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Secure Interchange Routing

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Abstract

Locations that connect tracks from different rail-road companies—referred to as interchange points—exchange crew, locomotives, and their associated consists. Because trains have a single degree of freedom in movement, that is, they can only operate along the tracks, any delay occurring at an interchange point causes cascading delays in connecting tracks. In addition, authentication and authorization that is expected to take place at interchanges in PTC controlled train movement may add extra delays due to mutual authentication between two security domains. In this paper we propose a model that can address safety and security concerns and their interrelationships that govern train movement through an interchange point. We show how a profile of safe operations can be computed for operating an interchange point.

Keywords: Railroad, Routing, Interchange, Safety, and Security

1. Introduction

The primary objective of inter-domain rail operation is to minimize rail traffic delay at interchange points while maintaining safe operating conditions. Delays add to a railroads cost of business and can have a significant impact on the US economy. Techniques used to minimize delays are categorized as tactical (*i.e.* addresses local scheduling decisions) and strategic (*i.e.* addresses global scheduling decisions over regions). Taken together they control the end-to-end delays encountered by a trains moving from point A to point B. We address the specific case where points A and B are on different sides of a single rail track that connects two regions belonging to two railroad companies that is commonly referred to as an interchange point. This problem is significant because, if both regions are controlled by the proposed Positive Train Control (PTC) systems, then each side has its own authentication and authorization system that must communicate with the other side to allow an approaching train to go through the interchange point. Our model shows how the two regions can control the movements of trains while maintaining safe inter-train distance and authenticating the crew, and locomotives.

The rest of the paper is written as follows. Section 2 discuses delay in the trail environment as it applies to secure interchange operations. Section 3 outlines our proposed model, and the conditions required for safe secure interchange operation. Section 4 takes the conditions for safe secure interchange operations and relates them to underlying physics associated with train operations and communications. Section 5 illustrates the application of our model. Finally Section 6 discusses the limitations of our model, and outlines areas of further research to reduce those limitations.

2. Delays and Delay Modeling

Delays impact train operations significantly. For example, in 1997, due to service delays on the Union Pacific (UP) railroad, the State of Texas alone encountered excess costs of over $1.0 billion [1-2]. General delay minimization planning must take into account a whole host of issues such as particular rail lines that are used (line planning), customer service requirements (demand analysis), consist management (allocation of train cars and locomotives), and crew management (distribution and allocation of the train and crew). Each of these has different, and often competing goals. Computing an optimal system wide (strategic) solution requires the ability to schedule the right trains frequently enough to be service-responsive to customers, long enough to be cost effective, and spaced so as to minimize transfer time in yards and congestion over the right of way, including interchange points. In this larger planning and scheduling problem, we model the tactical behavior of regarding inter-domain operations.

Figure 1 shows three railroads referred to as Railroad *A*, Railroad *B* and Railroad *C*, where we concentrate on the interchange point between Railroad A and Railroad *B*. As independent entities, each one operates its own trust management system within its own security domain, and consequently has Certificate authorities C_A, C_B and Dispatcher systems DS_A and DS_B respectively. We consider the case where trains arriving on Railroad *A*'s track attempts to enter the interchange point to Railroad *B*'s side (that is from the bottom right hand side to the bottom left hand track in **Figure 1**). The trains are named $T_1, \cdots, T_X, T_{X+N}$ where *X* and *N* are integers.

When Railroad *A* wishes to send Train $T_X, \cdots, T_{X+N}$ to Railroad *B*'s tracks, two communications may occur. The first is that C_A and C_B may exchange certificates L_X, and DS_A and DS_B may exchange messages (say M_X) in addition to DS_A and/or DS_B exchanging messages with trains. Figure 1, only illustrate the communications of DS_A with C_A, T_X with DS_B and DS_A with C_A, where other trust management messages may flow.

Traffic delays can be a combination of two separate, but interrelated elements. First are delays resulting from the specific physical operating characteristics of the trust management, dispatching and communication systems. The physical operating characteristics include slack time built into the train schedule, traffic congestion, scheduled stops, authorized speeds, location of other trains, on track equipment, maintenance of way work zones, track physical condition, status of signals and communication bandwidth. Although there is an extensive body of work on optimization of network wide routing in general, and railroad networks in particular, such as those described in [3-10], we do not attempt to either develop new, or improve upon existing dispatching and routing methodologies or consider more complex interchange configurations in this paper.

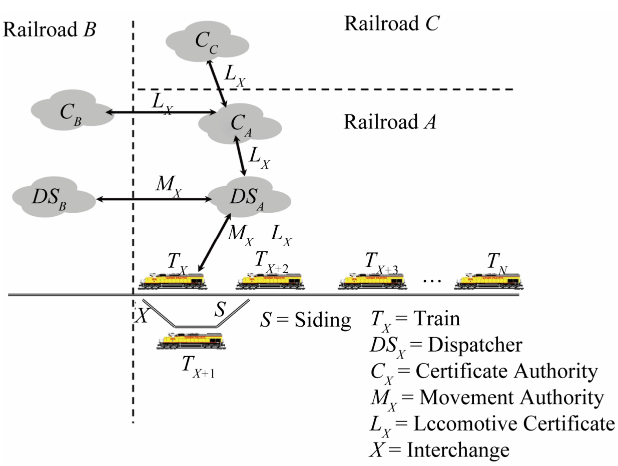

Figure 1. Railroad security domains.

The second category of delays arise due to scheduleing at interchange points, where two pre-requisites must be satisfied before movement authority is granted: 1) Lo- comotive and the crew must be authenticated and 2) Tra- ck space must be available in the second domain.

Assuming a single unidirectional track with a single siding but no other merging or branching greatly simplifies the optimization of delay at interchanges. Although there are numerous approaches ([11-21]), addressing this configuration these solutions do not consider authentication delays that may occur due to the imposition of a trust management system. Although other more complex track configurations such as using multiple parallel facing or reverse spurs can be built or combinations of facing and reverse spurs can be considered, these cost more money to construct [22].

Having one siding gives the dispatcher much needed room to rearrange the order of trains that proceed to the interchange. For example, the delay of Train T_X at the interchange point may be mitigated to some extent by the availability of a siding *S*. If the train dispatcher for Company *A* is aware, sufficiently in advance of the arrival of T_X , to the interchange point of a potential delay, the dispatcher could direct T_X into the siding *S*, allowing Train T_{X+1} to proceed along the main line to the interchange point. However, if the siding S is not available, or T_X has passed the point in which will allow the dispatcher to direct T_X into the siding *S*, T_X will block the following trains from reaching the interchange point. Even if the dispatcher was able to safely divert T_X into the siding *S*, allowing T_{X+1} to proceed along the mainline to the interchange point, any delay encountered in the process of moving Train T_{X+1} at the interchange point will delay the following Trains T_{X+2} through T_{X+N} .

3. Cross Domain Operations

Our model of the tactical behaviors of Dispatcher *A* and Dispatcher *B* relies on the following assumptions:

- There is a main track and a single siding in domain *A* and a single main track in domain *B*.
- All trains in domain *A* are of the same length, but may have different priorities for movement.
- Train movements are from Domain *A* to Domain *B*.
- Dispatcher *A* (DS_A) and B (DS_B) have exchanged a session key between each other. Dispatcher *A* (DS_A) has authenticated locomotive T_X and the associated engineer E_X prior to receiving movement requests.
- Dispatcher *A* (DS_A) controls the signal whose aspect controls the movement of a train from domain *A* while Dispatcher *B* (DS_B) controls the signal whose aspect controls the movement of a train into domain

B.

- For a train to leave domain A and enter domain B, both the Dispatcher A and Dispatcher B have to authorize movement, coordinating the signal aspects.
- The siding S is of length L and can contain only one train. The main track parallel to the siding may also contain one train.
- There are up to N trains in the queue awaiting authorization to enter domain B.
- Requests for authorizations from A to B are in order of increasing distance of trains from interchange point.
- A train T_X is comprised of E_X the engineer's certificate, L_X the locomotive certificate, PTC_X, the installed PTC system, V_X, the initial train velocity, and DB_X the safe stopping (braking) distance.
- CA_A is the certificate authority of domain A. CA_B is the certificate authority of domain B.
- MA_X is a movement authority.

These conditions reflect actual railroad operating practices.

A train T_X that has requested entry from one domain to another is prohibited from proceeding into the new domain until the movement authority M_{AA} has been approved by the dispatcher of the new domain. In the event that T_X does not receive a response to a request, or the response to a request is delayed, T_X proceeds to the limit of its currently granted authority and stops. If T_X is already at the limits of the authority, then T_X remains halted until the authority to proceed is received. The movement of subsequent trains, T_i for $i > (X + 1)$ and $i \le N$, are rescheduled by the dispatcher in the cur- rent domain by modifying the movement authorities to preclude collisions and overrun of authority limits as necessary. If the dispatcher DS_B approves MA_X for T_X (*i.e.* the track in domain B is available), dispatcher DS_A relays the approved MA_X to T_X , and T_X transitions from domain A to domain B. Dispatcher DS_A may then reschedule T_{X+1} to advance to the block vacated by T_X and advance subsequent trains T_i for $i \ge (X + 2)$.

This process is illustrated in **Figure 2**. This scenario assumes that Dispatcher A is already in possession of the authentication information associated with E_X and L_X. A train T_X that intends to move from domain A to domain B submits the requested movement authority MA_X, the engineers certificate E_X and the locomotive certificate, L_X , (the Access Request in **Figure 2**) to the Dispatcher A. . Dispatcher A, already being in possession of the necessary certificate information authenticates the requests and forwards it to the Dispatcher in Domain B. Dispatcher B evaluates the feasibility of allowing T_X to enter B's domain. If Dispatcher B approves the movement, he approves MA_X and returns it to Dispatcher A. Dispatcher A then

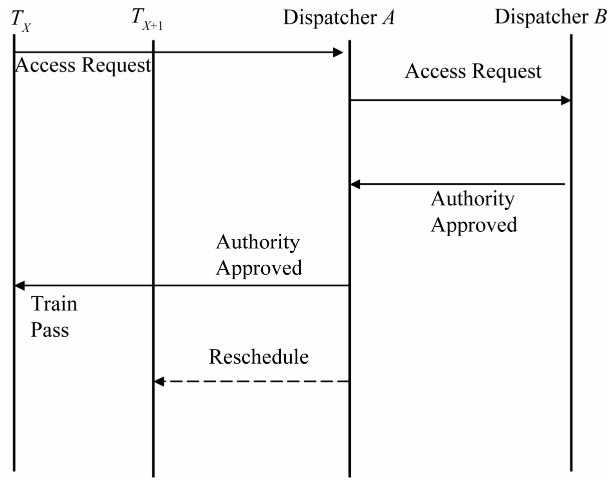

Figure 2. Movement authority approval.

passes MA_X back to T_X. T_X enters Railroad B's domain, and Dispatcher A reschedules the movement of T_{X+1}. Additional scenarios are described in [22].

There are three possible situations that may be encountered by a train T_{X+1} that is following train T_X in Domain A with a single siding.

- If the main line and siding are clear, T_{X+1} may take the main or siding and proceed to the interchange point without delay.
- If the main is clear and the siding is blocked or the main is blocked and the siding is cleared, T_{X+1} may take the clear track and proceed to the interchange point without delay.
- If the main and siding are blocked T_{X+1} may have to wait until the main or siding is clear in order to proceed to the interchange point.

In the later situation T_{X+1} can continue movement to the interchange point if the length of time it takes for T_X to receive their authority MA_A and move beyond the interchange point is less than the time it takes to stop T_{X+1}.

In the simplest case, where there is a single mainline running between domains A and B, denial of entry of Train T_X will require rescheduling of the movement of subsequent trains $T_{X+1}, T_{X+2}, \cdots, T_N$. In order to preclude a train-to-train collision between the end of Train T_X with the head of train T_{X+1}, train T_{X+1} must receive notification of the requirement to stop before it proceeds beyond the safe stopping distance BD_{X+1}. If the movement of train T_{X+1} is not rescheduled, and train T_{X+1} does not stop before reaching the location of T_X, T_{X+1}, and T_X may collide. If the stopped train T_X is released to proceed into the next domain before the train T_{X+1}, reaches the safe stopping distance, a collision can be avoided.

The potential for a collision between train T_{X+1} and train T_X will be affected by the velocity of train T_{X+1}, the time of release of a stopped train T_X, the communication delays associated with information exchanges between CA_A and CA_B, the dispatcher processing delays DS_A and DS_B, as well as the *PTC* system processing times PTC_X, and PTC_{X+1}. The velocity V_{X+1} of train T_{X+1} directly affects the safe stopping distance BD_{X+1}. As V_{X+1} increases, the safe stopping distance BD_{X+1} increases, requiring greater separation of trains T_X and T_{X+1} to preclude a collision."

3.1. Safe Stopping Distance

Stopping distances and times for train have been extensively studied (for example [23-26]). Commercial tools to calculate this information using more complex models are exist, most notably the RailSim Train Performance Calculator (TPC) by Systra Consulting, and the Train Operation and Energy Simulator (TOES) by the Association of American Railroads. These estimators reflect a railroads operating philosophy, the type of train (for example passenger or freight), the mass and its distribution of the train, the gradient of the territory the train is operating on at the time of braking, the crews reaction time, and the type of braking (full service, dynamic, or emergency) and the associated deceleration rate induced by the brakes. The braking calculation variables include the types of cars (*i.e.* tank, box, railrider, etc.), variations in the methods and type of braking (emergency or dynamic, conventional air or electronic pneumatic), track profile (grades and curves), behavior of the locomotive power based on track conditions, details of consist loading and position in the consist of power (head end, middle, or pushing). More approximate estimates for to calculate braking distance exist. For example, [27] is used to predict braking distances for the European Train Control System (ETCS) system. The International Union of Railways (UIC) has promulgated standard 546 [28]. A similar standard is under development by the IEEE [29]. Additional work on braking curves can be found in References [30-35].

3.2. Delay

In general, delays of trains proceeding from *A* to *B* are prevented when the total delay time associated with certificate authentication and movement authorization is less than the time required to stop the train. If the former is less than the later, then the dispatcher is able to pass the appropriate authorizations to an on-coming train sufficiently in advance of the required safe stopping distance to enable the oncoming train to pass at speed. Prevention of a collision requires that the delays for a train occupying either a siding or mainline block and the clearance time for the train to clear the block must be less or equal to the time it takes for a following train to brake to a zero velocity.

At maximum capacity, the movement of a train from one location to the next requires that the lead train clear the location it is occupying before the trailing train can stop in the location just cleared. This worst-case scenario may occur as a consequence of communication delays compounded by initial authentication of the actors and the first message exchanged. To obtain the total time for a consist to clear, or a consist to stop, the communications overhead times T_{OH} must added to the time to clear of T_X and time to stop T_{X+1}. Provided T_X and T_{X+1} require the same length of time to authenticate (*i.e.* T_{OH} is a constant for train T_X or train T_{X+1}, the delay T_{OH} cancels out and the delay between individual trains (T_X and T_{X+1}) remains the same as previously calculated.

The assumption that there are no authentication or communications delays is, however, unrealistic. Even in a benign environment, communications disruptions may occur as a consequence of phenomena such as normal atmospheric interference, electromagnetic interference by the AC or DC generators onboard the locomotive, or physical items such as buildings or foliage. To ensure that collisions between a leading train T_X and a following train T_{X+1} do not occur, the authentication and the communications delays $T_{COMMDELAYX}$ associated with train T_X must be less than the communications delays $T_{COMMDELAYX+1}$ associated with train T_{X+1}. If the difference in communications delays is greater than the allowable delay between T_X and T_{X+1}, then the potential exists for the trains to collide.

System designs assume that communications disruptions are likely to occur. To mitigate against this eventuality, not only are the commands retransmitted several times to ensure receipt and acknowledgement, each transmitting and receiving device is equipped with a timer. In the event of a communications disruption that precludes receipt of a valid message, a timer on the device will expire, forcing the device to its most restrictive safe state. This ensures the safety of following trains, albeit with a decrease in system throughput.

4. Physics of Braking and Accelerating Trains

The approximate estimate for time to stop assumes constant deceleration in ideal track conditions (*i.e.* straight (no curvature), level (no up or down grade, and dry). It also assumes the same constant variables (train length, train mass, braking efficiency, target speed, gradient, and distance to target) and that all cars in a particular consist are identical and have similar braking characteristics. Likewise, the time to clear a block assumes an identical train operating under the same conditions.

4.1. Time to Clear T_x

Assuming constant acceleration from an initial velocity of 0, the time for a train T_X stopped at an interchange point (in seconds) where the corresponds to the consist length can be estimated as follows:

$$TC_X = \sqrt{\frac{(2)(L_X)(M_X)}{\left(\frac{(375)(F_X)}{V_X}\right)-(M_X)(R_A)}} \quad (1)$$

R_A is estimated using the Davis equation. First developed in the mid 1920's, and modified in the late 1970's, it provides an estimate of the rolling resistance in pounds per ton [28].

$$R_A = (M_X)\left(0.6+\frac{20}{\omega_X}+(0.01)(V_X) + \left(\frac{(K_a)(V_X)^2}{(Car_X)(\omega_X)(n_X)}\right)\right) \quad (2)$$

Where
M_X is the weight of the train T_X (tons)
L_X is the length of the T_X (feet)
V_X is the final velocity of T_X (mph)
F_X is the tractive force of T_X locomotives (HP)
R_A is the drag of the consist when accelerating (lb/ton)
w_X is the weight per axle per consist car in T_X (tons)
n_X is the number of axles per consist car in T_X
Car_X is the number of cars in the consist in T_X
K_a is the acceleration drag coefficient $K_a = 0.07$
The tractive force F_X is given by

$$F_X = (N_{Loco})(HP)(E) \quad (3)$$

Where
N_{Loco} is the number of locomotives in *TX*
HP is the Horsepower per locomotive in *TX*
E is the locomotive efficiency %.

4.2. Time to Stop T_{X+1}

Assuming constant deceleration, the time to stop TS_{X+1} (*i.e.* final velocity $V_{X+1} = 0$) in seconds is

$$TS_{X+1} = \frac{(0.04583)(M_{X+1})(V_{X+1})}{F_{X+1}+R_D} \quad (4)$$

and the drag R_D of T_{X+1} is given by

$$R_D = (M_{X+1})\left(0.6+\frac{20}{\omega_{X+1}}+(0.01)(V_{X+1}) + \left(\frac{(K_b)(V_{X+1})^2}{(Car_{X+1})(\omega_{X+1})(n_{X+1})}\right)\right) \quad (5)$$

Where
M_{X+1} is the mass of the train T_{X+1} (tons)
V_{X+1} is the initial velocity of T_{X+1} (mph)
F_{X+1} is the braking force of consist T_{X+1}
R_D is the drag of the consist T_{X+1} when decelerating
ω_{X+1} is weight per axle per consist car in T_{X+1}
n_{X+1} is the number of axles per consist car in T_{X+1}
K_b is the braking drag coefficient. $K_b = 1.4667$
Car_{X+1} is the number of cars in the consist in T_{X+1}
The braking force F_{X+1} is given by

$$F_{X+1} = (Car_{X+1})(CarWeight_{X+1})(BF)(Brake_{Avail})(2000) \quad (6)$$

Where
Car_{X+1} is the number of cars in the consist T_{X+1}
$CarWeight_{X+1}$ is the weight of a car in the consist T_{X+1} (tons)
BF is the brake ratio (5%)
$Brake_{Avail}$ is the % operable brakes.

4.3. Consist Delay and Safety

Safe operation of the railroad requires that any Train T_{X+1} not run into the preceding Train T_X. For this safety criterion to occur the consist delay between Train T_X and T_{X+1} must satisfy the equation.

$$ConsistDelay + TC_X \le TS_{X+1} \quad (7)$$

Solving Equation (7) for Consist Delay and substituting Equations (1) and (4) yields the maximum delay that between two trains T_X and T_{X+1}.

$$ConsistDelay < \left(\left(\frac{(0.04583)(M_{X+1})(V_{X+1})}{F_{X+1}+R_D}\right) - \left(\sqrt{\frac{(2)(L_X)(M_X)}{\left(\frac{(375)(F_X)}{V_X}\right)-(M_X)(R_A)}}\right)\right) \quad (8)$$

where R_A and R_B are as defined in Equations (2) and (5).

At maximum capacity, the movement of a train from one block to the next requires that the lead train clear the block it is occupying before the trailing train can stop in the block just cleared. This is no different than the case of advancing through the interchange point, the interchange point is simply a special case of a block boundary. Instead of being the boundary between two adjacent blocks in the same domain, it is simply the boundary between two adjacent blocks, one of which is one domain, the other of which is a second domain. If trains T_X and T_{X+1} occupy the main and siding, subsequent trains T_{X+2} through T_{X+N} are blocked from advancing since the trains are restricted to a single degree of motion along the track.

4.4. Communications Delay

The physics of train movement, and the impact of communications and authentication delays can be combined into a single equation. The right hand of the inequality is Equation (8), while the left hand side is the time delay due to padding, propagation, and processing delays plus the system response time ($SYS_{RESPONSETIME}$ and $SYS_{PROPAGATION}$) and the operators response time ($OP_{RESPON- SETIME}$). See Equation (9), where M_{X+1}, M_X, VX, V_{X+1}, L_X, L_{X+1}, L_X, L_{X+1}, R_D, R_A, F_X, and $FX + 1$ are as previously defined and

$B_{SENDERADDRES}$ is the number of bytes of information to identify the sender

$B_{RECEIVERADDRESS}$ is the number of bytes of information required to identify the receiver

$P_{INFORMATION}$ is the number of bytes of information required to format the information I for transmission

C_{DATA} is the number of bytes of information required to control the transmission across the media

$C_{PADDING}$ is the number of bytes of information required to format C_{DATA}

S_{DATA} is the number of bytes required to convey any security information required for integrity and authenticity

$S_{PADDING}$ is the number of bytes required to format S_{DATA},

TR is the communication transmission rate

$SYS_{RESPONSETIME}$ is the length of time it takes for the system to process the data once received and change it into information

$OP_{RESPONSETIME}$ is the length of time it takes for the operator to respond to a command once received.

$SY_{SPROPAGATION}$ is the propagation delay for the communications medium

$SYS_{RESPONSETIME}$ is a function of the performance characteristics of the office subsystem, wayside subsystem, and the onboard subsystem involved in a particular message exchange. $OP_{RESPONSETIME}$ is a function of human factors behavior in receiving, processing, and executing a received command.

The advantage of establishing this single safety equation relating all elements is that it allows for the designer to develop risk based performance budgets for the various elements in their design. As long as the overall equation remains true, the designer is free to experiment with various options to achieve the required performance at a particular cost point.

5. An Illustrative Example

The behavioral characteristics of the railroad vary greatly depending upon the operating parameters of the trains operating along the railroad. Finding the optimal combination of train parameters that minimizes Consist Delay is a complex problem in operations research. The following example, however, illustrates the use of these equations. For the purposes of this example we will assume T_X and T_{X+1} are identical with properties as follows:

- Number of Locomotives = 3
- Length of locomotive = 100 feet
- Horsepower per locomotive = 4500 HP
- Weight per locomotive = 200 tons
- Locomotive Efficiency = 95%
- Number of Cars = 100
- Weight of a Car = 60 tons
- Length of a Car = 100 feet
- Braking Efficiency = 5%
- Axles per Car = 2
- Percent of Brakes Operable = 85% (Minimum operating brakes allowed by Federal Regulations)
- Train Length = 10300 Feet
- Communications Bandwidth = 4800 bps

All braking is provided by consist cars, locomotive dynamic braking is not considered. More complex scenarios are analyzed in [22].

$$\left(\left(B_{SenderAddress}+B_{ReceiverAddress}+P_{Information}+C_{Data}+C_{Padding}+\frac{S_{Data}+S_{Padding}}{TR}\right)+\left(SYS_{ResponseTime}+OP_{ResponseTime}+SYS_{Propagation}\right)\right)$$
$$<\left(\left(\frac{(0.04583)(M_{X+1})(V_{X+1})}{F_{X+1}+R_D}\right)-\sqrt{\frac{(2)(L_X)(M_X)}{\left(\frac{(375)(F_X)}{V_X}\right)-(M_X)(R_A)}}\right) \tag{9}$$

Based on the assumptions in the example, the time required for T_X to accelerate and clear, the time for the following T_{X+1} to decelerate and stop, and the associated delays between the two is shown in **Table 1**.

Negative numbers indicate that a collision can occur. Train T_X will not have cleared the interchange point before Train T_{X+1} arrives. An alternative way to view combinations of leading train clearance time, and following train stopping time is with a radar chart (**Figure 3**). In this chart, the spokes represent the locomotive speeds, the rings represent clearance times in seconds. As can be seen, for the example configuration, in almost all cases, the time for a leading train to clear the block is less than the time it takes to stop the following train and some delay can occur without adversely impacting subsequent train movements. Changes in locomotive tractive effort and train length also can affect clearance and stopping times, This also is more fully discussed in [22].

The allowable delays previously calculated are based on the physical characteristics of the locomotive and consist as well as the communications bandwidth (4800 bps) available to exchange data. Provided T_X and T_{X+1} require the same length of time to authenticate (*i.e.* T_{OH} is a constant for train T_X or train T_{X+1}), the delay T_{OH} cancels out and the delay between individual trains (T_X and T_{X+1}) remains the same as previously calculated.

Table 1. Allowable delays $V_X = V_{X+1}$.

Velocity *TX* (MPH)	Velocity *TX*+1 (MPH)	Clearance Time *TX* (Seconds)	Stop Time *TX*+1 (Seconds)	Max Delay Time (Seconds)
10	10	17.05	11.27	−5.78
20	20	24.48	22.51	−1.97
30	30	30.53	33.69	3.17
40	40	36.00	44.81	8.81
50	50	41.28	55.86	14.58
60	60	46.57	66.82	20.25

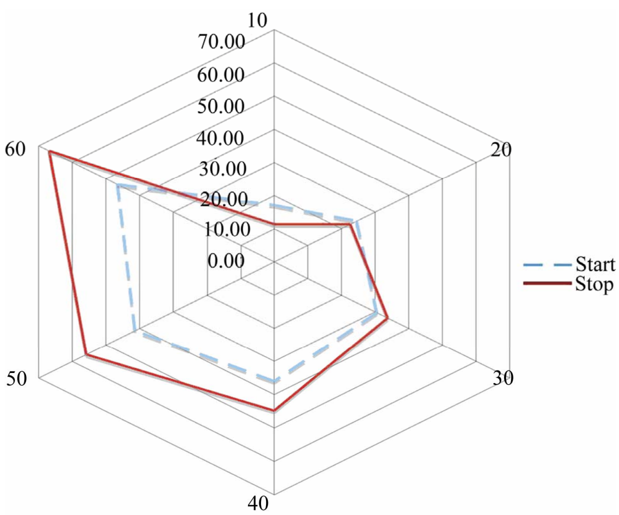

Figure 3. Clearance & stopping time.

With trains T_X and T_{X+1} operating with under condition of nearly simultaneous movement authorities (a method of operation known as moving block and a capability made possible with Positive Train Control (PTC), the required train separation is significantly less than if train movements were not simultaneously. PTC is a wireless communication SCADA system that utilizes a continuous high bandwidth RF data communications network that allows train-to-wayside and wayside-to-train exchange of control and status information. Wayside, office, and trainborne computers process received train status and control data to provide continuous train control [36,37].

With the moving block method of operations, the separation between trains moving at 60 mph can be as low as roughly 3/10th of a mile. When contrasted to the roughly 1.1 miles required by fixed blocks, the traffic density can be increase by roughly a factor of three. This makes significantly better use of the available track resources, and increases system throughput.

6. Conclusions

We presented a model for an interchange between two railroad domains governed by interoperating PTC systems for a unidirectional track with a single siding. We showed how to compute the safe conditions by using communication and trust management delays between the two domains. This work provides the signal engineer designing interchanges of some idea of the feasibility of the proposed design. The work needs to be expanded to account for bidirectional train movements on a single track, multiple mainline track with crossovers, multiple sidings, and spurs. Once these more complex tactical routing configurations have be addressed, they can be integrated into strategic models, Establishing these relationships is essential to determine the optimum use of limited resources and continues to remain an open research area.

A closed form solution for determining the optimal combination of resources is unlikely, making statistical evaluation of open form solutions necessary and is a subject of future research. There are also a number of implementation related issues that have not been fully addressed in this work. In a operational environment where rail traffic is heavy and close together, the volume of operational and environmental data that must be transmitted may exceed the communications bandwidth. The complete unification of tactical and strategic routing can only be determined in the context of the railroads operating environment and the particular implementation mechanisms. Ongoing research in this will provide us with more accurate estimators to support detailed system design and cost evaluation.

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