Potential for Moving Blocks and Train Fleets to Enable Faster Train Meets on Single-Track Rail Corridors

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Abstract: On single-track rail corridors, meets between trains are a significant source of train delay. From the stopping train's perspective, a meet can be divided into three distinct phases: braking into a siding, waiting for higher-priority trains to pass, and accelerating to operating speed on the main track. Meet delay can be further divided into fixed and variable components depending on the number of trains partaking in the meet. Advanced train control systems incorporating moving blocks and innovative dispatching strategies such as train fleeting promise to reduce minimum meet times. Using a spreadsheet-based calculation, it was found that train fleeting distributes fixed delays among more train conflicts, resulting in more efficient conflict resolution. Complementarily, moving blocks minimize variable delays. Combining moving blocks and fleeting can be highly effective, producing the lowest meet delay across a variety of track speeds and dispatching strategies. The results from this study can help railway practitioners evaluate the benefits of train fleeting, moving blocks, shorter train lengths, and extended fleet-length sidings when developing operating and capital plans. **DOI: 10.1061/JTEPBS.0000403.** *© 2020 American Society of Civil Engineers.*

Introduction

Approximately two-thirds of the principal mainline corridors in the United States railway network consists of single-track with passing sidings (Richards and Cobb 2006). In North America, where operations do not use a preplanned timetable, conflicts between opposing trains on single-track mainlines are resolved by train meets arranged by train dispatchers in real time. During a train meet, a train given lower priority by the dispatcher or operating plan exits the main track onto a passing siding to allow a higher-priority train to pass on the main track. While the superior train passing on the main track incurs minimal delay from the meet, the inferior train can experience significant delays waiting in the siding. A survey of four US Class I railroads ranked meets and passes as the top or one of the top causes of train delay in mainline operations (Martland 2008). An econometric analysis of data from a Class I railroad identified train conflicts such as meets and passes as primary contributors to congestion-related delay (Gorman 2009).

Among major transportation modes, rail transportation is typically the most fuel-, space-, and cost-efficient way to move goods long distances over land (Rodrigue and Slack 2020). In the US, railroads form a vital part of the transportation network, carrying approximately one-third of US exports by volume (AAR 2019b). While in general, capacity across the Class I rail network is sufficient to meet current needs (ASCE 2017), long-term economic growth is expected to increase demand for railway transportation in the US by 45% between 2016 and 2045 (USDOT 2016). Each train added to a single-track mainline rail corridor to accommodate future growth imposes an additional train conflict on every other existing train operating on the corridor. Therefore, train meets will likely remain a substantial source of delay for the foreseeable future. Increases in train delay impose substantial burdens on railroad stakeholders, with direct and indirect costs to railroads, shippers, and the public exceeding $1,000 per hour of train delay (Lovett et al. 2015; Lovett 2017). Because congestion arising from train delay limits capacity for future traffic and revenue growth, reducing delays associated with train meets represents an excellent opportunity for rail operators to lower costs and improve the long-term delay performance and capacity of a rail corridor. While incremental addition of a second main track is one approach to eliminate conflicts and effectively manage train delay (Lindfeldt 2012; Shih et al. 2014; Sogin et al. 2016), the high cost of track construction and maintenance favors approaches that maximize the use of existing track infrastructure.

This paper investigates the individual and combined potential of advanced train control systems, train fleeting, and varying passing siding lengths to improve the efficiency of train meets on single track and reduce train delay. After discussing the fundamentals of train meets and train control systems and overviewing previous research, a deterministic spreadsheet-based calculation is developed and validated to generate realistic meet delay values for a range of input values. The results of the detailed calculations are then used to answer the primary research questions.

Train Meets

A conventional train meet between two opposing trains can be divided into three distinct phases defined by the source of delay incurred by the inferior train: braking, waiting, and acceleration. The total time to execute a train meet (i.e., meet time)

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Note. This manuscript was submitted on November 22, 2019; approved on March 17, 2020; published online on May 31, 2020. Discussion period open until October 31, 2020; separate discussions must be submitted for individual papers. This paper is part of the ***Journal of Transportation Engineering, Part A: Systems***, © ASCE, ISSN 2473-2907.

is the sum of the time required for each of these three phases [Eq. (1)]

$$T_{Meet} = T_{Brake} + T_{Wait} + T_{Accel} \quad (1)$$

During the braking phase, the inferior train is routed into a passing siding and initially decelerates from track speed to the maximum allowable speed through the diverging route of the turnout at the end of the passing sidings (i.e., turnout speed) before braking to a stop clear of the main track. Train braking performance and the train traffic control system determine the length of the braking phase.

The waiting phase represents the time the inferior train spends stopped in the siding waiting for the superior train to pass. The minimum length of the waiting phase is determined by the sum of the time required to line all relevant switches and signals for the superior train initially and later for the inferior train, the running time for the superior train to arrive at the passing siding and then clear the siding exit switch and turnout, and crew reaction time. The length of the waiting phase can increase depending on the number of passing superior trains, how late the first superior train arrives after the inferior train clears the main track, and the number of stopping inferior trains.

The acceleration phase begins as soon as the inferior train starts moving after waiting for the opposing trains to pass on the main track, and ends once the inferior train has reached maximum authorized track speed. The length of this phase depends on the acceleration characteristics of the train and if the turnout speed limit constrains how quickly the train can accelerate before the end of the train is clear of the passing siding.

All three phases of a meet impose delay on the inferior stopping train. Train delay, defined as the difference between actual train running time and ideal minimum running time assuming no train conflicts, is commonly used to measure the performance of rail corridors in North America (White 2005; Pouryousef et al. 2015). Due to the improvised nature of North American rail operations, meets between trains are not scheduled for a specific location and time and contribute to rail corridor delay metrics. Assuming a constant maximum authorized track speed (V_{MAS}), meet delay can be defined as the difference between T_{Meet} and the minimum train running time over the distance between the point where braking is initiated and the point where the train stops in the siding (D_{Brake}), and the additional distance to the point where the train finishes accelerating to V_{MAS} after a meet (D_{Accel}) [Eq. (2)]

$$Meet\,Delay = T_{Meet} - \frac{D_{Brake} + D_{Accel}}{V_{MAS}} \quad (2)$$

Meet delay can be separated into fixed and variable components (Moore Ede et al. 2007). Fixed delay remains the same regardless of the number of opposing trains being met and, for a given inferior train, is a function of control system and track infrastructure. Fixed delay is caused by:

- Inferior train(s) braking to a stop in a siding,
- Signal and switch clear times, and
- Inferior train(s) accelerating to maximum authorized speed.

Effectively, every time a train stops, it goes through one braking and acceleration cycle regardless of the number of trains met. In contrast, variable delay is caused by:

- Inferior train(s) waiting while the superior train(s) passes, and
- Fleet delays such as a lead inferior train waiting for following trains to stop and following inferior train(s) waiting for the lead train to obtain a minimum separation distance (and clear its signal block) during the acceleration phase.

One delay reduction strategy that leverages knowledge of fixed and variable meet delays is fleeting trains. A train fleet is comprised of two or more similar-performing trains operating in the same direction at minimum headway. To illustrate how such a strategy achieves more efficient meets, consider a fleet of two inferior trains meeting a fleet of two superior trains on a single-track line. If dispatched as single trains operating at longer headways, four individual train meets resolving four total train conflicts are necessary [Fig. 1(a)]. If the superior trains are fleeted, two meets and associated fixed delays are removed with the remaining two meets each resolving two train conflicts [Fig. 1(b)]. If the inferior trains are also fleeted, the four original individual meets become one longer meet resolving four train conflicts [Fig. 1(c)]. Combining train conflicts into a single meet achieves a certain economy of scale because each inferior train only undergoes a single braking and acceleration cycle while still meeting the same number of superior trains. However, from the perspective of the inferior trains, there is a trade-off between reducing the number of braking and acceleration cycles and increasing time spent waiting for multiple superior trains to pass. The optimum point for this trade-off between fixed and variable delays depends on the train control system, operating speed, and train braking and acceleration characteristics.

Avoiding a stop entirely with a running meet minimizes total meet delay. In a running meet, opposing trains do not have to stop while passing each other and the passing siding effectively functions as a short section of double track. However, running meets require the opposing trains to nearly simultaneously arrive at a passing siding. The feasibility of a running meet then depends on if the siding is long enough to maintain appropriate separation between opposing moving trains given the train control system and train lengths (Dick, "Impact of Positive Train Control on Railway

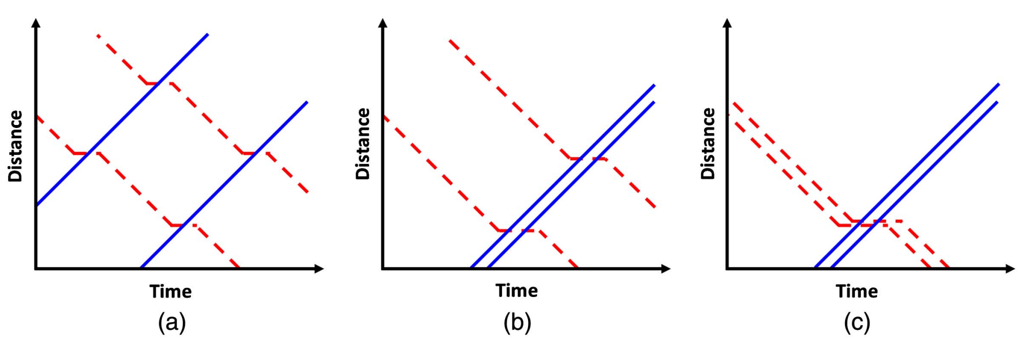

Fig. 1. Hypothetical time-distance diagrams showing four train conflicts resolved through: (a) four individual train meets; (b) two longer train meets created by fleeting the superior trains; and (c) one long meet between two-train fleets.

Capacity," unpublished report). Ideally, trains operate at maximum authorized speed in a running meet. However, one or more trains may slow down (and incur some delay) to make a running meet possible on shorter sidings and minimize overall delay to all trains involved (Petersen and Taylor 1987). Many Class I railroads are lengthening existing sidings and constructing new long sidings on single-track mainlines to accommodate longer trains in conventional stopping meets (Stagl 2018a). These longer sidings can also enable running meets between shorter trains.

Train Control Systems and Moving Blocks

Conventional train control systems protect trains from conflicting movements by dividing track into a series of fixed signal blocks that usually can only be occupied by a single train. From the perspective of a train crew, block occupancy information is only available at discrete points where wayside signals govern the entrance to signal blocks, introducing a level of uncertainty about the specific location of trains ahead. Therefore, block length, typically set for the braking characteristics of a design train operating on the line, is a primary factor determining minimum train separation distance. Block length can be decreased by physically or virtually increasing the number of signal aspects in the primary progression from stop to clear, improving the frequency and accuracy of occupancy information updates provided to the train crew.

In a train control system incorporating moving blocks, fixed blocks are replaced by a control block customized to a train's length and braking characteristics. The control block updates very frequently and moves with the train along the track. In a true moving block system, block length is theoretically infinitely small because the location of the train is continuously updated, allowing minimum train separation to be reduced to absolute braking distance plus a margin of safety. In simple cases of directional traffic, moving blocks can theoretically reduce minimum train distance headways to 50% below a 3-aspect fixed block control system, and 33% below a 4-aspect system (Dick et al. 2019a). 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%–40% over ETCS Level 1, which is a safety-focused system overlaid on existing fixed block signals (Institute for Transport Science RWTH Aachen 2008). Positive Train Control (PTC), expected to be fully implemented across the US Class I rail network by the end of 2020, provides the opportunity to replace fixed block wayside signals with moving blocks (AAR 2019a; Stagl 2018b; Machalaba 2019). While current PTC systems are safety-focused systems overlaid on existing fixed block signal systems, they involve installation of a robust new communications and network infrastructure that could provide the foundation for advanced train control systems with moving blocks (Resor et al. 2005; FRA 2012). Outside of North America, moving blocks have been implemented on heavy haul railways in Western Australia for several years and are being actively investigated as part of the development of ETCS Level 3 in Europe (Barrow 2015; Harriss 2016). For a given level of service, experiments simulating a typical North American freight rail corridor have shown that moving block implementation would generally increase capacity relative to fixed block systems, partly because lower minimum train separation improves meet efficiency (Dick et al. 2019a).

In a "perfect" train meet where opposing trains arrive simultaneously at the meet location, minimum train separation distance determines the latest time the inferior train can clear the main track to avoid impacting the superior train's operation and increasing meet delay. In cases where the superior trains are fleeted, the train control system, in addition to train length and running speed, dictates train headways and how long an inferior train must wait for the superior trains to pass. To calculate minimum headways for fixed block systems, the number of blocks required to accommodate stopping distance (B_{Stop}) is determined using block length (L_{Block}) and braking distance from maximum authorized speed to zero ($D(V_{MAS}, 0)$) [Eq. (3)]

$$B_{Stop} = \frac{D(V_{MAS}, 0)}{L_{Block}} \tag{3}$$

Under fixed blocks, uncertainty about occupancy of the track ahead requires a train crew to conservatively maintain one more block of separation than is necessary to accommodate stopping distance. Under moving blocks, occupancy information is continuously updated, and train crews must only maintain stopping distance plus a safety distance behind a train ahead. Given train length (L_{Train}), approximate minimum distance headways $[H_{Min}(V_{MAS})]$ can be calculated for fixed and moving block control systems [Eq. (4)]. Minimum time headway at the maximum authorized speed $[T_{Min}(V_{MAS})]$ is then related to distance headway by speed [Eq. (5)]

$$H_{Min}(V_{MAS}) = \begin{cases} (B_{Stop}+1) \times L_{Block} + L_{Train}, & fixed\ block \\ D(V_{MAS},0) + Safety\ Distance + L_{Train}, & moving\ block \end{cases} \tag{4}$$

$$T_{Min}(V_{MAS}) = \frac{H_{Min}(V_{MAS})}{V_{MAS}} \tag{5}$$

Previous Research

In the North American context, several researchers have examined the delay effects of train meets and potential mitigation measures. Moore Ede et al. (2007) identified reducing delays due to train conflicts as one of four primary methods of improving line capacity. Adding sidings, increasing turnout speed limits, extending sidings, equalizing train priorities, installing double track, and upgrading control systems were all identified as effective ways to reduce train conflict delays. Dingler et al. (2010) simulated typical North American freight rail corridors and found that train meets are the leading cause of delays. As traffic heterogeneity increased, time spent by lower priority trains waiting during a meet accounted for the greatest proportion of delay. Some proposed solutions included increasing train speeds, reducing siding spacing, removing priorities, and adding a second track. Sogin et al. (2011) found that adding higher priority trains to a single-track rail corridor degraded performance in part because existing traffic was favored in fewer train conflicts and train meets were more complex. Diaz de Rivera et al. (2020) simulated the operations of fleets on single-track freight rail corridors, finding that fleeting trains operating under moving blocks can improve delay performance in part through more efficient meets.

In the context of structured operations, Frank (1966) proposed capacity equations describing two-way traffic on a single-track rail line. The maximum capacity when passing locations accommodate one stopped train was approximately one-third the capacity of the same line with unidirectional traffic. When passing locations accommodated two stopped trains in a double siding, allowing for meets between multiple trains, maximum capacity increased to about half that of unidirectional traffic. Harrod (2007) presented a hypergraph-based railway scheduling model capable of modeling train interactions more complex than pairwise meets and passes involving only two trains. It was found that adding a train significantly faster than existing traffic to a single-track network with sidings allowing complex multitrain meets imposed a lower marginal network cost than adding the same train to a single-track network only capable of pairwise train meets. Afonso and Bispo (2011) developed an optimization model solving the meet and pass problem to improve dispatcher decisions and more efficiently resolve conflicts on single-track railways. Poole (1962) provided a detailed cost estimation framework that relied in part on a line capacity method that calculated expected delay per meet as a function of time spent decelerating from track speed, entering the siding, running the length of the siding, waiting, leaving the siding, and accelerating back to track speed. Expected waiting time depended on the time for an opposing train to run at speed from an adjacent siding. Boysen (2013) calculated train paths to determine consumed capacity and evaluate measures to improve train throughput on the Iron Ore Line in Sweden. The time a train occupied a line section between sidings was calculated as the sum of running time, acceleration and braking time before and after a stop, waiting time, and signal delay time. New sidings, extended sidings, and control systems permitting running meets were shown to effectively decrease consumed capacity on congested segments by allowing quicker meets. This research builds on previous knowledge by more closely examining the fundamental processes of a train meet and their relationship to fixed and variable components of meet delay to investigate new strategies to minimize overall train delay.

Research Questions

This study does not aim to provide specific guidelines on absolute time savings associated with different approaches but instead seeks to provide railway practitioners with relative recommendations on reducing delays associated with train meets. To achieve this goal, this paper addresses three specific research questions:

- 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?

Methodology

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. Simulation software was used to validate the results of the spreadsheet for base combinations of experiment variables.

Train Braking and Acceleration Calculation

A key component of the train meet process is the braking and acceleration characteristics of inferior trains stopping in a siding. Higher-performing trains capable of braking and accelerating in shorter distances and times will incur less delay from a train meet than worse-performing trains. However, the lowest priority trains, such as bulk commodity unit trains, typically have relatively poor train braking and accelerating characteristics (Dingler et al. 2009). To calculate reasonable braking and acceleration times and distances for the study train, this work used equations discussed in detail in Dick ("Impact of Positive Train Control on Railway Capacity," unpublished report). This method calculates train resistance of locomotives and railcars, braking force provided by each railcar and locomotive in the train consist, and acceleration force produced by the locomotives.

Inputs for the train resistance and brake force calculations of each railcar or locomotive included gross rail load, design braking ratio, number of axles, bearing and truck type, brake efficiency, brake shoe type, brake valve type, temperature, wind speed, initial speed, and average track gradient. Total train resistance was calculated by equations from the Association of American Railroads (AAR) train energy model, and is the sum of bearing resistance, rolling resistance, curve resistance, grade resistance, and aerodynamic resistance (Drish and Singh 1991). The braking force calculation assumed a conventional North American train air brake system with 100% operable, fully charged brakes at the time of application, and typical values for other input parameters. The calculation of braking force provided by each railcar considered air brake propagation time, based on the length of brake pipe from the lead locomotive, and build-up time for the brakes to fully apply on each railcar (Carlson 1999). Dick's equations were modified to model brake propagation from locomotives acting as distributed power units. Because locomotive dynamic brakes are not considered fail-safe, forces from dynamic brakes were not included in the braking calculation.

It was assumed that average total resistance and applied braking force provide constant deceleration for small speed decrements. Consequently, braking time and distance was calculated iteratively and the train braking rate was dynamic throughout the braking process. Based on previous work on braking distance sensitivity (Andersen 1995), the cumulative calculated braking distance was multiplied by a safety factor of 1.25 to produce a conservative estimate of the safe braking distance. Similarly, acceleration time and distance were calculated iteratively over small speed increments, incorporating the same average total resistance as the braking calculation. Tractive effort and adhesion limit were calculated according to chapter 7 of the Hay (1982) textbook. While recent research has developed more fine-grained and accurate adaptive predictive braking enforcement algorithms (Brosseau et al. 2013), the braking and acceleration calculations used in this research were only meant to provide reasonable estimates.

Theoretical Train Meet Delay Calculation

To evaluate the relative contributions of specific components of the train meet process to overall meet delay, a set of theoretical equations was developed and encoded in a spreadsheet tool. Fig. 2 depicts most terms and relative distances defined in this section for the 4-Aspect fixed block case with fleets and a 6.4-km-long siding. A complete list of symbols used in the equations is provided in the notation section. Primary inputs include train control system, siding length (L_{Siding}), maximum authorized speed (V_{MAS}), fleeting strategy, and train length (L_{Train}). Other general parameters that can be specified are turnout speed limits (V_{TO}), block length (L_{Block}), turnout foul length (L_{Foul}), and a combined parameter incorporating signal clear time, crew reaction time, and switch throw time (T_{Clear}). The spreadsheet also references braking and acceleration distances and times between different speeds [*D(initial speed, target speed), T(initial speed, target speed)*] calculated as previously described.

Before making any computations, a feasibility check is performed for each scenario. For cases with a fixed block control system, a scenario is infeasible if the stopping distance $D(V_{MAS}, 0)$ exceeds one or two block lengths for 3-aspect and 4-aspect fixed block control systems, respectively. A scenario is also considered

J. Transp. Eng., Part A: Systems, 2020, 146(8): 04020077

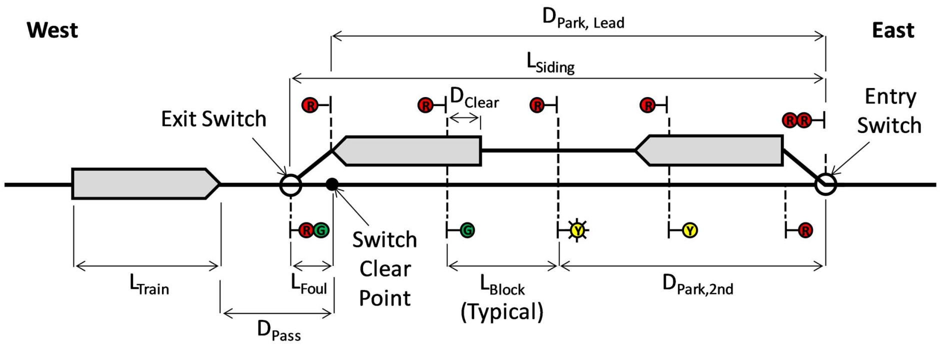

Fig. 2. Reference diagram with labelled variables and distances from the theoretical train meet calculation.

infeasible if the maximum authorized speed exceeds the balancing speed where tractive effort equals train resistance as determined by the train acceleration calculation.

The theoretical train meet delay calculation is divided into three phases to reflect the three distinct phases of a meet: braking, waiting, and acceleration. When there are two inferior trains, the length of each phase is calculated separately for each train. Assuming that V_{TO} is less than the siding speed limit, the braking phase calculation involves a series of time-distance calculations that depend on if V_{TO} limits train braking behavior [Eqs. (6) and (7)]

$$D_{Park} = \begin{cases} L_{Siding} - L_{Foul}, & lead\ inferior\ train \\ L_{Siding} - L_{Foul} - D_{Offset}, & 2nd\ inferior\ train \end{cases} \tag{6}$$

$$V_{TO} \begin{cases} limits\, braking, & D(V_{TO},0) < D_{Park}\, AND\, V_{TO} < V_{MAS} \\ does\, not\, limit\, braking, & Otherwise \end{cases} \tag{7}$$

If V_{TO} does not limit braking, then D_{Brake} and T_{Brake} are $D(V_{MAS}, 0)$ and $T(V_{MAS}, , 0)$, respectively. If there are two inferior trains, it is assumed that the second train has the same braking characteristics and arrives at a later time such that it is not impeded by the lead train's signal wake. If V_{TO} does constrain braking, the braking phase is extended to include trains initially decelerating to V_{TO}, traversing some distance within the siding at constant speed, and then braking to a stop the appropriate distance from the entry switch ($D_{Park,Lead}, D_{Park,2nd}$) [Eqs. (8) and (9)]

$$D_{Brake} = D(V_{MAS}, V_{TO}) + D_{Park,[Lead\ or\ 2nd]} \tag{8}$$

$$T_{Brake} = T(V_{MAS}, V_{TO}) + \frac{D_{Park,[Lead\, or\, 2nd]} - D(V_{TO}, 0)}{V_{TO}} + T(V_{TO}, 0) \tag{9}$$

Because it is assumed trains are homogenous within a fleet, both inferior trains start braking to V_{TO} at the same location. At this location, it is assumed the trains are temporally separated by $T_{\mathrm{Min}}(V_{MAS})$ [Eq. (5)]. At the entry switch, separation is assumed to be $T_{\mathrm{Min}}(V_{TO})$. In effect, this delays the time when the second train comes to a stop, causing a delay for the lead train due to fleeting operations (i.e., fleet delay), which extends the waiting phase of the lead train.

The waiting phase for each inferior train accounts for all the time each train spends stopped during a meet, which primarily depends on how long it takes the superior train(s) to pass the switch clear point located a distance D_{Foul} away from the exit switch location (Fig. 2). First, it is assumed the arrival of the superior train(s) is offset such that they never encounter a restrictive signal. Then, the minimum distance the first superior train can be from the nearest switch clear point when the last inferior train clears the main track at the opposite end of the siding (D_{Pass}) is calculated [Eq. (10)]. D_{Pass} may be negative, indicating that the front of the first superior train can safely operate the clear point of the turnout at one end of the siding while an inferior train still occupies the main track at the opposite end

$$D_{Pass} = \begin{cases} V_{MAS} \times (T_{Clear}) + B_{Stop} \times L_{Block} - L_{Siding}, & fixed\ block \\ V_{MAS} \times (T_{Clear}) + D(V_{MAS}, 0) + Safety\ Distance - L_{Siding}, & moving\ block \end{cases} \tag{10}$$

The time it takes for the superior train(s) to clear the exit switch and allow the inferior train(s) to begin moving again (T_{Pass}) and the departure time of the lead inferior train are then determined assuming the superior train(s) are operating at V_{MAS} [Eq. (11)]. If D_{Pass} is negative and has absolute value greater than the distance from the front of the lead superior train to the end of all following superior trains, T_{Pass} will be zero, indicating that when the inferior train clears the main track, the superior train(s) has already cleared the exit turnout, and the inferior train can proceed to exit the siding as soon as the switch is lined with no waiting delay

$$T_{Pass} = Max\left(0, \frac{D_{Pass} + L_{Train}}{V_{MAS}} + (\#Superior\,Trains - 1) \times T_{\mathrm{Min}}(V_{MAS})\right) \tag{11}$$

While the waiting phase of the lead inferior train may be extended to account for time waiting for the second inferior train to finish its braking phase, the waiting phase for the second inferior train is extended to account for fleet delay from the greater of two sources. The first source is fleet delay incurred waiting for the lead inferior train to clear its signal block for the fixed block case or to reach a speed of 1.6 km/h (1 mi/h) for the moving blocks case. The earliest departure time for the second train is calculated by using the lead train acceleration curve to determine how long it takes the lead train to travel the distance between the end of the lead train and the beginning of the next control block (D_{Clear}). The second source is fleet delay incurred to ensure that minimum separation between inferior trains is maintained. Minimum separation is checked by assuming trains operate at minimum time headways at V_{TO} and V_{MAS}. The earliest departure time for the second train is then back-calculated using its acceleration curve. Fleet delay for the second inferior train is then the difference between departure time of the lead train and the latest of the two calculated departure times for the second train. Waiting time (T_{Wait}) is then calculated for each inferior train [Eq. (12)]

$$T_{Wait} = T_{Pass} + T_{Clear} + Fleet\,Delay \tag{12}$$

Similar to the braking phase, the length of the acceleration phase depends on if V_{TO} limits train acceleration, calculated separately for each inferior train [Eq. (13)]

$$V_{TO}\begin{cases} limits\,lead\,train\,accel., & L_{Foul} + L_{Train} < D(0, V_{TO})\,AND\,V_{TO} < V_{MAS} \\ limits\,2nd\,train\,accel., & L_{Foul} + L_{Train} + D_{Park,Lead} - D_{Park,2nd} < D(0, V_{TO})\,AND\,V_{TO} < V_{MAS} \\ does\,not\,limit\,accel., & Otherwise \end{cases} \tag{13}$$

If V_{TO} does not limit acceleration, then D_{Accel} and T_{Accel} are $D(0, V_{MAS})$ and $T(0, V_{MAS})$, respectively, for all inferior trains. If V_{TO} does limit acceleration, the acceleration phase is extended to include trains first accelerating to V_{TO}, traversing part of the siding at V_{TO}, and then accelerating to V_{MAS} once the end of the inferior train has cleared the exit siding switch [Eqs. (14) and (15)]

$$D_{Accel} = L_{Train} + (L_{Siding} - D_{Park,[Lead\,or\,2nd]}) + D(V_{TO}, V_{MAS}) \tag{14}$$

$$T_{Accel} = T(0, V_{TO}) + \frac{L_{Train} + (L_{Siding} - D_{Park,[Lead\,or\,2nd]}) - D(0, V_{TO})}{V_{TO}} + T(V_{TO}, V_{MAS}) \tag{15}$$

Assuming all superior trains do not incur any meet delay, total meet delay is then calculated as shown in Eqs. (1) and (2). For cases with inferior fleets, all inferior trains incur delay simultaneously while waiting. To normalize across fleeting strategies, total meet delay summed over all inferior trains is divided by the total number of train conflicts being resolved. For example, when one train meets one opposing train, one train conflict is resolved. When a two-train fleet meets an opposing two-train fleet, four train conflicts are resolved. Normalized meet delay is then measured in minutes per train conflict.

Lastly, the feasibility of full speed running meets is checked for the parameters of each scenario. Assuming both inferior and superior trains arrive at the siding at optimal times, if a running meet is possible without any trains reducing speed, total meet delay is reset to zero. Dick ("Impact of Positive Train Control on Railway Capacity," unpublished report) calculates if running meets are possible by comparing siding length to train length and train spacing. A similar approach is used in this study to determine if full speed running meets are possible [Eq. (16)]

$$Full\,speed\,running\,meets\,possible\,IF:$$

$$L_{Siding} > D_{Pass} + L_{Siding} + L_{Train} + (\#of\,Superior\,Trains - 1) \times H_{\mathrm{Min}}(V_{MAS})\,AND\,V_{MAS} \le V_{TO} \tag{16}$$

Study Parameters and Experiment Design

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 (Table 1). The experiment design included four variable factors: train control system, fleeting strategy (and corresponding siding infrastructure configuration), train length, and maximum authorized operating speed. Each factor was simulated over a range of values or levels (Table 2) in a full-factorial design.

Table 1. Track infrastructure parameters

Parameter	Characteristic
No Fleets and EB Fleets track layout	Single-track with 3.2-km (2-mi) passing sidings
Fleets track layout	Single-track with 6.4-km (4-mi) passing sidings
Turnout speed limit (V_{TO})	64.4 km/h (40 mi/h) (for #20 turnout)
3-Aspect fixed block length	3.2 km (2 mi)
4-Aspect fixed block length	1.6 km (1 mi)

Table 2. Experiment design factor levels

Factor	Levels	Level specification
Train control system	3	3-Aspect CTC with fixed blocks (3A) 4-Aspect CTC with fixed blocks (4A) Advanced PTC with moving blocks (MB)
Fleeting strategy	3	No Fleets 2-Train fleets in one direction (EB Fleets) 2-Train fleets in both directions (Fleets)
Train length	3	Short (2 locomotives +80 railcars) Medium (3 locomotives +120 railcars) Long (4 locomotives +160 railcars)
Maximum authorized speed (V_{MAS})	64	25.7–127.1 km/h (16–79 mi/h)

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Table 3. Unit train parameters and characteristics

Parameter	Short train	Medium train	Long train
Number of railcars	80	120	160
Locomotives per train	2	3	4
Locomotive power	3,266 kW (4,380 hp)	3,266 kW (4,380 hp)	3,266 kW (4,380 hp)
Total train length	1,508 m (4,946 ft)	2,261 m (7,419 ft)	3,015 m (9,892 ft)
Total train weight	10,759 metric tons (11,860 US tons)	16,139 metric tons (17,790 US tons)	21,518 metric tons (23,720 US tons)

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 study 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"). The No Fleets and EB Fleets cases were supported by 3.2-km (2-mi) sidings capable of holding one train and representative of typical sidings on primary North American freight rail corridors. The Fleets cases used extended 6.4-km (4-mi) sidings capable of holding a two-train fleet. As implemented, all cases assumed homogenous train traffic consisting of bulk unit trains, a common low-priority train on the North American freight network (Table 3). While train length was varied from 80 to 160 railcars, the power-to-weight ratio was kept consistent. All locomotives were located at the front of each study train except the "Long" train, where one locomotive acted as a midtrain distributed power unit. All calculations were performed for operating speeds ranging from a minimum of 25.7 km/h (16 mi/h), below which special restricted speed operating rules usually take effect, to a maximum of 127.1 km/h (79 mi/h), the maximum freight operating speed for most mainlines in North America. Table 4 displays a selection of calculated braking and acceleration distances and times for a Long train. Typical values of other general inputs for the train meet delay calculations were used (Table 5).

Table 4. Selected calculated acceleration and braking distances and times

Initial speed km/h (mi/h)	Target speed km/h (mi/h)	Distance m (ft)	Time (s)
80.5 (50)	0 (0)	1,457 (4,781)	99
80.5 (50)	64.4 (40)	815 (2,673)	29
64.4 (40)	0 (0)	961 (3,154)	80
0 (0)	64.4 (40)	5,951 (19,525)	502
64.4 (40)	80.5 (50)	7,979 (26,178)	393
0 (0)	80.5 (50)	13,930 (45,702)	896

Table 5. Theoretical train meet delay calculation parameters

Parameter	Value
Switch throw time	10 s
Fixed block signal clear time	10 s
Moving block signal clear time	0 s
Reaction time	2.5 s
Moving block safety distance	30.5 m (100 ft)

Rail Traffic Controller

Rail Traffic Controller (RTC) simulation software was used for validation of the train meet calculation results. RTC combines a robust train performance calculator (TPC) with advanced dispatching logic to simulate rail operations reflective of North American train control systems and operating practices. RTC has been widely used by the North American rail industry for capacity studies and has been itself validated against numerous real rail operations (Pouryousef et al. 2015).

To validate the train performance and meet calculations presented earlier, small single track networks with a 3.2-km (2-mi) or 6.4-km (4-mi) siding were analyzed in RTC incorporating either 4-aspect CTC fixed block (with 1.6-km- or 2-mi-long signal blocks) or moving block control systems. The simulation of each scenario consisted of a single meet between two individual or four fleeted study trains (set as the Long unit train). The simulations were deterministic, with train schedules set using a trial-and-error approach to minimize the time required to accomplish the meet. The frequency of train performance calculations was set at an aggressive interval of 7.6 m (25 ft) to get more fine-grained TPC results than typically used for RTC simulations.

Typical North American practice calculates train delay as the difference between actual running time for a given train and its minimum running time operating at maximum authorized speeds without any impedances. To analyze the RTC results, the running time and average speed of each train between fixed points on either side of the siding was measured. The average speed of the superior train (s) which neither stopped nor incurred delay was used to calculate a minimum run time across the corridor. Aggregate train delay was obtained as the sum of the differences between simulated run time and minimum run time for the inferior train(s). Because all delay in the experiment is attributable to train meets, aggregate train delay was divided by the number of train conflicts in the scenario (one or four) in order to obtain normalized meet delay. One limitation of RTC is that trains can only be dispatched to the nearest minute and certain fine-grained inputs of the TPC are built-in, affecting the ability to evaluate theoretical minimum meet times using the process described earlier in the paper. Therefore, RTC was used for general validation while the theoretical train meet delay calculation was the primary methodology.

Results

RTC Simulation/Validation

Individual meets between two Long trains were simulated in RTC under fixed block and moving block control systems with the delay outputs normalized for the number of train conflicts in each meet (Table 6). Meets were simulated for 64.4 and 80.5 km/h (40 and 50 mi/h) maximum authorized speeds to test realistic operating speeds for the study train and cases where the maximum authorized turnout speed [64.4 km/h (40 mi/h)] does not and does affect train handling during the meet, respectively. Because RTC only allows

Table 6. Train meet delay calculation validation results

Scenario	Maximum authorized speed (km/h, mi/h)	Meet delay per train conflict (min)		
		RTC	Theoretical	Difference
4A no fleets	64.4, 40	5.7	5.3	−0.4
4A no fleets	80.5, 50	6.8	7.2	+0.4
MB no fleets	64.4, 40	5.4	4.4	−1.0
MB no fleets	80.5, 50	6.7	6.8	+0.1

trains to be dispatched to the nearest minute, the margin of error is taken as ±1 min. For all four No Fleets cases, the theoretical calculation produces a meet delay per train conflict within 1 min of the equivalent RTC result. On this basis, the theoretical approach and its component braking and acceleration calculations described earlier in the paper are expected to produce reasonable estimates of train meet delay.

Effect of Control System, Fleeting, and Speed

For a Long train, different train control systems and fleeting strategies produced significantly different normalized meet delay responses as maximum authorized speed increased (Fig. 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. In the 4-aspect fixed block curves, there was a discontinuity around 85 km/h (52.8 mi/h), reflecting the speed at which calculated braking distance exceeded one control block length and minimum train headways correspondingly increased. Minimum train separation at speeds higher than 85 km/h was similar to minimum train separation under 3-aspect fixed blocks, with the 3A No Fleets and 4A No Fleets delay curves overlapping.

The calculated balancing speed was approximately 112.7 km/h (70 mi/h) and was approximately the same for all study train lengths. As maximum authorized speed approached this point, it took increasingly longer time and distance to accelerate to the highest allowable speed. Correspondingly, meet delay was very high for all cases near the balancing speed. For the given study train consist, operations at speeds above the balancing speed were infeasible.

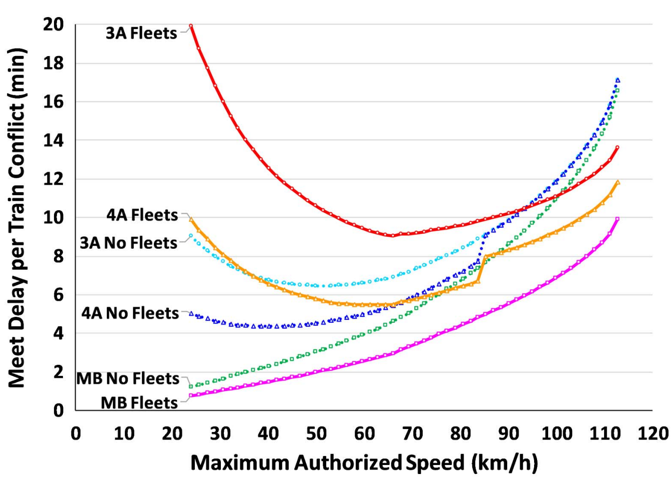

Fig. 3. Normalized meet delay response curves for varying maximum authorized speeds and combinations of train control system and fleeting strategy.

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 suboptimal, 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. The 3A Fleets case, with the largest minimum headways, was the worst performing of all cases, except at higher speeds. At lower speeds, operating fleets under 3-aspect and 4-aspect fixed blocks resulted in inefficient meets because 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 MB No Fleets case. When the effectiveness of fleets was boosted by moving blocks, the result was the MB Fleets case producing the lowest meet delay across all speeds.

Effect of Train Length

Under 4-aspect fixed block signals, increasing train length generally corresponded to higher meet delay for both the Fleets and No Fleets cases [Fig. 4(a)]. For a given fleeting strategy, the shape of the curve for each train length remained similar and converged to a high delay value as speed approached the balancing speed. Shifts in the exact location of the discontinuity where braking distance began to exceed one block length were due to the distributed power unit in the Long train slightly improving braking performance. Under moving blocks, shorter trains could perform full-speed running meets at lower speeds with minimal delay [Fig. 4(b)]. The combination of shorter train lengths, corresponding shorter braking distances, and moving blocks allowing decreased train separation effectively reduced the length of siding required to perform a full-speed running meet. This threshold occurred between the Medium and Long trains for the 3.2-km-long siding in the No Fleets cases and the 6.4-km-long siding in the Fleets cases.

Fixed versus Variable Meet Delay

As described earlier, fixed meet delays do not change depending on the number of trains partaking in the meet and include delays due to braking, acceleration, and signal and switch clear times. Variable delays include waiting for oncoming trains to pass and fleet delays. Dividing four selected delay curves from Fig. 3 into fixed and variable delays explained the different delay responses to changes in speed, control system, and fleeting strategy (Fig. 5). For the 4A No Fleets case, the impact of longer braking and acceleration times and distances was illustrated by the drastic increase in fixed delays as maximum authorized speed increased [Fig. 5(a)]. In particular, acceleration delays became excessive as speed approached the balancing speed. As speed increased, the distribution of delays shifted from being mostly variable delays to mostly fixed delays.

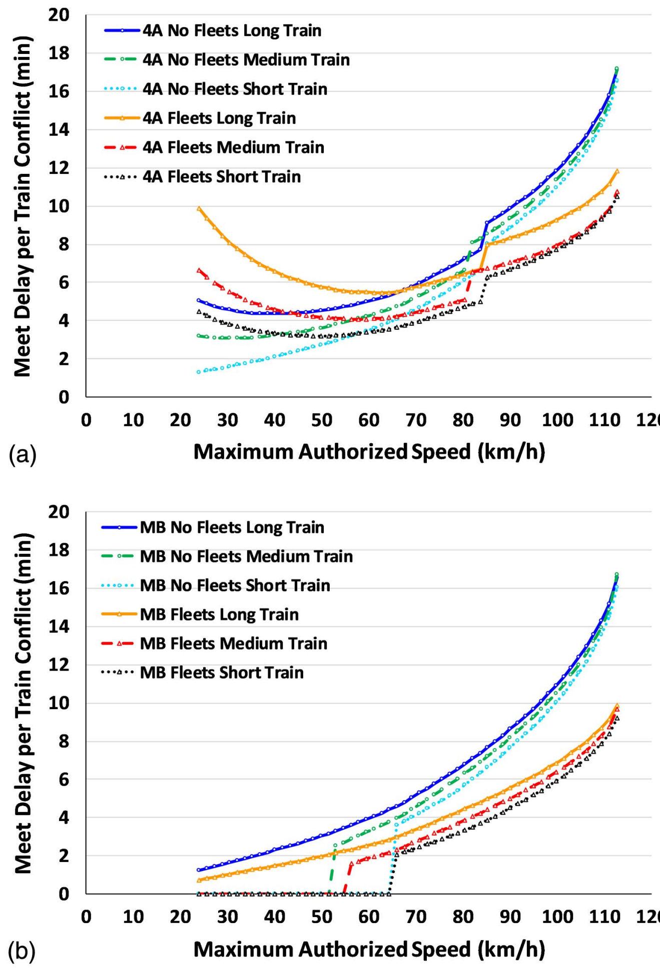

Fig. 4. Normalized meet delay response curves for varying maximum authorized speeds, train lengths, and fleeting strategies under: (a) 4-aspect fixed block signals; and (b) moving blocks.

At low speeds, it took longer for the superior train to pass and traverse suboptimal block lengths, increasing waiting time (variable delay) and total meet delay. For the MB No Fleets case, fixed delays similarly caused a large increase in meet delay as speed approached balancing speed [Fig. 5(b)]. However, the customization of moving blocks minimized variable waiting time delays at all speeds, preventing the low-speed meet delay increase observed in the fixed block case.

Examining fleets of trains operating under 4-aspect fixed blocks and moving blocks [Figs. 5(c and d)] demonstrated how fleets amplified the existing fundamental differences between the two train control systems. Under fixed blocks, variable delays were significantly higher, largely driven by the need for the inferior trains to wait longer to account for the headway between passing superior trains. However, at higher speeds, fixed delays again became the majority of meet delays. Under moving blocks, superior trains operated closer together and passed faster than under fixed blocks, allowing the inferior trains to spend significantly less time waiting. At the same time, fixed delays were minimized by allowing four separate train conflicts to be resolved in a single meet. Further dividing the 4A Fleets delay curve into individual processes reveals the interactions driving the fixed and variable delay responses (Fig. 6). Among the variable delay sources, the majority of delay was due to waiting for opposing trains to pass, especially at low speeds. Among the sources of fixed delays, acceleration delays grew more rapidly than braking delays as speed approached the balancing speed, reflecting the difficulty in accelerating a slow, heavy unit train to higher speeds. Meanwhile, delays waiting for switches and signals to clear were a constant but minor component of fixed delays.

Directional Fleeting

Dispatching trains in fleets only in the superior direction [eastbound (EB) in this study] removed one source of variable delays: fleet delays that extend the waiting phase of the meet process. With this fleeting strategy, an inferior train meeting a superior two-train fleet resolved two train conflicts per meet. Examining delay responses for all three fleeting strategies under 4-aspect fixed blocks and moving blocks revealed that the delay response curves of one-way fleets exhibited characteristics of both the No Fleets and two-way fleeting strategies (Fig. 7). At lower speeds, reduction in fleet delay in the 4A EB Fleets case was overcome by the need to wait longer for the superior train fleet to pass, performing similarly to the 4A Fleets case. Because the siding was only 3.2 km (2 mi) long, the lead superior train could not operate as far beyond the siding exit switch as it could for the 6.4 km (4 mi) siding used in the two-way fleets case (i.e., D_{Pass} became less negative with a shorter siding). Therefore, a greater portion of the superior fleet still had to clear the siding exit switch when the inferior train's waiting phase began. At higher speeds, fleet delays made up a bigger proportion of total meet delay while the superior fleet could pass quicker, reducing the impact of a shorter siding and resulting in a lower total meet delay than even the two-way fleets case. Under moving blocks, a similar phenomenon occurred, with the inferior train waiting longer for the superior trains to pass due to the shorter siding length. In contrast to the fixed block comparison, the MB Fleets case performed significantly better than the MB EB Fleets case, illustrating the effectiveness of moving blocks in maximizing the advantages of fleeting trains. Only at high speeds did the MB EB Fleets and MB Fleets cases converge.

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. As demonstrated, 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. Comparing the MB EB Fleets and MB No Fleets cases, which share the same infrastructure configuration, revealed an intersection around 60 km/h (37.3 mi/h) to the right of which one-way fleet meets were more efficient. 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. Operating one-way fleets with fleet-length sidings may shift this intersection point to much lower speeds by removing fleet delay as well as minimizing the time it takes a superior fleet to pass.

Sensitivity Analysis

One of the key variable inputs to the theoretical meet delay calculation was the calculated braking and acceleration distances and times, because they affected minimum train separation and the magnitude of fixed delays. A sensitivity analysis was performed to check the robustness of the train meet calculation for a 64.4 km/h (40 mi/h) maximum authorized speed and a Long study train. Input braking distances and times were uniformly changed by plus or minus 20% and acceleration distances and times were similarly varied. The corresponding percent change in meet delay per train

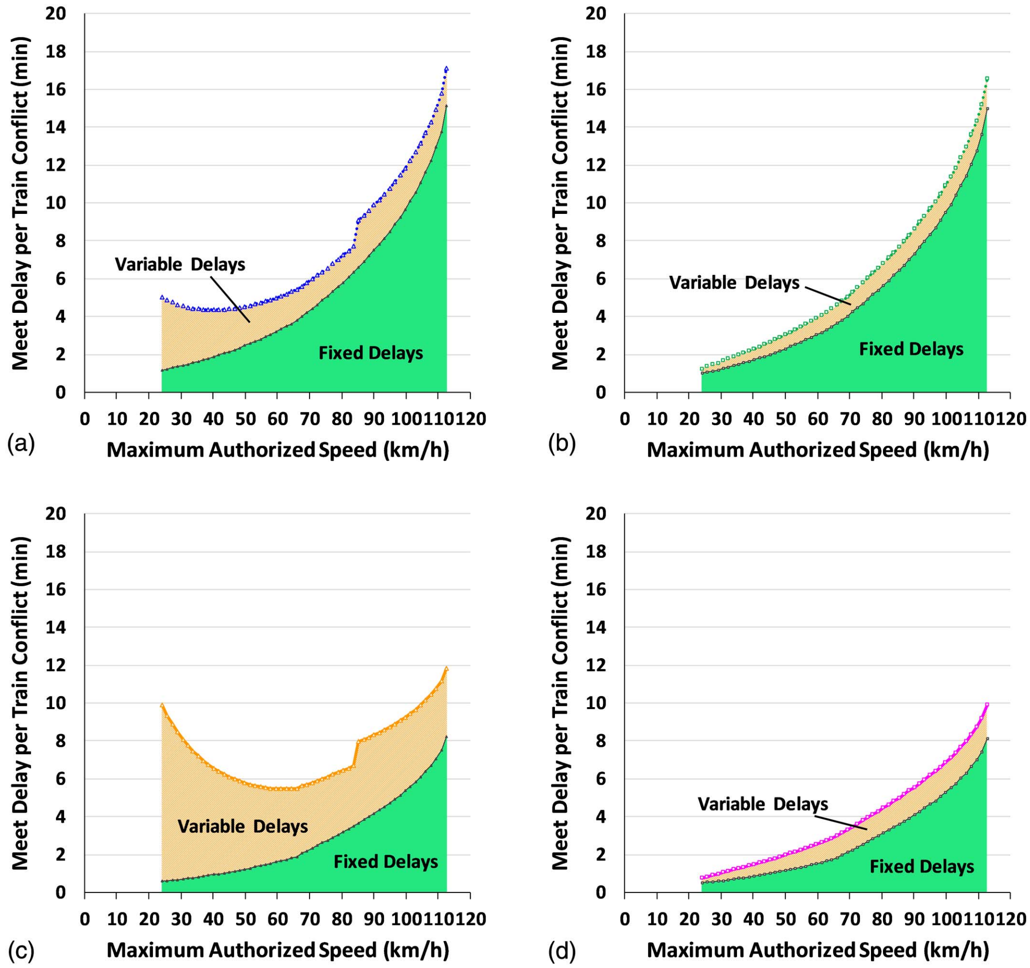

Fig. 5. Fixed and variable delay response curves with varying maximum authorized speeds for: (a) 4-aspect fixed block signals without fleets; (b) moving blocks without fleets; (c) 4-aspect fixed block signals with fleets; and (d) moving blocks with fleets.

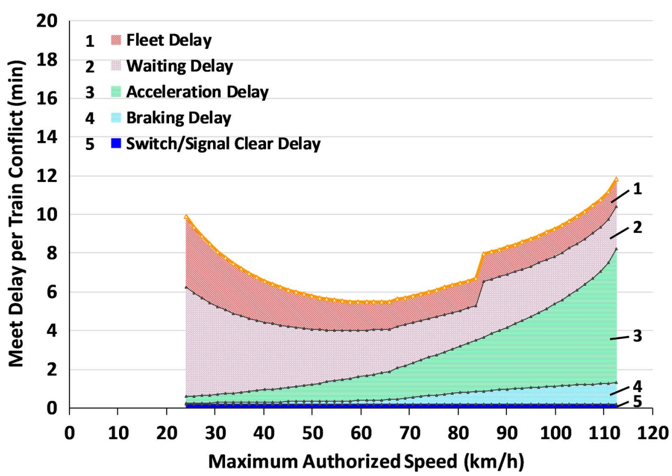

Fig. 6. Component delay response curves for the 4A Fleets scenario comprised of fixed delay sources (acceleration, braking, and switch/signal clear delay) and variable delay sources (fleet and waiting delay).

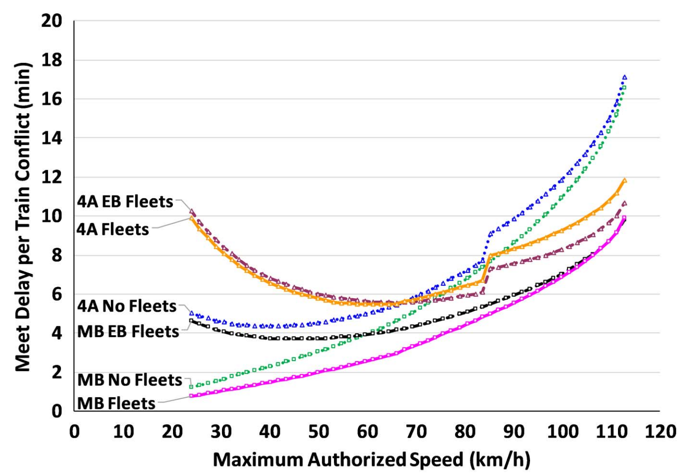

Fig. 7. Meet delay response curves with varying maximum authorized speeds for moving block and 4-aspect fixed block scenarios with superior train fleets only (EB Fleets), fleets in both directions (Fleets), and individually dispatched trains (No Fleets).

conflict was recorded for each combination of control system and fleeting strategy, and arc elasticity calculated as the percent change in meet delay divided by the percent change in the input variable (Fig. 8). Generally, meet delay was more sensitive to changes in acceleration inputs than braking inputs. All tested variable combinations had an arc elasticity below 1.0, indicating that meet delay is not disproportionately sensitive to changes in acceleration and braking inputs.

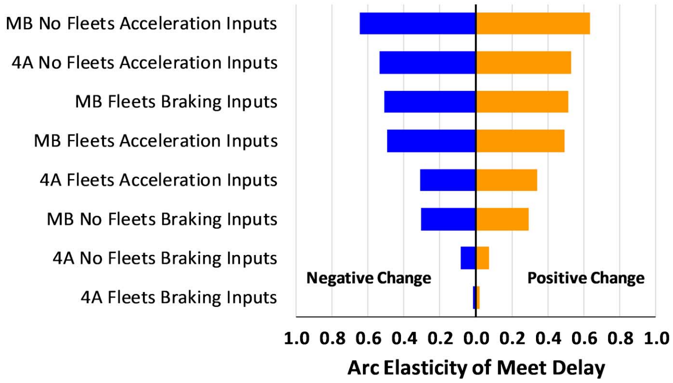

Fig. 8. Arc elasticity of normalized meet delay for negative and positive changes in braking and acceleration inputs for selected base cases.

Conclusions

On high-tonnage single-track rail corridors, train meets are a major source of overall delay, primarily affecting low-priority trains. On busy lines, low-priority trains can accrue excessive delays from frequent stops, resulting in higher costs from more frequent crew expirations, reduced fuel efficiency, lower equipment utilization, and longer travel and cycle times. Moving low-priority trains more quickly across a corridor indirectly helps high-value high-priority trains by freeing up passing sidings for use in resolving other train conflicts and reducing the number of meets for later high-priority traffic.

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. This study contributes to the rail domain's overall body of knowledge by investigating several strategies for reducing the minimum delay penalty associated with train meets that take advantage of interactions between fixed and variable delays.

Meet efficiency can be improved in the near term by only dispatching high-priority trains in fleets in one direction (i.e., EB Fleets scenarios). Utilizing existing fixed block signals and single-train-length sidings, fleeting high-priority trains shows promise in reducing meet delay per train conflict at higher speeds compared to dispatching trains individually. Keeping high-priority fleets together across an entire corridor would be operationally feasible since they would be expected to bypass short sidings making few, if any, stops, and can operate at relatively constant speeds. In the medium term, previous investments in PTC or other train control technology may be leveraged to implement moving blocks. 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. In contrast to moving block fleets, fleeting both low- and high-priority trains under fixed block signals is of limited effectiveness due to greater minimum train separation requirements.

To determine the minimum amount of delay associated with various meet interactions, this study analyzed "perfect" meets where opposing trains arrive at the meet location at optimal times. However, operations in North America follow an unstructured philosophy (Pouryousef et al. 2015). Improvised operations mean that meet locations are not known ahead of time and that "perfect" meets are unlikely. The train deemed inferior in the meet will almost always arrive in the siding first and wait until the superior train arrives. High levels of schedule flexibility have been associated with high levels of delay on single-track rail corridors (Dick and Mussanov 2016; Dick et al. 2019b). Furthermore, uncertainty about train arrival time reduces the feasibility of running meets. The scale of delay reductions achievable using the strategies proposed in this work may be dwarfed by the delays due to schedule flexibility. However, reducing delay due to the fundamental interactions in a train meet still provides relative benefits and decreases in the base amount of time spent waiting for superior trains to pass. In addition to the direct waiting time reductions, fleeting trains increases the number of gaps during which low priority trains can move between adjacent sidings. Moving blocks can allow low priority trains to utilize shorter gaps between opposing trains than would otherwise be possible. In railway networks that follow a structured or timetabled operation with preplanned meets, such as is common in Europe and Asia, meets are much more predictable. When trains are running on or close to schedule, meet delay is controlled by fundamental meet interactions rather than schedule flexibility and the results of this study become directly applicable. Reducing meet delay decreases the impact of meets on a timetable, potentially creating new train slots and improving capacity on scheduled railroads.

General validation was performed using RTC simulations. Future work should include further validation of the theoretical train meet delay calculation through additional simulation experiments and comparison to real-life data to address the limitations of the RTC software. One limitation of this study is that it was conducted assuming North American train characteristics, control systems, and operating practices. Therefore, the magnitude of meet delay values presented is specific to the study train and experiment parameters. However, the general trends are based on basic interactions between the various components of a train meet and are expected to be applicable to other heavy haul rail contexts. Future work should also consider the effect of changing inputs such as siding and signal block length as well as the efficiency of meets between different train types with significantly dissimilar train handling characteristics. To provide better context for these results, it would be helpful to analyze the effects of schedule flexibility on train meets (i.e., "imperfect" meets). Lastly, future work should more closely investigate the ramifications of operating fleets of short trains on existing siding infrastructure built for one long train. This may increase the feasibility of running more frequent, shorter trains to improve customer service with direct point-to-point transportation enabled by future efficiency improvements in rail operations.

While the absolute delay reduction results are limited to the specific experimental parameters and assumptions of this study, understanding fixed and variable meet delays and relative meet efficiency differences across varying combinations of train control system and fleeting strategy will be useful to railway practitioners evaluating future operating and capital plans and investments in moving blocks.

Data Availability Statement

Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request. The following spreadsheets and incorporated macros were used in this research: Braking and Acceleration Calculator, Train Meet Calculator, RTC Delay Calculator, and Figure Data.

Acknowledgments

This research was supported by the National University Rail Center (NURail), a US DOT OST Tier 1 University Transportation Center, and the Association of American Railroads. The first author was partially supported by the CN Research Fellowship in Railroad Engineering. The authors thank Eric Wilson of Berkeley Simulation Software, LLC, for the use of Rail Traffic Controller simulation software and technical support.

Notation

The following symbols are used in this paper:

B_{Stop} = number of control blocks needed to accommodate stopping distance;
D(initial speed, target speed) = acceleration or braking distance from initial to target speed;
D_{Accel} = total distance required for meet acceleration phase;
D_{Brake} = total distance required for meet braking phase;
D_{Clear} = distance a stopped lead train must travel to clear its control block;
$D_{Park,Lead}$ = distance from entry switch to stop location in siding for lead inferior train;
$D_{Park,2nd}$ = distance from entry switch to stop location in siding for second inferior train (if fleets);
D_{Pass} = minimum distance between the head-end of the first superior train, and the clear point of the siding exit switch at the instant the last inferior train clears the main track, to avoid slowing down the first superior train;
$H_{Min}(Speed)$ = minimum distance headway for indicated speed;
L_{Block} = control block length;
L_{Foul} = turnout foul length;
L_{Siding} = total passing siding length;
L_{Train} = train length;
T(initial speed, target speed) = acceleration or braking time from initial speed to target speed;
T_{Accel} = time required for meet acceleration phase;
T_{Brake} = time required for meet braking phase;
T_{Clear} = total time for signal to clear, crew to react, and switch to be thrown;
$T_{Min}(Speed)$ = minimum time headway for indicated speed;
T_{Pass} = time for the superior train(s) to clear exit siding switch and complete pass;
T_{Wait} = time required for meet waiting phase;
V_{MAS} = maximum authorized track speed; and
V_{TO} = maximum authorized turnout speed.

References

AAR (Association of American Railroads). 2019a. "Positive train control fact sheet." Accessed September 13, 2019. https://www.aar.org/wp-content/uploads/2019/03/AAR-PTC-Fact-Sheet-2019.pdf.

AAR (Association of American Railroads). 2019b. "The economic impact of America's freight railroads." Accessed February 24, 2020. https://www.aar.org/wp-content/uploads/2018/05/AAR-Economic-Impact-US-Freight-Railroads.pdf.

Afonso, P. A., and C. F. Bispo. 2011. "Railway traffic management: Meet and pass problem." *J. Syst. Manage. Sci.* 1 (6): 1–26.

Andersen, D. R. 1995. *Study of the sensitivity of predicted stopping distance to changes to input parameters*. Pueblo, CO: Association of American Railroads.

ASCE. 2017. *2017 infrastructure report card*. Reston, VA: ASCE.

Barrow, K. 2015. "Pilbara's heavyweight champion flexes its muscles." *Int. Railway J.* 55 (11): 20–24.

Boysen, H. 2013. "Quicker meets, heavier loads and faster empties—Effects on transportation capacity and cycle time." In *Proc., 10th Int. Heavy Haul Association (IHHA) Conf.* Virginia Beach, VA: IHHA.

Brosseau, J., B. M. Ede, S. Pate, R. Wiley, and J. Drapa. 2013. *Development of an operationally efficient PTC braking enforcement algorithm for freight trains*. Washington, DC: Federal Railroad Administration.

Carlson, F. 1999. *Braking considerations for positive train control*. Pueblo, CO: Transportation Technology Center.

Diaz de Rivera, A., C. T. Dick, and L. E. Evans. 2020. "Improving railway operational efficiency with moving blocks, train fleeting, and alternative single-track configurations." *Transp. Res. Rec.* 2674 (2): 146–157. https://doi.org/10.1177/0361198120905842.

Dick, C. T., and D. Mussanov. 2016. "Operational schedule flexibility and infrastructure investment: Capacity trade-off on single-track railways." *Transp. Res. Record* 2546 (1): 1–8. https://doi.org/10.3141/2546-01.

Dick, C. T., D. Mussanov, L. E. Evans, G. S. Roscoe, and T.-Y. Chang. 2019a. "Relative capacity and performance of fixed and moving block control systems on North American freight railway lines and shared passenger corridors." *Transp. Res. Rec.* 2673 (5): 250–261. https://doi.org/10.1177/0361198119841852.

Dick, C. T., D. Mussanov, and N. Nishio. 2019b. "Transitioning from flexible to structured heavy haul operations to expand the capacity of single-track shared corridors in North America." *Proc. Inst. Mech. Eng. Part F: J. Rail Rapid Transit* 233 (6): 629–639. https://doi.org/10.1177/0954409718804427.

Dingler, M., A. Koenig, S. Sogin, and C. P. L. Barkan. 2010. "Determining the causes of train delay." In *Proc., 2010 American Railway Engineering and Maintenance-of-Way Association (AREMA) Annual Conf.* Lanham, MD: AREMA.

Dingler, M. H., Y.-C. Lai (Rex), and C. P. L. Barkan. 2009. "Impact of train type heterogeneity on single-track railway capacity." *Transp. Res. Rec.* 2117 (1): 41–49. https://doi.org/10.3141/2117-06.

Drish, W. F., and S. P. Singh. 1991. *Train energy model validation using revenue service unit coal train data*. Chicago: Association of American Railroads.

FRA (Federal Railroad Administration). 2012. *Positive train control implementation status, issues, and impacts*. Washington, DC: FRA.

Frank, O. 1966. "Two-way traffic on a single line of railway." *Oper. Res.* 14 (5): 801–811. https://doi.org/10.1287/opre.14.5.801.

Gorman, M. F. 2009. "Statistical estimation of railroad congestion delay." *Transp. Res. Part E: Logist. Transp. Rev.* 45 (3): 446–456. https://doi.org/10.1016/j.tre.2008.08.004.

Harriss, L. 2016. "Moving block signalling." In *POSTbrief*. London: Parliamentary Office of Science and Technology.

Harrod, S. 2007. "Railway capacity management and planning." Ph.D. thesis, Dept. of Quantitative Analysis and Operations Management, College of Business, Univ. of Cincinnati.

Hay, W. W. 1982. *Railroad engineering*. New York: Wiley.

Institute for Transport Science RWTH Aachen. 2008. *Influence of ETCS on line capacity.* Paris: Generic Study, International Union of Railways.

Lindfeldt, O. 2012. "From single to double track: Effects of alternative extension measures." In *Computers in railways XIII*, 313–324. New Forest, UK: WIT Press.

Lovett, A. H. 2017. "Railroad decision support tools for track maintenance." Ph.D. Dissertation, Dept. of Civil and Environmental Engineering, Univ. of Illinois at Urbana-Champaign.

Lovett, A. H., C. T. Dick, and C. P. L. Barkan. 2015. "Determining freight train delay costs on railroad lines in North America." In *Proc., Int.*

Association of Railway Operations Research (IAROR) 6th Int. Conf. on Railway Operations Modelling and Analysis, Delft, Netherlands: IAROR.

Machalaba, D. 2019. "Past prime: No technology is forever; we're living that lesson now." In *Trains*, 30–37. Milwaukee WI: Kalmbach Media.

Martland, C. D. 2008. *Railroad train delay and network reliability*. Pueblo, CO: Transportation Technology Center.

Moore Ede, W. J., A. Polivka, and J. Tunna. 2007. "Optimizing capacity by trade-offs among train control, infrastructure, mechanical, and engineering considerations." In *Proc., International Heavy Haul Association (IHHA) Specialist Technical Session*. Virginia Beach, VA: IHHA.

Petersen, E. R., and A. J. Taylor. 1987. "Design of a single track rail line for high speed trains." *Transp. Res. Part A* 21A (1): 47–57. https://doi.org/10.1016/0191-2607(87)90023-9.

Poole, E. C. 1962. *Costs—A Tool for railroad management*. New York: Simmons-Boardman Publishing Corporation.

Pouryousef, H., P. Lautala, and T. White. 2015. "Railroad capacity tools and methodologies in the U.S. and Europe." *J. Modern Transp.* 23 (1): 30–42. https://doi.org/10.1007/s40534-015-0069-z.

Resor, R. R., M. E. Smith, and P. K. Patel. 2005. "Positive train control (PTC): Calculating benefits and costs of a new railroad control technology." *J. Transp. Res. Forum* 44 (2): 77–98. https://doi.org/10.5399/osu/jtrf.44.2.841.

Richards and Cobb. 2006. "Multiple-track main lines." In *Trains*.

Rodrigue, J.-P., and B. Slack. 2020. "Rail transportation and pipelines." In *The geography of transport systems*. 5th ed. New York: Routledge.

Shih, M.-C., C. T. Dick, S. L. Sogin, and C. P. L. Barkan. 2014. "Comparison of capacity expansion strategies for single-track railway lines with sparse sidings." *Transp. Res. Rec.* 2448 (1): 53–61. https://doi.org/10.3141/2448-07.

Sogin, S., C. P. L. Barkan, and M. R. Saat. 2011. "Simulating the effects of higher speed passenger trains in single track freight networks." In *Proc., Winter Simulation Conf.*, 3679–3687. New York: Institute of Electrical and Electronics Engineers.

Sogin, S. L., Y.-C. Lai (Rex), C. T. Dick, and C. P. Barkan. 2016. "Analyzing the transition from single- to double-track railway lines with nonlinear regression analysis." *Proc. Inst. Mech. Eng. Part F: J. Rail Rapid Transit* 230 (8): 1877–1889. https://doi.org/10.1177/0954409715616998.

Stagl, J. 2018a. "Class I railroads continue the longer-train trend." In *Progressive railroading*. Milwaukee WI: Trade Press Media Group.

Stagl, J. 2018b. "On a high-tech trek: Norfolk Southern notes progress in its quest to become a 'technology-enabled railroad of the future'." In *Progressive railroading*. Milwaukee WI: Trade Press Media Group.

USDOT. 2016. *Beyond traffic 2045*. Washington, DC: USDOT.

White, T. 2005. "Alternatives for railroad traffic simulation analysis." *Transp. Res. Rec.* 1916 (1): 34–41. https://doi.org/10.1177/0361198105191600106.