale favor longer trains. Advanced train control systems enabling single-person crews or driverless trains promise to reduce the fixed cost of operating a train, removing a significant incentive for increasing train lengths. Operating shorter trains provides an opportunity for railways to improve the level of service provided to shippers by increasing train frequencies on existing routes (and reducing the penalty for missed yard connections) or by operating more direct trains bypassing intermediate yards. However, operating a given number of railcars in shorter trains increases the number of trains operating on a corridor, increasing congestion and delay. There is therefore a distinct short trains service trade-off balancing potential yard connection time benefits with incremental mainline delay costs (**Figure 4**). For a network with efficient yards and long or congested mainlines, the mainline delay impacts of short trains will likely outweigh their yard benefits, favoring longer train lengths. Conversely, for a network with unreliable yards and shorter or less congested mainlines, the scale would tip the other way, favoring shorter train lengths.

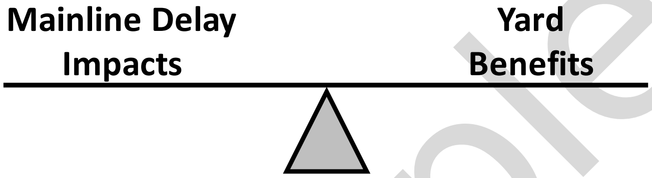

FIGURE 4 Reducing railcar transit times and variability with shorter trains requires weighing incremental mainline delay impacts with yard connection time benefits.

In order to better understand the mainline performance implications of operating shorter trains, RTC software was used to simulate mainline corridors under different combinations of control system, siding configuration, train type heterogeneity, and train length heterogeneity. Moving blocks can partially mitigate the delay impacts of operating a given railcar volume on shorter trains. The effectiveness of moving blocks is increased when train type heterogeneity, and associated differences in priorities, speeds, and handling characteristics, is introduced. Mid-siding crossovers are only effective delay mitigation measures when trains are short enough to use them and train type heterogeneity results in complicated train conflicts. When a corridor is operating well below capacity, the delay impact of short trains is reduced.

Potential areas of future research include simulating operating short trains with higher priorities, different combinations of train type heterogeneity, and different ratios of long train length to short train length beyond the 2:1 ratio tested in this work. The effect of dispatching more, shorter trains on classification yard operations should be further explored to help rail operators determine desirable train lengths. Quantifying the relative capacity consumption of short versus long trains would also be useful.

The economics of certain segments of the freight rail market, such as bulk commodities, will likely favor longer train lengths for the foreseeable future. However, for other market segments such as manifest or intermodal traffic, the advent of advanced train control systems reducing the fixed costs of operating trains provides an opportunity to improve the quality of transportation service provided to shippers. Understanding the mainline delay impacts of short trains can assist railroad practitioners developing long-term capital investment plans and operating strategies. The results of this research are of particular use to rail operators looking to increase transportation market share using a short trains strategy. While the experiments conducted in this work are intended to be representative of North American operating environments and train characteristics, the fundamental capacity and economic principles discussed can be applied to most freight-dominated rail corridors around the world.

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TABLE TITLES AND FIGURE CAPTIONS

TABLE 1 Train parameters and characteristics

TABLE 2 Primary experiment design factor levels

FIGURE 1 Experiment track layout with 2-mile passing sidings every 10 miles featuring a) a conventional layout and b) mid-siding crossovers.

FIGURE 2 Average train delay per combination of control system and percent mid-siding crossovers for (a) *Carload* and (b) *Mixed* traffic mixes as a function of percent of railcars on short trains.

FIGURE 3 Average train delay per combination of control system and transportation demand for *Carload* traffic mix as a function of percent of railcars on short trains.

FIGURE 4 Reducing railcar transit times and variability with shorter trains requires weighing incremental mainline delay impacts with yard connection time benefits.