EVALUATING FIXED, VIRTUAL, AND MOVING BLOCK CONTROL SYSTEMS ON A DOUBLE TRACK NORTH AMERICAN FREIGHT RAIL CORRIDOR

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ABSTRACT

This paper evaluates the potential for virtual and moving block control systems to increase the capacity of existing North American freight rail corridors to meet future traffic demand. In 2019, US Class I railroads transported 1.6 billion tons of freight across their rail network. To create capacity for a projected increase in freight rail transportation demand of 24% by 2045, billions of dollars must be invested yearly in the mainline route network. As for-profit companies with limited capital budgets, US Class I railroads have a strong economic incentive to properly match mainline capacity to traffic demand. While investing in new track infrastructure does increase network capacity, recently installed Positive Train Control technology and its associated modern communications network may allow virtual and moving block systems to be developed as lower cost alternatives to manage projected traffic increases. Thus, the potential capacity and performance benefits of virtual and moving block systems relative to existing fixed block wayside signal systems should be quantified in a realistic mainline corridor operating scenario. The authors obtained actual route topology and historical train operating data for a long-distance (>2,000 km long) double-track US Class I railroad mainline and developed a novel dispatching algorithm and train simulation framework to compare average train speed under each control system and several levels of projected future train traffic. The simulation results indicate that virtual and moving block systems can substantially increase average train speed compared to existing fixed block systems, especially under high levels of train traffic. Alternatively, virtual and moving block systems can be used to preserve the existing average train speed while increasing the total number of trains handled. The quantitative results of these simulation experiments enable railway practitioners to more accurately evaluate the costs and benefits of investing in these emerging train traffic control technologies.
Keywords: Positive Train Control, moving block, virtual block, freight rail, capacity analysis, simulation.

1 INTRODUCTION

Freight transportation demand by rail in the United States was 1.6 billion tons in 2019 [1]. This is projected to increase by 24% by the year 2045 [2]. As US Class I railroads are for-profit companies, they will work to match their network capacity to this ever-increasing freight rail demand. Positive Train Control (PTC) technology was mandated by the Rail Safety Improvement Act of 2008 and was recently installed on all medium- and high-volume US rail corridors [3]. PTC is a technology designed to prevent train-to-train collisions, overspeed derailments, incursions into work zones, and the movement of trains through misaligned turnouts [3]. The most widely adopted implementation of PTC technology utilizes over-the-air radio connections between locomotives, waysides, and back-office servers (Fig. 1) to continually transmit current wayside state to all active locomotives, and to provide dispatchers with more frequent and precise train location and wayside state information [4]. To address future demand for rail freight transportation, the robust PTC radio communication network may potentially be used to develop virtual and moving block control systems as lower cost alternatives to expanding mainline route infrastructure by building more tracks.

Previous research has found that a 20-30% capacity increase from upgrading a fixed block control system to moving block is reasonable for high-speed passenger rail systems [5]-[7]. In

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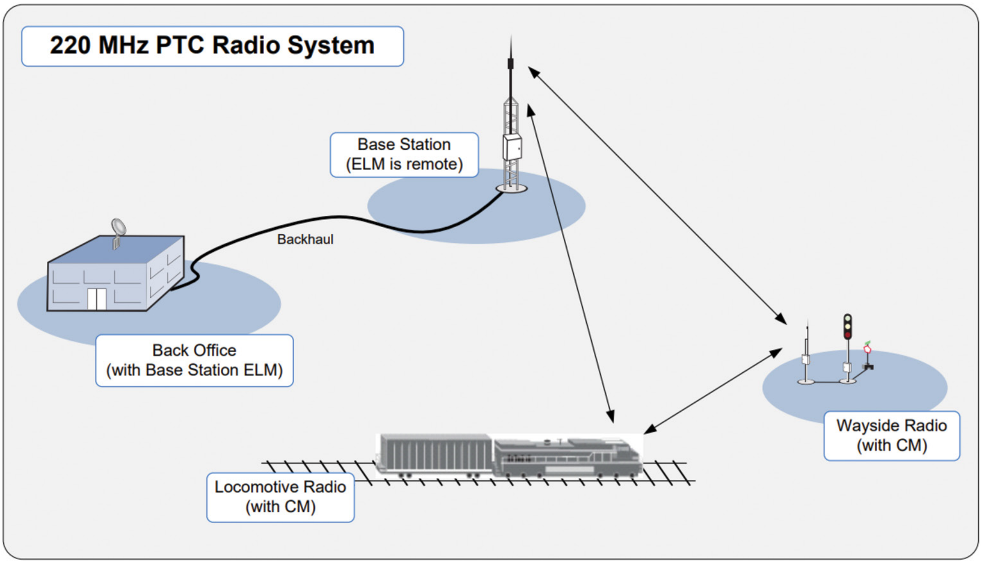

Figure 1: High level 220 MHz radio network system diagram. *[4]*

the North American freight rail context, previous analytical capacity analysis indicates that a 50% throughput increase from upgrading fixed block to moving block is the maximum achievable benefit (perfect train following) [8]-[10]. More recent research has used commercial railway capacity analysis tools to compare fixed, virtual, and moving block systems over 300 km long corridors, finding that the largest benefits of moving block occur for high-volume double-track corridors (most like the analytical train following case) [11]-[13]. However, virtual and moving block control systems may cause fundamentally different train traffic flows compared to fixed block, requiring complete mainline corridors to be simulated to avoid introducing arbitrary boundary conditions [14]. Recent advances in automated dispatching logic have made simulating full-length corridors feasible [15]. This research will describe a complete rail corridor simulation model designed to compare the performance of fixed, virtual, and moving block control systems, and will use this model to evaluate their use on a >2,000 km long double track US freight rail corridor.

2 METHODOLOGY

The complete simulation model that was developed is composed of the input data plus three major components: dispatching logic (and an associated train travel time estimator), a train performance calculator (used for individual train simulation), and an event-based rail network simulator, which manages train occupancy and enforces sufficient train separation. This simulation model architecture is detailed in Fig. 2. The following sub-sections explain each of these four model components in greater detail. A description of each of the three train control systems simulated is located in the rail network simulator section.

2.1 Input data

The input data is composed of the track topology for the railroad corridor, the fixed signal aspects currently in use for fixed block scenarios, a set of proposed virtual block signal locations for each virtual block scenario, and all planned train movements. The planned train

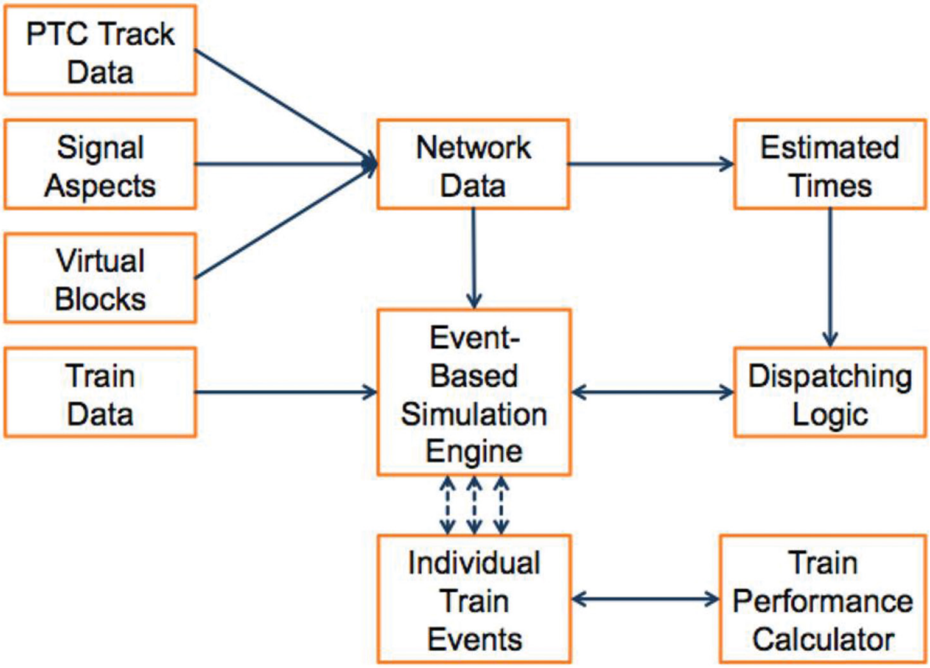

Figure 2: Simulation model architecture.

movements specify origin, destination, and all necessary train consist parameters to be used by the train performance calculator. This data will vary considerably depending on the corridor being evaluated, and is explained in more detail in the experimental design.

2.2 Dispatching logic

The dispatching algorithm used in the simulation model is a deadlock avoidance heuristic algorithm. It operates by ensuring that all trains currently on the network or entering at any point in the future have a free path to their destination at all valid intermediate steps. Free paths are allowed to pass through same-direction trains but may never pass through opposite-direction trains. Thus, from any valid intermediate step, an algorithm can be developed that advances the train that has been waiting the longest until it reaches a valid intermediate step, rewinding and choosing a different train if the train first advances into the back of a same-direction train. This algorithm will always succeed in routing all trains to their destinations so long as it starts from a valid intermediate step. Starting the simulation with all trains off the network ensures that this condition is met. Roscoe [15] provides full documentation of this dispatching algorithm. The output from the dispatching logic is the planned path for each train across the rail corridor and the order in which trains should pass each turnout (points).

2.3 Train performance calculator

To accurately simulate trains operating under each control system, a moderately detailed and very fast train performance calculator was developed. At a high level, all forces acting on the simulated train are calculated at every one-second time step. Control actions are selected to minimize running time subject to train performance characteristics, maximum track speed profiles, and a maximum allowable deceleration rate. In addition, the associated changes in speed and position for each time step are calculated using Euler integration. While Euler integration is one of the simplest integration schemes, analytically integrating the grade and curvature profiles that trains traverse would require numerical approximation, reducing the advantages of more complex integration schemes like Gaussian integration [16].

Five forces are calculated at each time step: rolling resistance, aerodynamic resistance, grade resistance, curve resistance, and maximum locomotive tractive effort at the rail. The train is modelled as a uniformly distributed mass "strap" with its total weight spread over its length and averaged over the gradient and curvature falling within. Acceleration of the train at each time step is calculated with eqn (1),

$$a_{max} = \frac{TE_{max} - D_R - D_A - D_G - D_C}{m}, \tag{1}$$

where TE_{max} is the current maximum tractive effort at the rail that the locomotives can produce, D_R is the current rolling resistance, D_A is the current aerodynamic resistance, D_G is the current grade resistance, D_c is the current curve resistance, m is the total mass of the train, and a_{max} is the current maximum acceleration of the train.

Each of the first five terms has a more detailed expression, starting with rolling resistance:

$$D_R = a_n n + a_Q mg, \tag{2}$$

where a_n is the average bearing resistance per axle, n is the number of axles, a_Q is the average rolling resistance per weight, and g = 9.81 m/s^2 (gravitational acceleration).

Aerodynamic resistance is calculated using eqn (3):

$$D_A = \frac{1}{2}\rho C_D A v^2, \tag{3}$$

where ρ = 1.3 kg/m^3 is the density of air, $C_D A$ is the drag coefficient multiplied by the drag area of the entire train, and v is the current velocity of the train. The $C_D A$ term includes cross-sectional drag as well as skin friction. There are no terms directly proportional to velocity in eqns (2) or (3) because these terms are negligible for freight trains.

Grade resistance is calculated with the following equation:

$$D_G = mg \times \frac{h_f - h_b}{L}, \tag{4}$$

where h_f is the front of train elevation, h_b is the back of train elevation, and L is the train length. The fraction term is the current average gradient over the train length. Thus, it is implicitly assumed that train mass is evenly distributed along the length of the train.

To calculate curve resistance, coefficients for resistance versus degree of curvature and truck (bogie) type were taken from the AAR Train Energy Model [17]. A least squares regression was used to determine the best fit quadratic polynomial to obtain curve resistance as a function of degree of curvature and type of truck. Information describing the cumulative length and degree of curvature was added to each block in the rail network such that the positions of the front and back of the train are sufficient for calculating the curve resistance for the entire train (after joining the blocks together using the dispatching path result). The resulting equation in matrix form is:

$$D_C = \boldsymbol{C_T} \cdot \left(\boldsymbol{CP_f} - \boldsymbol{CP_b}\right) \tag{5}$$

where $\boldsymbol{C_T}$ is the vector of weighted averages of curve resistance coefficients for the train based on the truck type distribution, $\boldsymbol{CP_f}$ is the vector of curve properties at the front of the train, and $\boldsymbol{CP_b}$ is the vector of curve properties at the back of the train. A dot product is used to determine the final scalar value for curve resistance. This equation assumes that the truck type distribution is uniform throughout the train.

The equation for maximum locomotive tractive effort at the rail is:

$$TE_{max} = \min\left(F_{max}, \frac{P_{max}}{v}\right), \tag{6}$$

where F_{max} is the maximum possible tractive effort for all locomotives, typically determined by the traction motor current rating, the coefficient of friction between wheel and rail, and the weight of all locomotives, and P_{max} is the maximum available power at the rail, determined by multiplying the available rated power by an efficiency factor of 0.8.

To simplify train control, acceleration is the only control variable and may be changed instantaneously to any value currently achievable by the train. The control algorithm assumes trains accelerate at their maximum rate unless limited by the current speed limit or an upcoming speed restriction. If the train would exceed the current speed limit in the next time step, its acceleration is limited such that the train matches the speed limit. If the train is approaching an upcoming speed restriction (including those generated for stop signals), the acceleration is set using the kinematics equation below.

$$a_{min} = \frac{v_0^2 - v_f^2}{2\Delta \mathrm{x}}, \tag{7}$$

The range of allowed train deceleration rates was between 0.08 and 0.09 m/s^2. This range ensures that the train reacts to upcoming speed restrictions near the location that a typical train crew would begin to slow the train. Additionally, the maximum deceleration rate of 0.09 m/s^2 is conservative and achievable by typical trains in real operations regardless of the actual track and train characteristics.

2.4 Rail network simulator

The rail network simulation engine functions at the core of the model, emulating the operation of trains across the network as directed by the dispatching logic result and subject to the constraints of the rail traffic control system being considered. The rail network simulator also gathers performance statistics of interest.

For both wayside and virtual signals, the network simulator must monitor the position and direction of all trains on the corridor and determine if each block is occupied or unoccupied. Based on the occupancy status of protected blocks, wayside and/or virtual signals must be set to the proper aspect to provide protection against following trains. When trains clear blocks (block transitions from occupied to unoccupied), the simulation engine must update the status of all wayside or virtual signals accordingly. In contrast, the moving block system must track the end of each train as a stop location as the trains progress along the corridor.

For wayside, virtual, and moving blocks, the network simulator must track the limits of movement authority granted to each train by the dispatching logic. Either the end of movement authority or a conflicting train route planned by dispatching logic may cause a block ahead to be effectively "occupied" even if no train is currently present. The status of wayside and virtual signals must be updated to reflect this condition, and the moving block system must place a corresponding stop location.

Train head (front) and tail (rear) locations (tracked as distance offsets in each occupied block along the corridor) are stored for each time step in an array. This data effectively represents all train occupancy and corresponds to the information known by a moving block system operating on a one-second update interval. To simulate fixed and virtual block systems, signals are overlaid at their appropriate location offset and occupancy is checked along the active path to the next signal. If any trains are present along this path, the signal is set to stop. Otherwise, the signal is set to the aspect appropriate for the chain of signals in front of it (i.e., using signal control line logic). The train position and signal aspect data are used by the train performance calculator to maintain safe train separation.

To improve model running time, the train performance calculator is run asynchronously for each train. Each train is run until reaching a point where it may be restricted by another train, typically either through a signal (train following) or by the dispatching plan (train meet or pass conflicts). To ensure that the asynchronous simulation matches the real-world synchronous system, the train performance calculator exits, the train updates its occupancy through time in the global occupancy table, and it schedules itself to continue simulating after the restricting train is updated.

2.4.1 Fixed block

In the simulation model, the fixed block control system is based on existing wayside signals included in the route data. A pre-processing algorithm is used to iteratively path through the network to define fixed signal blocks and create the signal "control line" logic. Control line logic links the signal aspect displayed by one signal to that displayed by the next signal.

In this research, the simulation assumes that all existing wayside signals can display all possible aspects, except for those associated with restricting, stop and proceed, and stop. These three aspects are excluded because the appropriate aspect is instead selected based on signal type information available in the input route data. For simplicity in control line logic, a four-aspect based system with no repeating aspects was assumed to be in place over the entire corridor, regardless of signal spacing. The standard signal sequences defined by the rules of the Class I railroad sponsor were used, except for a small number of signal aspects with very similar behaviour, which were combined.

Additional speed controls for the fixed block control system were provided by using "hold", "immediate", and "next" target speeds for each signal and aspects as follows:

- The "hold" speed is used when a train is taking the diverging route, ensuring that the train holds the specified speed through all diverging turnouts following the specified signal. This speed is thus only applicable for diverging aspects and is set to track speed for all other aspects.

- The “immediate” speed is used to ensure that a train immediately starts slowing down to the specified speed upon passing a signal. For example, the difference in speeds specified between the approach medium aspect (next speed of 65 kph) and the approach aspect (immediate speed of 50 kph) will result in the train beginning to slow to the immediate speed as it passes the approach aspect.
- The “next” speed is used to specify the speed of the train when passing the next signal. This “next” speed also has a parameter specifying which next signal should be considered. This parameter allows for an advance approach aspect that requires the passing train to stop at the second signal rather than necessarily taking an action prior to the next signal.

2.4.2 Virtual block

The simulated virtual block control system was constructed by altering the fixed block signal logic and subdividing the signal blocks. The signal logic was altered by:

1. Simplifying the fixed block system to have only two aspects (restricting and clear)
2. Changing part of the signal speed restriction code to have knowledge of all nearby signals (possible using PTC radio links)
3. Immediately propagating signal updates to all trains (possible using PTC radio links)

To support the new logic, each of the existing signal blocks within the baseline fixed block system were split into equal sections, called virtual blocks. A virtual signal was created to guard the entrance to each virtual block. Because each existing fixed block is divided into virtual blocks, the length of virtual blocks is consistent within each fixed block. However, virtual block length will be different between fixed blocks of different lengths along the corridor (see Fig. 3). This methodology of defining virtual blocks retains the original braking distance estimates embedded in the fixed wayside block signal installation and approximates optimal virtual signal placement.

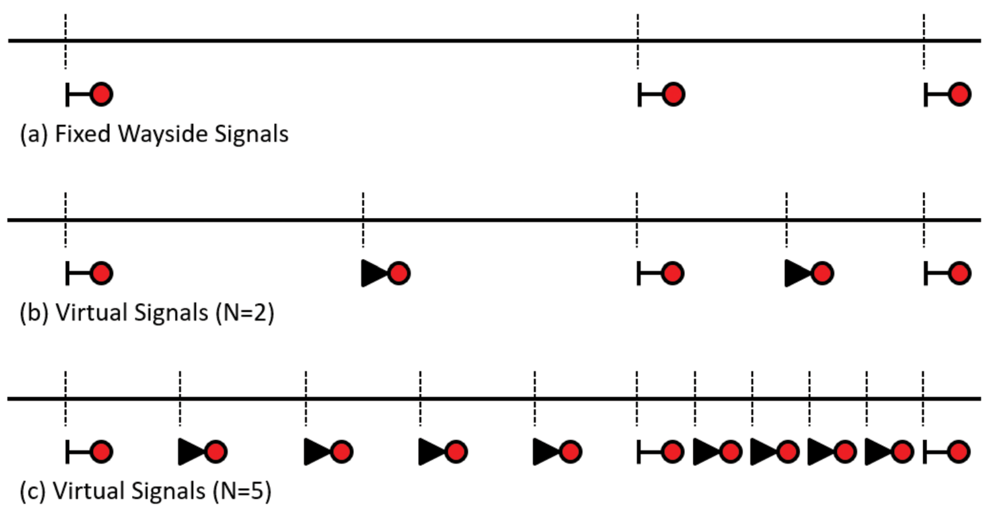

Figure 3: Virtual signal placement example.

2.4.3 Moving block

In the simulation model, the moving block system is assumed to enforce an absolute braking distance to the train ahead. An absolute braking distance approach requires that following trains must always be able to brake to a stop before reaching the current position of the tail of their preceding train. This differs from the relative braking distance approach used in "virtual coupling", where trains can follow at even closer headways so long as the following train can brake to a stop before passing the tail of the preceding train if the preceding train were to decelerate according to some maximum braking performance [18]-[19]. The absolute braking approach follows PTC requirements by providing sufficient train separation to prevent a collision in the case where the lead train derails or otherwise stops instantaneously. In the model, the absolute braking distance is calculated in the train performance calculator for each train at each time step based on its individual parameters and current state.

The moving block control system logic was constructed by ignoring signals entirely, instead using only the underlying train occupancy representation. This contains the locations of all trains (head-end and tail-end) along the route at each time step. Since a one second time step was used in the occupancy representation, moving block with a one-second update interval was simulated.

3 EXPERIMENTAL DESIGN

The detailed rail network simulation model described above was used to determine and compare the performance of fixed, virtual, and moving block control systems on a >2,000 km long double track North American freight rail corridor controlled by a centralized dispatcher. The following sub-sections detail each factor in the experiment design.

3.1 Traffic data

Existing train traffic on this corridor was simulated along with six levels of future traffic growth, ranging from a 10% increase to a 60% increase. Operations from September 15th to October 14th, 2017, were simulated, but only the 21 days from September 18th to October 8th were used for analysis to allow for warmup and cooldown. The baseline traffic data is composed of 2,664 train starts and was derived from actual train operations in this timeframe. To realistically increase the traffic volume, a list of all trains sorted by scheduled origination time was created. To increase traffic volume by 20%, two out of every sequential set of ten trains was duplicated with its departure time offset by 12 hours. For a 30% increase, three out of every ten trains were duplicated. Thus, the added trains were distributed randomly across the origin-destination pairs and evenly over time.

3.2 Train control system

Three types of train control system were tested, namely fixed, virtual, and moving block. Because a unique virtual block system can be created by dividing existing fixed blocks into any number of virtual blocks, multiple virtual block versions were simulated. Each fixed block was split into a constant number of virtual blocks to retain the original braking distance based fixed block placement. Simulating a range of virtual block densities (different N) explores the hypothesis that virtual block approaches moving block performance at high values of N [14]. A total of six different train control systems were tested:

- FB: existing fixed block signal system;
- VB1: existing fixed block signal system converted to virtual blocks ($N = 1$);

- VB2: two virtual blocks per existing fixed signal block ($N = 2$);
- VB5: five virtual blocks per existing fixed signal block ($N = 5$);
- VB10: ten virtual blocks per existing fixed signal block ($N = 10$);
- MB: moving blocks.

3.3 Overall

Combining the seven traffic levels and six train control systems gives a total of 42 unique simulation scenarios. The key output metric from each scenario is average train speed, which will be used to compare performance across control systems and across traffic volumes. Note that US rail corridors with active PTC systems operate as either FB or VB1 depending on if the operating railroad allows PTC signal aspects to be used as cab signals and has no specified speeds (other than stop and restricting) in its signal aspect rules. For this research, FB was assumed to be the baseline. However, because the upgrade from FB to VB1 can be accomplished with minimal capital investment on all PTC corridors, railroads should consider making this upgrade and using VB1 as a baseline for future cost/benefit analyses.

4 RESULTS

To evaluate the performance of each control system, average train speed for each simulated scenario was plotted versus control system and traffic level (Fig. 4).

Average speed drops by approximately 14 kph for fixed block (worst performing control system tested) when transitioning from the baseline (100%) traffic volume to 160% volume. At baseline volume, moving block increases average train speed by 5 kph. At 140% volume, moving block maintains the average train speed of fixed block in the baseline volume scenario. Thus, moving block can reliably maintain the current level of service at a 40% traffic volume increase. Many control systems counterintuitively performed better at higher train volumes. This is likely due to the random selections made in adding future trains to the train plan; each incremental increase in train volume does not require that the same trains added in the previous traffic volume levels also be present in all successive traffic volume increments. Thus, some extremely poorly performing trains can drop the average speed for only one specific future traffic volume without being included in higher traffic volumes.

To make the differences between control systems more apparent, the incremental benefit over fixed block for each of the other control systems was plotted (Fig. 5). The incremental

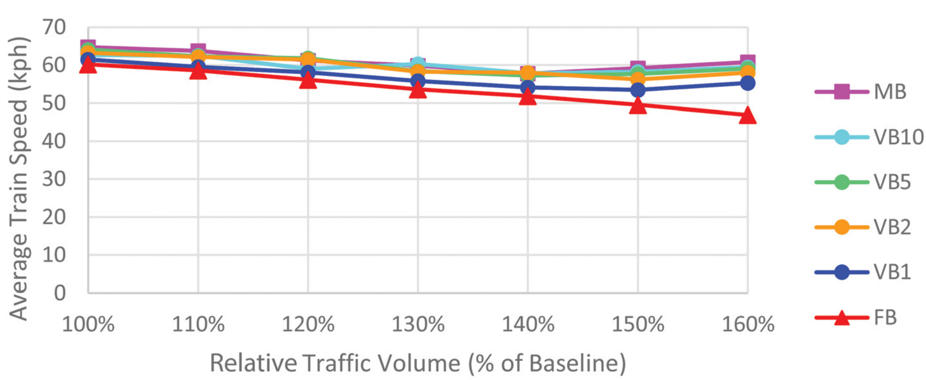

Figure 4: Average train speed for all tested control systems and traffic levels.

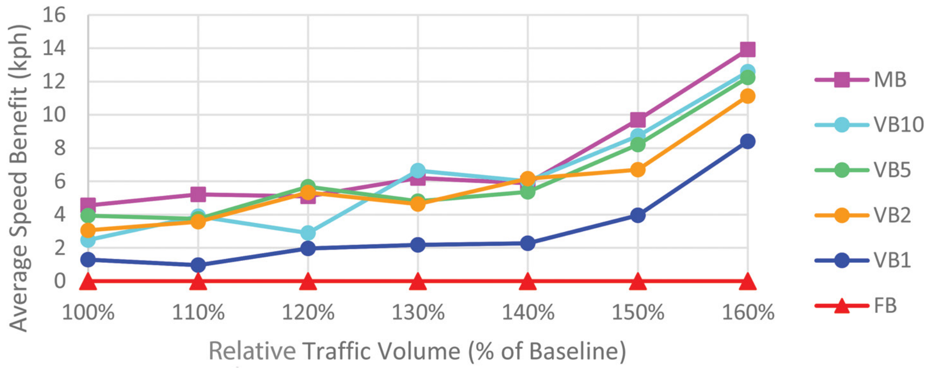

Figure 5: Incremental average train speed benefit relative to fixed block for each traffic level and control system.

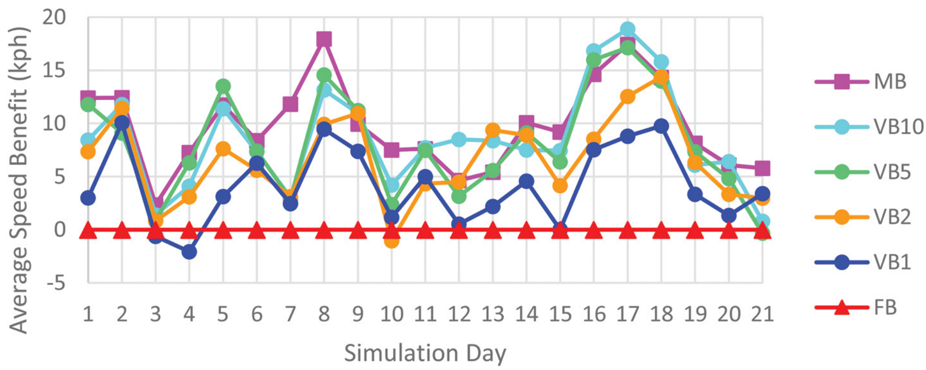

Figure 6: Daily incremental average train speed benefit relative to fixed block for each control system at 150% of baseline traffic volume.

benefits of switching to a more advanced control system are higher with increasing traffic volume. This effect is most pronounced at high volumes because any poorly performing trains will severely limit capacity and create large fleets of trains. Since following trains do not pass the lead train due to limitations in the dispatching algorithm, control systems that enable fleets to run closer together show substantially higher performance. Also note that the benefits are exaggerated at the highest two volumes because all control systems except for fixed block saw an improvement in train speed compared with the 140% volume results.

To evaluate the consistency of the control system benefits, the incremental average train speed benefit is broken out by individual day for the 150% traffic volume scenario in Fig. 6. Even though the averages of the data in Fig. 6 (x=150% in Fig. 5) correspond to the expected behaviour of the control systems, where each step from FB to VB1, VB2, VB5, VB10, and MB shows a clear incremental improvement, there is substantial noise in the daily averages. Fixed block is not even the worst performing control system on days 3, 4, 10, and 21. However, this severe noise is likely because the more advanced control systems push trains into bottleneck sections, changing the timing of the highest train densities and lowest average train speeds. While single-track bottleneck sections do not exist for this fully double-track network, low performance trains can function as slow-moving bottlenecks since the dispatching logic only resolves opposite-direction train meets. Thus, advanced train control systems can shift the time when fast-moving trains queue behind slow-moving trains.

5 CONCLUSIONS

Development of a rail corridor simulation tool capable of evaluating complete corridors at once is essential to understanding the potential benefits of virtual and moving block systems for North American freight rail. On the fully double-track corridor that was evaluated, it was found that implementing moving blocks can increase average train speed by 5 kph relative to the existing fixed block system for baseline (fall 2017) traffic volumes. Additionally, much of the benefit of moving blocks can be obtained by implementing a virtual block system that subdivides each existing fixed signal block into five virtual blocks. Depending on the cost of each of these alternatives, railroads can choose which system to implement. Virtual and moving block control systems also create capacity for future traffic growth; the average speed observed for baseline operations with fixed blocks was matched by moving blocks with a 40% increase in traffic volume. However, on a day-to-day basis, the train speed benefit relative to fixed block is extremely variable for all control systems, indicating that effective dispatching is necessary to take advantage of these advanced control systems.

There are several important limitations to these results. Firstly, the dispatching algorithm used in the simulation model is not designed to pass trains traveling in the same direction and cannot simulate trains that reverse direction, requiring them to be excluded from the train plan. While there were relatively few of these trains, excluding them is a deviation from the real traffic data. Additionally, some assumptions were made when correcting raw data errors related to train weight and locomotive power, further deviating the simulations from the real train traffic.

Another key limitation of this study is that intermediate work events were not included. Only origin and destination events are simulated, and therefore the result is not fully representative of real-world practice. The omission of intermediate work events affects the overall dispatching plan and performance relative to observed average train speed. Moreover, train performance parameters such as train length, weight, and horsepower that change at intermediate stops were not properly included in the simulation without these intermediate events. Fixing train parameters at the origin caused a small number of trains to exhibit poor performance on steep grades, causing additional delay and simulation inaccuracy.

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REFERENCES

[1] Association of American Railroads (AAR), *Railroad Facts, 2020 Edition*, Association of American Railroads: Washington, D.C., USA, 2020.

[2] U.S. Department of Transporation (USDOT), *Beyond Traffic 2045,* U.S. Department of Transportation: Washington, D.C., USA, 2016.

[3] Rail Safety Improvement Act (RSIA), *Rail Safety Improvement Act of 2008*. H. R. 2095, 110th Congress, 2nd session, 2008.

[4] Meteorcomm LLC, *ITCR 1.1 System Architecture Specification*, Federal Railroad Administration: Washington, D.C., USA, 2012.

[5] Xishi, W., Bin, N., Yun, L., & Ming, Z., Analysis of moving autoblock system (MAS) and its computer simulation method. *Computers in Railways V, Vol 2*, WIT Press: Southampton, UK, pp. 267–279, 1996.

[6] Lee, J.D., Lee, L.H., Cho, C.H., Jeong, P.G., Kim, K.H., & Kim, Y.J., Analysis of moving and fixed autoblock systems for Korean high-speed railway. *Computers in Railways VII*, WIT Press: Southampton, UK, pp. 842–851, 2000.

[7] Institute of Transport Science RWTH Aachen, *Influence of ETCS on Line Capacity - Generic Study,* International Union of Railways (UIC): Paris, France, 2008.

[8] Dick, C.T., *Impact of Positive Train Control on Railway Capacity,* University of Illinois at Urbana-Champaign, Department of Civil and Environmental Engineering: Urbana, IL, USA, 2000.

[9] Moore Ede, W.J., How CBTC Can Increase Capacity. *Railway Age*, April, pp. 49–50, 2001.

[10] Moore Ede, W.J., *Moving Block in Communication-Based Train Control: Boon or Boondoggle?* Transportation Technology Center, Inc.: Pueblo, CO, USA, 2005.

[11] Dick, C.T., Mussanov, D., Evans, L.E., Roscoe, G.S., & Chang, T.Y., Relative capacity and performance of fixed and moving block control systems on North American freight railway lines and shared passenger corridors. *Transportation Research Record: Journal of the Transportation Research Board*, **2673**(5), pp. 250–261, 2019. doi.org/10.1177/0361198119841852

[12] Diaz de Rivera, A., Dick, C.T., & Evans, L.E., Improving railway operational efficiency with moving blocks, train fleeting and alternative single-track configurations. *Transportation Research Record: Journal of the Transportation Research Board*, **2674**(2), pp. 146–157, 2020. doi.org/10.1177/0361198120905842

[13] Diaz de Rivera, A., Dick, C.T., & Evans, L.E., Potential for moving blocks and train fleets to enable faster train meets on single-track rail corridors. *Journal of Transportation Engineering, Part A: Systems*, **146**(8), 04020077, 2020. doi.org/10.1061/JTEPBS.0000403

[14] Diaz de Rivera, A. & Dick, C.T., Illustrating the implications of moving blocks on railway traffic flow behavior with fundamental diagrams. *Transportation Research Part C: Emerging Technologies*, **123**, 102982, 2021. doi.org/10.1016/j.trc.2021.102982

[15] Roscoe, G.S., *Dispatching Logic, Corridor Simulation, and Train Following Algorithms to Quantify the Benefits of Virtual and Moving Block Control Systems on North American Freight Railroad Mainlines*, Master's Thesis, University of Illinois at Urbana-Champaign, Department of Civil and Environmental Engineering: Urbana, IL, USA, 2021.

[16] Jaekel, B. & Albrecht, T., Comparative analysis of algorithms and models for train running simulation. *Journal of Rail Transport Planning and Management*, **4**(1-2), pp. 14–27, 2014. doi.org/10.1016/j.jrtpm.2014.06.002

[17] Dirsh, W.F. & Singh, S.P., *Train Energy Model Validation Using Revenue Service Unit Coal Train Data*, Association of American Railroads: Chicago, IL, USA, 1991.

[18] Ning, B., Absolute braking and relative distance braking train operation control modes in moving block systems. *Transactions on the Built Environment*, **34**, 1998.

[19] Li, K., Gao, Z., & Ning, B., Modeling the railway traffic using cellular automata model. *International Journal of Modern Physics C*, **16**(6), pp. 921–932, 2005. doi.org/10.1142/S0129183105007613