Improving Railway Operational Efficiency with Moving Blocks, Train Fleeting, and Alternative Single-Track Configurations

Adrian Diaz de Rivera1, C. Tyler Dick1, and Leonel E. Evans1

Abstract
With installation of positive train control (PTC) on many U.S. rail corridors, Class I railroads may soon leverage these investments in communications network infrastructure to implement “advanced PTC” systems incorporating moving blocks. Train control with moving blocks can benefit operating strategies that dispatch fleets of multiple trains running at minimum headways. On single-track corridors with passing sidings long enough to hold multiple trains, fleeting may increase the efficiency of train meets, reduce train delay, and yield incremental capacity benefits. Alternative single-track configurations with fleet-length sidings at double the spacing of conventional single-train sidings can facilitate these operating strategies while minimizing additional track infrastructure and associated capital and maintenance costs. To investigate the operational synergies between moving blocks, fleeting, and longer but less frequent sidings, Rail Traffic Controller software is used to simulate and compare the delay performance of train operations on representative rail corridors for different combinations of fleeting strategy, train control system, siding configuration, and freight traffic composition. Operating fleets in conjunction with moving blocks produces the lowest overall train delay in specific cases of low schedule flexibility and heterogeneous traffic. With more efficient meets, moving blocks and/or fleeting primarily benefit low priority trains that typically wait for opposing traffic during train meets. Such incremental line capacity benefits have short-term financial consequences as they allow additional capital investments in double track to be deferred. Knowledge of train delay performance under moving blocks and fleeting will aid railway practitioners evaluating investments in advanced PTC systems and track infrastructure expansion.

Positive train control (PTC) is a “system designed to prevent train-to-train collisions, over-speed derailments, incursions into established work zone limits, and the movement of a train through a switch left in the wrong position” (1). In the U.S.A., PTC is mandated on most railway mainlines where passenger services operate or hazardous materials are transported, covering 54,000 route-miles of track. All Class I railroads expect to fully implement PTC by the end of 2020 at a cost of over $10 billion (2).

Many different train control technologies and architectures can satisfy the legal requirements of PTC. The North American rail industry is implementing an overlay-type system that enforces movement authorities granted by existing control systems through track warrants or wayside signals and centralized traffic control. PTC systems consist of three main elements: (i) a locomotive onboard system that monitors train location, calculates train-specific braking distance, and automatically stops the train before violating movement authority or other restrictions; (ii) a wayside system that transmits track signal, track circuit, and switch status to the onboard system; and (iii) a back office server integrated with the network operations center that stores information such as speed restrictions or movement authorities and communicates with the onboard system (2). A robust digital communications link is required to transmit information between the three elements. Precise train location, direction, and speed information are provided by GPS signals, inertial locomotive navigation systems, and/or transponders in the track (3–5). Once fully implemented, PTC technology may provide the foundation for a number of efficiency improvements railroads are actively investigating, such as one-person crews, moving

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blocks, autonomous trains, or the elimination of existing wayside signals (6, 7).

**Advanced PTC**

Installation of a robust communications and systems infrastructure across the North American rail network, along with train location systems onboard locomotives, provides the opportunity for future upgrades to “advanced PTC” control systems with virtual or moving blocks, also known as “PTC 2.0.” Throughout its development, PTC has been described as having both safety and business benefits (8). However, as currently implemented, PTC systems are primarily safety overlays on existing fixed block control systems with limited business benefits. Advanced PTC systems promise both to improve safety and to increase line capacity on existing track infrastructure, primarily by increasing the availability and accuracy of operational and train location information, and reducing the minimum separation required between trains (9).

Existing signalized train control systems maintain train separation by dividing track segments into a series of fixed control blocks that can usually only be occupied by one train at a time. Wayside signals at the entrance to each block communicate information about block occupancy to the train crew with varying indications progressing from stop to clear. Block lengths are set for braking characteristics of a design train, which is typically the train with the poorest braking performance that is expected to operate regularly over the line. If a train requires significantly shorter braking distance than the design train, it must still maintain the same fixed separation distance from occupied track ahead. Block occupancy information is only available at discrete points (i.e., where wayside signals are located). At these locations, the presence of a train ahead is communicated to the train crew, but no information is provided on how close that train may be to clearing a signal block. Because of this uncertainty regarding when upcoming blocks will clear, the train crew must maintain more separation between themselves and the train ahead than is physically necessary to ensure safety.

Adding an aspect to the primary signal progression, such as transitioning from “3-aspect” to “4-aspect” signals, addresses some inefficiencies of fixed blocks. The additional indication provides flexibility for trains with different braking characteristics, allowing a train to proceed past an advance warning signal (such as advance approach) at maximum authorized track speed if the train requires less braking distance than the design train. Generally, increasing the number of aspects reduces block size, decreases minimum train separation, and may increase capacity by more closely matching block length to train length and train-specific braking characteristics. In advanced PTC systems with moving blocks, there are no fixed block boundaries, and the number of aspects is theoretically infinite since the boundaries of a train’s movement authority are customized to the train’s length, its predicted absolute braking distance, and a margin of safety. Using a train’s real-time location, the movement authority boundaries constantly update to define a “moving block” protecting the train as it travels along the mainline. In simple cases, moving blocks can reduce minimum train distance headways by as much as 50% below a 3-aspect fixed block control system, and 33% below a 4-aspect system (9). On mainline railways in Europe, implementation of European Train Control System (ETCS) Level 3, a moving block system, has been shown to increase line capacity by 35% to 40% over ETCS Level 1, which is a safety-focused system overlaid on existing fixed block signals (10).

Advanced PTC systems can take advantage of these headway benefits to increase line capacity without expanding track infrastructure. Such systems may also allow existing wayside block signals, and their associated maintenance costs, to be eliminated. However, advanced PTC requires more sophisticated and reliable communications and network capabilities than those being implemented for overlay-type PTC systems. The additional investment in advanced PTC must be justified by the potential business benefits resulting from decreased train headways and greater train location data availability, resolution, and accuracy.

**Train Fleets**

Fleets of trains are groups of two or more trains with similar performance characteristics moving in the same direction at minimum headways. When trains operate in fleets on single-track, opposing traffic must wait for the entire fleet to pass before proceeding. Since North American freight rail operations do not follow a preplanned timetable with prescribed train meets and overtakes, trains are often fleeted on an ad hoc basis by dispatchers managing congested train corridors. For example, on lines with large amounts of double track, a dispatcher may successively route several trains operating in the same direction over a single-track section before allowing trains to proceed in the opposite direction. Another case is fleets of trains traversing a congested urban rail network or freight terminal with numerous traffic conflicts. Fleet operations clear train queues caused by capacity bottlenecks in these cases. Similarly, holding freight trains outside urban areas to avoid peak periods of commuter rail operations can create train fleets.
Besides operational convenience, there may be fundamental capacity and performance benefits to operating trains in fleets on single-track corridors with long passing sidings. Fleeting may be able to resolve meet conflicts more efficiently along a particular corridor. For example, consider a meet between two fleets, each composed of two trains. At a location with a long siding, the four trains can pass each other in a single interaction. Had the trains been dispatched individually, four separate train meets must occur. Separate meets create inefficiencies because there is a fixed delay imposed by each meet regardless of the number of trains involved (11). For the lower-priority train, each meet requires the train to brake, enter the siding, and clear the main track before the higher-priority train arrives. Once the higher-priority train has passed, the lower-priority train waits for the relevant signal instruments to line a route before exiting the siding and accelerating back to track speed. With two-train fleets, each lower-priority train experiences one fewer braking and acceleration cycle than when each opposing train is met separately. However, this reduction in acceleration and braking delay may be offset by the additional time the lower-priority train must wait to account for the time separation between the two higher-priority trains being met. Since moving blocks reduce time headways within fleets, this trade-off is minimized, and there are potential synergies between advanced PTC systems and fleet operations on corridors with single or partial double track.

Fleets, especially when used in conjunction with virtual or moving blocks, can also be used to mitigate loss of capacity because of temporary track outages, speed restrictions, or delays (12). In these cases, there will likely be a queue of trains waiting to traverse a slow-speed single-track section. While fleeting is possible under fixed block wayside signals, there is a fixed minimum train separation regardless of actual traffic speed and train braking characteristics. Trains often must maintain unnecessarily long headways since the signal spacing is designed for a poorly performing train operating at maximum authorized track speed. Under moving blocks, trains operate at headways appropriate for actual operating speed and braking characteristics, and fleeting is more effective for recovering from disruptions (13).

To operate fleets in both directions for the length of a single-track mainline corridor, passing sidings must be long enough to accommodate entire fleets. Otherwise, when two fleets meet, the lower-priority fleet must be broken up and accrue delay waiting for the higher-priority fleet in two separate sidings (14). Once the trains in a fleet become separated, any benefits of fleets at minimum headways are lost for all subsequent meets involving those trains. In an effort to take advantage of the economies of scale offered by increasing train lengths, many Class I railroads are actively lengthening sidings and constructing new longer sidings on single-track mainlines (15). In addition to accommodating longer trains, such sidings could be used to hold fleets of shorter trains for meets and passes. To improve operational flexibility, certain railroads have also installed double-length “super sidings” with mid-siding crossovers that are ideal for meeting two-train fleets (16). Although there are many practical, engineering, environmental and physical constraints that may prevent a particular siding from being extended to accommodate fleets, previous research on operation of over-length trains that exceed the length of passing sidings suggests that fleets can be operated efficiently while only extending a fraction of the passing sidings along a corridor (17, 18).

**Previous Research**

Dick et al. examined the relative capacity benefits of moving blocks in the North American freight railway context by simulating and comparing operations under fixed and moving block control systems across various combinations of traffic volume, traffic composition, and percent second main track (9). Operations under moving blocks exhibited consistently lower average train delay than those under fixed block signals. Moving blocks demonstrated the greatest benefit on lines with a high proportion of double track where headway controls capacity. This study advances this previous work by considering additional factors including train fleeting strategies, different single-track infrastructure configurations, and schedule flexibility. Dick also developed simple formulas to calculate capacity of a single-track railway line with passing sidings for bulk unit freight trains dispatched individually and in fleets (19). Operating fleets under fixed blocks with sidings long enough to hold two trains was found to increase capacity slightly over dispatching trains individually. Fleeting trains under moving blocks resulted in almost 50% greater capacity than fleeting trains under fixed blocks. A primary factor was that moving blocks effectively decrease the length of passing siding required to allow a running meet where trains do not stop.

Dingler et al. used similar simulation methods to investigate the root causes of train delays on a typical North American freight rail corridor, finding meets to be the leading cause of delays (20). While time stopped accounted for the greatest proportion of meet delays, braking and acceleration cycles also contributed significantly to delay. Higher levels of traffic heterogeneity were associated with more complex conflicts and inefficient meets. Gorman performed statistical analysis on data from a Class I railroad to determine the factors contributing to congestion-related delay, identifying train
conflicts such as meets and passes as primary contributors (21).

Various researchers have examined the potential for virtual coupling, which would allow trains to operate in platoons at very short headways based on relative braking distances, to increase capacity (22, 23). Virtual coupling can decrease minimum distance headways by 66% compared with a moving block system conforming to ETCS Level 3. One prerequisite for virtual coupling is automatic train operation, which is currently being developed and implemented on mainline passenger and freight railways (24, 25). Both virtual coupling and partially or fully automated trains would substantially boost the effectiveness of fleeting trains on mainline corridors. To control the experimental factors and provide a more basic comparison of fleeting strategies in a typical heavy-haul freight rail operating environment, however, this study only considers driver-operated trains controlled by fixed and moving block control systems.

Research Questions

This research aims to investigate the potential for synergies between advanced PTC, planned fleeting of trains, and track configuration to improve delay performance and line capacity of a typical North American Class I mainline corridor. To accomplish this goal, this paper addresses the following research questions:

- How do different train fleeting strategies under fixed and moving block control systems on alternative single-track configurations with less frequent but longer fleet-length passing sidings affect train delay performance?
- Are the benefits of certain combinations of control system, fleeting strategy, and siding configuration sensitive to traffic composition and schedule flexibility?

Methodology

This research conducts simulation experiments to determine train delay responses for various factorial combinations of fleeting strategy, track configuration, traffic composition and schedule flexibility on a representative single-track rail corridor with passing sidings under 4-aspect fixed block and moving block control systems.

Rail Traffic Controller

The train delay response for each experimental scenario described in subsequent sections is determined using Rail Traffic Controller (RTC) simulation software. RTC is a railway traffic simulation software used by most passenger and Class I freight railways, consultants and rail capacity researchers in North America (26). RTC simulates train movements on mainline rail corridors by emulating realistic real-time decisions made by train dispatchers to resolve train conflicts according to North American train control systems and operating practices. General RTC model inputs include track layout, signaling, train plan, train characteristics, and grade. In 2017, the developers of RTC added the capability for RTC to simulate rail corridors operating under moving block control systems. This research takes advantage of this new detailed simulation capability to investigate the operational effects of dispatching trains in fleets on different track configurations under fixed and moving block control systems.

Study Parameters and Experiment Design

Simulation experiments considered a 242-mi single-track mainline with passing sidings intended to be representative of a typical North American Class I freight rail corridor (Table 1). While the distribution of passing sidings changed according to the experiment design, the total number of track-miles, including 50 mi of siding track, remained constant at 292 mi. Keeping track-miles constant minimizes differences in track maintenance costs between scenarios, along with the construction cost to build-out a new corridor or significantly upgrade an existing corridor with insufficient passing sidings. For scenarios where a fixed block control system was used, the signal block length was set at 1 mi.

Rail traffic on the freight-only study corridor consists of 48 trains per day in total, divided between intermodal and unit coal trains (Table 2). These two train types were chosen for their ubiquity on North American railways and significant performance differences. Intermodal trains are generally shorter and lighter than unit coal trains, with better braking and acceleration characteristics. Trains were dispatched with an even directional split. The baseline train plan includes train departures evenly distributed throughout the day, and every train traverses the entire corridor without planned stops.

The experiment design includes five variable factors: train control system, siding infrastructure configuration, general RTC model inputs include track layout, signaling, train plan, train characteristics, and grade. In 2017, the developers of RTC added the capability for RTC to simulate rail corridors operating under moving block control systems. This research takes advantage of this new detailed simulation capability to investigate the operational effects of dispatching trains in fleets on different track configurations under fixed and moving block control systems.

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fleeting strategy, traffic composition, and schedule flexibility. Each factor was simulated over a range of values or “levels” (Table 3) in a fractional-factorial design. A fractional-factorial design was used to reduce the scope of the simulation experiment and eliminate combinations of factors not of primary interest given the research questions.

Two train control systems enabling different minimum headways within fleets are examined for all combinations of other factors: centralized traffic control (CTC) with 4-aspect wayside block signals, and advanced PTC with moving blocks. Four-aspect CTC represents one of the best performing conventional fixed block train control systems widely adopted across the North American rail network. Each simulation scenario uses one control system for the entire corridor. It is hypothesized that fleeting trains under moving blocks will perform better than under fixed blocks or without fleeting.

This study examines the feasibility and effectiveness of three different fleeting strategies: no fleets (all trains dispatched individually), trains dispatched as two-train fleets in one direction, and trains dispatched as two-train fleets in both directions. The RTC dispatching logic was set to favor keeping fleets together and trains in fleets were dispatched together for the relevant scenarios. However, any individual fleet could be broken up depending on the specific sequence of train conflicts encountered. Larger fleets of more than two trains could also be formed en route. The three fleeting strategies are supported by two different siding infrastructure configurations: 2-mi long sidings located every 10 mi capable of holding one train, and 4-mi long sidings located every 20 mi capable of holding a two-train fleet.

Examining the first three experiment design factors reveals four primary operating scenarios of interest where the siding infrastructure matches the fleeting strategy, resulting in substantially different train meet sequences (Figure 1). This experiment focuses on these four primary scenarios:

- 4-aspect fixed block signals, 2-mi sidings every 10 mi, trains dispatched individually (4A 2 × 10 No Fleets) (Figure 1a)
- Moving blocks, 2-mi sidings every 10 mi, trains dispatched individually (MB 2 × 10 No Fleets) (Figure 1b)
- 4-aspect fixed block signals, 4-mi sidings every 20 mi, trains dispatched in fleets (4A 4 × 20 Fleets) (Figure 1c)
- Moving blocks, 4-mi sidings every 20 mi, trains dispatched in fleets (MB 4 × 20 Fleets) (Figure 1d)

Different traffic compositions are included to investigate the effect of heterogeneity and relative train characteristics on the ability of fleeting, advanced PTC, and track configuration to improve performance. The Fast Freight case consists of 75% intermodal trains, the Even Freight case has equal numbers of intermodal and unit coal trains, and the Heavy Freight case is 75% unit coal trains. Cases with higher proportions of intermodal trains are expected to perform better than cases with more unit coal trains since the intermodal trains are able to execute train meets more efficiently.

North American freight railways generally do not operate to strict timetables (27, 28). Instead, trains have some amount of schedule flexibility where a train may be

### Table 2. Train Parameters and Characteristics

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Intermodal train</th>
<th>Unit coal train</th>
</tr>
</thead>
<tbody>
<tr>
<td>Locomotive power (hp)</td>
<td>4,380</td>
<td>4,380</td>
</tr>
<tr>
<td>Locomotives per train</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>Number of railcars</td>
<td>80</td>
<td>105</td>
</tr>
<tr>
<td>Train length (feet)</td>
<td>5,250</td>
<td>6,520</td>
</tr>
<tr>
<td>Train weight (tons)</td>
<td>9,680</td>
<td>14,280</td>
</tr>
<tr>
<td>Hp per ton</td>
<td>1.81</td>
<td>0.92</td>
</tr>
<tr>
<td>Average RTC priority assignment</td>
<td>6,000</td>
<td>3,000</td>
</tr>
</tbody>
</table>

*Note: RTC = Rail Traffic Controller.*

### Table 3. Experiment Design Factor Levels

<table>
<thead>
<tr>
<th>Factor</th>
<th>Levels</th>
<th>Level specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Train control system</td>
<td>2</td>
<td>4-aspect CTC with fixed blocks (4A)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Advanced PTC with moving blocks (MB)</td>
</tr>
<tr>
<td>Siding infrastructure config</td>
<td>2</td>
<td>2-mi sidings every 10 mi (2 × 10)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4-mi sidings every 20 mi (4 × 20)</td>
</tr>
<tr>
<td>Fleeting strategy</td>
<td>3</td>
<td>No fleets</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Two-train fleets in one direction (EB Fleets)*</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Two-train fleets in both directions (Fleets)</td>
</tr>
<tr>
<td>Traffic composition</td>
<td>3</td>
<td>Fast freight: 75% intermodal, 25% unit</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Even freight: 50% intermodal, 50% unit</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Heavy freight: 25% intermodal, 75% unit</td>
</tr>
<tr>
<td>Schedule flexibility</td>
<td>3</td>
<td>Low: ≤ 10 min</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Medium: ≤ 60 min</td>
</tr>
<tr>
<td></td>
<td></td>
<td>High: ≤ 360 min</td>
</tr>
</tbody>
</table>

*Note: EB = eastbound. CTC = centralized traffic control; PTC = positive train control.*

*Two-train fleets in one direction is not included in the primary experiment design.
dispatched earlier or later depending on a range of factors such as crew and equipment availability, network congestion, lading availability, and yard and terminal operations. Since train meets and other conflicts are not typically planned, increasing schedule flexibility has been shown to be detrimental to mainline performance and capacity (28, 29). To determine how this schedule uncertainty may influence the four primary scenarios of interest, three levels of schedule flexibility are included in the experiment design: "Low" with +/– 10 min of schedule flexibility, "Medium" with +/– 60 min, and "High" with +/– 360 min of flexibility. The amount of schedule flexibility defines the period of time around the planned train departure time over which trains (or fleets) randomly depart. For example, if a train is planned to depart at 9:00 a.m. with 60 min of schedule flexibility, on a given day of a particular simulation, the train will randomly depart between 8:00 a.m. and 10:00 a.m. according to a random uniform distribution. All train plans are randomized outside RTC to ensure that, for scenarios with fleets, once the departure of the first train is randomized, the second train in the fleet departs at a 6-min headway under fixed blocks and 4-min headway under moving blocks. No scenarios with zero minutes of flexibility (i.e., structured schedules) were examined in an effort to overcome potential biases in the baseline schedules.

**Analysis and Hypothetical Relationships**

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 whether the conflict is planned or not. Average train delay can be used to estimate capacity, with several Class I railroads using 60 min of average train delay per 100 train-miles as an indicator of a line operating at capacity.

For each scenario in the experiment design, 30 simulation seeds were generated. Each seed 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 recorded for each simulation. In cases where RTC determined a particular seed of a scenario was infeasible, the relevant seed was also deemed invalid. Since invalid cases likely represent the worst-performing replicates of each scenario, the 10 seeds with the highest average train delay from each scenario were discarded, including any invalid seeds. Scenarios with more than 10 invalid seeds were deemed invalid overall. Finally, at a p-value of 0.05, confidence intervals were calculated to represent the variation in average train delay for the remaining 20 replicates.

Four hypothetical average train delay distributions for the four primary scenarios were developed for possible experimental results. The control outcome is no significant improvements even with fleeting and moving blocks (Figure 2a). Based on previous research (9, 10), it is expected that moving block implementation will provide an incremental delay benefit relative to fixed blocks (Figure 2b). Fleeting trains can also affect corridor performance depending on a large number of factors including train length, traffic heterogeneity, train braking characteristics, traffic level, and maximum authorized track speed. There is likely a threshold factorial combination beyond which fleeting trains produces significant overall benefits by reducing delay (Figure 2c).

Below this threshold, particularly when combined with fixed block signals, fleeting could produce increased train delay (Figure 2d).

![Figure 1](image_url)
Results

Average train delay values and 95% confidence intervals for each operating scenario were determined from RTC simulation outputs and grouped by level of schedule flexibility. 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, poorly performing scenario.

Primary Scenario Delay Response

For the Even Freight traffic mixture, the worst-performing scenario operated under 4-aspect CTC without fleets on 2-mi sidings spaced every 10 mi (4A 2 × 10 No Fleets) (Figure 3). Consistent with past research (28, 29), increasing schedule flexibility produced increases in average train delay. At low schedule flexibility, the delay distribution shows benefits from both moving blocks and fleets. At high flexibility, results show benefits from moving block implementation only, largely because the moving block with fleets scenario degrades quickly with increasing schedule flexibility. One possible explanation is that since the fleets consist of two trains departing together, as schedule flexibility increases, there is a greater likelihood of a large number of trains clustering at specific times to create complex train conflicts.

Figure 2. Hypothetical delay distributions for the primary operating scenarios depicting: (a) no delay benefits from moving blocks or fleets, (b) delay benefits from moving blocks only, (c) delay benefits from both moving blocks and fleets, and (d) disbenefit of fleets.
In contrast, under moving blocks with the $2 \times 10$ siding configuration and no fleets (MB $2 \times 10$ No Fleets), flexibility has a much less pronounced effect. The combination of more frequent sidings and moving blocks is more capable of handling traffic peaks caused by schedule flexibility. Generally, for the *Even Freight* traffic mix, the fixed block scenarios performed the same or worse than the moving blocks scenarios, building on previous findings that moving blocks allow for reduced train delay on existing infrastructure (9).

Examining the *Even Freight* results by train type suggests that intermodal trains (Figure 4a) have a different response to the various experimental scenarios than unit coal trains (Figure 4b). Unit trains incur significant delay in the 4A $2 \times 10$ No Fleets scenarios while intermodal trains generally have the lowest delay for the same scenarios. Unit train delay appears to be more sensitive to changes in control system and fleeting strategy than intermodal train delay. At a low level of schedule flexibility, fleeting and moving blocks benefit unit trains but do not improve the performance of intermodal trains. To understand this result, consider that the leading cause of delay on single-track routes is time spent stopped in sidings for meets with higher-priority trains (20, 30). If a network is capacity-constrained, train meets tend to take longer, and the priority of a train has a much greater effect on its performance. The dispatcher will strongly favor higher-priority trains in conflicts while tolerating greater delays for slower, lower-priority trains. This is likely the situation for the 4A $2 \times 10$ No Fleets scenarios which are expected to have the lowest line capacity (9).

By introducing fleets and moving blocks to the network, the train meet process becomes more efficient with less delay incurred by the stopped train. Since there is a lower penalty associated with each train meet, it becomes acceptable for the dispatcher to stop a higher-priority intermodal train for a small delay if the overall corridor efficiency is improved. Therefore, the lower-priority unit trains benefit significantly more from the introduction of fleets, moving blocks, or both, than the already high-performing intermodal trains.

The overall average train delay values for the *Fast Freight* traffic mix, dominated by intermodal trains, do not match any of the predicted delay distributions but do match the delay pattern for intermodal trains from the *Even Freight* traffic mix (Figure 5a). Correspondingly, the delay values for the *Heavy Freight* traffic mix, dominated by unit coal trains, follow the same pattern as the delay values for unit trains from the *Even Freight* traffic mix (Figure 5b). Overall, average train delay values increased for all scenarios as the traffic composition transitioned from more intermodal trains to more unit trains across all levels of schedule flexibility.

With the *Heavy Freight* mix (Figure 5b), the fleets scenarios performed similarly regardless of control system and were slightly better than the MB $2 \times 10$ No Fleets scenario at low levels of flexibility. A possible explanation is that unit coal trains are likely to be similar to the
design train used to set the lengths of signal blocks for the fixed block control system. Since the unit train braking distances more closely match the signal block lengths, the amount of excess fixed block train separation caused by a disparity between actual and design train safe braking distances is reduced, decreasing the incremental capacity benefit of moving blocks. Since the Heavy Freight traffic mix has a higher proportion of unit coal trains, the disparity between minimum headways under fixed blocks and moving blocks is lower.

Partial Fleeting

When trains were dispatched in two-train fleets in one direction, but individually in the other direction, the 4A $2 \times 10$ EB Fleets scenario has the highest overall train delay for the Even Freight traffic mix under medium (+/– 60 min) schedule flexibility (Figure 6). Examining the results by direction and train type reveals that both eastbound and westbound unit trains experience very high delays in this scenario. The 4A $2 \times 10$ EB Fleets scenario also has the highest delay values for eastbound intermodal trains but the lowest delay values for westbound intermodal trains. Since sidings cannot accommodate entire fleets, low priority unit train fleets have a high chance of breaking up en route (14). Meanwhile, high priority intermodal train fleets are likely to be routed nonstop through the corridor, imposing compounding delays on stopped trains. In a scenario with constrained capacity, intermodal trains are given strong preference in meet conflicts at the expense of very high delays for both individual and fleeted unit trains, consistent with previous findings (Figures 4a and b).

Implementing moving blocks improves the effectiveness of partial fleeting, leading to significant reductions in delay for fleeted eastbound trains and particularly large improvements for fleeted eastbound unit trains (Figure 6). For the same scenarios, westbound intermodal trains incurred significantly higher delays than in the 4A $2 \times 10$ EB Fleets scenario. One reason is that despite equal directional priorities, the fleeted eastbound direction generally receives preference in meet conflicts because it is more costly to hold or break up the fleet than to hold an individual westbound train. Looking at overall train delay results, the MB $2 \times 10$ EB Fleets scenario, which combines the flexibility of more frequent sidings with the benefits of fleets with moving blocks, performed the best.

A key benefit of partial fleeting is the ability to utilize existing siding infrastructure that is only capable of accommodating a single train. For medium (+/– 60 min) schedule flexibility, an Even Freight traffic mixture, and the same siding configuration, the overall results can be compared with the corresponding values from the primary 4A $2 \times 10$ No Fleets and MB $2 \times 10$ No Fleets scenarios. Partial fleeting under moving blocks results in
lower average train delay. Expanding the comparison, the MB 2 x 10 EB Fleets scenario produces lower average train delay than all four of the primary scenarios, including the MB 4 x 20 Fleets case (Figure 3). One reason is that when a fleet of trains must stop, the following train in the fleet incurs delay reacting to the braking and acceleration of the leading train. The two trains cannot operate perfectly in sync, introducing an inefficiency that is removed if the lower-priority trains operate independently as single trains. Therefore, in cases where traffic in one direction has significantly higher priority than opposing traffic, it may be an effective delay-reduction strategy to invest in moving blocks enabling fleted trains in the higher-priority direction while utilizing existing siding infrastructure.

Conclusions and Future Work

Past investments in PTC by North American railroads may soon be leveraged to implement advanced PTC with moving blocks. Moving blocks promise to reduce the minimum separation required between trains, allowing for new operational strategies such as fleeting trains through a corridor. When supported by track infrastructure that can accommodate train fleets, fleeting strategies that take advantage of the shorter headways made possible by moving blocks can improve corridor operational efficiency by reducing delays associated with the train meet process.

Results from RTC simulations indicate that fleeting trains under moving blocks at low levels of schedule flexibility can reduce overall average train delay for heterogeneous freight traffic. Fleeting trains is most effective when paired with sidings that can accommodate full fleets. With increasing schedule flexibility and increasing traffic homogeneity, implementing moving blocks without fleets can be a more effective strategy depending on the specific traffic mix. Low priority trains, such as unit coal trains, benefit the most from investments in moving blocks or fleeting since such improvements allow trains to spend less time waiting for higher-priority trains to pass during a meet. High priority traffic, such as premium intermodal trains, see minimal delay benefit since they are already given preference by dispatchers regardless of infrastructure configuration or control system. However, such treatment can come at the expense of high delays imposed on the lower-priority traffic. When supported by investments in moving blocks, alternative strategies such as operating trains in fleets in one direction can produce average train delay values even lower than operating trains individually or in fleets in both directions. Such a strategy could utilize existing siding infrastructure and be implemented on corridors where traffic in one direction has higher priority.

Future work should conduct further simulations with different traffic mixes incorporating passenger trains and other types of freight traffic across a range of daily train volumes. Additional simulations would also help validate the effectiveness of the operating and infrastructure strategies presented in this work. Future work should also examine mainline corridor performance under virtual block control systems or with fleted high priority trains for different traffic compositions.

While moving blocks and fleeting can produce significant delay reductions over the baseline scenario with no fleets and fixed blocks, in all other comparisons, the differences in average train delay only range between 5 and 10 min per 100 train-miles. While it is possible to improve capacity incrementally through control system and train plan changes, track infrastructure imposes a fixed limit on the benefits of such improvements. With train fleeting, moving blocks, or both, short-term capacity improvements can lengthen the required timeline for expending scarce resources on track infrastructure construction such as additional passing sidings and double track. Understanding the feasibility and effectiveness of fleeting strategies under conventional fixed block control systems and advanced PTC systems with moving blocks, while maintaining a similar amount of track infrastructure and subject to operational schedule flexibility, can assist railroad practitioners developing long-term capital plans, train operating strategies, or methods for improving short-term capacity on single-track corridors. The results of this research can also inform railway operators considering investments in advanced control systems incorporating moving blocks. While the experiments conducted in this work are intended to be representative of North American operating environments and train characteristics, the positive results for scenarios with low levels of schedule flexibility indicate the general approach can be applicable to railways in Europe, Asia, or other locations where structured schedules for freight trains are standard.

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Author Contributions

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