Impact of CBTC and ECP Brakes on Capacity

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ABSTRACT

Railroads are expected to face capacity constraints due to longer-term prospects for substantial growth in both freight and passenger traffic. To prepare for this, railroads need to understand the factors that affect rail capacity and the options to cost-effectively improve it. Two technologies that have been touted as beneficial to capacity are Communications Based Train Control (CBTC) and electronically controlled pneumatic (ECP) brakes, but the actual effect is more complex. These technologies can enhance capacity under some circumstances, have little or no effect, or even reduce capacity in others. Consequently, understanding their net effect on a particular rail line or network requires understanding both the particular aspects of these technologies that affect capacity, and the system they are being introduced into. In this paper we review CBTC and ECP brakes and compare them to current technologies to understand their incremental effect on capacity. We also identify each element of CBTC and ECP brakes with the potential to affect capacity and consider what this affect will be under various implementation circumstances. If the capacity impacts of these two technologies can be quantified for various circumstances, it will help railroads better understand when, where and to what extent their introduction will affect capacity.

INTRODUCTION

Beginning in the early 2000s major North American railroads were increasingly experiencing capacity constraints. Although the economic recession has temporarily abated this, long term prospects call for substantial growth in freight traffic *(1,2)*. Furthermore, new initiatives to develop intercity passenger rail will have a disproportionate impact on capacity due to the differences in operational characteristics between freight and passenger trains *(3,4)*. Consequently understanding factors that affect rail capacity and the options available to cost-effectively improve it are important.

Infrastructure expansion will undoubtedly play an important role in accommodating new traffic demand; however, two new technologies are being introduced that will also affect rail capacity; Communications Based Train Control (CBTC) (often referred to as Positive Train Control or "PTC" in the U.S.) 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 they are being introduced into, and in what manner they are being introduced. In this paper we attempt to identify each critical aspect of these technologies that has the potential to affect capacity and consider what this affect will be under which conditions of implementation. Our work is part of a larger effort in which we are conducting simulation analyses of a range of operating scenarios in order to quantify the effect of these technologies on rail capacity. Railroads planning for the implementation of CBTC and

ECP brakes will need to conduct similar assessments in order 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 *(5)*. 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 *(6,7,8)* and freight railroad ECP brake technology since the early 1990s *(9)*; however, wide-scale adoption has not occurred due to technical, practical, economic and institutional barriers *(10)* Recent regulations and legislation have altered the situation. The Federal Railroad Administration is encouraging implementation of ECP brakes by offering relief from certain requirements pertaining to pneumatic brake operation *(11,12)*. With regard to PTC, the Rail Safety Improvement Act of 2008 *(13)* mandated its implementation on select U.S. rail lines by 2015.

A number of previous studies have investigated the impact of CBTC on capacity. Lee et al *(14)* determined that moving blocks could increase the capacity of the Korean high speed railway. Another study quantified the capacity benefits of the European Train Control System (ETCS), Europe's version of CBTC *(15)*. In the United States, Resor et al *(16,17,18,19)* studied the potential benefits of the Burlington Northern's Advanced Railroad Electronics System (ARES) and other possible CBTC systems. They calculated how the more efficient meet/pass planning and the increased dispatching effectiveness possible with CBTC will affect capacity. Martland calculated the potential terminal efficiency improvements resulting from the estimated increases in reliability offered by CBTC *(20)*. While many authors have claimed that a CBTC system with moving blocks will increase capacity, there has been some debate about whether this will in fact be the case *(7,10,19,21,22,23,24,25,26)*.

There has been less work addressing the capacity effects of ECP brakes. Most agree that they will reduce stopping distances thereby allowing 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 traffic control system.

As discussed above, the effect of CBTC and ECP brakes will be context specific, that is, in some circumstances one or both technologies have the potential to increase capacity, either alone or in combination, in other cases they will have little or no effect, and in some 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 that they occur over a particular route or network.

ELEMENTS OF A CBTC SYSTEM THAT WILL AFFECT CAPACITY

The data links in a CBTC system provide real time data to the dispatcher and train crew. This has the potential to increase efficiency though better train management and control *(27)*. However, in order for a CBTC system to comply with the legislative requirements for PTC it must also "prevent train to-train collisions, over-speed derailments, incursions into established work zone limits, and the movement of a train through a switch left in the wrong position *(13,28)*." 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 *(6).* Furthermore, if CBTC does not include enforcement braking it will not meet the PTC requirements; therefore this capability is being incorporated into the systems being developed and marketed in the U.S. It is also technically possible to meet the PTC requirements without use of a pure CBTC system; however, most PTC systems in the U.S. will likely be some form of pure or hybrid CBTC system with enforcement. Therefore, in this paper we define CBTC as including the capabilities specified in the PTC legislation.

Current Traffic-Control Systems

Most current automatic traffic control systems use wayside signals to manage train speed and headway. Signal spacing is typically set based on the distance 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. Since the signals are designed for this worst-case train many trains may have stopping distances shorter than the line's signal system was engineered for. Additionally, individual railroads' rules vary on the exact language but normally an engineer is required to begin reducing speed when they pass a signal displaying a restrictive signal. This means that in order 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. Due to these operating rules and use of worst-case braking distances, trains are separated by a distance several times longer than their braking distance.

There are a variety of traffic control systems currently in use on North American railroads but they can be broadly categorized into two types: those in which a manual system of verbal or written messages conveys movement authority to trains, and those in which the dispatcher conveys this authority directly via the wayside signals. Lower density lines tend to use a manual system such as track warrants or similar system. Capacity on these can be increased by overlaying them with automatic block signals (ABS) 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 and all CTC systems the dispatcher is able to remotely control switches allowing for 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, some of which provide more information to train crews and others that help dispatchers. The oldest of these is cab signals that 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 take advantage of it right away. Another technology that assists the dispatcher in managing all the traffic on a line is computer-aided dispatching. 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. This can reduce trains' time over the road in several ways thereby improving line capacity.

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 display
- Moving blocks

Enforcement braking is necessary in order to comply with the PTC requirements. Real-time train operating and location data for the dispatcher is possible due to the additional information that is available with CBTC. This additional information can also be provided to the locomotive on an in-cab display allowing the engineer to more efficiently operate the train. The integration of train location data permits the use of moving blocks. Each of these components will impact railroad operations and capacity and will be considered separately.

Enforcement Braking

The key element of a PTC system is the enforced braking in order 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. In order to provide continuous enforcement, an on-board computer must determine when a train must begin braking. This computed braking curve is composed of the distances traveled during *(29)*:

- Equipment reaction time
- Propulsion removal
- Brake build-up
- Full service brake application

These distances are highly dependent on factors including initial train speed, train length, car weights, braking efficiency, operative brakes, brake propagation rate, adhesion and rail condition. Unfortunately these factors are not accurately known when a train leaves the terminal resulting in considerable uncertainty in the exact braking distance required *(10,30)* (Figure 1). If these factors can be more accurately determined using new or improved technologies, or calculated using an adaptive braking algorithm *(10)*, the estimation of braking distance can more accurately represent the true braking distance, and the uncertainty reduced. However, even with many of the factors known there will still be some difference between the calculated braking distance and the actual or performance braking distance *(29)*. The target location where a train is to stop is a point that the train must not pass and hence there must be close to zero probability of overshoot (FRA has targeted 0.000005, or 5 chances in a million *(10)*). This requires the safe braking distance to be greater than the average braking distance *(29)*, causing a train to stop sooner than the engineer intends. Further discussion and explanation of braking enforcement, adaptive braking and their implications can be found in papers by Thurston *(29)* and Moore Ede et. al. *(10).*

Another characteristic of braking enforcement that will increase headway distances is the warning of enforcement. Its purpose is to provide advance notice to train crews of an impending enforcement (Figure 2). By definition, a warning must begin at a distance greater than the enforcement distance. When the warning curve passes a restriction where action will be required, an alert is displayed in the locomotive cab. If no action is taken by the time the enforcement curve reaches the location of the restriction, there will be an automatic, full service, penalty-brake application. This will be costly in terms of fuel and time (and hence capacity) and railroads can be expected to discourage crews from allowing this to occur. Consequently, in order to prevent these enforcement brake applications, locomotive engineers are expected to start braking shortly after the warning curve alert occurs.

For the reasons discussed above, the enforcement braking distance is already longer than is generally necessary under normal operating conditions, and the warning curve will further extend the braking distance. This will require trains to start slowing earlier than normal service braking thereby slowing overall operations. The extent of this effect will be affected by the duration of the warning, which is the difference between the warning and enforcement times, with longer times having a greater impact. Additionally, there is a potential that trains may stop short of the target, delaying train crews' ability to approach the target stopping point, such as a siding *(10)*. These technical problems need to be resolved or there will be increased travel times for the affected train, and they may also delay following trains, further reducing capacity.

Real-time Train and Location Data

Real-time train and location data offer the dispatcher additional information. The dispatcher is able to accurately know where a train is and its current speed. This information will allow train dispatchers to respond more quickly to any disruptions or changes and to more quickly formulate alternative dispatching plans as circumstances change. In their study, Resor et al. stated that this aspect had the potential to reduce line haul travel times up to 12 percent *(16)*. CBTC will provide this capability, but as mentioned above, there are already systems in operation that provide this capability and its attendant benefits.

In-Cab Display

In-cab displays offer additional information to the locomotive engineer permitting him to more efficiently operate the train. An in-cab display will most likely have the following information *(31)*:

- Location information
- Authority and speed limits
- Route and route integrity
- Start of warning and enforcement braking
- Location of maintenance-of-way work limits
- Position 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 only updated at discrete points as the train approaches and passes each block signal. If the signal is anything less favorable than clear, the engineer will begin to reduce speed. Although the status of the block ahead may change after the front of the train has passed, the engineer has no way of knowing and will continue reducing speed prepared to stop until the next signal comes into view displaying a more favorable indication. However, if the engineer has access to continuously updated information on the status of the block ahead they may not have to reduce speed as much if the block ahead clears. An in-cab display also has benefits in territories where movement authority is transmitted through verbal communication because it eliminates the time required for voice transmission and confirmation *(21)*. However, cab signals technologies provide some of the benefits of a CBTC in-cab display *(29)*. However, most locomotives and routes in North America are not presently equipped with these technologies so in these cases, CBTC will provide these incremental benefits.

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 normal track speed are typically separated by two blocks, irrespective of their individual stopping characteristics. By contrast, in a moving block system trains can be separated by little more than a single block, and potentially by a distance related to each train's individual stopping distance. This effectively reduces normal train separation from two 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 where 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 or commuter trains, will be able to more closely follow other train traffic. This might help mitigate the disproportionate impact of certain types of heterogeneity due to mixing of passenger and freight traffic *(3,4)*.

Moving blocks also offer a benefit when recovering from temporary track outages or delays. Successive trains will be able to follow each other more closely because of their shorter braking distance at slower speeds. With a single track, in order 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 with conventional signal systems. This fleeting may also be of value when a double-track section has to be single-tracked during maintenance *(21)*.

Moving block capability can also reduce delays due to passes on single track lines with passing sidings. 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 *(21)*.

ELEMENTS OF AN ECP BRAKE SYSTEM THAT WILL AFFECT CAPACITY

ECP brakes change how the brake signal is transmitted. The signal will be transmitted using an electronic signal instead of a change in 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 in addition to the air line each car will be connected by an electrical connection. Unfortunately ECP brakes are not reverse compatible to the current braking systems making the transition to ECP brakes more difficult.

Current Systems

The current pneumatic brake system uses air pressure both to transmit the braking signal and to charge the brake reservoirs of cars in the train. A reduction in air pressure along the brake line causes the control valve to admit air into the brake cylinder causing the brakes to apply. Two important limitations in this system are that in typical North American freight train applications, it does not permit the reservoirs to be recharged while the brakes are being applied, nor does it permit graduated release. Repeated application and release of the brakes can deplete air pressure 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 air pressure signal is transmitted along the length of the train at approximately two-thirds the speed of sound *(32)*. With longer trains there is a time lag between application and release at the rear of the train compared to the front, causing significant in-train forces. This means there is a direct relationship between propagation time and braking distances. Distributed power permits the braking signal to be started at more locations reducing brake signal propagation time.

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
- Continuous charging of the brake line
- Self-monitoring capabilities

Using an electronic signal instead of air pressure to transmit the brake signal allows for instantaneous transmission enabling nearly simultaneous application or release of the brakes along the entire length of the train. It is also possible to continuously charge the brake line even while 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 that inform the train crew when maintenance is needed *(33)*. Each of these characteristics will be considered for their impact on capacity.

Instantaneous Transmission of Brake Signal

With current brake systems there is a delay during the propagation of the brake signal whereas with ECP brakes this is eliminated. This will reduce braking distance by about 40 to 60 percent compared to conventional braking distance *(32)*. Since headway between trains is limited by 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 instantaneous brake signal can be used for quicker brake release as well, reducing the time for a train to restart after a meet. This has a direct impact on single track where meets and passes are a major capacity constraint. However distributed power can provide some of the same benefits in reduced braking distances, but not the reduction in signal spacing, that ECP brakes provide, so in many instances, railroads are already deriving some of the benefit that this aspect of ECP brakes offers.

Continuous Charging of Train Brake Line

Continuous charging of the train brake line facilitates greater use of the braking system and reduces the time lost waiting to recharge brake pipe pressure after an application. With conventional freight train brakes, once the engineer has selected a brake level, it cannot be reduced without completely releasing and reapplying the brakes. Trains must sometimes travel with more applied braking force than necessary due to the lack of graduated release, resulting in slower operations *(32)*. The continuous charging of the brake line enables graduated release of the brakes. The greater braking flexibility offered by ECP brakes allows a train to more closely conform to appropriate track speed limits. Another benefit is the shorter restarting time after stops. With current brake technology, in areas of descending grades, the auxiliary reservoirs on each car of the train must be recharged before restarting from a stop *(32,12)*. With ECP brakes this is not necessary, reducing dwell time on routes with large grades.

Self-Monitoring Capabilities

An electrical signal to control the brakes has the added benefit of enabling transmission of brake condition data to the locomotive. The engineer can monitor brake condition and be immediately informed of any failure in any car on the train. In response to these capabilities the FRA issued a new regulation that permits intermediate brake inspections to be performed every 3,500 miles instead of the 1,000 miles that is required with conventional brakes *(34)*. This allows an ECP brake-equipped intermodal train originating from the ports of Los Angeles-Long Beach to travel all the way to Chicago 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 *(34)*. This not only decreases cycle times but may also reduce congestion at terminals where these inspections currently take place.

IMPACT OF CBTC AND ECP BRAKES ON CAPACITY

The potential impact of these new technologies on capacity will depend on the type of implementation of each system, traffic mix, track configuration, and the topography of the route. For CBTC there are three different possible implementations, a non-vital overlay to an existing control system, integrated, or vital overlay, with an existing control system and as a stand-alone system *(22)*. In an overlay system the underlying control system provides movement authority, but CBTC provides a backup to prevent unsafe conditions. With an integrated CBTC system, both the underlying system and CBTC verify and convey authority. In a stand-alone system, CBTC plays the sole role in verifying, conveying, and enforcing authority *(22)*. An overlay and integrated system will still require the use of the current signal system, while a stand-alone system will permit moving blocks. Whether or not a route has single or multiple tracks will also affect the impact of these systems. A single track route is constrained due to 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 Overlay

A CBTC overlay provides enforcement per the PTC requirements in addition to the current signal and traffic control systems. This type of implementation can only make use of moving blocks in non signaled territory; therefore, in wayside signal territory closer train spacing is generally not possible. However, due to enforcement the engineer will have to begin slowing down before he generally would under current operations. In “dark” territory (i.e. without signals) an overlay system provides a more effective means of train separation than the current system of verbal authorities. Much like a signal system, installation of CBTC would efficiently allow closer spacing of trains thereby increasing 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. The potential capacity losses are greatest on a signalized, single track line where enforcement will have a greater effect due to the more frequent stops from meets and passes.

CBTC Integrated System

A CBTC integrated system will have similar capacity constraints as an overlay system due to the inability to take advantage of moving blocks. However with an integrated system the signal, traffic control, and CBTC system are interconnected and authorities can be issued immediately to the in-cab display of the locomotive. Capacity under an integrated system will generally be the same or slightly higher compared to an overlay system.

CBTC Stand-alone System

A stand-alone CBTC system permits the use of real-time train and location data, in-cab displays, moving blocks and the benefits they provide. However, the potential capacity losses of braking enforcement still apply. The greatest potential benefit will be on busy multiple-track routes where reduced headways offer the greatest advantage. If moving blocks are used, this is likely to more than offset the potential loss in capacity due to longer enforced braking distances resulting in a net benefit with regard to capacity.

Impact of ECP Brakes on Capacity

ECP brakes instantly transmit the brake signal, continuously charge the brake line, and reduce the frequency of intermediate brake inspections. ECP brakes provide the greatest benefit compared to current systems on severe grades. Grades can be bottlenecks on a railroad network and the improved train handling and reduced dwell while traveling on these grades can provide benefits. On both single and multiple-track lines capacity can be improved through less time lost during stops and shorter headways respectively. Terminal capacity may be increased as well through a reduction in the number of intermediate brake inspections.

Impact of the Combination of CBTC and ECP Brakes

The combination of CBTC and ECP brakes may allow better exploitation of the benefits that each offers. Although a PTC-compliant CBTC system will enforce braking, ECP brakes on the other hand will make safe-stopping distances shorter; thereby potentially compensating for the loss in capacity if conventional brakes are used. Both of these systems increase the data available, and together the additional train data obtained from ECP brakes can be transmitted to the dispatcher or other relevant groups via the CBTC data network. This information can create a more efficient railroad network. A stand-alone system will take greatest advantage of ECP brakes because moving blocks will permit railroads to take advantage of the reduced headways that ECP brakes permit without the need to modify signal spacing. Since 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 trains ahead, thereby providing incremental capacity benefits before the the entire rail car fleet has been equipped with ECP brakes. A related benefit of CBTC with 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 distance and potentially closer train spacing.

DISCUSSION

CBTC and ECP brakes have the potential to increase railroad efficiency and capacity in a number of respects because they will make the train, signal and traffic control systems more "intelligent" *(27)*. The additional information that will be available to the dispatcher and engineer may increase capacity on portions of the North American network. However, braking enforcement has the potential to have the opposite effect, although work is underway to mitigate this effect *(10)*.

Although implementation of both technologies appears likely, there remain unanswered questions on how they will affect capacity. Even when reduction in headways is possible this may not translate into additional network capacity due to 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. Another question regards the effect on the overall network. Terminals are considered major bottlenecks in many railroad networks *(35)* so improved line haul times due to efficiencies gained from CBTC and ECP brakes may subsequently be lost in terminals due to capacity constraints there.

When calculating the impact of these new technologies the incremental benefit compared to existing technologies should be accounted for. For instance, how does the capacity gained from CBTC or ECP brakes compare to potential benefits gained from other current systems? Also while it is likely that CBTC will increase capacity when there is no signal system or signals are widely spaced as they were in the original ARES test installation, will there be additional capacity benefits from CBTC when blocks are shorter in length, as is the case in many areas that are currently facing the greatest capacity constraints?

CONCLUSIONS AND FUTURE WORK

Implementation of CBTC and ECP brakes will have direct effects on capacity. In this paper we attempt to consider each critical characteristic of these technologies with respect to their capacity. All CBTC implementation types are expected to increase braking distances due to enforcement braking but as CBTC systems become more fully integrated, the potential for capacity enhancement improves. ECP brakes will provide benefits in most operational scenarios due to shorter braking distances and reduced dwell times. Furthermore, CBTC may enable one of the principal benefits of ECP brakes - shorter stopping distances - to be more effectively and efficiently taken advantage of. However, it is not clear what the net effect of these systems will be relative to what is possible through use of various current technologies. These results will tend to be route and network specific so individual railroads will need to conduct these analyses to understand the effect on their own systems.

In future work we will be using simulation software and theoretical models to quantify these impacts under a variety of scenarios of interest. Tests are planned using single and two-main track lines, flat and mountainous terrain, and with homogenous and heterogeneous traffic. A better understanding of which combinations of conditions result in line capacity being gained or lost can be used to calculate how the railroad network as a whole will be affected by these technologies.

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LIST OF FIGURES

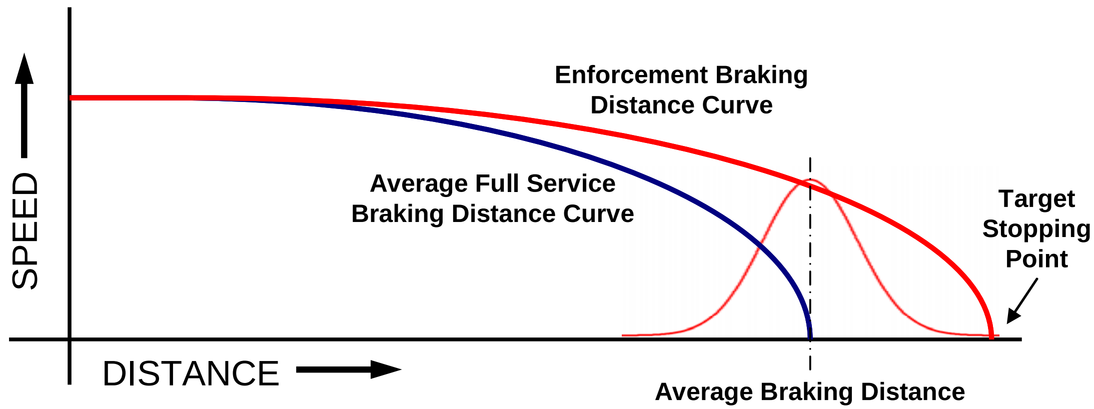

FIGURE 1: Speed, Uncertainty in Average Braking Distance, and Resultant Safe Braking Distance

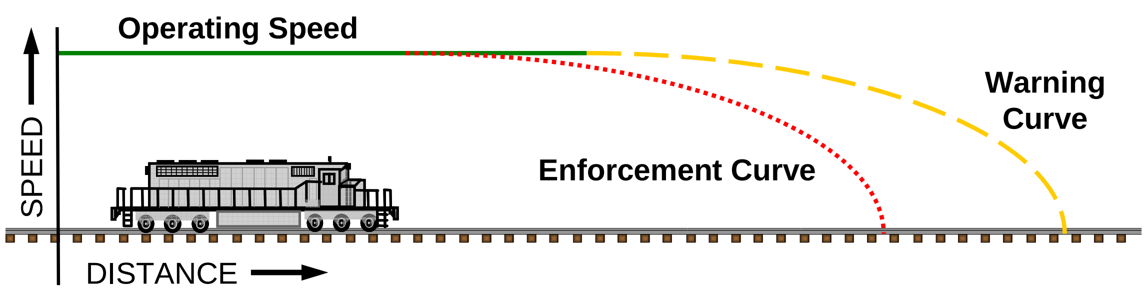

FIGURE 2: Braking Curves under CBTC System