

Effects of Communications-Based Train Control and Electronically Controlled Pneumatic Brakes on Railroad Capacity

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Railroads are increasingly using new technologies to improve capacity and operating efficiency. To plan their investments and prepare for the implementation of these technologies, railroads must understand their net effect on operations. This requires understanding both the particular aspects of these technologies that affect capacity and the characteristics of the systems into which they are being introduced. Two important technologies in this regard are communications-based train control (CBTC) and electronically controlled pneumatic (ECP) brakes. Each element of CBTC and ECP brakes with the potential to affect capacity was identified, and its effect under various implementation scenarios was evaluated. The potential impact of each element was assessed and compared with the various baseline conditions and conventional technologies to understand the incremental effect. An extensive review of the literature on the subject was conducted in support of these evaluations. CBTC implementation with enforcement braking will generally result in a loss of capacity, but as these systems become more fully integrated, the potential for capacity enhancement improves. ECP brakes will provide benefits under most operational scenarios because of the shorter braking distances and thus the potential for the closer spacing of trains. The two technologies have a potential interactive effect: CBTC may make it possible to more effectively take advantage of one of the principal benefits of ECP brakes: shorter stopping distances. The results for either technology will be route and network specific, so individual railroads will need to conduct analyses to understand the net effect on the capacity of their systems.

Beginning in the early 2000s, major North American railroads were increasingly experiencing capacity constraints, and long-term projections indicate substantial further growth in freight traffic (1, 2). Furthermore, new initiatives to expand intercity passenger rail operations on freight railroads will have a disproportionate impact on capacity because of the differences in operational characteristics between freight and passenger trains (3–6). Consequently,

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understanding of the factors that affect rail capacity and the options available to improve it cost-effectively is important.

Infrastructure expansion will undoubtedly play an important role in accommodating new traffic demand; however, two new technologies that will also affect rail capacity are being introduced: communications-based train control (CBTC) [often referred to as positive train control (PTC) in the United States] and electronically controlled pneumatic (ECP) brakes. Both offer safety benefits, and both have been touted as offering capacity benefits as well, but in actuality, the situation is more complicated. These technologies can enhance capacity under some circumstances, have little or no effect under others, and in some cases may actually reduce capacity. Consequently, understanding their net effect on a particular rail line or network requires understanding the status quo of the system into which they are being introduced and in what manner they are being introduced. This paper attempts to identify each critical aspect of these technologies that has the potential to affect capacity and consider what this effect will be under which implementation conditions. Because both of these systems require significant investment from the railroads [estimates range up to \$10 billion for PTC (7) and over \$6.5 billion for full ECP brake implementation (8)], if the capacity impacts of these two technologies can be better understood, railroads can make more informed decisions about their implementation.

The work described here is part of a larger effort in which simulation analyses are being conducted and mathematical models are being developed to quantify the effects of these technologies on rail capacity. Railroads planning for the implementation of CBTC and ECP brakes will need to conduct similar assessments to understand the particular effect on their own networks.

CBTC is a system in which train monitoring and train control are integrated into a single system via data links between vehicles, central office computers, and wayside computers (IEEE Standard 1474.2-2003). ECP brakes use an electronic signal instead of the train-line air pressure to transmit braking signals. CBTC has been under development since the mid-1980s (9–11), and freight railroad ECP brake technology has been under development since the early 1990s (12); however, wide-scale adoption has not occurred because of technical, practical, economic, and institutional barriers (13). Recent regulations and legislation have altered the situation. FRA is encouraging the implementation of ECP brakes by offering relief from certain requirements pertaining to conventional pneumatic brake operation (14, 15). With regard to PTC, the Rail Safety Improvement Act of 2008 (H.R. 2095, 110th Cong., 2nd session, 2008) and the subsequent regulations issued by FRA (16) have mandated its implementation on a large portion of the main lines of Class 1 railroads by 2015.

A number of previous studies have investigated the impact of CBTC on capacity. Lee et al. determined that moving blocks could increase the capacity of the Korean high-speed railway (17). Another study quantified the capacity benefits of the European Train Control System (ETCS), Europe's version of CBTC (18). In the United States, Smith and colleagues studied the potential benefits of Burlington Northern's Advanced Railroad Electronics System and other possible CBTC systems (19–22). They calculated how the more efficient meet–pass planning and the increased dispatching effectiveness possible with CBTC will affect capacity. Martland and Smith calculated the potential terminal efficiency improvements resulting from the estimated increases in reliability offered by CBTC (23). Although many authors have claimed that a CBTC system with moving blocks will increase capacity (7, 10, 22–27), there has been some debate about whether this will in fact be the case (13, 28).

Less work has addressed the capacity effects of ECP brakes. Most agree that they will reduce stopping distances and, when they are fully implemented, will allow closer spacing of trains; however, the incremental effect of this reduction will be affected by what other technologies are already in use. Furthermore, taking advantage of this will often require changes in the signal system.

As discussed above, the effects of CBTC and ECP brakes will be context specific; that is, under some circumstances one or both technologies, either alone or in combination, will have the potential to increase capacity, in other cases they will have little or no effect, and in some cases they may reduce capacity. Consequently, the net effect of these technologies on capacity will be determined by the magnitude of these context-specific impacts and the relative frequency at which they occur over a particular route or network.

ELEMENTS OF A CBTC SYSTEM THAT WILL AFFECT CAPACITY

In North America most of the potential CBTC systems are still under development. Although the specific technical details remain unclear, in general, each will have similar features and capabilities. These systems are characterized by the data links that provide better information to dispatchers and train crews. This has the potential to increase efficiency though better train management and control (29). However, to comply with the legislative requirements for PTC, they must also prevent train-to-train collisions, overspeed derailments, incursions into established work zone limits, and the movement of a train through a switch left in the wrong position (16; Rail Safety Improvement Act of 2008, H. R. 2095, 110th Cong., 2nd session, 2008). The legislation is a performance standard and does not specify the technology that must be used to meet the requirements. In principle, CBTC can be implemented without enforcement braking; however, this has been envisioned as an element of CBTC since the earliest concepts of its development (9). It is also technically possible to meet the PTC requirements without the use of a pure CBTC system (30); however, most PTC systems in the United States will likely be some form of pure or hybrid CBTC system with enforcement. Because they are not part of the PTC regulation, the additional elements available with a CBTC system will not necessarily be part of a PTC-compliant system, and therefore, the potential benefits or costs of PTC and CBTC are different. This paper considers the potential elements of a CBTC system that may affect capacity, including those required to meet the PTC requirements.

CURRENT TRAFFIC CONTROL SYSTEMS

Most current automatic traffic control systems use wayside signals to manage train speed and headway. Signal spacing is typically set on the basis of the distance that it takes for the worst-case train that normally operates on a line using normal service braking to stop from the maximum permitted train speed at a location. Because the signals are designed for this worst-case train, many trains may have stopping distances shorter than the signal system of the line was engineered for. Furthermore, although the rules of individual railroads vary on the exact language, an engineer is usually required to begin reducing the speed when the train passes a signal displaying a restrictive signal. This means that for a train to continuously maintain normal track speed, it must not encounter signals less favorable than "clear." Consequently, trains must generally be separated by at least two blocks in a three-aspect system and three blocks in a four-aspect system. Because of these operating rules and the use of worst-case braking distances, trains are separated by a distance several times longer than their braking distance.

A variety of traffic control systems are currently in use on North American railroads, but they can be broadly categorized into two types: (a) those in which a manual system of spoken or written messages conveys movement authority to trains and (b) those in which the dispatcher conveys this authority directly via the wayside signals. Track warrants are the most commonly used manual system, especially on lower-density lines. The capacity on these lines can be increased by overlaying them with automatic block signals, but the authority is still conveyed manually. If more capacity is needed, it can be upgraded to centralized traffic control (CTC), in which the signals themselves convey movement authority. On some track warrant systems and all CTC systems, the dispatcher is able to remotely control switches, allowing the more efficient planning and management of meets and passes of multiple trains on a line.

There are technologies that offer further improvement in operational efficiency, and some of these provide more information to train crews and others that help dispatchers. The oldest of these is cab signals, which take advantage of the coded track circuits in the rails that communicate the aspect information to the wayside signals. Specialized equipment on the locomotive enables the current signal block aspect to be displayed in the cab. With wayside signals, a signal ahead may change to a more favorable indication but the locomotive engineer does not know this until the next signal comes into view. Cab signals allow the engineer to know immediately if a more favorable indication applies and to take advantage of it immediately. Another technology that assists the dispatcher in managing all the traffic on a line is computer-aided dispatching (CAD). In these systems the computer accounts for the operational characteristics of trains and the features of a route to help the dispatcher better plan meets and passes.

ELEMENTS OF A CBTC SYSTEM

A PTC-compliant CBTC system has several components and features that have the potential to affect capacity, either positively or negatively. These are

- Enforcement braking,
- Real-time train operating and location data,
- In-cab displays, and
- Flexible moving blocks.

Enforcement braking is necessary to comply with PTC requirements. Real-time train operating and location data give the dispatcher additional information. This additional information can also be provided to the locomotive on an in-cab display. CBTC also potentially permits the use of flexible moving blocks. Each of these components will affect railroad operations and capacity and will be considered separately.

Enforcement Braking

The element of a PTC system mandated by regulation is enforced braking to prevent unsafe situations. The intent is that the system will stop the train automatically if the engineer fails to take appropriate action to prevent the train from violating its authority limits or speed restrictions. To provide continuous enforcement, an onboard computer must determine when a train must begin braking. This computed braking curve is composed of the distances traveled during (31)

- Equipment reaction time,
- Propulsion removal,
- Brake buildup, and
- Full-service brake application.

These distances are highly dependent on various factors, including the initial speed of the train, the train length, car weights, braking efficiency, operative brakes, the brake propagation rate, adhesion, and rail condition. These factors are not accurately known when a train leaves the terminal, resulting in considerable uncertainty in the exact braking distance required (13, 32) (Figure 1). For safe operations, a train must have close to a zero probability of an overshoot [FRA has targeted 0.000005, or 5 chances in a million (13, 33)]. This necessitates a conservative braking algorithm that considers the worst-case condition for each of the unknown variables. This causes the enforced braking distance to be greater than the average braking distance (31). Consequently, the brake application with a PTC system will begin earlier than required for a typical full-service brake application. With or without braking enforcement, a train will brake in the same distance; consequently, an earlier application will cause the train to stop sooner than the engineer intends (33). Simulations have shown that the difference between the average stopping distance and the enforced target can be greater than 1,700 ft (33).

Braking enforcement can have several negative effects on capacity, including the following:

- An unacceptably large number of trains are forced to start slowing much earlier than normal service braking to prevent enforcement from taking over, slowing the overall operation.
- Train crews are not able to prevent enforcement and thus stop well short of the target.
- Train crews experience difficulty closely approaching a target stopping point, such as when they are pulling into a siding, potentially causing the back of the train to remain on the main line, blocking traffic (13).

Work is under way to create more accurate and adaptive braking algorithms (13). However, trains may travel long distances after they depart a terminal without making enough brake applications to obtain data adequate for the development of sufficiently accurate, updated estimations of braking distance (33), and there will always be some difference between the calculated braking distance and the actual or performance braking distance (31). The magnitude of this difference is dependent on the conservativeness of the braking algorithm used; a more conservative algorithm will increase the difference between the actual and the enforcement braking distances. The probability of overshoot used is dependent on the current specifications regarding enforcement braking; consequently, the manner in which those specifications are interpreted will have a direct impact on the effect of enforcement braking on capacity.

It is also possible that enforcement may have little or no impact on operations or capacity. Current wayside signal spacing is based on the braking distance of the worst-case train plus an additional margin of safety. Signal spacing may be greater than the enforced braking distance; therefore, if signals are still used, trains will begin to slow down in response to them instead of the enforcement. Additionally, enforcement algorithms are based on a full-service brake application. In most cases the engineer makes use of dynamic brakes and slows the train at a more gradual rate than with a full-service brake application, potentially preventing enforcement.

Depending on the railroad's operations and rules, enforcement braking has the potential to either increase travel times for the affected train or have no impact at all. If trains are slowed, they may also delay following trains, further reducing capacity. Further discussions and explanations of braking enforcement, adaptive braking, and their implications can be found in papers by Thurston (31) and Moore Ede et al. (13).

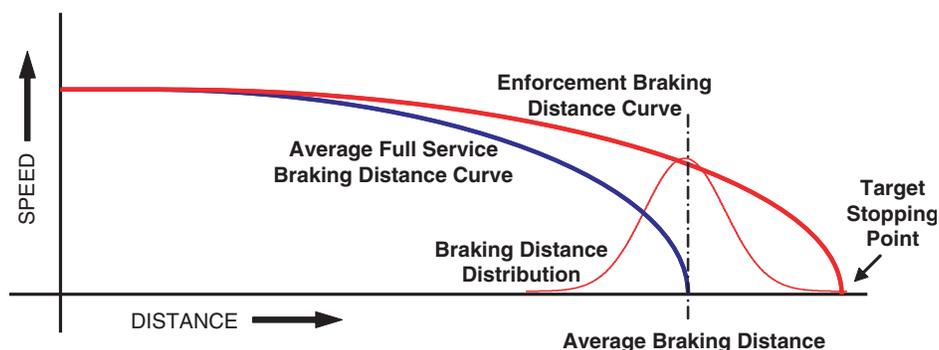


FIGURE 1 Speed, uncertainty in average braking distance, and resultant safe braking distance.

Real-Time Train and Location Data

Real-time train and location data offer the dispatcher additional information. The dispatcher is able to know a train's location and current speed with accuracy and with more precision than existing train control systems provide. This information will allow train dispatchers to respond more quickly to any disruptions or changes and to formulate alternative dispatching plans more quickly as circumstances change. This information also permits more effective meet-pass planning. When these data are combined with a CAD system, they can potentially decrease run times by reducing the time that trains wait for meets and passes (19, 21).

Real-time train and location data are also vital to braking enforcement and moving blocks. A technical challenge that has been encountered with real-time data is communications delay in the data links. In a CBTC system, a train's movement depends on the receipt of periodic authority updates as the track ahead clears. Any limitations in the data link throughput and message reliability could limit train capacity. If the data link delivers a movement authority too late, the train may have to reduce speed. Unreliability in the system could result in train position information being inaccurate, to the extent that the uncertainty buffer distances must be increased, increasing train headways (33). If the communications delay is not excessive, real-time train and location data can increase capacity.

In-Cab Displays

In-cab displays offer additional information to the locomotive engineer, permitting the engineer to operate the train more efficiently. An in-cab display will most likely have the following information (34):

- Location information,
- Authority and speed limits,
- Route and route integrity,
- Start of warning and enforcement braking,
- Location of maintenance-of-way work limits, and
- Positions of other track vehicles.

An in-cab display offers the engineer near real-time information on the status of blocks ahead. With wayside signals, this information is updated only at discrete points as the train approaches and passes each block signal. If the signal is anything less favorable than clear, the engineer will immediately or soon need to reduce speed, unless the train is already traveling at the speed indicated by the signal. Although the status of the block ahead may improve after the front of the train has passed, the engineer has no way of knowing this and will continue reducing the speed until the next signal comes into view and is displaying a more favorable indication. However, if the engineer has access to continuously updated information on the status of the block ahead, the engineer may not have to reduce speed as much if the block ahead clears. A CBTC in-cab display can also have benefits in territories where movement authority is given through a manual system because it eliminates the time required for voice transmission and confirmation (24). Cab signal technology provides some of the capacity benefits of a CBTC in-cab display by displaying the aspect of the next block (31); however, most locomotives and routes in North America are not equipped with these technologies, so in these cases, CBTC will provide these incremental benefits.

Flexible Moving Blocks

Moving blocks provide continuous train separation and have the potential for this to be based on each train's individual stopping characteristics rather than the discrete fixed blocks characteristic of current signal systems. Moving blocks thus have the potential to reduce minimum headways. With a fixed-block system, trains outside of terminals or interlocking limits traveling at the normal track speed are typically separated by at least two blocks, irrespective of their individual stopping characteristics. In contrast, in a moving block system, trains can be separated by little more than a single block and potentially by a distance related to the individual stopping distance of each train. This effectively reduces the minimum train separation from two or more blocks, as required with a fixed-block system, to a single block (or even less for some trains) of separation.

This is probably the greatest opportunity for enhanced capacity attributable to CBTC, especially on lines on which there is traffic with similar speeds but heterogeneous stopping distances. With a fixed-block system, the signals are spaced for the train with the longest braking distance, and therefore, the headway is longer than needed for much of the traffic. Slower or lighter trains with shorter braking distances, such as passenger and commuter trains, will be able to follow other train traffic more closely. This might help mitigate the disproportionate impact of certain types of heterogeneity due to the mixing of passenger and freight traffic (3–6).

Moving blocks also offer a benefit during recovery from temporary track outages or delays. Successive trains will be able to follow each other more closely because of their shorter braking distances at slower speeds. With a single track, to get operations back to normal as quickly as possible, moving blocks will allow trains to be fleeted through the work area with much closer spacing than is possible with conventional signal systems. This fleeting may also be of value when a double-track section must be made into a single track during maintenance (24).

Moving block capability can also reduce the delays due to passes on single-track lines. Shorter headways reduce the time that the overtaken train waits in the siding (33). Also, when a train leaves the siding, new movement authority can be issued to a train immediately after an overtaking train has passed the exit switch and the switch has been lined. It is not necessary to wait until the first block has been cleared, as may sometimes be required with conventional traffic control systems (24).

ELEMENTS OF AN ECP BRAKE SYSTEM THAT WILL AFFECT CAPACITY

ECP brakes change how the brake signal is transmitted. The signal will be transmitted through an electronic signal instead of a reduction in train line air pressure. Currently, each car is connected with an air line that is used to charge the brakes and transmit the braking signal. With ECP brakes, each car will also be connected by an electrical connection.

Current Systems

The current pneumatic brake system uses air pressure both to transmit the braking signal and to charge the brake reservoirs of the cars in the train. A reduction in air pressure along the brake line causes

the control valve to admit air into the brake cylinder applying the brakes. Two important limitations in this system in typical North American freight train applications are that the system does not permit the reservoirs to be recharged while the brakes are being applied, and it does not permit graduated release. Repeated application and release of the brakes can deplete the air pressure in the reservoirs and substantially reduce the braking force available. Avoiding this poses several operational limitations that affect capacity and potential safety problems if the brake system is not handled properly. The other limitation is that the air pressure signal is transmitted along the length of the train at approximately two-thirds the speed of sound (8). With longer trains there is a lag between the time of application and release at the rear of the train and that at the front of the train, causing significant in-train forces. Consequently, this means that there is a direct relationship between propagation time and braking distances. This problem is reduced when distributed power (DP) is used because it permits the braking signal to be initiated at more locations in the train, thereby reducing the brake signal propagation time and, thus, the braking distance (35). Railroads are increasingly using DP, and one major railroad estimates that 50% of its operation now uses DP.

Elements of an ECP Brake System

ECP brakes have several characteristics that have the potential to affect capacity. These are

- Instantaneous transmission of the brake signal,
- Steady brake line pressure, and
- Self-monitoring capabilities.

Use of an electronic signal instead of air pressure to transmit the brake signal allows virtually instantaneous transmission, enabling the nearly simultaneous application or release of the brakes along the entire length of the train. ECP brakes have a steady brake pipe pressure that allows continuous charging of the brake reservoirs and charging even while the brakes are being applied. The use of a train line cable also allows real-time, self-diagnostic “health check” functions to be incorporated into the brake system; the information from these functions informs the train crew when maintenance is needed (8). Each of these characteristics will be considered for their impact on capacity. Several proposed elements of an ECP brake system, including tricouplers and the ability to remotely uncouple cars, have the potential to affect capacity. These have not been included in any of the systems that have been developed, and therefore, they are not considered in this analysis.

Instantaneous Transmission of Brake Signal

With current brake systems, there is a delay during the propagation of the brake signal, whereas this delay is eliminated with ECP brakes. It is estimated that this will reduce the braking distance by about 40% to 60% compared with the conventional braking distance (8). Because the headway between trains is limited by the safe braking distance, if ECP brakes are installed on all trains, such a reduction will permit closer train spacing, if the traffic control system can accommodate it. The alternative to shorter headways is the ability to travel at higher speeds with the same signal spacing (36). Another benefit

to having all the brakes on a train apply simultaneously is the reduction of in-train forces, permitting longer trains. Fewer, longer trains free up train slots, thereby allowing additional traffic. However, DP can provide some of the same benefits of reduced braking distances and longer train lengths but not the reduction in signal spacing that ECP brakes provide. Consequently, in some instances, railroads are already deriving some of the benefit that this aspect of ECP brakes offers.

Steady Brake Line Pressure

Steady brake line pressure allows the continuous charging of the brake reservoirs. This facilitates greater use of the braking system and reduces the time lost waiting to recharge the brake line and reservoir pressure after an application. With conventional freight train brakes, once the engineer has selected a brake level, the braking force cannot be reduced without completely releasing and reapplying the brakes. Trains must sometimes travel with more braking force applied than is necessary, resulting in slower operations (8). The continuous charging of brake reservoirs enables the graduated release of brakes, offering greater braking flexibility. This will potentially allow a train to conform more closely to appropriate track speed limits and increase average speeds. Another benefit is the shorter restarting time after stops. With the current brake technology, in areas of descending grades, the auxiliary reservoirs on each car of the train must be recharged before a train restarts from a stop (8, 15). This is not necessary with ECP brakes, reducing the dwell time on routes with large grades.

Self-Monitoring Capabilities

Use of an electrical signal to control the brakes has the added benefit of enabling the transmission of brake condition data to the locomotive. The engineer can monitor the brake condition and immediately be informed of any failure in any car on the train. In response to these capabilities, FRA issued a new regulation that requires brake inspections to be performed every 3,500 mi instead of every 1,000 mi, as is required with conventional brakes (14). This potentially allows an ECP-brake-equipped intermodal train originating from the ports of Los Angeles–Long Beach in California to travel all the way to Chicago, Illinois, without stopping for routine brake tests. Similarly, ECP-brake-equipped coal trains will be able to make quicker deliveries from western coal fields to power plants in the eastern and southern states (37). This not only decreases the cycle times but may also reduce the congestion at the terminals where these inspections currently take place. To achieve these results, the reconfiguration of terminal points and the resulting expenditures may be required.

IMPACT OF CBTC AND ECP BRAKES ON CAPACITY

The potential impact of CBTC and ECP brakes on capacity will depend on the type of implementation of each system, the traffic mix, the track configuration, and the topography of the route. For CBTC there are three different possible implementations: as a nonvital or a vital overlay to an existing control system or as a stand-alone system

(25). When CBTC is implemented as a nonvital overlay, the underlying control system provides movement authority, but CBTC provides an additional, automatic backup to prevent unsafe conditions. When it is implemented as a vital overlay, both the underlying system and CBTC verify and convey authority. In a stand-alone system, CBTC plays the sole role of verifying, conveying, and enforcing authority (25). Nonvital and vital overlay systems will still require the use of the current signal system, whereas a stand-alone system will permit moving blocks. Whether a route has single or multiple tracks will also affect the impacts of these systems. A single-track route is constrained because of the need for meets and passes, whereas with a multiple-track route, headway may be a more important constraint. The topography of the route also affects train handling and, consequently, capacity.

CBTC Nonvital Overlay System

A CBTC overlay provides enforcement according to the requirements of PTC, in addition to the current signal and traffic control systems. This type of implementation makes use of the current signal and traffic control system, and therefore, closer train spacing is not possible in wayside signal territory. However, in unsignaled (“dark”) territory, an overlay system provides a more effective means of train separation. Much like a signal system, the installation of CBTC would efficiently allow the closer spacing of trains, thereby increasing capacity. Conversely, enforcement braking will result in trains slowing down sooner than they might otherwise, thereby reducing capacity. With or without a signal system, a CBTC overlay does not provide movement authority, and therefore, the current methods for this will remain in place, limiting some of the benefits of the in-cab display. In Europe the overlay version of ETCS has been found to reduce network capacity (38). In North America, the potential impact on capacity will be the greatest on signalized, single-track lines on which enforcement has a greater effect because of the more frequent stops from meets and passes.

CBTC Vital Overlay System

A CBTC vital overlay system will have capacity constraints similar to those of an overlay system because of the inability to take advantage of moving blocks. However, with a vital overlay system, the signal, traffic control, and CBTC systems are interconnected and authorities can be issued immediately via the in-cab display of the locomotive. Capacity under a vital overlay system will generally be the same or slightly higher than under that a nonvital system.

CBTC Stand-Alone System

A stand-alone CBTC system permits the use of real-time train and location data, in-cab displays, and moving blocks and the benefits that they provide. However, the potential capacity losses of braking enforcement still apply. The greatest potential benefit will be on multiple-track routes, on which reduced headways offer the greatest advantage. If moving blocks are used, this is likely to more than offset any potential capacity losses due to enforcement braking, which will have a resultant benefit to capacity.

Impact of ECP Brakes on Capacity

In an ECP brake system, the brake signal is transmitted instantaneously, the brake reservoirs are continuously charged, and the frequency of brake inspections is reduced. ECP brakes provide the greatest benefit relative to current systems for trains on severe grades (8). Grades can be bottlenecks on a railroad network, and ECP brakes provide improved train handling and reduced dwell time while the trains are traveling on these grades. Capacity can be improved on single-track lines because less time is lost during stops, and capacity can be improved on multiple-track lines because shorter headways are possible. Shorter cycles and increased terminal capacity can be achieved as well because of a reduction in the number of intermediate brake inspections.

Impact of Combination of CBTC and ECP Brakes

Use of the combination of CBTC and ECP brakes may allow better exploitation of the benefits that each system offers. It has been suggested that the data from ECP brakes will increase the accuracy of the braking algorithms, thereby reducing the impact of enforcement braking. Both of these systems increase the information available, and in combination, the additional train data from ECP brakes can be transmitted to the dispatcher or other relevant groups via the CBTC data network. Effective use of this information will permit a railroad to plan and manage its operations more efficiently. A stand-alone CBTC system will take the greatest advantage of ECP brakes because the use of moving blocks will permit railroads to reduce headways, which ECP brakes permit, without the need to modify signal spacing. Because it will take time for all trains to be equipped with ECP brakes, a stand-alone system will permit those trains equipped with ECP brakes to follow more closely behind the trains ahead, thereby providing incremental capacity benefits before the entire railcar fleet has been equipped with ECP brakes. A related benefit of CBTC with a moving block is that it will offer flexibility in train spacing if the train mix changes on a line or as further improvements in brake system effectiveness lead to shorter stopping distances and potentially closer train spacing.

DISCUSSION OF RESULTS

CBTC and ECP brakes make the train, signal, and traffic control systems more “intelligent” (29). This allows the railroad to better plan and control train movements, increasing railroad efficiency and capacity. However, braking enforcement will not increase capacity and may reduce it (13, 33). As the implementation of these technologies is considered, unanswered questions on their net effect on capacity remain.

Although railroads are planning to implement overlay CBTC systems and are testing ECP-brake-equipped unit trains, technical challenges remain. Conservative braking algorithms and excessive communications delays within CBTC may reduce capacity. Moving blocks also have not yet been proven to be technically feasible in the North American operating environment. CBTC may permit the removal of existing signal systems; however, to date there is no practical alternative to track circuits for the detection of broken rails. If track circuit systems cannot be eliminated, it may not be possible or economically justifiable to invest in a stand-alone CBTC system. Some authors have argued that even if it is possi-

ble, it may not be advisable to implement a completely stand-alone system (39).

Even when a reduction in headways is possible, this may not translate into additional network capacity because of other capacity bottlenecks. Headway is just one factor influencing capacity; other operational and infrastructure factors may continue to constrain a route. Sidings, interlockings, yards, and junctions are fixed points in the network; and reduced headways will not improve these capacity constraints. Additionally, terminals are considered major bottlenecks in many railroad networks (40). Consequently, although there may be reductions in the over-the-road time due to the use of CBTC and ECP brakes, increases in line capacity may not improve network capacity if the principal constraints are the terminals.

When the impacts of these new technologies are calculated, it is necessary to understand how their potential capacity benefits compare with what can be obtained from current systems. With ECP brakes, the comparative benefits of DP need to be considered. With CBTC the current train control technology on a line will affect the potential benefits of the system. In areas where there is no signal system or signals are widely spaced, CBTC will likely increase capacity. However, many of the areas that are currently facing the greatest capacity constraints are urban areas, where the signals are closely spaced. Lastly, the incremental benefit of CBTC is dependent on the implementation; in some cases, there may be no benefit without the use of a stand-alone system.

CONCLUSIONS AND FUTURE WORK

The implementation of CBTC and ECP brakes will have a direct effect on capacity. This paper has attempted to consider each critical characteristic of these technologies with respect to their capacity. All CBTC implementation types with enforcement braking have the potential for a loss of capacity, but as CBTC systems become more fully integrated, the potential for capacity enhancement improves. ECP brakes will provide benefits in most operational scenarios because of the shorter braking distances that they allow. Furthermore, CBTC may enable one of the principal benefits of ECP brakes—shorter stopping distances—to be more effectively and efficiently taken advantage of. These results will tend to be route and network specific, so individual railroads will need to conduct these analyses to understand the effects on their own systems.

Future work will use simulation software and mathematical models to quantify these impacts under a variety of scenarios of interest. Tests are planned with one and two main track lines, flat and mountainous terrain, and homogeneous and heterogeneous traffic. A better understanding of which combinations of conditions result in a gain or a loss of line capacity can be used to calculate how the railroad network as a whole will be affected by these technologies.

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