Timely Delivery of Messages in Positive Train Control

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Chapter 10

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Abstract In the railway infrastructure, positive train control (PTC) is an automated method for controlling and monitoring train movements to ensure safe travel by enforcing safe braking distances and speed limits, even if the locomotive driver fails to act within the specified guidelines. Obviously, it is vital to assure the timely delivery of control messages to the on-board computer system that implements PTC for a locomotive. In particular, the parameters for the timely delivery of control messages must be evaluated and specified. The delivery times of the control messages are directly impacted by the locomotive speed and braking characteristics. Train braking is characterized by braking curves that express speed as a function of distance or position. This paper utilizes numerical techniques to convert braking curves into functions of time to specify safety-driven requirements for the upper bounds on message delivery delays. Message delivery time requirements are combined with the requirement that the probability of erroneously stopping a train is very small. Rules are derived for scheduling re-transmissions of train control messages to ensure timely train braking in the event of driver error.

Keywords: Railroad security, positive train control, control messages

1. Introduction

The United States has mandated that positive train control (PTC) must be implemented in railroads that carry passengers, freight and hazardous materials by 2015 [7]. PTC enables the control and monitoring of train movements to enhance collision avoidance, enforce line speed and provide alerts about temporary speed restrictions. Trains receive information about their locations and where they are allowed to travel in a safe manner, also known as movement authorities. The equipment on board the trains then enforces specified policies to prevent unsafe movements.

In order to assess PTC vulnerabilities, the engineering properties of the infrastructure must be considered and analyzed. Indeed, the timely delivery of train control messages in automated signaling systems is essential to assuring the safety of railway travel. The locomotive driver must receive notice of a stop signal early enough to allow the manual application of the brakes, or the automated system must apply emergency braking in the event that the driver fails to act in a timely manner. Equally important is the timely delivery of green signals and authorities to proceed. The requirements make it imperative to understand the performance requirements of automatic signaling systems and, in particular, the performance of mechanisms that deliver messages to on-board automatic train control systems.

PTC ensures that trains do not pass stop signals or exceed speed restrictions, even if locomotive drivers do not obey them. Various systems have been proposed for PTC implementation, including ACSES (used by Amtrak) and Interoperable Train Control-PTC (ITC-PTC) [10]. This paper focuses on ITC-PTC, which has been developed by four major freight railroads under the auspices of the American Association of Railroads. In ITC-PTC, a wayside interface unit (WIU) wirelessly transmits beacon messages containing information about the status of wayside equipment (e.g., signals, switches, grade crossing barriers and track condition sensors) to on-board control systems.

The timing requirements for delivering control messages to a train are dependent on its speed and braking properties. To ensure the safe operation of control equipment, it is important to understand the performance requirements of the control system. In previous work [4], we provided a brief overview of the performance and security aspects of train identity management as trains move from one railroad to another. This paper presents an analysis of braking properties as they relate to performance requirements. Train braking properties are typically evaluated using braking curves, which specify train speed as a function of distance. Train speeds are represented as functions of time because braking directly impacts the requirements for message delivery delays.

The clarity of radio signals is also a factor that affects the timely delivery of control messages from a WIU to a locomotive. In the presence of heavy interference, the locomotive may not receive messages often enough to operate safely. In such a scenario, fail-safe braking procedures are invoked to bring the train to a stop, whether or not it is otherwise safe to proceed. The probability of such an invocation, when it is otherwise safe to proceed, should be minimal to avoid the costs imposed by unnecessary braking. Using repetitive beaconing, rather than single messages, allows the loss probability of wayside status messages (WSMs) to be rather large, while maintaining safety. This requires beaconing to be robust when radio interference is severe enough to prevent the delivery of a sizable portion of the WSMs.

This paper shows that the braking times can be used to derive guidelines for setting beaconing intervals between the transmissions of WSMs sent by WIUs.

The remainder of this paper is organized as follows. First, the details of ITC-PTC are provided. Then, an analysis of braking curves is employed to derive delay requirements for control message delivery. A rule is then specified for configuring the times between the transmissions of beaconed WSMs based on the probability of losing packets in the beaconing stream. This rule accounts for railroad guidelines related to the maximum acceptable delay of WSMs. Finally, the operational impact of the findings is discussed.

2. ITC-PTC Overview

The ITC-PTC version of PTC incorporates the existing signaling, switching and track monitoring systems. The basic components of ITC-PTC include the wayside interface unit (WIU), on-board unit (OBU) and back office server (BOS) [4]. The locomotive driver's control panel is equipped with a display that shows the status of wayside equipment on the line ahead, including the signal aspects, switch positions and indicators of track defects.

WIUs are positioned at various locations along the track. Each WIU monitors the settings of a defined set of signals and switches, as well as the status of grade crossing barriers and track defect monitors. WIUs beacon the status of wayside equipment to all trains within their broadcast ranges at regular intervals. Note that beaconing may occur continuously in congested areas. In lightly traveled areas, however, WIUs rely on battery power and only beacon the status upon receiving requests from approaching trains to conserve power.

Each locomotive is equipped with an OBU containing a track database that identifies the signals, switches and permanent speed restrictions that it may encounter. The messages received by the train provide information about signal aspects (e.g., stop, proceed slowly, proceed with moderate speed and clear), switch alignment, track conditions and special notifications (e.g., work crews present on the track). Note that the track database is consulted to select only the status fields that relate to the designated path [2]. The OBU enforces signal-based and form-based movement authorities along with speed restrictions by automatically intervening to apply the brakes if they are ignored by the locomotive driver. The shorter the time available for a train to come to rest, the quicker the response to changes in wayside equipment status.

The BOS is responsible for speed restriction, track geometry and OBU configuration. The BOS provides the track database, along with form-based movement authorities, dispatch messages, crew authorities and track directives. Additionally, it sends notices of temporary speed restrictions. If a locomotive is not within the range of a WIU, it can register to receive change-of-status messages from the BOS [8]. The OBU relays the train speed and position to the BOS, along with other information specified by the railroad [1].

3. Key Parameters

This section discusses the key parameters, which include braking curves, braking distance, stopping times and train speed.

The performance requirements for the delivery time of movement authorities and stop messages must take into account the braking characteristics. In the current PTC specifications, the requirements are based on the notion that braking on freight trains is a binary activity [9]. For trains with non-binary braking, the performance requirements are based on the maximum tolerable loss of speed (and by extension, kinetic energy) should a movement authority arrive after brake application has commenced.

Because the performance requirements for delivering control messages to a train are expressed in terms of time, braking is computed using braking curves, which provide train speed in terms of the distance traveled. In previous work [4], we derived and illustrated a numerical method for computing deceleration curves and stopping times from braking curves. Under PTC, brakes are applied by the OBU if an infraction has occurred. Emergency braking is invoked when the penalty brake does not sufficiently reduce train speed to a level below the braking curve.

On a freight train, once the air brakes are applied, they cannot be partially released because brake application entails the release of air pressure within the braking system. Note that for emergency braking, the release of air pressure is more rapid than for penalty braking. As a result, the brake is either applied or not applied. Thus, the braking of freight trains is a binary activity. The degree of brake application is more refined with electronic controls that manage the release of air pressure, but this is not currently the vision for freight trains operating under PTC. Nevertheless, we discuss the performance requirements for both cases.

The time required for a train to respond to a command depends on the following conditions:

- The current distance from the train to the point at which the train must execute the command. This is referred to in the railroad industry as the "point of protection."
- The reaction time of the driver.
- The speed of the train.
- The time required for PTC to intervene if the driver has not acted on a signal.
- The braking capabilities of the train as described by the shape of the braking curve.

The braking curve represents the speed of the train as a function of distance traveled under expected actions, such as the application of brakes. The message delivery time requirements can be derived using the braking curve as a basis for computing the time to decelerate by a given speed [4].

Leveraging the work described in [5], we illustrate the concept of a braking curve for a train with an initial speed of 40 mph and an anticipated stopping distance of 6,000 feet from the point of initial brake application. Note that these

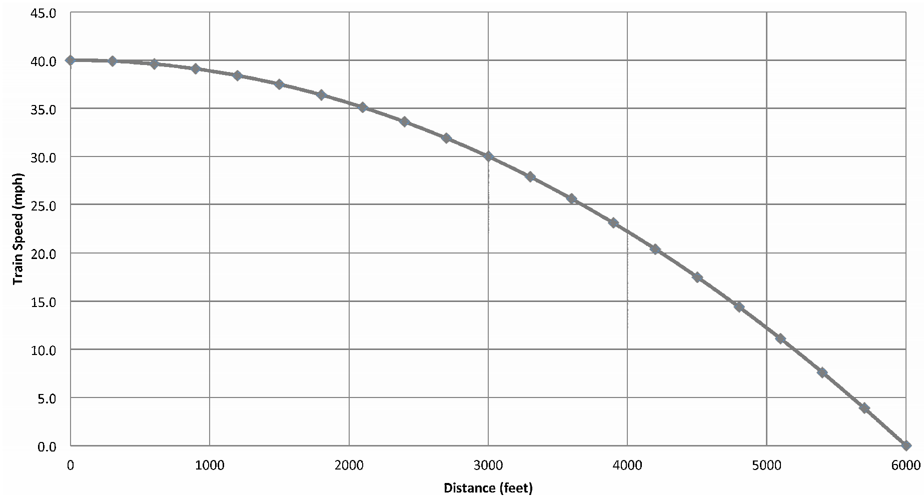

Figure 1. Synthetic braking curve.

conditions are consistent with long freight train operations. Figure 1 shows a braking curve associated with these conditions.

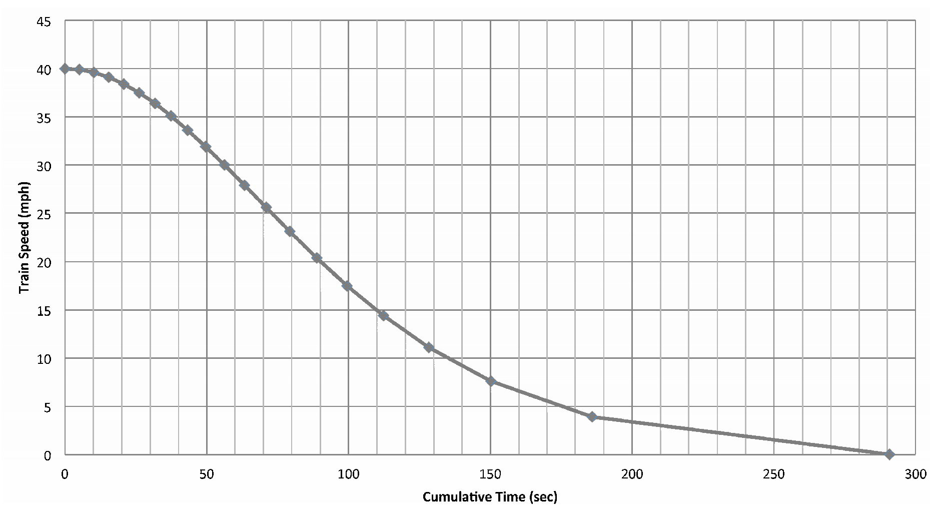

Figure 2. Train speed as a function of time.

Figure 2 shows the corresponding curve for speed as a function of time. The point of inflection in the speed versus time curve occurs because the curve is continuous and the acceleration is zero before brake application. Since the acceleration is non-positive, there must be an instant at which it reaches a local minimum. Figure 2 shows that it takes approximately five minutes to bring the train to a complete stop. To limit the amount of deceleration that occurs as a result of the late delivery of a WSM, a limit can be specified for the acceptable reduction from the initial speed and the corresponding maximum delivery time.

4. QoS and Performance Requirements

Factors affecting timely message delivery from the WIU to the OBU include radio interference, processing delays and propagation delays. Our focus is on quality of service (QoS) requirements to include message delivery in a beaconing environment and message delivery delays.

4.1 Beaconing and Forced Train Stops

A train within the receiving range of a WIU either passively receives status messages at regular intervals or receives status messages in response to a `getWIUstatus` (5201) request [2]. The messages contain the status of the signals, switches, grade crossing sensors, track defect sensors and other wayside devices monitored by the WIU. Note that the devices notify the WIU directly whenever their status changes.

The OBU classifies a wayside status message as current or stale. The wayside status message is considered to be stale if it is received more than time T_w seconds after the preceding message, invoking the fail-safe stopping procedure. Because the clocks on the WIU, BOS and OBU are synchronized using GPS, clock drift is not severe enough to prevent the fail-safe stopping procedure from functioning properly. The WIU has a functional requirement that the drift should be less than $\pm 2,000$ seconds in any eight-hour period [3]. In addition, the possibility that braking on freight trains is a binary activity must be considered (i.e., braking is applied all at once or not at all). Penalty braking is always applied first; emergency braking is only applied when the penalty brake does not bring the train to a speed no greater than that specified in the braking curve. Note that this in contrast with computer controlled dynamic braking, in which brakes are applied automatically according to the speed, gradient and other track conditions, as in the case of the more nuanced braking used for passenger trains to ensure platform access to and from all passenger cars.

In the previous example (Figure 2), the speed versus time curve that corresponds to the synthetic braking curve has a negative slope and point of inflection where the deceleration is maximum. It is desirable for the extension of the signal-based movement authority to be provided as soon as possible, preferably to the left of (i.e., before) the point of inflection. This action minimizes the speed reduction while the permission to proceed is en route to the OBU. It is unlikely that the permission to proceed is rescinded for operational reasons; however, a penalty braking curve requires invocation as quickly as possible.

To ensure timely delivery, the following two conditions require consideration.

- If the permission to proceed is granted after brake application, then the message delivery time should be short enough to prevent a slowdown greater than a specified level.

- If the permission to proceed is rescinded or a stop or restrictive signal is sent, then the corresponding message delivery time should be short enough to prevent the train from traveling a specified distance before it stops.

In both cases, the time between beacon transmissions t_b must be less than the maximum chosen value of $t_D - t_0$, where t_D is the time at which notification occurs and t_0 is the time at which monitoring for brake enforcement starts.

Subject to calculations, the foregoing suggests that the higher the speed of an approaching train and/or the heavier the train, the shorter the maximum required time between beacons. If the train is subject to binary braking, the train requires a receive status message to stop or proceed at least T seconds before it arrives at the point of automated brake application. For example, if the train is traveling at 40 mph, a delivery time requirement of ten seconds would result in the train moving 0.1111 miles before the commencement of brake application. If the train is subject to a more refined braking policy with a requirement that it lose no more than 5 mph from its initial speed of 40 mph, then the delivery of a message to proceed should arrive no more than 37 seconds after brake application based on the quadratic braking curve shown in Figure 2. Note that the performance requirement is specified in terms of time, not distance. As demonstrated in Figure 2, the time required to reduce the speed from 40 mph to 35 mph is just under 50 seconds, with the distance traveled equating to approximately 2,800 feet.

4.2 QoS Models

Suppose that a railroad decrees that the maximum permissible time between successful wayside status message arrivals is T_w and that the configured time between WIU beacon transmissions is $t_b < T_w$. Thus, the maximum number of beacon transmissions that can occur without being received before the brakes are automatically applied is $N_B = \lfloor \frac{T_w}{t_b} \rfloor$. Note that T_w should be chosen with respect to the braking curve properties that determine the distance between the point of earliest reception of a wayside status message and the point at which braking must commence.

The probability that beacon messages may be lost must also be considered. Taking into account that a wayside status message may be lost or corrupted because of radio interference or other reason (e.g., buffer overflow, jamming or a replay attack), it can be assumed that the number of beacons transmitted before the successive message arrives at the train has a geometric distribution, with parameter p equal to the probability of wayside status message loss. The following probabilities further characterize message arrival:

- The probability that two successive beacon messages are successfully received without interruption is $1 - p$.

- The probability that one beacon message is not received between two successful arrivals is $p(1 - p)$.

- The probability that two successive beacon messages are not received between two successful arrivals is $p^2(1-p)$.
- The probability that k successive messages are not received between two successful arrivals is $p^k(1-p)$ where $k < N_B$.
- The probability that the train comes to a stop because at least N_B successive messages have failed to arrive between two successful arrivals is given by:

$$\begin{aligned} p_{stop} &= 1-(1-p)\sum_{k=0}^{N_B-1} p^k \\ &= 1-(1-p)\frac{(1-p^{N_B})}{(1-p)} \\ &= p^{N_B}. \end{aligned} \tag{1}$$

Equation (1) leads to the specification of the probability of a message being lost. If the probability that a train needlessly comes to a stop is less than a specified quantity ϵ, then a constraint on the probability is discerned that specifies message loss due to radio interference or other cause $p^{N_B} < \epsilon$, such that:

$$p < \sqrt[N_B]{\epsilon}. \tag{2}$$

For example, suppose the probability that a train is stopped unnecessarily because of radio interference is less than 10^{-6} (i.e., $\epsilon = 10^{-6}$). If the wayside status messages are sent one second apart with the allotted time between successful transmissions set to twelve seconds, then $N_B = \frac{12}{1} = 12$ and $p < \sqrt[12]{10^{-6}} = 0.316$.

This example demonstrates the requirement of a low probability for stopping can be met with a maximum allowed time of twelve seconds if message transmissions occur every second, even if one-third of all WIU status messages are lost. This makes the communication method quite robust in the face of a very high probability of message loss. If the constraint on the message loss probability cannot be met, then the railroad must tolerate a larger value of ϵ. In operational terms, this means that, if the probability of message loss due to interference is too high, then the railroad must tolerate a larger probability of unnecessarily stopping a train because a permissive message is not received.

Suppose that wayside messages have to be transmitted less frequently due to bandwidth limitations. If the maximum allowed time of a wayside status message is twelve seconds and the messages are transmitted every four seconds (instead of every second), then $N_B = \frac{12}{4} = 3$ and the corresponding probability of non-delivery of a valid wayside status message must be less than $\sqrt[3]{10^{-6}} = 0.01$. Note that the required loss probability is non-linear with respect to the ratio of the maximum allowed time between beacon messages. A higher ratio makes the system much more robust, since more beacon messages can

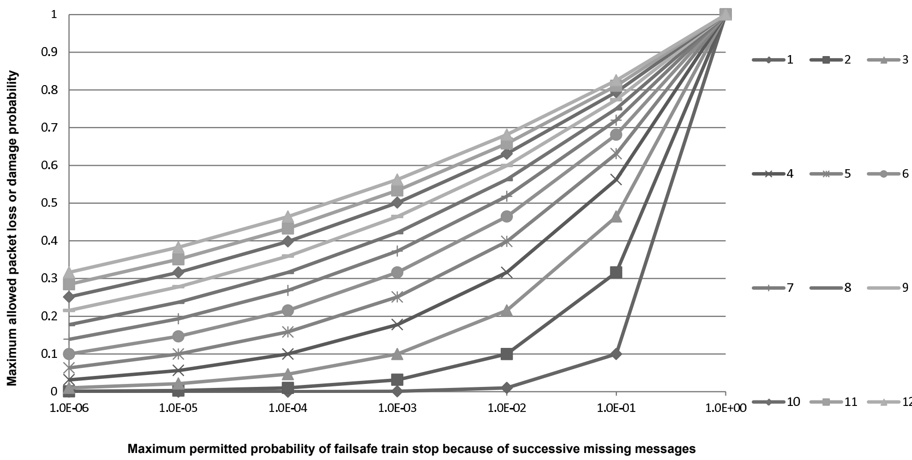

Figure 3. Maximum permitted probability of lost/damaged wayside status messages.

be transmitted during the maximum allowed time, provided that the increased number of beacons does not result in increased message loss because of radio interference or excessive bandwidth use.

Since the number of consecutive transmissions that are unsuccessful is geometrically distributed with parameter p, the mean number of consecutive unsuccessful transmissions is $\frac{p}{(1-p)}$. As such, $p = 0$ is considered to represent pure transmission. Alternatively, if $p = 1$, then every message transmission is unsuccessful and wayside status messages do not reach their destinations. Interestingly, the expected number of consecutive successful transmissions of beacons is the reciprocal of the expected number of unsuccessful transmissions (i.e., $\frac{(1-p)}{p}$). Note that if $p = 1 - p = \frac{1}{2}$, the expected consecutive number of either successful or unsuccessful beacon transmissions is one, meaning that on the average every other message is successfully received.

The results demonstrate that PTC is fairly robust in the face of radio interference considering the transmission interval and timeout value for automatic brake application. Even if the probability of losing a wayside status message is 0.5 (an indicator of severe interference), fewer than three in 10,000 trains would be stopped when braking is triggered by twelve consecutive losses. Normal operations can continue if the risk level of unnecessary delay is deemed tolerable.

Figure 3 shows the maximum permitted probability of a wayside status message not being received by the OBU as a function of the probability that a fail-safe stop must be invoked given that the train does not have to stop, for different numbers of successive lost messages between arriving messages. The plot shows that allowing large numbers of consecutive lost messages increases the maximum allowed probability of losing a message, regardless of the probability that a train is stopped because of consecutive message losses, as might be expected. The degenerate case of allowing erroneous stops without restriction

($p_{stop} = 1$) means that all status messages can be lost. Restricting the probability of an unnecessary stop to one in a million train movements means that the probability of an undelivered packet should not exceed 0.32 when braking occurs after twelve consecutive undelivered beacon messages. When the number of consecutive undelivered messages is restricted to three messages sent four seconds apart, the maximum allowed message loss probability decreases to 0.01.

4.3 Beacon Interval Configuration Guidelines

Equation (2) provides a guide for railroad planners to configure beacon frequency based on known or estimated values of the probability of losing messages and the desired maximum probability of a train being stopped due to wayside status message loss. If the probability of status message loss is high, then the risk of erroneously stopping a train because of message loss can be reduced by shortening the interval t_b between beacons. This increases the number of wayside status messages sent within time T_w. For example, if the probability that a valid wayside status message is not delivered within twelve seconds is 0.3, then the odds of an erroneous stop is approximately one in a million if beacons are sent at intervals of $t_b = \frac{12}{12} = 1$ every second. The odds are one in a thousand if the interval is $t_b = \frac{12}{6} = 2$ seconds and one in ten if the interval is $t_b = \frac{12}{2} = 6$ seconds. Note that the choices of t_b and T_w also create the requirement that the OBU should process incoming wayside status messages at a rate that is no less than $\frac{1}{t_b}$ messages per second. If the OBU is designed to meet the requirement of processing one wayside status message every T_C seconds, then $T_C < t_b$.

4.4 Delay Requirements for Message Delivery

The numerical method suggested in [4] can be used to compute the message delivery and other delay requirements for a train approaching a WIU that guards an entrance to PTC territory. Since the train is PTC-enabled, it is aware of the existence and position of the WIU and listens for the status beacon or issues a `getWIUstatus` request when it is within range of the WIU radio transmitter. After the locomotive is within range, the following events occur:

- The locomotive authenticates the identity of the WIU; this requires time t_a. Note that, if HMAC is the sole means of authentication, as is the case for ITC-PTC, then this step is performed for every message.

- The WIU sends a beacon at regular intervals, or the locomotive issues a `getWIUstatus` request to start the beacon. The time taken to receive a beacon is the expected time between successful beacon transmissions t_s plus the time t_g taken for the WIU to respond to a `getWIUstatus` request. If the WIU is beaconing steadily without waiting for a `BeaconRequest` message, then $t_g = 0$.

- The locomotive driver takes time t_R to react to the OBU display or wayside signal or, if the signal indicates danger and the driver ignores it, then the OBU begins to activate the brakes according to the braking curve, which takes time t_{OBU}.

United States Government regulations 49 CFR 236.563 and 49 CFR 236.831 state that if a train is required to stop, the time elapsed from when the onboard apparatus detects a more restrictive indication until brake application commences shall not exceed eight seconds [6]. Hence, $t_{OBU} < 8$ seconds. For a probability of failed beacon transmission p, the expected time to receive a successful beacon is the expected time between successful transmissions or, equivalently, the expected number of failed transmissions multiplied by the beacon interval time, plus the expected time to the next beacon emission $\frac{t_b}{2}$. Thus,

$$t_s = \frac{(p \times t_b)}{(1-p)} + \frac{t_b}{2} = \frac{(1+p)t_b}{2(1-p)}. \tag{3}$$

For safety reasons, the time between successful receptions of beacon transmissions cannot be greater than the maximum permitted reception time of a wayside status message. Thus, $t_b < T_W$ or equivalently,

$$t_b < \frac{2T_w(1-p)}{1+p}. \tag{4}$$

When $p = 0$, the expected time to successfully receive a wayside status message is $\frac{t_b}{2}$. Alternatively, when $p = 1$, the expected time is infinite because all WIU transmissions fail, as one would intuitively expect. Note also that, when $p = 0$, the requirement for the time between beacons is less than twice the maximum allotted time of a wayside status message T_W.

Consider the track distance from the initial point of a train when a wayside status message is received to the point at which brakes are applied B. Additionally, assume that the train is traveling with constant speed v. If the braking curve is followed and the train is to be stopped before the signal of interest, then:

$$v(t_a + t_s + t_g + t_R + t_{OBU}) < B. \tag{5}$$

If $x_R = v \times t_R$ is the distance traveled during the driver's reaction time, during which time the speed of the train is assumed to be constant, then the following upper bound on the time is obtained for a locomotive to activate the brakes in response to a WIU status message:

$$t_a + t_s + t_g + t_{OBU} < \frac{(B - x_R)}{v}, \; x_R < B. \tag{6}$$

This equation shows that a long reaction time decreases the maximum permissible time to activate the brakes according to the braking curve, and that the maximum allowable activation time is inversely proportional to the speed of the train. Moreover, the reaction distance must be less than the distance such that the train speed must follow the braking curve. Interpreted another way, if the brake activation time cannot be reduced, then either the speed v in the approach zone to the PTC-controlled track must be decreased accordingly or the braking distance B must be increased accordingly. Combining Equations (2) through (6) provides a relationship between the successful transmission probability, the desired probability of the train braking incorrectly, speed and braking distance. Substituting for p yields:

$$t_a + t_{OBU} + \frac{1 + \sqrt[N_R]{\epsilon} t_b}{2(1 - \sqrt[N_R]{\epsilon})} + t_g < \frac{B - x_R}{v}, \; x_R < B. \tag{7}$$

If the inequality in Equation (7) cannot be satisfied by a reasonable set of parameters, the train cannot be brought to a stop within the requisite distance while keeping the probability of an erroneous stop below the desired level.

If the train is eligible to proceed in a more permissive manner than is enforced by the PTC mechanism, it is desirable that the OBU be notified as early as possible so that enforcement can be rescinded. This minimizes the adverse effect of unnecessary braking, especially in the case where braking is a non-binary as opposed to a binary activity. It is desirable to rescind enforcement either before the application of the brakes, or as soon as possible after their application. If brake application begins after enforcement, cancellation should occur at the earliest point at which the absolute value of the intended acceleration (i.e., the slope of the speed with respect to time) is as small as possible. Put another way, the desire is to minimize the loss of kinetic energy due to unnecessary braking by setting the maximum desired message delivery time $t_D - t_0$ to ensure that the change in kinetic energy $\frac{1}{2}m(v_0^2 - v_D^2)$ is as small as possible.

5. Impact on Engineering and Operations

The preceding discussion shows that the braking properties, beacon transmission quality requirements and the desired probability of erroneously stopping a train are closely related. The impact of this relationship is that transmission quality cannot be engineered independently of service and braking properties, or vice versa. Competing stakeholders and entities that coordinate their activities must weigh the tradeoffs between the bandwidth associated with the frequent transmission of wayside status messages, the cost of engineering braking capability to accommodate radio interference and the cost of minimizing radio interference. The braking properties of a train are dependent on its composition, how slippery the tracks are, whether the approach to a signal is on a curve or slope and the characteristics of the brakes themselves.

The effects of radio interference can be mitigated by broadcasting wayside status messages to trains more frequently. Determining how often to broadcast wayside status messages allows a railroad to transmit messages less frequently when higher radio interference is present and to choose the lowest rate of transmission that meets safety needs, while containing the risk of stopping a train when there is no need to do so. It should be noted that the causes of radio interference may be outside the control of the railroad. Moreover, interference could have seemingly mundane and unexpected causes, such as the presence of a refrigerator with poor electrical grounding or other undesirable properties in the locomotive cab. The possibility of unexpected and/or uncontrolled causes of message loss implies that wayside status messages should be transmitted more often to increase their chances of reception by the OBU, to the extent that bandwidth is not exhausted.

6. Conclusions

Ensuring the timely delivery of control messages is vital to creating a safer and more efficient railway infrastructure. In particular, the guidelines derived in this paper for configuring the operating parameters of a positive train control specification help contain the risk of unnecessarily braking locomotives. By associating message delivery time requirements with a low probability of erroneously stopping a train, the rules derived for scheduling control message transmission rates ensure timely braking. Another key contribution is the demonstration of the need to consider operating conditions and braking properties when formulating performance and QoS requirements for control message delivery. By utilizing numerical techniques to convert braking curves into functions of time, it is possible to specify safety-driven requirements for the upper bounds on message delivery delays. As a result, railroad authorities can assess message delivery rates to minimize unnecessary braking while enhancing safe travel.

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