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Relative Capacity and Performance of Fixed- and Moving-Block Control Systems on North American Freight Railway Lines and Shared Passenger Corridors

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Abstract

North American railroads are facing increasing demand for safe, efficient, and reliable freight and passenger transportation. The high cost of constructing additional track infrastructure to increase capacity and improve reliability provides railroads with a strong financial motivation to increase the productivity of their existing mainlines by reducing the headway between trains. The objective of this research is to assess potential for advanced Positive Train Control (PTC) systems with virtual and moving blocks to improve the capacity and performance of Class 1 railroad mainline corridors. Rail Traffic Controller software is used to simulate and compare the delay performance and capacity of train operations on a representative rail corridor under fixed wayside block signals and moving blocks. The experiment also investigates possible interactions between the capacity benefits of moving blocks and traffic volume, traffic composition, and amount of second main track. Moving blocks can increase the capacity of single-track corridors by several trains per day, serving as an effective substitute to construction of additional second main track infrastructure in the short term. Moving blocks are shown to have the greatest capacity benefit when the corridor has more second main track and traffic volumes are high. Compared with three-aspect signal systems, much of the benefits of moving blocks can be obtained from adding signals and implementing a four-aspect signal system. Knowledge of train delay performance and line capacity under moving blocks will aid railway practitioners in determining if the benefits of these systems justify the required incremental investment over current PTC overlay implementations.

Positive Train Control (PTC) systems are integrated command, control, communications, and information systems for controlling train movements with safety, security, precision, and efficiency (*1*). Through the use of a digital data link and real-time train location information, a PTC system is designed to enforce movement authority and prevent train-to-train collisions, overspeed derailments, incursion into work zones, and the movement of a train through a switch left in the wrong position (*2*). The Rail Safety Improvement Act of 2008 mandated that PTC be implemented on over 70,000 mi of track in the United States (U.S.) (*1*).

The Rail Safety Improvement Act does not mandate a specific architecture for PTC systems as many different technologies can satisfy the safety requirements for PTC. PTC can be implemented as an overlay to enforce movement authority granted by existing control systems using wayside signals (centralized traffic control). If a train crew does not initiate a brake application when they encounter a restrictive signal or does not brake in advance of a speed restriction, the PTC system will impose a penalty brake application and stop the train. This safety overlay approach has been adopted by most Class 1 railroads on mainline corridors currently operating with centralized traffic control.

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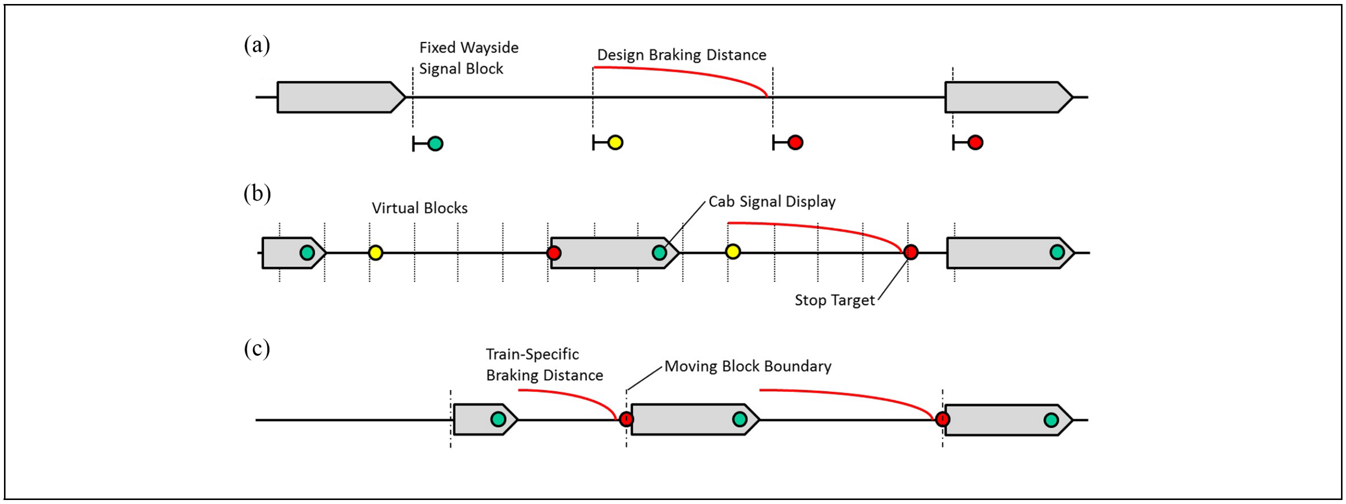

Figure 1. Train operations with (*a*) three-aspect wayside block signals, (*b*) virtual blocks, and (*c*) moving blocks.

Throughout its development, PTC has been described as having both safety and business benefits (*3*). Real-time train location information can improve train dispatching and rail traffic management decisions with the potential to increase system performance (*4*). Some researchers have claimed that improved dispatching decisions will lead to increased capacity in an overlay application (*5*). Others have claimed that any capacity benefits of a PTC overlay will be offset by uncertainty in the train braking algorithm and initialization time of the system (*6*).

Many researchers have proposed that additional business benefits in the form of increased capacity can be obtained by using real-time fine-grained PTC train position information to enhance or supplant the wayside block signal system (*6*). Such applications, frequently termed "advanced PTC systems" can use virtual or moving blocks to decrease train headways compared with wayside block signal systems (Figure 1). Advanced PTC systems with virtual blocks subdivide existing wayside signal blocks into shorter virtual segments defined by mileposts. Virtual signal indications and train movement authority are updated by the advanced PTC system as trains pass into each virtual block. Because the virtual blocks are shorter, each train occupies a shorter segment compared with the current wayside signal block system. As a train moves along a corridor, it will more rapidly release the track it has passed, potentially decreasing minimum headways between trains travelling in the same direction at the same speed.

Advanced PTC systems can also use moving blocks in place of a fixed wayside or virtual block system. A moving-block system maintains safe train separation by continually comparing the calculated braking distance of a train to the distance to the next train ahead of it or other speed reduction and stop targets. The block of track occupied by each train is customized to the length of each train and is constantly updated as it travels along the mainline; effectively the occupied block moves along with the train, hence the term "moving block". Because each train only occupies a length of the corridor equal to its physical train length plus a margin of safety, train separation is reduced to the braking distance of each train. Where a particular train has a much shorter braking distance compared with the design train used to establish the original wayside signal blocks, headways between trains can be greatly reduced.

Advanced PTC systems require sophisticated capability that comes at additional expense compared with the overlay PTC systems currently being implemented by U.S. Class 1 railroads. The additional cost of advanced PTC must be justified by incremental business benefits. A potential source of business benefits is increased capacity and the ability to increase traffic (and revenues) without the need for additional investment in track infrastructure. Additional capacity can also increase network velocity, reducing the number of locomotives and railcars on line and associated railway operating expenses. The objective of this research is to investigate the potential for advanced PTC systems with moving blocks to improve the capacity and performance of Class 1 railroad mainline corridors under typical North American track layout and traffic compositions. Knowledge of train delay performance and line capacity under advanced PTC system operations will aid railway practitioners in determining if the benefits of these systems justify the required incremental investment over current PTC implementations.

Development of Virtual and Moving-Block Control Systems

Moving-block operations and coordinated train control has been demonstrated and deployed on several subway lines worldwide, including the Docklands Light Railway in London, L Line in New York, and Subway Line 2 in Beijing (*7*). In addition, the SkyTrain in Vancouver, Canada, opened in 1986, is notable for its use of both autonomous trains and moving blocks managed from a wayside computer control system. Transit systems typically feature vehicles of similar length, acceleration and braking properties, consistent operating speeds, highly structured schedules, and double track. Under these conditions, it is easier to achieve minimum train headways and obtain the hypothetical capacity benefits from moving blocks on double track that will be described in the next section.

In Europe, the European Train Control System (ECTS) Level 3 has provisions for operations with moving blocks. Currently, there are no short-term plans to introduce ECTS Level 3 on European rail lines, but many lines are expected to test ECTS levels with moving blocks in the coming years. Like previous transit applications, the ETCS experience with moving blocks is not directly applicable to North American mainline heavy-haul freight railways and shared corridors. European railway operations typically feature double track, use electric traction, have a focus on passenger trains, and impose limits on the length and weight of freight trains that constrain train sizes to be far less than those operated on North American railways (*8*). Greater homogeneity in train size and weight normalizes train performance, making it easier to obtain capacity benefits from moving blocks on double track, but, at the same time, also makes it easier to design efficient fixed-block signal systems.

In the context of mainline line-haul freight and commuter, regional, and intercity passenger rail operations in North America, advanced PTC with moving blocks is still under development. In the early 2000s, the North American Joint Positive Train Control (NAJPTC) project was conducted to develop, test, and demonstrate PTC capabilities, including moving-block operations, in a corridor with both freight and passenger service (*9*). In 2001, The NAJPTC system was developed and tested on a 120-mi Union Pacific Railroad corridor in Illinois. Development work moved to the Transportation Technology Center in 2006. Although current PTC installations incorporate many elements developed under the NAJPTC project, the moving-block architecture was not among them. The NAJPTC project highlighted many important technical challenges associated with moving blocks, including bandwidth of the radio links, data latency, and the need for more adaptive and robust braking and control algorithms.

Although further development is required to implement advanced PTC with moving blocks in the North American mainline operating environment, several newly constructed iron ore railways in Western Australia have implemented moving-block PTC to reduce train headways and maximize capacity (*10*). Compared with North American line-haul freight and passenger operations involving trains with a wide range of performance characteristics, trains on the iron ore lines are of relatively consistent length and weight and use Electronically Controlled Pneumatic (ECP) brakes. Although the homogeneous operations on the iron ore lines benefit from reduced headways under moving blocks, the potential capacity benefits on shared corridors with heterogeneous train operations are less clear and are the subject of this paper.

Hypothetical Capacity Benefits of Advanced PTC

The simple case of two identical trains following each other in the same direction most easily illustrates the ability of advanced PTC with virtual or moving blocks to reduce train headways (Figure 2). Existing wayside signal systems divide track segments into a series of fixed control blocks that, in most cases, can only be occupied by one train at a time. A wayside signal located at the entrance to each block communicates information about block occupancy to the train crew. The length of each control block is related to the safe stopping distance of a design train and the number of approach signal indications in the primary progression from stop to clear.

In a "three-aspect" signal system, there is only one approach indication. A train passing a signal displaying the approach aspect must expect to encounter a stop indication at the next signal. To ensure that all trains can safely brake to a stop prior to passing the next signal, the distance between signals must be greater than the safe braking distance. Thus, for a three-aspect signal system, the block length is equal to the safe stopping distance. To see nothing but clear signals, the following train must remain at least three block lengths behind the end of the lead train (Figure 2*a*). For a three-aspect control system, this corresponds to a following distance equal to three times the safe braking distance. The excess train separation arises because, as the end of the lead train is about to pass a signal and leave a control block, the wayside signal system treats this mostly empty block as being occupied. Similarly, because the wayside signal system only provides information to the train crew at discrete intervals, an additional block length of separation is necessary to ensure the train crew sees clear signals instead of running up on an approach signal right before it clears.

To reduce the amount of excess separation distance between trains, railways can employ signal systems with additional approach indications. A "four-aspect" signal system includes an "advance approach" indication between clear and approach. Upon passing a signal

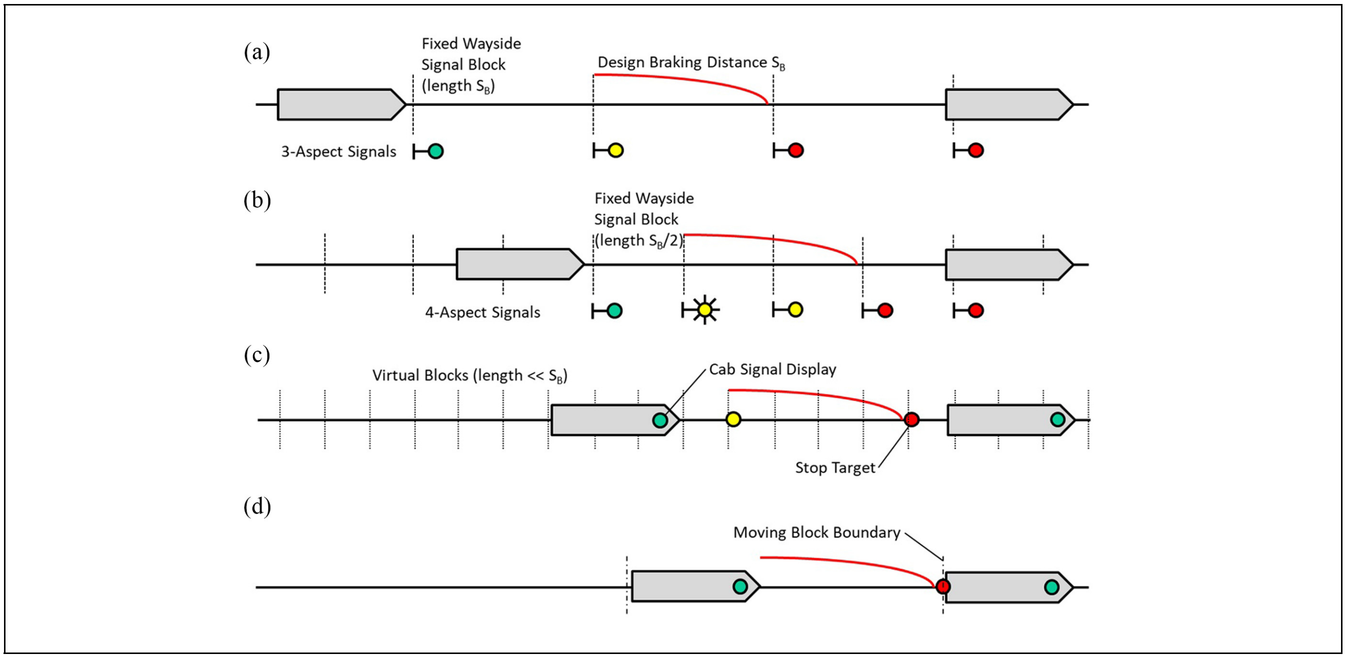

Figure 2. Comparison of train headway with (*a*) three-aspect wayside block signals, (*b*) four-aspect wayside block signals, (*c*) virtual blocks, and (*d*) moving blocks.

displaying advance approach, a train will have two blocks to brake to a stop prior to a stop indication. Thus, for a four-aspect signal system, the block length is equal to one-half the safe stopping distance. Reducing the block size decreases the minimum train separation relative to a three-aspect system. Although the following train must remain at least four block lengths behind the end of the lead train to see clear signals in the four-aspect system (Figure 2*b*), because the block size is one half of the three-aspect block length, the overall separation distance is less. Similarly, a five-aspect signal system can further decrease train separation by using block lengths equal to one-third of the braking distance.

In general, the signal block length is related to the safe braking distance and number of signal indications in the primary progression from stop to clear by the following equation:

$$B = \frac{S_B}{N - 2}$$

where:
B = signal block length
S_B = safe braking distance of the design train
N = number of signal indications in the primary progression from stop to clear

In order for the following train to constantly see clear signals, the headway distance between trains (i.e., train separation plus train length) is calculated as:

$$H = L_T + S_B + 2B = L_T + S_B + \frac{2S_B}{N - 2}$$

where:
H = train headway distance
L_T = train length

For the simple case of homogeneous train operations in a single direction (i.e., in one direction on double track), the line capacity in trains per unit time in one direction can be calculated by dividing the average train speed by the headway distance. From the form of the equation above, as the number of signal aspects increases, the headway distance decreases and the line capacity increases.

For illustrative purposes, a reasonable assumption for North American freight operations is that the safe braking distance is approximately equal to the train length. Under this assumption, the expressions for headway and capacity are:

$$H = 2S_B + \frac{2S_B}{N - 2}$$

$$C = \frac{V}{2S_B + \frac{2S_B}{N-2}}$$

where:
C = line capacity in trains per unit time (in one direction)
V = average train speed

Table 1. Hypothetical Line Capacity of Homogeneous Operation in Single Direction

System	Indications (N)	Block length (B)	Train headway* (H)	Percent change in headway from Three-aspect (%)	Percent change in headway from Four-aspect (%)	Line capacity* (C)	Percent change in capacity from Three-aspect (%)	Percent change in capacity from Four-aspect (%)
Three-aspect	3	S_B	$4S_B$	–	33	$V / 4S_B$	–	–25
Four-aspect	4	$S_B/2$	$3S_B$	–25	–	$V / 3S_B$	33	–
Five-aspect	5	$S_B/3$	$2.66S_B$	–33	–11	$V / 2.66S_B$	50	13
Virtual block**	22	$S_B/20$	$2.10S_B$	–48	–30	$V / 2.10S_B$	90	43
Moving block	∞	0	$2S_B$	–50	–33	$V / 2S_B$	100	50

Note: *Assuming train length is equal to safe braking distance (S_B); **Will vary with specific density of virtual blocks.

This simple model illustrates the capacity gained by additional signal indications (aspects) for the simple case of homogeneous operations in a single direction on double track (Table 1). Transitioning from a three-aspect to a four-aspect signal system decreases hypothetical train headway by 25% and increases hypothetical line capacity by 33%.

Advanced PTC systems with virtual blocks subdivide existing wayside signal blocks into shorter virtual segments (Figure 2*c*). Creating additional virtual blocks is equivalent to increasing the number of signal indications. For example, under a system with virtual blocks that are 0.1 mi in length, a train with a braking distance of 2 mi passes through 20 virtual blocks while braking to a stop. Adding clear and stop indications, this virtual block system is equivalent to a "22-aspect" fixed-block signal system and $N = 22$ can be substituted into the headway and capacity equations. Given the previous assumption, compared with a three-aspect wayside signal system, the virtual block system at 0.1-mi intervals will reduce hypothetical train headway by 48% and increase hypothetical line capacity by 90%. Headway is reduced by 30% and capacity increased by 43% relative to a four-aspect wayside signal system. Different gains in headway and capacity can be achieved by selecting a different density of virtual blocks.

Advanced PTC systems with moving blocks monitor the exact length of track occupied by each train. The following train continuously receives information on the exact position of the end of the lead train to serve as a stop target for safe braking distance calculations (Figure 2*d*). By moving the stop target along with the lead train, the excess distance between the end of the lead train and the first block signal displaying stop is eliminated. Similarly, by continuously updating train location relative to braking distance, the extra distance from the last clear signal to the first approach signal in the block signal system is also eliminated. The separation distance between trains is reduced to the safe braking distance. Effectively, the moving-block system functions as a block signal system with an infinite number of very short blocks. For virtual blocks, $N \rightarrow \infty$ and the block length $B \rightarrow 0$ in the hypothetical capacity calculation (Table 1). Under the assumed hypothetical conditions of homogeneous operations on double track, moving blocks can double capacity relative to a three-aspect wayside signal system and increase capacity 50% compared with a four-aspect block signal system.

The values in Table 1 represent an upper bound on the potential capacity gains from advanced PTC under the ideal conditions of homogeneous operations on double track. Only in very few instances, such as transit systems, is headway the controlling factor in determining line capacity. On single track, line capacity is largely determined by the running time between passing sidings and not the headway between trains. Heterogeneity in train speed can limit the amount of time that trains operate at minimum headways on double track. Under these conditions, the reduced train headways under virtual and moving blocks may have less capacity benefit. This research seeks to quantify the capacity benefits of advanced PTC with moving blocks under more representative North American operating conditions.

Previous Research

Previous researchers have examined the potential benefits of moving blocks in a qualitative and quantitative manner. In the North American context, it has been suggested that capacity benefits could be anticipated on single track where passing sidings were long enough to facilitate faster running meets under moving-block operations (*11*). The study also concluded that capacity benefits were greater where the braking distance of a typical train was far shorter than the braking distance of the rare design train used to establish the lengths of wayside signal blocks. This last finding was revisited in a follow-up paper by Lai and Barkan (*12*). A subsequent study of the impact of Communications Based Train Control and ECP brakes on line capacity concluded that the greatest potential benefits were on busy multiple-track routes where headways could be reduced through moving blocks (*6*, *13*). A limitation of this previous research is that it evaluated line capacity under moving blocks in an idealized context over a short segment of track. The research in this paper improves upon this previous work by simulating heterogeneous train operations over an entire corridor.

Internationally, Lee et al. determined that moving blocks could increase the capacity of the Korean high speed railway (*14*). Xishi et al. quantified the benefit of moving block relative to fixed-block systems using simulation on a passenger corridor in China (*15*). Another study quantified the capacity benefits of the European ETCS (*16*). In all cases, it is difficult to extrapolate these results to typical North American freight lines and shared corridors.

Overall, researchers and industry practitioners have conflicting thoughts on where and when moving blocks will benefit capacity (*3*, *4*, *17–21*). Moving blocks may help mitigate the disproportionate impact of certain types of train heterogeneity because of mixing passenger and freight traffic on shared corridors (*22*, *23*). Moving blocks may improve recovery from temporary track outages or delays because moving blocks allow trains to be fleeted through work areas with much closer spacing than conventional signal systems. This fleeting capability may also be of value when a double-track section has to be single-tracked during maintenance (*18*). Moving block capability may also reduce delays because of passes on single-track lines with passing sidings. Shorter headways reduce the time that the train being overtaken waits in the passing siding (*9*). New movement authority can be issued to a train immediately after an overtaking train has passed the exit turnout and the switch has been lined. It is not necessary for the train departing the siding to wait until the first block beyond the turnout has been cleared by the overtaking train, as is often required with conventional block signal systems (*18*). These potential capacity benefits are more difficult to quantify with simple headway models; more robust simulation experiments are required.

Research Questions

This research seeks to develop a more fundamental understanding of the relationship between route infrastructure, traffic composition, and the relative capacity of conventional wayside block signals and advanced PTC with moving blocks on single-track railway lines typical of North American freight and shared passenger corridors. Through a better understanding of the potential capacity and performance benefits of advanced PTC across a range of route infrastructure and traffic conditions, railway practitioners can make more informed investment decisions regarding advanced PTC with moving blocks and line capacity expansion projects. It is hypothesized that under certain route infrastructure and traffic conditions, advanced PTC with moving blocks may be a more economical approach to increase capacity compared with investment in additional second main track infrastructure.

To achieve this goal, this paper aims to address three specific research questions:

- For a given level of service and traffic composition, what is the capacity benefit for transitioning from three-aspect and four-aspect block signals to moving blocks on corridors with single track or various amounts of second main track?
- For a given level of service, and traffic composition, how much less route infrastructure is required to provide the same capacity with moving blocks as compared with three-aspect and four-aspect block signals?
- For a given route infrastructure and traffic composition, is the capacity of moving blocks more or less sensitive to changes in the required level of service compared with three-aspect and four-aspect block signals?

To answer these questions, simulation experiments are conducted to determine the train delay for various combinations of traffic volume and traffic composition on a representative single-track rail corridor as it transitions from single track with passing sidings to full two main tracks under three-aspect, four-aspect, and moving-block control systems.

Rail Traffic Controller

The train delay response for each experiment scenario described in the methodology section is determined via Rail Traffic Controller (RTC) simulation software. RTC is a rail traffic simulation software widely used in the rail industry, including, but not limited to, Amtrak, Class I railroads, and consultants. RTC simulates dispatcher decisions in guiding trains along specific routes to resolve meet and pass conflicts. General RTC model inputs include track layout, signaling, curvature, grades, train characteristics, and so forth.

In summer 2017, the capabilities of RTC were expanded to include simulation of advanced PTC with moving blocks. Previously, RTC did not have this capability and researchers and practitioners had to adopt other qualitative and quantitative approaches to estimate the benefits of moving blocks relative to existing wayside signal systems. With moving block capability within RTC, researchers and practitioners can now directly compare the performance and capacity of moving blocks

Table 2. Route Infrastructure Parameters for All Scenarios

Parameter	Characteristic
Route length	242 mi
Maximum authorized speed	50 mph freight, 79 mph passenger
Passing siding length	2 mi
Initial passing siding spacing	10 mi (on center)
Two main track crossover spacing	10 mi
Amount of two main tracks	varies
Traffic control operating protocol	varies

with three-aspect and four-aspect block signal systems. The research presented here is one of the first academic studies to apply this new RTC capability to better quantify the benefits of advanced PTC with moving blocks.

Methodology

All of the simulation scenarios share certain baseline route infrastructure and train parameters. The baseline route infrastructure is designed to be representative of North American infrastructure and operating conditions (Table 2). The baseline route consists of 242 mi of single-track mainline with terminals at each end and passing sidings spaced at 10-mi intervals. As described in the following section, for different experiment scenarios, the baseline route infrastructure is modified by connecting passing sidings to form segments of two main tracks. On extended segments of two main tracks, universal crossovers are located every 10 mi. The type of traffic control system is varied according to the experiment design.

Rail traffic on the simulated corridor is composed of regional intercity passenger trains, premium intermodal trains, and unit coal trains. The specific train consists are designed to be representative of typical North American freight and shared rail corridor operations (Table 3).

A limitation of this approach to line capacity is that the simulated mainline corridors do not explicitly capture the effects of yard and terminals. In practice, the resources required to process outbound trains and time required to line turnouts can limit the ability of trains to depart terminals at minimum headways and reduce the potential benefits of moving blocks.

Experiment Design

The experiment design includes four variable factors: traffic control system, percentage of second main track, traffic volume, and traffic composition. Each factor was simulated over a range of values or "levels" (Table 4) in a full-factorial design. Simulating all factorial combinations of the experimental factors was necessary to capture the non-linear response of train delay and to ensure

Table 3. Train Parameters and Characteristics

Parameter	Intercity passenger train	Premium intermodal train	Unit coal train
Locomotive power (hp)	3,200	4,380	4,380
Locomotives per train	2	4	3
Number of railcars	10	80	105
Train length (feet)	816	5,893	6,520
Train weight (tons)	655	6,936	14,280
Schedule flexibility (+ /- minutes)	720	720	720
Average RTC priority assignment	8,000	6,000	3,000

Table 4. Experiment Design Factor Levels

Experiment design factor	Number of levels	Level specification
Traffic control operating protocol	3	Three-aspect centralized traffic control (CTC), Four-aspect CTC, moving-block PTC
Amount of second main track on the corridor (%)	5	19.7 (dense single track), 40, 59.8, 80, 100 (full two main tracks)
Traffic volume (trains per day)	3	36, 48, 60
Traffic composition	4	Bulk Freight: 25% intermodal and 75% unit Even Freight: 50% intermodal and 50% unit Bulk Shared: 4 passenger plus 25% intermodal, and 75% unit Even Shared: 4 passenger plus 50% intermodal, and 50% unit

sufficient resolution to transform average train delay into estimates of line capacity.

The experiment compares the performance and capacity of three traffic control systems (or operating protocols): Centralized Traffic Control (CTC) with three-aspect wayside block signals, CTC with four-aspect wayside block signals, and advanced PTC with moving blocks. Each simulation scenario uses one of the three traffic control systems over the entire length of the corridor. The three-aspect wayside block signals are spaced at a block length of 2 mi. The four-aspect wayside block signals are spaced at a block length of 1 mi with every second signal corresponding to the same signal locations as the three-aspect system. The advanced PTC with moving blocks scenarios eliminates wayside signals.

The percentage of a second main track is the ratio of total length of second main track, including passing sidings, to the total length of the corridor, expressed as a percentage. The higher the percentage, the greater the length of second main track available for trains to meet and pass. It is hypothesized that the reduced headway of moving blocks will have a greater capacity benefit where there is a greater percentage of second main track. With additional second main track infrastructure, capacity is governed less by the pattern of meets at passing sidings and more by overtakes because of differences in train speed and priority that are related to train headway (*24*).

To achieve different factor levels of percent second main track, the initial dense single-track infrastructure at 10-mi spacing (corresponding to factor level 19.7% second main track) was incrementally expanded by adding sections of second main track connecting existing passing sidings. Connection of the passing sidings into double-track segments followed the "alternate" double-track allocation strategy outlined by Sogin (*24*). The second main track was built out in both directions from five points along the corridor until the whole route had two main tracks. Crossovers in each newly built double-track segment were placed at one end of the original passing siding, leading to crossovers spaced every 10 mi.

Multiple traffic volumes must be simulated to transform the resulting train delay into line capacity at a given level of service (maximum allowable train delay). The experiment design includes three traffic volumes: 36, 48, and 60 trains per day. The initial train plan includes evenly spaced train departures during each 24-h period. To represent North American operations with schedule flexibility, RTC randomly departs each train according to a uniform distribution extending 12 h before and 12 h after its planned departure time. Train departures are directionally balanced between the two end terminals (which have unlimited capacity). The traffic volumes are representative of typical North American rail corridors and produce reasonable train delay results across track infrastructure layouts ranging from single track with passing sidings to full two main tracks. The results can also illustrate interactions between traffic volume and the capacity benefits of moving blocks. It is hypothesized that moving blocks will have a greater benefit at higher traffic volumes where trains spend more time travelling at closer headways.

To investigate possible interactions between capacity benefits and traffic mixture, the experiment design contains four different traffic compositions. Two traffic mixtures represent freight-only corridors: "Bulk Freight" with 75% unit trains and 25% intermodal trains, and "Even Freight" where the traffic volume is evenly split between intermodal and unit trains. The other two traffic mixtures represent shared corridors. "Bulk Shared" includes four passenger trains per day and the remaining traffic volume composed of 75% unit trains and 25% intermodal trains. For example, at 36 trains per day, "Bulk Shared" includes four passenger trains, 24 unit trains and eight priority intermodal trains. "Even Shared" includes four passenger trains per day and the remaining traffic volume evenly split between intermodal and unit trains. Varying the proportion of slower unit trains to passenger and intermodal trains changes the level of interference caused by differences between train types; this process allows the study to consider both lines that are dominated by freight traffic and lines that are dominated by passenger traffic. One hypothesis is that scenarios with less train heterogeneity are more likely to have homogeneous train fleets that benefit from the shorter headways of moving blocks. An alternative hypothesis is that scenarios with more train heterogeneity will feature more complex operations with train conflicts that are more efficiently resolved with moving blocks.

Analysis

The primary output of the RTC simulations is train delay. In North America, under freight operations with schedule flexibility, train delay for a particular train is defined as the difference between its minimum running time and its actual running time. The minimum running time is the time required for a train to traverse the corridor with no stops for meets or conflicts with other trains, while obeying all maximum authorized speeds and considering the acceleration and braking capabilities of the train. The actual running time includes the time the train is in motion and the time the train is stopped waiting for other trains or other unexpected sources of delay once the train departs its origin terminal. Train delay includes the time a train is stopped waiting for other trains. This is different from other international definitions of train delay where scheduled time spent dwelling in stations or for planned train meets is not considered as delay.

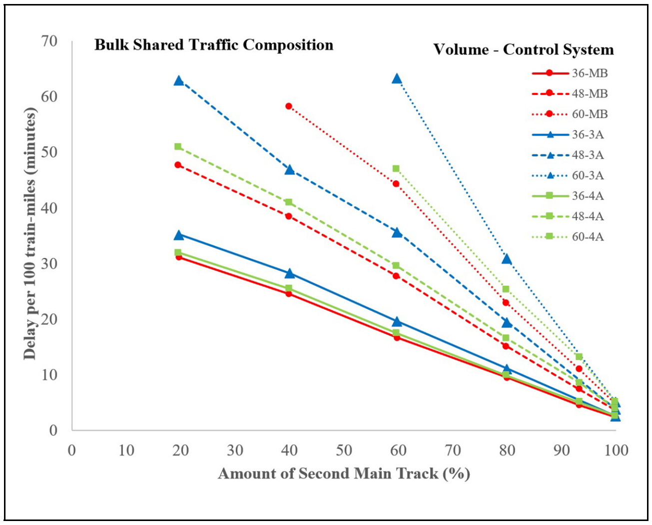

Figure 3. Comparison of train delay for different control systems across a range of percent second main track and traffic volumes for the Bulk Shared traffic composition.

To determine the train delay response, each unique combination of traffic volume, traffic composition, route infrastructure, and control system in the experiment design is simulated in RTC for five days of rail traffic. To allow for variation in train departure times, each simulation is replicated eight times, providing 40 days of train operations data. Each replication represents a specific departure time set by a uniform distribution around the baseline departure time in the train plan. Delay accumulated by individual trains during this 40-day period is averaged to determine the average train delay response associated with a given experiment design scenario and plotted as a single data point in the results.

Average train delay for scenarios with different traffic volumes can be used to calculate line capacity by setting a desired level of service (LOS) defined by a maximum allowable average train delay (*25*). Interpolating between simulated volumes and corresponding train delay values creates a delay-volume curve. The intersection of this curve with the required LOS corresponds to a traffic volume that defines line capacity in trains per day.

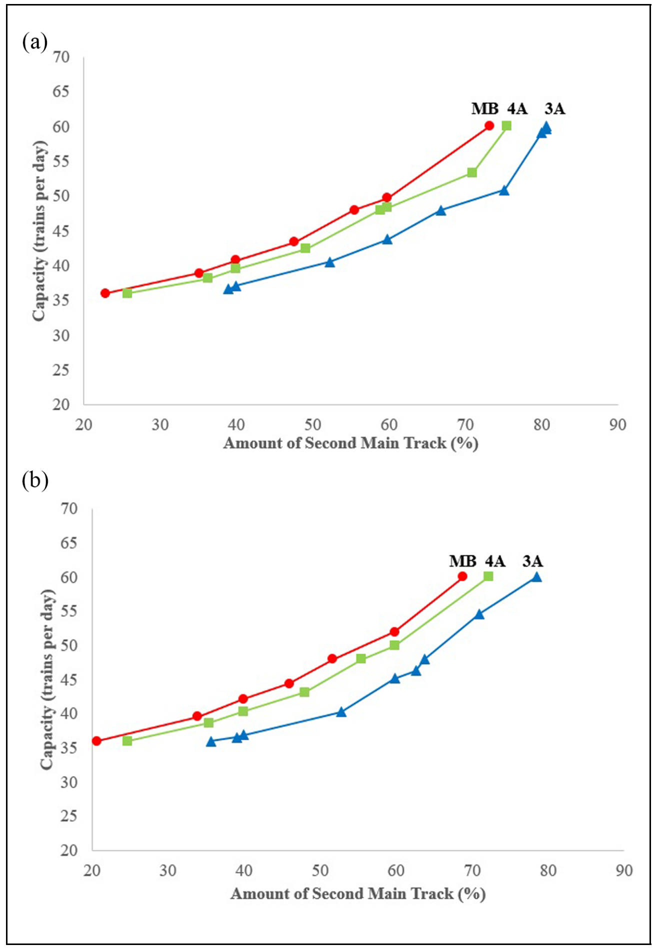

Figure 4. Line capacity as a function of control system and amount of second main track for (*a*) Bulk Shared and (*b*) Bulk Freight traffic compositions.

Results

Relative Performance and Capacity of Wayside Signals and Moving Blocks

Average train delay values for each control system at the three simulated traffic volumes show the expected linear decline with increasing amounts of second main track (Figure 3). As expected, the moving-block system consistently exhibits lower average train delay than either the three-aspect or four-aspect block signal systems. For a given amount of second main track, the delay reduction of transitioning from a three-aspect signal system to moving blocks can largely be achieved by implementing a four-aspect block signal system; the incremental benefit of transitioning from four-aspects to moving blocks is comparatively less than the incremental benefit of transitioning from three- to four-aspect block signal systems.

By setting a maximum allowable delay LOS of 30 min per train mile, the train delay response can be transformed into a relationship between line capacity, amount of second main track, and control system (Figure 4*a* and *b*). Changing the traffic control system to increase the number of aspects shifts the capacity curve to the left, increasing line capacity for a given amount of second main track. For Bulk Freight (Figure 4*b*) with 60% second main, line capacity is 45, 50, and 52 trains per day for three-aspect, four-aspect, and moving-block control systems respectively. This is equivalent to a 15% increase in capacity relative to three-aspect block signals and a 4% increase relative to four-aspect blocks signals.

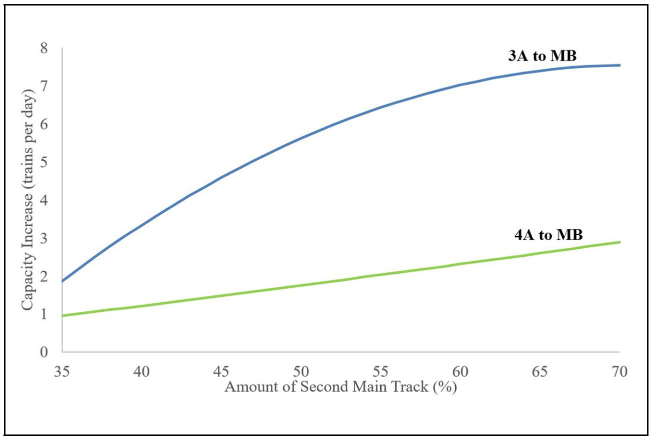

Figure 5. Line capacity gained by moving blocks relative to fixed-block signals across a range of second main track for Bulk Shared traffic composition.

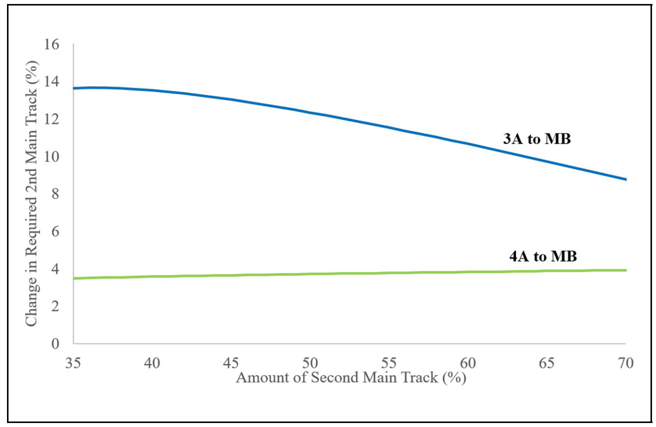

Figure 6. Second main track infrastructure saved by moving blocks relative to fixed-block signals for equivalent capacity across different levels of second main track and Bulk Shared traffic composition.

These percent increases in capacity for moving blocks on single track are much lower than the hypothetical homogenous double-track values presented in Table 1. As with train delay, the incremental benefit in transitioning from three- to four-aspect block signals is greater than the incremental capacity benefit in transitioning from four-aspect block signals to moving blocks.

Comparing the Bulk Shared (Figure 4*a*) and Bulk Freight (Figure 4*b*) results, there appears to be little change in the overall capacity benefits of moving blocks despite one scenario having the additional heterogeneity of four passenger trains. With respect to interactions between traffic composition and the incremental capacity benefit of moving blocks, the simulation results are inconclusive. Future work should simulate additional traffic scenarios with a greater proportion of passenger trains, such as a freight line that also hosts commuter traffic, to determine if traffic composition influences the capacity benefits of moving blocks.

Across the range of second main track where all three capacity relationships are defined, the absolute magnitude of the capacity benefit of moving blocks in trains per day continually increases as the amount of second main track increases (Figure 5). For the simulated conditions and 30-min LOS, advanced PTC with moving blocks increases capacity by one or two trains per day compared with four-aspect block signals and two to seven trains per day compared with three-aspect block signals. The general trend is that the capacity benefits of moving blocks are more apparent on corridors that have already seen large investments in second main track.

Infrastructure Savings of Moving Blocks

The horizontal distance between capacity curves in Figure 4 shows how much less second main track infrastructure is required to provide a given level of capacity with moving blocks compared with the fixed-block signal systems (Figure 6). Moving blocks consistently require less second main track infrastructure to provide a given amount of line capacity. For the Bulk Freight traffic composition, a line capacity of 48 trains per day requires 64%, 56% and 51% second main track for three-aspect, four-aspect and moving-block systems respectively. At this level of capacity, if transitioning from a three-aspect signal system, moving blocks eliminate the need to construct a second main track along 13% of the corridor (32 mi), and 5% of the corridor (12 mi) relative to four-aspect block signals. On longer corridors, the amount of track infrastructure saved would be proportionately greater. Since the incremental capacity benefit of each additional second main track segment increases as the amount of second main track increases, the infrastructure savings of moving blocks decreases as the corridor has more second main track.

Sensitivity of Moving Block Benefits to LOS

The observations presented in the previous subsections are all based on a required LOS of an average of 30 min of train delay across all train types. By examining the combinations of traffic volume and average delay that correspond to a given level of second main track infrastructure and traffic composition, the simulation data can be transformed to illustrate the relationship between required LOS and line capacity for different control systems (Figure 7). As the required LOS is relaxed (maximum allowable average train delay increases), the line capacity of all three control systems increases. With the steepest slope, the moving-block system shows the greatest sensitivity to the required LOS. At higher LOS,

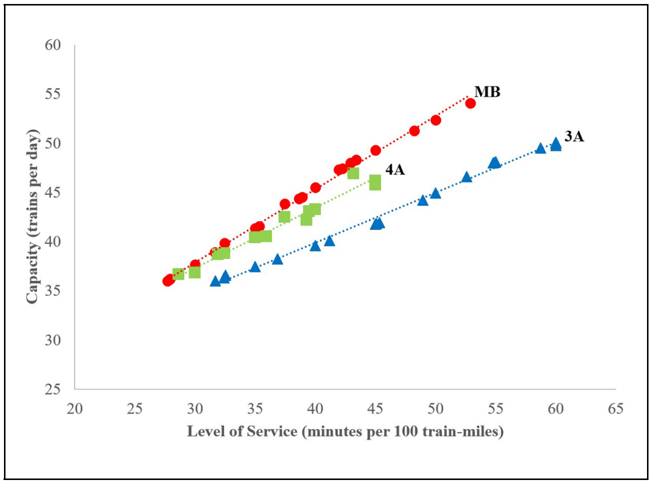

Figure 7. Sensitivity of line capacity of different traffic control systems to LOS for Bulk Shared traffic composition and 30% second main track.

moving block shows greater capacity benefits relative to the wayside signal systems. As the LOS decreases, there is relatively less difference in capacity between four-aspect block signals and moving blocks. This finding suggests that when the LOS is strict (low delay), capacity is largely constrained by the fundamental delays associated with train meets. These delays are largely unaffected by the reduced headways allowed under moving blocks, leading to less capacity benefit from implementing moving blocks. When the allowable LOS is higher, reductions in train delay from reduced headways appear to be more effective at increasing line capacity.

Conclusions and Future Work

On North American single-track freight and shared passenger corridors with heterogeneous train operations, advanced PTC with moving blocks consistently exhibits lower average train delay than either the three-aspect or four-aspect block signal systems. The incremental benefit of transitioning from four-aspects to moving blocks is comparatively less than the incremental benefit of transitioning from three- to four-aspect block signal systems. Across a range of corridors with different amounts of second main track, the absolute magnitude of the capacity benefit of moving blocks in trains per day continually increases as the amount of second main track increases. The capacity benefits of moving blocks are more apparent on corridors that have already seen large investments in second main track. Conversely, the infrastructure savings of moving blocks at a given capacity level decreases as the corridor has more second main track. Moving blocks are less effective at increasing capacity when the desired LOS is strict and corresponds to a low average train delay.

Future work should simulate additional traffic scenarios with a greater proportion of passenger trains, such as a freight line that also hosts commuter traffic, to clarify if traffic composition influences the capacity benefits of moving blocks. The research in this paper considered a corridor with level grades and uniform maximum authorized train speeds. When operating at high throughput volumes, grades and other speed restrictions may create shockwaves that ripple through the virtual and moving-block systems to limit the amount of time trains travel at close headways and reduce capacity benefits. Future research should investigate this phenomenon. Finally, this research simulates the same train departure plan and track configuration for both fixed- and moving-block control systems. Additional research is required to determine if there are certain train departure plans or track configurations that may particularly favor operation with moving blocks and show larger capacity benefits. Quantifying the benefits and costs of these different operating and infrastructure conditions may help practitioners better evaluate where to invest in advanced PTC with moving blocks.

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Author Contributions

The authors confirm contribution to the paper as follows—study conception and design: CTD, DM, GSR, T-YC; data collection: LEE, DM; analysis and interpretation of results: CTD, DM, GSR; draft manuscript preparation: DM, CTD. All authors reviewed the results and approved the final version of the manuscript.

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