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Relative Capacity and Performance of Fixed and Moving Block Train Control Systems

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TECHNICAL SUMMARY

Title

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Introduction

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. 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.

Approach and Methodology

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. 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. To see nothing but clear signals, the following train must remain at least three block lengths behind the end of the lead train. 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 and a 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. Similarly, a five-aspect signal system can further decrease train separation by sing block lengths equal to one-third of the braking distance.

Advanced PTC systems with virtual blocks subdivide existing wayside signal blocks into shorter virtual segments. Creating additional virtual blocks is equivalent to increasing the number of signal indications. 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. 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.

To investigate the potential benefits of these Advanced PTC systems with virtual and moving blocks, a series of experiments was conducted. 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 to investment in additional second main track infrastructure.

Experiment 1: Incremental Capacity of Moving Block Relative to 3 and 4-Aspect Systems

The first experiment aims to address three specific research questions:

- For a given level of service and traffic composition, what is the capacity benefit for transitioning from 3-aspect and 4-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 to 3-aspect and 4-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 to 3-aspect and 4-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 3-aspect, 4-aspect and moving block control systems. The train delay response for each experiment scenario is determined via Rail Traffic Controller (RTC) simulation software. The baseline route consists of 242 miles of single-track mainline with terminals at each end and passing sidings spaced at 10-mile intervals. For different experiment scenarios, the baseline route infrastructure is modified by connecting passing sidings to form segments of two main tracks. Rail traffic on the simulated corridor is composed of regional intercity passenger trains, premium intermodal trains and unit coal trains.

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" in a full-factorial design. 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. 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. 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. To investigate possible interactions between capacity benefits and traffic mixture, the experiment design contains four different traffic compositions involving different combinations of unit, intermodal and passenger trains.

Experiment 2: Moving Blocks with Train Fleets and Alternative Track Configurations

The second experiment 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?

To answer these research questions, RTC simulation experiments are conducted 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. Simulation experiments considered a 242-mile single-track mainline with passing sidings intended to be representative of a typical North American Class I freight rail corridor. While the distribution of passing sidings changed according to the experiment design, the total number of track-miles, including 50 miles of siding track, remained constant at 292 miles. Rail traffic on the freight-only study corridor consists of 48 total trains per day, divided between intermodal and unit coal trains.

The experiment design includes five variable factors: train control system, siding infrastructure configuration, fleeting strategy, traffic composition, and schedule flexibility. 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. 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 three fleeting strategies are supported by two different siding infrastructure configurations: 2-mile long sidings located every 10 miles capable of holding one train, and 4-mile long sidings located every 20 miles capable of holding a two-train fleet. 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. Finally, three levels of schedule flexibility are included in the experiment design: "Low" with +/-10 minutes of schedule flexibility, “Medium” with +/- 60 minutes, and “High” with +/- 360 minutes 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.

Experiment 3: Moving Blocks and Faster Train Meets

This experiment more closely examines the fundamental processes of a train meet and their relationship to fixed and variable components of meet delay to investigate the use of moving blocks and train fleets to minimize overall train delay. The specific research questions are:

- How do the fixed and variable components of the train meet process respond to changes in control system, fleeting strategy, maximum authorized speed, and train length?
- Does running trains in fleets of closely-following trains and/or under moving blocks reduce minimum delay associated with train meets relative to conventional practices?
- What are practical near-term strategies for reducing minimum train meet delays?

To address the research questions, a spreadsheet-based tool was developed to calculate minimum train meet delay for scenarios involving factorial combinations of train control system, fleeting strategy, and train length. RTC simulation software was used to validate the results of the spreadsheet for base combinations of experiment variables.

The analytical study considered track infrastructure parameters intended to be representative of a typical North American Class I freight railroad and assuming 0% grade and tangent track. The experiment design included four variable factors: train control system, fleeting strategy (and corresponding siding infrastructure configuration), train length, and maximum authorized operating speed. Three train control systems enabling different minimum headways within fleets were examined: centralized traffic control (CTC) with 3-aspect fixed block signals (“3A”), CTC with 4-aspect fixed block signals (“4A”), and advanced PTC with moving blocks (“MB”). Given the reduced minimum train separation and increased flexibility enabled by increasing the number of signal aspects, it was hypothesized that train meet delay would be highest under 3-aspect CTC and lowest under moving blocks. This experiment examined three different fleeting strategies: all trains dispatched individually (“No Fleets”), trains dispatched as two-train fleets in the superior direction only (“EB Fleets”), and trains dispatched as two-train fleets in both directions (“Fleets”). While train length was varied from 80 to 160 railcars, the power-to-weight ratio was kept consistent. Operating speeds ranged from a minimum of 16 mph, below which special restricted speed operating rules usually take effect, to a maximum of 79 mph, the maximum freight operating speed for most mainlines in North America.

Findings

Experiment 1: Incremental Capacity of Moving Block Relative to 3 and 4-Aspect Systems

Average train delay values for each control systems at the three simulated traffic volumes show the expected linear decline with increasing amounts of second main track. 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), the train delay response can be transformed into a relationship between line capacity, amount of second main track and control system. Changing the traffic control system to increase the number of aspects increases line capacity for a given amount of second main track. For one simulation scenario, moving blocks provide a 15-percent increase in capacity relative to three-aspect block signals and a four-percent increase relative to four-aspect blocks signals. These percent increases in capacity for moving blocks on single track are much lower than hypothetical homogenous double-track values. 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.

Moving blocks consistently require less second main track infrastructure to provide a given amount of line capacity. For one simulation scenario, a line capacity of 48 trains per day requires 64, 56 and 51 percent 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 percent of the corridor (32 miles), and 5 percent of the corridor (12 miles) 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.

The moving block system shows the greatest sensitivity to the required LOS. At higher LOS, 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.

Experiment 2: Moving Blocks with Train Fleets and Alternative Track Configurations

At low schedule flexibility, the delay distribution shows both a moving blocks and fleets benefit. 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. The combination of more frequent sidings and moving blocks is more capable of handling traffic peaks caused by schedule flexibility.

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. 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 and/or moving blocks than the already high-performing intermodal trains.

Implementing moving blocks improves the effectiveness of partial fleeting, leading to significant reductions in delay for fleeted trains. A key benefit of partial fleeting is the ability to utilize existing siding infrastructure that is only capable of accommodating a single train. 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 fleeted trains in the higher-priority direction while utilizing existing siding infrastructure.

Experiment 3: Moving Blocks and Faster Train Meets

For a "Long" train, different train control systems and fleeting strategies produced significantly different normalized meet delay responses as maximum authorized speed increased (Figure 3). For a given fleeting strategy, using CTC with 3-aspect fixed block signals generally resulted in the highest minimum meet delay while moving blocks resulted in the lowest.

For both 3-aspect and 4-aspect fixed block signals, the delay response curves took on a concave shape with an optimum maximum authorized speed producing the lowest meet delay. At lower speeds, block lengths became sub-optimal, causing inferior trains to wait longer for superior trains to pass. As speed increased, fixed delays caused by braking and acceleration times and distances increased as speed approached the balancing speed. In contrast, the moving block curves took on a more exponential shape with the lowest meet delay occurring at the lowest speeds, illustrating how moving blocks are always customized to specific train and operating conditions regardless of speed.

The effectiveness of fleeting trains was highly dependent on the minimum achievable headways between trains. At lower speeds, operating fleets under 3-aspect and 4-aspect fixed blocks resulted in inefficient meets since inferior trains had to wait for two slow-moving superior trains as well as the headway between them. At speeds above the optimum point, however, the slopes of the fixed block "Fleets" delay curves increased more slowly than the corresponding "No Fleets" curves. With train fleets, the higher fixed delays caused by higher speeds were distributed across multiple train conflicts, resulting in a more efficient meet process that overcame the impact of higher variable delays. Above certain speeds, these efficiencies caused the fixed block "Fleets" cases to produce lower meet delay than even the case with moving locks but no fleets. When the effectiveness of fleets was boosted by moving blocks, the result produced the lowest meet delay across all speeds.

Dispatching trains in fleets only in the superior direction (eastbound or EB in this study) removed one source of variable delays: fleet delays that extend the waiting phase of the meet process. A major benefit of fleeting high-priority trains in only one direction is that existing sidings can be utilized and do not have to be lengthened to accommodate fleets. A drawback of this arrangement is that the superior train fleet takes longer to pass than would be possible with a longer fleet-length siding. At higher speeds under moving blocks, it may be possible to maximize the effectiveness of conventional-length sidings by fleeting high-priority trains in one direction to improve meet efficiency.

Conclusions

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.

Moving blocks allow 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. 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, alternate 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.

Meet delay can be divided into fixed and variable components that depend on the number of trains partaking in the meet. Running trains in fleets results in fewer but more complicated meets with higher variable delays associated with maintaining minimum train separation. However, a meet between fleets achieves certain efficiencies by resolving multiple train conflicts in a single interaction. Instead of accruing the fixed delay of multiple meets between individual trains (including braking and acceleration delay), four conflicts can be resolved while incurring the fixed delay of a single meet. Moving blocks can be used to reduce delays from meets between single trains relative to fixed block signals, particularly at lower speeds. Moving blocks improve the feasibility of low-delay running meets across a greater range of maximum authorized speeds and siding and train lengths compared to fixed blocks. Combining moving blocks with fleet-length sidings enables full meets between two fleets, resulting in the lowest-delay meets of all tested scenarios. Dispatching fleets of "Short" trains could actually provide some of these fleeting benefits while using existing sidings designed to accommodate a single "Long" train.

Recommendations

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. Experiment 1 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.

Publications

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