moderate to high volumes, equalizing priorities was beneficial with heterogeneous traffic. At the highest volumes, and when bulk was a majority of the traffic, sidings were the alternative with the best NPV.

TABLE 7.8: Best Alternative to Reduce Train Delay

		Volume							
		12	16	20	24	28	32	36	40
% of Bulk Trains	0	-	-	-	-	-	-	-	-
	12.5	-	=P	=P	=P	=P	=P	=P	=P
	25	-	=P	=P	=P	=P	=P	=P	+SD
	50	-	=P	=P	=P	=P	=P	+SD	+SD
	75	-	=P	=P	-	-	-	+SD	+SD
	87.5	-	=P	=P	=P	-	-	+SD	+SD
	100	-	-	-	-	-	-	+SD	+SD

TABLE 7.9: Alternative Nomenclature

=P	Equalizing Priorities
+SD	Adding Sidings

7.5 Discussion

With increasing demand for freight rail services, railroads must evaluate the most economical methods to reduce train delay and increase capacity. Depending on the volume and specific traffic mix the best alternative may be infrastructure expansion, operational changes or some combination.

Operational changes are advantageous because they can be implemented more rapidly, are more flexible than infrastructure changes, and may be less capital intensive. Such changes enable a railroad to respond to changing traffic levels and patterns, provide relief during short periods of high traffic volumes, or serve as an interim measure while additional infrastructure is built.

One of the most effective operational change is equalizing priorities. The only costs of equalizing priorities are the additional delays to higher valued traffic. On capacity constrained routes equalizing priorities is a rapid and flexible method that can be used to improve operations. Depending on the traffic level, a dispatcher can choose whether to utilize equal priorities as a operational strategy.

7.6 Conclusions

The projected, long-term demand for rail freight transportation and expanded rail passenger service on North American railroads will require considerable capital investment in new infrastructure. However, some additional capacity may be achieved though altering operations. This solution is often less expensive and faster to implement than building physical infrastructure. I performed analyses using dispatch simulation software to determine the benefits of various operational and infrastructure changes through the reduction of train delay. For each scenario a cost-benefit analysis was performed to determine the most cost-effective ways to improve railroad line capacity. Analysis showed that for moderate volumes and heterogeneous traffic, equalizing dispatching priorities is a cost-effective method of improving capacity. At higher volumes more cost intensive infrastructure expansion becomes a better investment option since it reduces the delay by a greater amount than operational changes.

CHAPTER 8: IMPACT OF CBTC AND ECP BRAKES ON CAPACITY

8.1 Introduction

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 *(AASHTO 2007, Cambridge Systematics 2007)*. Furthermore, new initiatives to expand intercity passenger rail operations on freight railroads will have a disproportionate impact on capacity due to the differences in operational characteristics between freight and passenger trains *(AREA 1921, Mostafa 1951, Harrod 2009)*. 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 chapter I 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 implementation conditions. Since both of these systems require significant investment from the railroads (estimates range up to $10 billion for PTC *(FRA 2009a)* and over

$6.5 billion for full ECP brake implementation *(FRA 2006*) if the capacity impacts of these two technologies can be better understood, railroads can make more informed decisions about their implementation.

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 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 *(RAC & AAR 1984, Detmold 1985, FRA 1999a)* and freight railroad ECP brake technology since the early 1990s *(FRA 1999b)*; however, wide-scale adoption has not occurred due to technical, practical, economic and institutional barriers *(Moore Ede et. al. 2009).* Recent regulations and legislation have altered the situation. The Federal Railroad Administration (FRA) is encouraging implementation of ECP brakes by offering relief from certain requirements pertaining to conventional pneumatic brake operation *(Rail Safety Improvement Act 2008, Blank et. al. 2009).* With regard to PTC, the Rail Safety Improvement Act of 2008 and the subsequent regulations issued by the FRA *(FRA 2010a)* have mandated its implementation on a large portion of the Class 1 railroads' mainlines by 2015.

A number of previous studies have investigated the impact of CBTC on capacity. Lee et. al. *(Lee et. al. 2000)* 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 *(Wendler 2009)*. In the United States, Smith, Resor and Patel *(Smith & Resor 1989, Smith et. al. 1990, Smith et. al. 1997, Resor et. al. 2005)* 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 and Smith *(1990)* calculated the potential terminal efficiency improvements resulting from the estimated increases in reliability offered by CBTC. While many authors have claimed that a CBTC system with moving blocks will increase capacity *(Detmold 1985, Martland & Smith 1990, Dick 2000, Moore Ede 2001, Resor et. al. 2005, Drapa et. al. 2007, Kull 2009, FRA 2009b)*, there has been some debate about whether this will in fact be the case *(Twombly 1991, Moore Ede et. al. 2009)*.

There has been less work addressing the capacity effects of ECP brakes. Most agree that they will reduce stopping distances and when fully implemented this 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 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.

8.2 Elements of a CBTC System that will Affect Capacity

In North America most of the potential CBTC systems are still under development. While 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 *(Ditmeyer 2006)*. However, in order to comply with the legislative requirements for PTC they 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 *(FRA 2010a)*." 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 *(RAC & AAR 1984).* It is also technically possible to meet the PTC requirements without use of a pure CBTC system *(Hoelschcer and Light 2001)*; however, most PTC systems in the U.S. will likely be some form of pure or hybrid CBTC system with enforcement. Since 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. For this work I consider the potential elements of a CBTC system that may affect capacity including those required to meet the PTC requirements.

8.2.1 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. Furthermore, although individual railroads' rules vary on the exact language, normally an engineer is required to begin reducing speed when their train passes 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 spoken or written messages convey 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 control, or something similar. 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 takes 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 can immediately take advantage of it. 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.

8.2.2 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 gives the dispatcher additional information. This 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 impact railroad operations and capacity and will be considered separately.

8.2.2.1 Enforcement Braking

The element of a PTC system mandated by regulation 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 *(Thurston 2004)*:

- 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. These factors are not accurately known when a train leaves the terminal resulting in considerable uncertainty in the exact braking distance required *(Anderson 1995, Moore Ede et. al. 2009)* (Figure 1). For safe operations a train must have close to zero probability of overshoot (FRA has targeted 0.000005, or 5 chances in a million *(Moore Ede et. al. 2009, FRA 2009)*). 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 *(Thurston 2004)*.

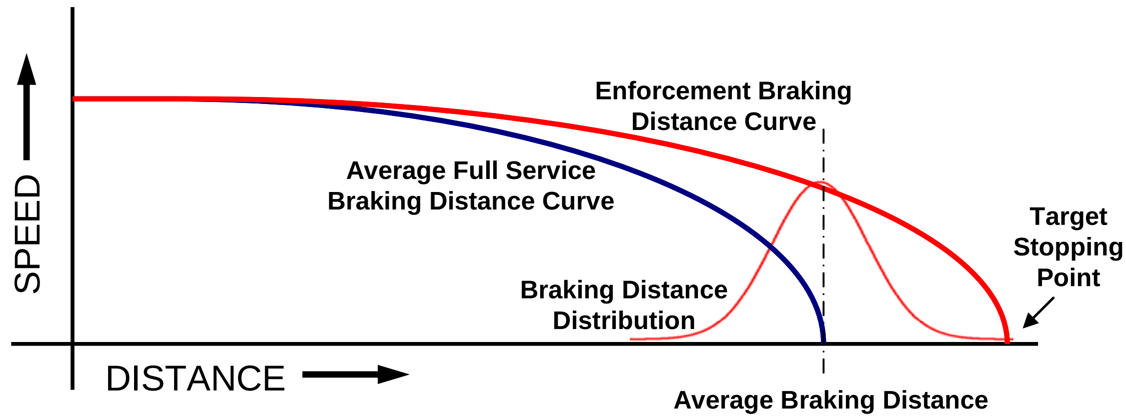

FIGURE 8.1: Speed, Uncertainty in Average Braking Distance, and Resultant Safe Braking Distance

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 *(FRA 2009b)*. Simulations have shown that the difference between the average stopping distance and enforced target can be greater than 1,700 ft *(FRA 2009b)*. Braking enforcement can have several negative effects on capacity including:

- 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, thus stopping well short of the target;
- Train crews experience difficulty closely approaching a target stopping point, such as when pulling into a siding potentially causing the back of the train to remain on the main line blocking traffic *(Moore Ede et. al. 2009)*.

Work is underway to create a more accurate and adaptive braking algorithms *(Moore Ede et. al. 2009)*. However, trains may travel long distances after departing a terminal without making enough brake applications to obtain adequate data to develop sufficiently accurate, updated estimations of braking distance *(FRA 2009b)*, and there will always be some difference between the calculated braking distance and the actual or performance braking distance *(Thurston 2004)*. 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 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 discussion and explanation of braking enforcement, adaptive braking and their implications can be found in papers by Thurston *(2004)* and Moore Ede et. al. *(2009).*

8.2.2.2 Real-time Train and Location Data

Real-time train and location data offer the dispatcher additional information. The dispatcher is able to accurately know a train's location and current speed 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 more quickly formulate alternative dispatching plans as circumstances change. This information also permits more effective meet pass planning. When combined with a CAD system this can potentially decrease run times by reducing the time trains wait for meets and passes *(Smith et. al. 1990, Smith et. al. 1997).*

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 receiving 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 *(FRA 2009b)*. If the communications delay is not excessive, real time train and location data can increase capacity.

8.2.2.3 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 *(FRA 2004)*:

- 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 need to reduce speed soon or immediately unless 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 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 they 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 the voice transmission and confirmation *(Moore Ede 2001)*. Cab signal technology provides some of the capacity benefits of a CBTC in-cab display by displaying the aspect of the next block *(Thurston 2004)*; however, most locomotives and routes in North America are not equipped with these technologies so in these cases, CBTC will provide these incremental benefits.

8.2.2.4 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 at least 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 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.

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Flexible moving blocks can have a significant benefit on routes with trains having 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 *(AREA 1921, Mostafa 1951, Harrod, 2009)*. Flexible 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 *(Moore Ede 2001)*.

Moving block capability can also reduce delays due to passes on single track lines. Shorter headways reduce the time the overtaken train waits in the siding *(FRA 2009b)*. Also when leaving 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 *(Moore Ede 2001)*.

8.3 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 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.

8.3.1 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, 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 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 *(FRA 2006)*. 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. Consequently, this means there is a direct relationship between propagation time and braking distances. This problem is reduced when using distributed power (DP) because it permits the braking signal to be initiated at more locations in the train, thereby reducing brake signal propagation time and thus braking distance *(Barrington & Peltz 2009, Petlz 2009)*. Railroads are increasingly using DP; one major railroad estimates that 50% of its operations are now using distributed power.

8.3.2 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

- Self-monitoring capabilities

Using an electronic signal instead of air pressure to transmit the brake signal allows for virtually instantaneous transmission enabling nearly simultaneous application or release of the brakes along the entire length of the train. ECP brakes have a steady brake pipe pressure allowing for continuous charging of the brake reservoirs 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 *(FRA 2006)*.

Each of these characteristics will be considered for their impact on capacity. There are several proposed elements of an ECP brake system, including tri-couplers and the ability to remotely uncouple cars, that have the potential to impact capacity. These have not been included in any of the developed systems and therefore they are not considered in this analysis.

8.3.2.1 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. It is estimated that this will reduce braking distance by about 40 to 60 percent compared to conventional braking distance *(FRA 2006)*. 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 alternative to shorter headways is the ability to travel at higher speeds with the same signal spacing *(Carlson 1994)*. Another benefit to having all the brakes on a train apply simultaneously is that it reduces in-train forces, permitting longer trains. Fewer, longer trains free up train slots, thereby allowing additional traffic. However distributed power can provide some of the same benefits in 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.

8.3.2.2 Steady Brake Line Pressure

A steady brake line pressure allows for the continuous charging of the brake reservoirs. This facilitates greater use of the braking system and reduces the time lost waiting to recharge 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 necessary resulting in slower operations *(FRA 2006)*. Continuous charging of brake reservoirs enables 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 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 *(FRA 2006, Blank et. al. 2009)*. With ECP brakes this is not necessary, reducing dwell time on routes with large grades.

8.3.2.3 Self-Monitoring Capabilities

An electrical signal to control the brakes has the added benefit of potentially enabling transmission of brake condition data to the locomotive. The engineer could monitor brake condition and be informed of any failure in any car on the train. In response to these capabilities the FRA issued a new regulation that requires brake inspections to be performed every 3,500 miles instead of 1,000 miles as is required with conventional brakes *(Class 1A brake tests-*

1,000-mile inspection 2004). This potentially 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 (*FRA 2010b)*. This not only decreases cycle times but may also reduce congestion at terminals where these inspections currently take place. To achieve these results reconfiguration of terminal points and the resulting expenditures may be required.

8.4 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 or vital overlay to an existing control system or as a stand-alone system *(Drapa et. al. 2007)*. In a non-vital overlay, the underlying control system provides movement authority, but CBTC provides an additional, automatic backup to prevent unsafe conditions. With a vital overlay, 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 *(Drapa et. al. 2007)*. Non-vital and vital overlay systems 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.

8.4.1 CBTC Non-Vital Overlay System

A CBTC overlay provides enforcement per the PTC requirements 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 (aka,"dark") territory an overlay system provides a more effective means of train separation. Much like a signal system, installation of CBTC would allow 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 *(SRA 2005)*. In North America, the potential capacity impact will be greatest on signalized, single track lines where enforcement has a greater effect due to the more frequent stops from meets and passes.

8.4.2 CBTC Vital Overlay System

A CBTC vital overlay system will have similar capacity constraints as an overlay system due to the inability to take advantage of moving blocks. However with a vital system the signal, traffic control, and CBTC system 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 compared to a non-vital system.

8.4.3 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 multiple-track routes where 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 with a resultant benefit in capacity.

8.4.4 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 *(FRA 2006)*. Grades can be bottlenecks on a railroad network and ECP brakes provide improved train handling and reduced dwell while traveling on these grades. On single-track lines capacity can be improved because less time is lost during stops and on multiple-track lines because shorter headways are possible. Shorter cycles and increased terminal capacity can be achieved as well due to a reduction in the number of intermediate brake inspections.

8.4.5 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. 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 more efficiently plan and manage its operations. A stand-alone CBTC system will take greatest advantage of ECP brakes because moving blocks will permit railroads to reduce 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 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.

8.5 Discussion

CBTC and ECP brakes make the train, signal and traffic control systems more "intelligent" *(Ditmeyer 2006)*. 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 *(Moore Ede et. al. 2009, FRA 2009b)*. As the implementation of these technologies is considered, there remain unanswered questions on their net effect on capacity.

Although railroads are planning to implement overlay CBTC systems and are testing ECP–brake-equipped unit trains, there remain technical challenges. Conservative braking algorithms and excessive communications delays within CBTC may reduce capacity. Also moving blocks have not yet been proven to be technically feasible in the North American operating environment. CBTC may permit removal of existing signal systems; however, to date there is no practical alternative to track circuits for 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 possible, it may not be advisable to implement a completely stand-alone system *(Baugher 2004)*.

Even when a 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. Additionally, terminals are considered major bottlenecks in many railroad networks *(Dirnberger 2007)*. Consequently, while there may be reductions in over-the-road time due to CBTC and ECP brakes, increases in line capacity may not improve network capacity if the principal constraints are the terminals.

When calculating the impact of these new technologies it is necessary to understand how their potential capacity benefits compares to 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 a stand-alone system.

8.6 Conclusions

Implementation of CBTC and ECP brakes will have a direct effect on capacity. In this analysis I considered 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 due to shorter braking distances. 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 effect on their own systems.

CHAPTER 9: FUTURE RESEARCH AND CONCLUSIONS

9.1 Future Work

In the course of this research, several topics were identified as potential areas for further research. These areas are discussed in the following sections.

9.1.1 Double Track Heterogeneity Study

Chapters 5, 6 and 7 consider operations on single track; however, many of the routes with the greatest traffic volume have two or more tracks. The characteristics of operations with multiple tracks are quite different. Multiple tracks allow directional running thereby, eliminating meets. Consequently headways are a greater capacity constraint than on single track. The different nature of multiple track operations means that the key factors contributing to lost capacity, and their relative impact due to train type heterogeneity, are also different. Future work should thoroughly investigate operational approaches to improve capacity on multiple tracks.

9.1.2 Sources of Delay

The methodology used in Chapter 6 can be expanded to better understand the impact of various operations. Additional work should be completed considering multiple volumes, no priorities, different infrastructure configurations and passenger traffic.

9.1.3 Quantitative Analysis of the Impact of CBTC and ECP brakes on Capacity

Chapter 8 is a comprehensive review of the potential effects of CBTC and ECP brakes. However, further work needs to be done to quantify the impact of each of these technologies on capacity. Some work was done trying to quantify the impacts of the technologies using RTC but further refinements to this software are needed to adequately account for the complexities of how these two technologies will affect capacity. ECP brakes permit shorter braking distances and better handling on grades, while PTC will cause a train to brake according to an enforcement algorithm and not the experience of an engineer. Therefore, in order to accurately quantify the impacts of these technologies the braking distance of various train types with various speeds and conditions must be accurate. Additional work needs to be done developing accurate braking data for various train types and understanding how enforcement braking will influence train handling.

9.1.4 Risk of Delays with Large Traffic Volumes and Levels of Heterogeneity

At higher traffic volumes and heterogeneity levels the probability of large delays due to an unplanned event or even in the course of normal operations increases. A route may have sufficient capacity for normal operations but is unstable because of its sensitivity to disruptions. Alternatively, greater amounts of capacity reduce the risk of train delays. Risk can be used as another capacity metric and utilized to determine the cost of new traffic and the benefit of expanded capacity.

9.1.5 Impact of Passenger Trains

There are numerous proposals for expanded and higher speed passenger rail operations on North American freight railroads. This new traffic will increase the heterogeneity of a route thereby increasing the delays to the remaining traffic. An investigation into the impact of additional and higher speed passenger traffic on new and existing routes should be completed in order to better understand its disproportionate impact.

9.1.6 Impact of Non-Scheduled Delays

The work done for this thesis only considers scheduled delays. A major challenge for railroads is recovering from non-scheduled delays, which include mechanical and infrastructure failures as well as train and grade crossing accidents. Using simulation it is possible to quantify the consequence of these different delays on other traffic. This information can support further analysis of the benefit of various technologies and methods to reduce the likelihood of these events.

9.2 Conclusions

Freight railroads are increasingly facing capacity constraints *(Cambridge Systematics 2007)*. Coinciding with projected increases in freight traffic are new proposals for expanded and higher speed passenger and commuter rail operations and the development of new technologies that have the potential to affect capacity. If railroads do not prepare in advance they will have insufficient capacity and service quality will deteriorate and operating costs will increase. Railroads must understand their operations in order to effectively use existing capacity and efficiently plan new capacity.

One factor that affects railroad operations and capacity is train type heterogeneity. Research was conducted determining the impact of train type heterogeneity, quantifying the specific operations and conflicts that cause delays and possible ways to mitigate delay. In Chapter 5 simulations were performed to look at the relationship between delay, volume and heterogeneity. These showed that delay increases with greater levels of heterogeneity. Further work was done to identify the contributing factors that cause the increased delays. This provided insight into how acceleration performance and priority together contribute to increased delays. Additional delays due to heterogeneity primarily accrue to lower priority trains, which often have the poorest operating characteristics and must make additional stops.

Chapter 6 investigates the sensitivity of various categories of delay to heterogeneity. For each conflict the delay was categorized by cause, offering insight into what types of delays are increased due to heterogeneity. The work showed that the conflict that results in the most delays are meets and that most of the delay occurs when a train is stopped in a siding.

Chapter 7 uses the data gained from the previous chapters to propose various methods to reduce train delays. On a single track line with wide spacing between sidings, various operational and infrastructure scenarios were considered. The benefit in terms of reduction in delay was compared to the cost in terms of greater delays for some train types and new infrastructure and maintenance costs.

Two new technologies that have been widely discussed for their potential benefits to railroad capacity are communications based train control (CBTC) and electronically controlled pneumatic (ECP) brakes. A comprehensive literature review of articles, papers, reports and regulations pertaining to each technology was conducted in order to identify the key elements of these technologies that will affect capacity. Using this information the potential impacts of each system and the type of locations that will have the greatest impact due to these technologies were identified.

Finally, it should be emphasized that the simulation results here represent general relationships based on idealized conditions on a hypothetical rail line. As such they are intended to provide insight on the relative importance of different factors thought to affect delay, not as absolute measures of capacity under the conditions described. Specific information about a particular infrastructure configuration and mixture of traffic would require a detailed study using appropriate data, specific to the conditions being studied. The methods described in this paper could be adapted for such an analysis and this work provides insight regarding what type of information is needed and likely to be important in such a study.

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