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Office of Research,
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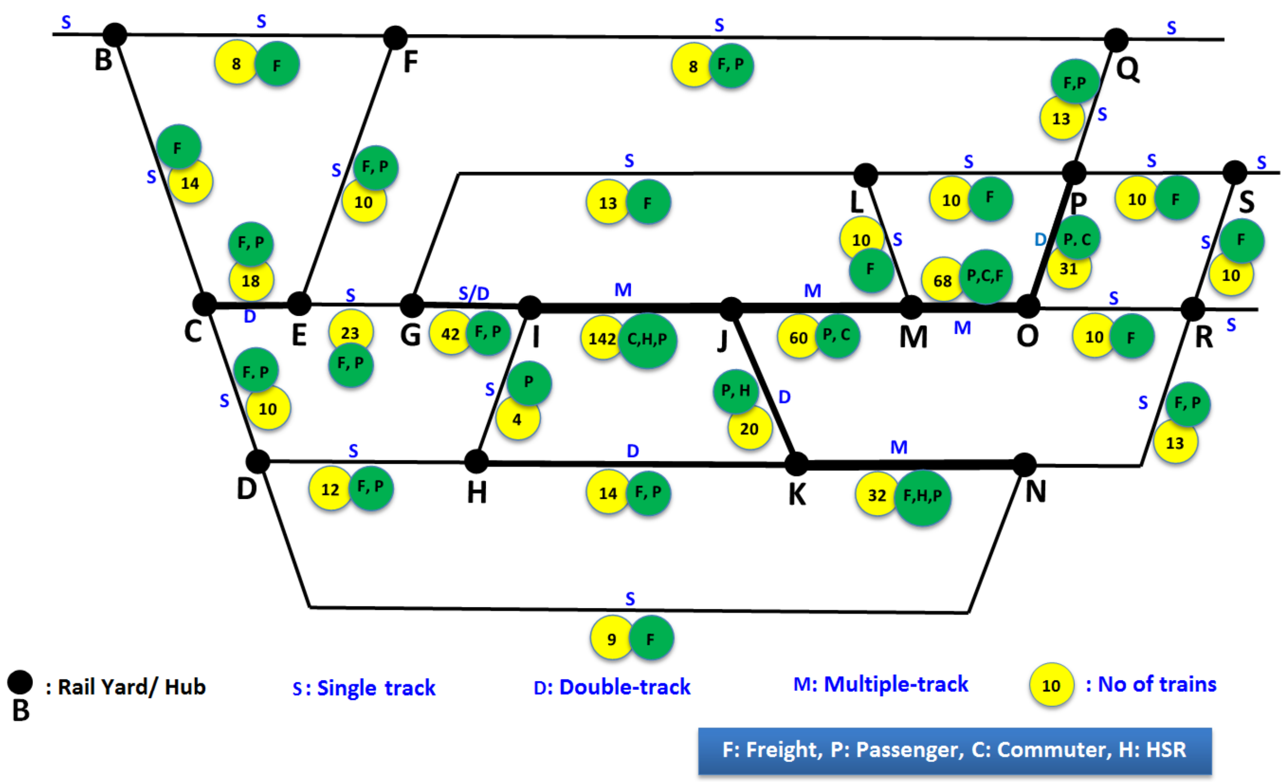
Washington, DC 20590

Impact of Advanced Train Control Technologies on Rail Network Safety and Operational Performance



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14. ABSTRACT
From September 2018 to September 2021, the Federal Railroad Administration contracted Sharma & Associates to conduct an analysis of simulation results from a 5,000-mile mini-network, scaled up to represent characteristics of the North American rail system. The results showed that implementation of an advanced braking system (ABS) nationwide could yield a reduction in network delay of 38.4 percent, a reduction in braking at signals of 16.7 percent, and a reduction of 8.4 percent in unnecessary signal stops. Other measures of network performance, such as network velocity and network capacity utilization, showed minor improvements.

15. SUBJECT TERMS
Advanced braking system, ABS, braking characteristics, freight train, network capacity, network velocity, passenger train, Positive Train Control, PTC, shared corridor, track utilization, train delay

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METRIC/ENGLISH CONVERSION FACTORS

ENGLISH TO METRIC

LENGTH (APPROXIMATE)

1 inch (in)	=	2.5 centimeters (cm)
1 foot (ft)	=	30 centimeters (cm)
1 yard (yd)	=	0.9 meter (m)
1 mile (mi)	=	1.6 kilometers (km)

AREA (APPROXIMATE)

1 square inch (sq in, in^2)	=	6.5 square centimeters (cm^2)
1 square foot (sq ft, ft^2)	=	0.09 square meter (m^2)
1 square yard (sq yd, yd^2)	=	0.8 square meter (m^2)
1 square mile (sq mi, mi^2)	=	2.6 square kilometers (km^2)
1 acre = 0.4 hectare (he)	=	4,000 square meters (m^2)

MASS - WEIGHT (APPROXIMATE)

1 ounce (oz)	=	28 grams (gm)
1 pound (lb)	=	0.45 kilogram (kg)
1 short ton = 2,000 pounds (lb)	=	0.9 tonne (t)

VOLUME (APPROXIMATE)

1 teaspoon (tsp)	=	5 milliliters (ml)
1 tablespoon (tbsp)	=	15 milliliters (ml)
1 fluid ounce (fl oz)	=	30 milliliters (ml)
1 cup (c)	=	0.24 liter (l)
1 pint (pt)	=	0.47 liter (l)
1 quart (qt)	=	0.96 liter (l)
1 gallon (gal)	=	3.8 liters (l)
1 cubic foot (cu ft, ft^3)	=	0.03 cubic meter (m^3)
1 cubic yard (cu yd, yd^3)	=	0.76 cubic meter (m^3)

TEMPERATURE (EXACT)

[(x-32)(5/9)] °F = y °C

METRIC TO ENGLISH

LENGTH (APPROXIMATE)

1 millimeter (mm)	=	0.04 inch (in)
1 centimeter (cm)	=	0.4 inch (in)
1 meter (m)	=	3.3 feet (ft)
1 meter (m)	=	1.1 yards (yd)
1 kilometer (km)	=	0.6 mile (mi)

AREA (APPROXIMATE)

1 square centimeter (cm^2)	=	0.16 square inch (sq in, in^2)
1 square meter (m^2)	=	1.2 square yards (sq yd, yd^2)
1 square kilometer (km^2)	=	0.4 square mile (sq mi, mi^2)
10,000 square meters (m^2)	=	1 hectare (ha) = 2.5 acres

MASS - WEIGHT (APPROXIMATE)

1 gram (gm)	=	0.036 ounce (oz)
1 kilogram (kg)	=	2.2 pounds (lb)
1 tonne (t)	=	1,000 kilograms (kg)
	=	1.1 short tons

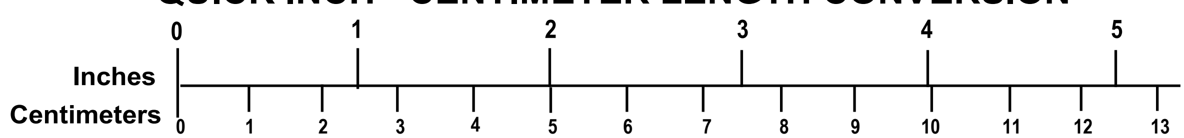
VOLUME (APPROXIMATE)

1 milliliter (ml)	=	0.03 fluid ounce (fl oz)
1 liter (l)	=	2.1 pints (pt)
1 liter (l)	=	1.06 quarts (qt)
1 liter (l)	=	0.26 gallon (gal)
1 cubic meter (m^3)	=	36 cubic feet (cu ft, ft^3)
1 cubic meter (m^3)	=	1.3 cubic yards (cu yd, yd^3)

TEMPERATURE (EXACT)

[(9/5) y + 32] °C = x °F

QUICK INCH - CENTIMETER LENGTH CONVERSION



QUICK FAHRENHEIT - CELSIUS TEMPERATURE CONVERSION

°F	-40°	-22°	-4°	14°	32°	50°	68°	86°	104°	122°	140°	158°	176°	194°	212°
°C	-40°	-30°	-20°	-10°	0°	10°	20°	30°	40°	50°	60°	70°	80°	90°	100°

For more exact and or other conversion factors, see NIST Miscellaneous Publication 286, Units of Weights and Measures. Price $2.50 SD Catalog No. C13 10286

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Executive Summary

Over the last two decades, the U.S. rail network has implemented advanced technologies to improve train safety and operational performance. Advanced Braking Systems (ABS) and Positive Train Control (PTC) are two examples of advanced train control technologies that can not only improve safety but may also enhance overall network performance.

From September 2018 to September 2021, the Federal Railroad Administration contracted Sharma & Associates to conduct an analysis of simulation results from a 5,000-mile mini-network, scaled up to represent characteristics of the North American rail system. This study evaluated the impact of ABS and PTC systems on the network safety and operational performance in a hypothetical benchmark mini-network using OpenTrack, a widely used network simulation software.

The research team modeled 5,000 miles of main line tracks in the hypothetical mini-network, including single-, double- and multi-track segments. The team added track segments representing 150 sidings and yards, resulting in a mini-network of approximately 6,200 miles of tracks. Researchers simulated 256 daily trains comprising a mix of 102 freight trains in 17 different configurations (e.g., intercity passenger, commuter and high-speed rail (HSR) services).

The simulation scenarios considered various combinations of the conventional signal and the overlay PTC (i.e., fixed signal block) systems, as well as conventional and advanced braking systems. The team analyzed various network performance parameters, including network delay, network velocity, maximum track utilization and capacity utilization rates, number of stops at stations, number of braking at signals (i.e., braking actions for route reservations), and number of stops at signals. The team developed a methodology to scale-up the results to the US rail network based on the ratios of the mini-network to the national network parameters (e.g., length of main line track miles, annual train-miles, number of sidings and yards, percentage of congested corridors, and age of freight cars).

Figure 1 shows a summary of the network level performance improvement results from this research.

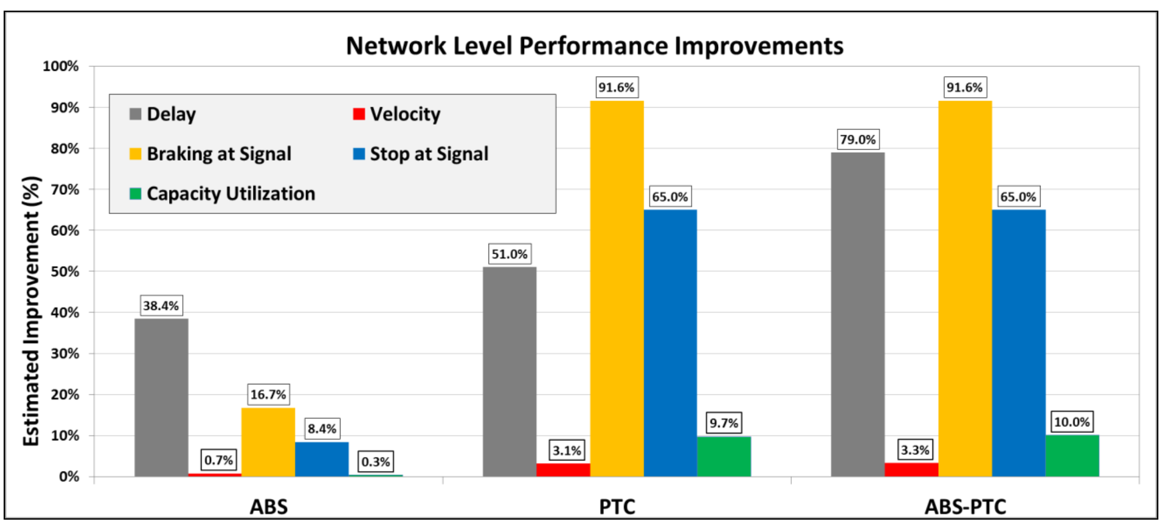

Figure 1. Network level performance improvement results

As shown in Figure 1, the most significant improvement over the U.S. rail network for freight trains with ABS is a reduction in network delay[1] of 38.4 percent, followed by a reduction in braking at signals (i.e., braking actions for route reservation) of 16.7 percent and a reduction in unnecessary signal stops of 8.4 percent. Other measures of network performance, such as network velocity[2] and network capacity utilization[3], showed minor improvements when ABS was the only advanced technology implemented through the network.

However, the team found that implementing a PTC system throughout the entire national rail network can improve all measures of network safety and operational performance discussed in this study, particularly by reducing braking at signals by 91.6 percent and signal stops by 65 percent compared to operating trains under a conventional signaling system. In addition, PTC can also increase the network velocity by 3 percent, lower capacity utilization by 9.7 percent, and reduce network delay by 51 percent. PTC systems could also significantly reduce the amount of braking at signals (~ 88 percent on average) particularly for freight (over 95 percent) and passenger trains (~ 82 percent). In addition, PTC could significantly reduce the number of stops at signals for HSR (~ 73 percent) and passenger trains (~54 percent).

Researchers found no significant benefit in capacity and track utilization rates when equipping freight trains with ABS systems. However, the team found that PTC could improve the maximum track utilization rate of most of the network corridors by approximately 30 percent on average, especially through double- and multi-track corridors, with an average reduction of 7 percent in capacity utilization throughout the mini-network. The team found that deploying both ABS and PTC systems together can reduce the national network delay by 79 percent. However, other metrics showed little improvement beyond the benefits provided by deploying a PTC system alone.

The research team recommends investigating further network performance and capacity improvements to meet the increased future traffic volume that will result from using PTC systems with moving block technologies.

[1] Network delay: Difference between actual and planned arrival times for any planned stop
[2] Network velocity: Average speed of all trains in a category weighted by their respective travel distances
[3] Capacity utilization metric shows how long a segment of track is occupied by trains during a certain period of time (e.g. per hour, per day)

1. Introduction

From September 2018 to September 2021, the Federal Railroad Administration (FRA) contracted Sharma & Associates to conduct an analysis of simulation results from a 5,000-mile mini-network, scaled up to represent characteristics of the North American rail system. This study evaluated the impact of ABS and PTC systems on the network safety and operational performance in a hypothetical benchmark mini-network using OpenTrack, a widely used network simulation software.

1.1 Background

FRA's research and development program includes promoting development and implementation of new technologies for safe, efficient, and reliable movement of people and goods by rail transportation.

For the acceptance and implementation of these technologies, it is crucial that the benefits and implementation risks be quantified at the network level, and measures of network performance that are affected by the implementation of these technologies must be identified and quantified.

Over the last few decades there have been major technology initiatives in the railroad industry to improve the safety and operational performance of freight rail equipment in shared corridors. These include advanced braking systems (ABS) and Positive Train Control (PTC) systems [1]. Advanced braking alternatives such as Electronically Controlled Pneumatic (ECP) brakes and dynamic brakes in trains with distributed power (DP) have been under development and evaluation for a longer period than PTC and implemented by several railroads in North America. They have also been deployed by major railroads across the world, particularly for very long trains [2, 3, 4, 5, 6]. The version of PTC mandated by Congress as part of the Rail Safety Improvement Act of 2008 (RSIA) [7] is now widely implemented [8].

1.1.1 Conventional Freight Car Braking System

Freight car conventional braking systems (CBS) use compressed air stored in a local reservoir on each car to produce a force between the brake shoe and wheel that slows the train. This air, generated by a locomotive compressor, is conveyed to each car's reservoir via the brake pipe, a continuous conduit running the length of the train.

In a conventional pneumatic brake system, the signals for controlling the brakes on each car are transmitted through the brake pipe in the form of pressure changes. The pneumatic brake system has evolved since its inception 150 years ago with continuous incremental improvements to increase the speed of the signal propagation. Features such as accelerated service release (introduced in the ABD valve) and accelerated application (i.e., ABDW and ABDX valves by Wabtec and DB-60 valves by Knorr) provided steady improvements in the response of the air brake system.

While the propagation rate of an emergency brake application approaches the speed of sound (i.e., the theoretical maximum for signal propagation in air), it is significantly slower for a service application signal. For a typical modern freight train, service brake initiation at the rear may be over 10 seconds later than at the front of the train. This delay can lead to high buff forces as lightly braked cars toward the rear-end run into more heavily braked cars in front.

1.1.2 Advanced Braking Systems

Like CBS, freight trains using DP and ECP systems also use compressed air delivered via the brake pipe and stored locally to provide the brake actuation force. The essential difference, however, is that ECP freight trains use electronic signaling and control, rather than a pneumatic signal, to control ECP brakes. In a DP configuration, the propagation time of brake application throughout the train also can be significantly reduced compared to head-end power trains, depending on the number and the position of DP locomotives.

Brake application and release signal propagation with ECP is essentially instantaneous; a braking command issued from the lead locomotive is received at each vehicle in the train simultaneously. In addition, the braking force build-up along the train is relatively uniform, thereby minimizing inter-car coupler forces due to disparate braking rates between cars. Unlike conventional pneumatic brakes, ECP brakes can be released in gradual steps. And, since the brake pipe is not used to convey braking signals, the car reservoirs are continuously charged, whether the brakes are applied or not. These characteristics make the ECP braking system significantly more controllable than the conventional pneumatic system.

Overall, the benefits of ECP and DP braking systems can improve the safety and operational performance of freight trains. These benefits were analyzed in this study using a range of performance metrics.

1.1.3 PTC Signaling System

FRA mandates that a PTC system be used for all intercity passenger and commuter railroads, as well as freight railroad corridors with annual traffic of at least 5 million gross tons (MGT) and certain hazardous and toxic materials [9]. PTC provides safety against operator errors by minimizing the potential of train collisions and over-speeds by timely application of train brakes if the engineer fails to act in a timely manner [10].

PTC has been developed to prevent train-to-train collisions, over-speed violations, unauthorized entry into established work zones, and movements through switches left in the wrong position. Forty-one different railroads (i.e., 7 Class I railroads, Amtrak, 28 commuter railroads, and 5 other freight railroads that host intercity or commuter rail services) aided in implementing the PTC system nationwide under FRA oversight. As of January 2021, all 57,536 required railroad route miles are operating under PTC signaling systems – approximately 41 percent of the total U.S. rail network [8].

1.2 Objective

The objective of this research was to analytically evaluate the safety and operational performance benefits of implementing advanced train control technologies (i.e., ABS for freight trains and PTC signaling systems) from the perspective of various measures of network performance. Such information is necessary to develop a strategy for network-wide implementation of these advanced train control technologies throughout the entire rail system.

1.3 Scope

The scope of this research included the following major efforts:

- Developing a mini-network with characteristics representative of the North American rail system and including various types of traffic, tracks, signaling systems, and train configurations
- Conducting network simulation scenarios including different configurations of advanced technologies (i.e., ABS and PTC systems) and conventional braking and conventional signaling (CS) systems on the mini-network
- Analyzing results from the mini-network simulations in terms of safety and operational performance metrics such as network delay, velocity, schedule conflicts (i.e., stops and braking actions at signals), track and capacity utilization rates, and number of stops at stations (i.e., sidings and yards)[4]
- Scaling up the results from the mini-network simulations to the national rail network

1.4 Overall Approach

In this study, simulations were conducted on a hypothetical mini-network representative of the North American rail network characteristics. This quantified the effects of operating freight trains with ABS as well as evaluating the impact of a PTC signaling system throughout the entire network on various measures of network safety and operational performance. A heuristic approach was then used to scale up the results from the mini-network to the U.S. rail network.

The research team modeled network simulations with the widely used OpenTrack software. The mini-network comprised over 5,000 miles of tracks, 150 sidings and yards, single-, double-, and multi-track corridors, different signaling systems, and several combinations of freight and passenger train configurations. Several measures of operational performance (e.g., network delay, network velocity, track and capacity utilization levels, and number of meet-pass and stops) and safety performance (i.e., braking actions at signals and unnecessary stops at signals) were analyzed for the full mini-network as well as for only the single-track corridors.

The following scenarios were simulated on the mini-network to investigate the impact of deploying advanced train control technologies:

Scenario 1

All freight trains are equipped with a CBS; the network uses a CS system (CBS-CS)

Scenario 2

All freight trains are equipped with an ABS; the network uses a CS system (ABS-CS)

Scenarios 3–5

A mix of freight trains with a combination of ABS and CBS systems; the network uses a hybrid CS system (Hyb-CS)

Scenario 6

All freight trains are equipped with CBS; the network uses a PTC signaling system (CBS-PTC

Scenario 7

All freight trains are equipped with an ABS; the network uses a PTC signaling system (ABS-PTC)

[4] In this study, "station" is used as a generic stop location for all passenger stations, freight yards/sidings, and mixed passenger/freight yards.

Scenarios 3 to 5 were intended to represent a practical approach in which freight trains with CBS are partially retrofitted with an ABS under CS systems.

Scenarios 6 and 7 were intended to compare the results of operating trains under PTC signaling systems when freight trains are either equipped with CBS (Scenario 6) or equipped with ABS (Scenario 7).

Since one of the main focuses of this study was to analyze the impact of ABS only on freight trains, the braking characteristics of passenger, commuter, and high-speed rail (HSR) trains were the same across all scenarios. In addition, each scenario had the same assumptions and inputs for train configurations, infrastructure, train routes, dispatching rules, initial train schedules, and signaling characteristics, except for Scenarios 6 and 7 that used PTC system (Scenarios 1–5 used CS systems).

1.5 Organization of the Report

This report is structured as follows:

Section 2 explains simulation assumptions and input models including the details of tracks, sidings and yards, signals, traffic specifications, train details, dispatching and operations rules.

Section 3 reviews simulation results in terms of train schedules and any major differences resulting from operating freight trains with different braking systems or operating trains under PTC vs. CS systems.

Section 4 details the simulation results and compares the scenarios in terms of operational performance (e.g., train speed and delay), overall network velocity, network delays, train miles, track and capacity utilization levels for critical sections of the network, and safety performance (e.g., number of meet-pass, number of stops at the signals, number of unnecessary braking actions at signals).

Section 5 extrapolates the results from simulation scenarios on the mini-network to the full U.S. rail network by considering major performance metrics and assumptions.

Section 6 summarizes the results of this study and makes recommendations for further research.

Appendix A includes figures providing additional details of the results of the simulated scenarios.

2. Network Simulation Inputs and Assumptions

A rail network simulation requires details of the network infrastructure, rolling stock, signaling, and operations for the results to be acceptable and representative.

The team used OpenTrack simulation software to analyze network scenarios related to train control technologies and various signaling and braking systems. The software has been used by private and public entities around the world, including rail operators, suppliers, governments, and academia, to simulate the impact of relevant factors on network safety and capacity.[5]

The team considered the following data points in the network simulation:

- Network characteristics
  - Single-track, double-track, and multi-track corridors with a variety of track chart characteristics typical of North America in terms of grades, curvatures, siding and yard specifications, as well as complexity of connections between corridors
- Train types
  - Passenger trains, including intercity, commuter, and HSR trains, as well as various types and configurations of freight trains, including local, intermodal, unit trains, and DP trains
- Braking systems
  - Freight trains with CBS (i.e., lower deceleration rates due to propagation delay in air brake system, and longer waiting time between releasing and reapplying brakes) or ABS (i.e., sharper deceleration rates and minimum delay between brake applications depending on the train weight, length, and configuration)
- Operating practices
  - Corridors under dedicated passenger traffic, dedicated freight traffic, and shared use
- Types of signaling systems
  - CS systems (i.e., wayside or cab signaling system with two, three, and four aspect signals), currently implemented PTC signaling system for certain parts of the network depending on traffic congestion level, fully implemented PTC system

Details of the data used in this study are described in the following sub-sections. Further details on the requirements and steps for developing a network simulation study are provided by Pachl (2002) [11]; Pouryousef, et al. (2015) [12]; Cambridge Systematics (2007) [13]; and Hansen et al. (2008) [14].

2.1 Network Characteristics

The U.S. rail network is comprised of approximately 140,000 miles of track. While there are corridors with double and multiple tracks to handle high volumes of traffic, nearly 85 percent of the rail corridors are single track [12]. Track gradients and horizontal curves are among the main components of track charts that affect the total train resistance and govern the traction

[5] OpenTrack Railway Technology website

horsepower required for the train to achieve and maintain desired operating speed on various segments.

The mini-network used in this study represented the main core of the U.S. rail network. It comprised a representative combination of single-, double-, and multi-track corridors, signaling, rolling stock, and train operations typical of the U.S. rail system. The research team developed the simulation scenarios with advanced control systems by applying respective changes on the characteristics of conventional train control systems, as explained further in Sections 2.2 through 2.4.

Figure 2 shows a schematic map of the mini-network. It identifies the following:

- Main yards and hubs shown as nodes (e.g., B, C, and D)
- Mainline tracks shown as links (e.g., B-C and B-F)
- Types of traffic (e.g., freight, passenger, commuter, and HSR)
- Types of corridor (e.g., single-, double-, and multi-track)
- Length of links between nodes (in miles)

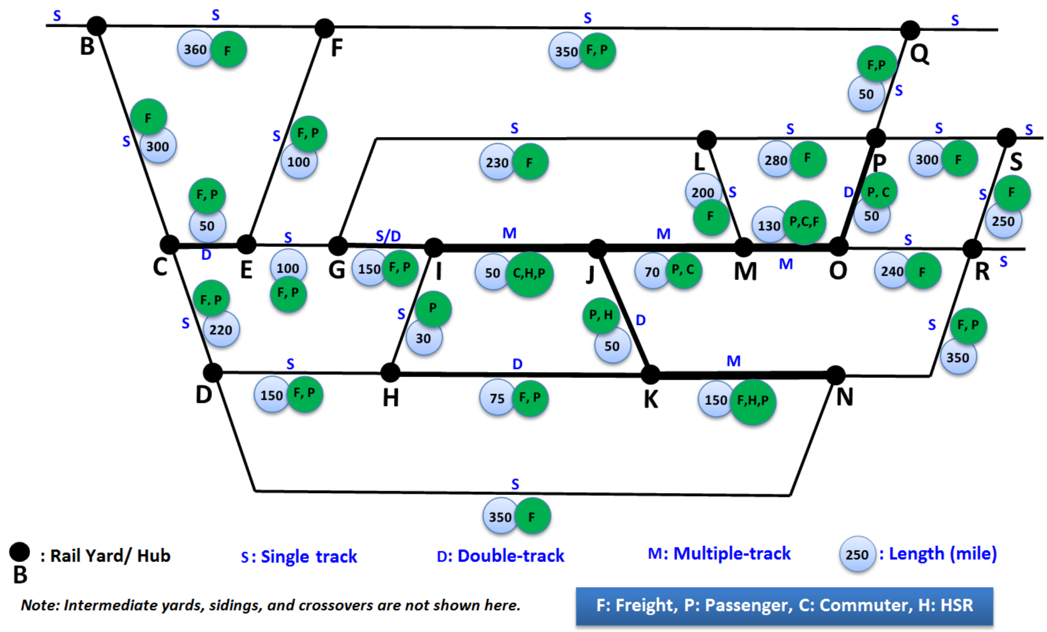

Figure 2. Mini-network schematic showing main rail hubs, tracks, length of tracks, traffic, and corridor types

Figure 2 shows a high-level view of the mini-network. The full OpenTrack simulation model includes details of the intermediate yards, track grades and curvatures, and signaling components, which were mostly based on real track and infrastructure data.

Figure 3 shows an example of the detailed infrastructure data at Yard P and its two adjacent sidings. The connectivity and main track layout between different corridors, and the types of track and traffic (Figure 3) match those shown in the schematic map (Figure 2).

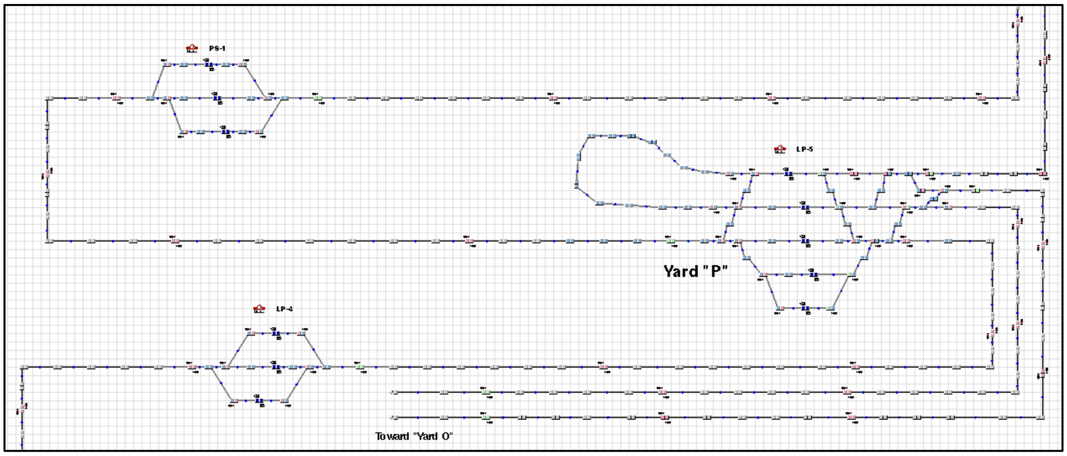

Figure 3. OpenTrack screenshot showing infrastructure details at Yard P and two adjacent sidings

Details of grade, curvature, tunnels, grade crossings, mileposts, and speed limits were included in the simulation. These enabled the calculation of train resistance, tractive effort, train speed, acceleration and deceleration, and other train performance characteristics.

The mini-network includes several shared-use corridors with congested freight and passenger traffic because such corridors have a high risk of accidents, particularly when service disruptions occur [12, 15]. Thus, any technology that increases capacity, service reliability, and train handling along these corridors, including ABS for freight trains or upgrading signaling systems under PTC, may provide safer operation and reduce the risk of train accidents [16]. In general, commuter and HSR trains operated within the central parts of the mini-network with either double- or triple-track segments, which had the highest traffic congestion. Freight trains did not typically operate along these segments (Figure 2). However, there were certain parts of the mini-network (i.e., M-O and K-N) in which the freight trains shared the main tracks with commuter and HSR traffic. In addition, there were various segments of the mini-network in which both intercity passenger and freight trains shared the tracks, while certain corridors (mostly single-track segments) were dedicated to freight traffic.

Overall, more than 4,880 miles of mainline tracks were modeled for this study. However, including the parts of the network with double- and multi-track segments, and including the length of sidings and yard tracks, the mini-network comprised approximately 6,230 miles of track.

Table 1 summarizes the major details of the mini-network. As shown in Figure 2 and presented in Table 1, about 85 percent of the corridors were single-track, mirroring the existing U.S. rail network.

Table 1. Summary of mini-network infrastructure

Parameter	Value	Note
Length of corridors	4,887 miles	Only main tracks
Length of all tracks	6,234 miles	Including 2nd and 3rd tracks, plus sidings and yard tracks
Number of sidings and yards	150	
Number of switches	758	Including crossovers and crossings
Number of signals	1,782	Including signals and transponders on main tracks and yards
Length of horizontal curves	1,162 miles	

Figure 4 shows the distribution of grades in the main tracks of the mini-network. Approximately 73 percent of the grades were within the range of 0 to 0.5 percent, and 20 percent were within the range of 0.5 to 1 percent. Approximately 4 percent of tracks had grades within 1 to 1.5 percent and less than 3 percent of the tracks had grades more than 1.5 percent.

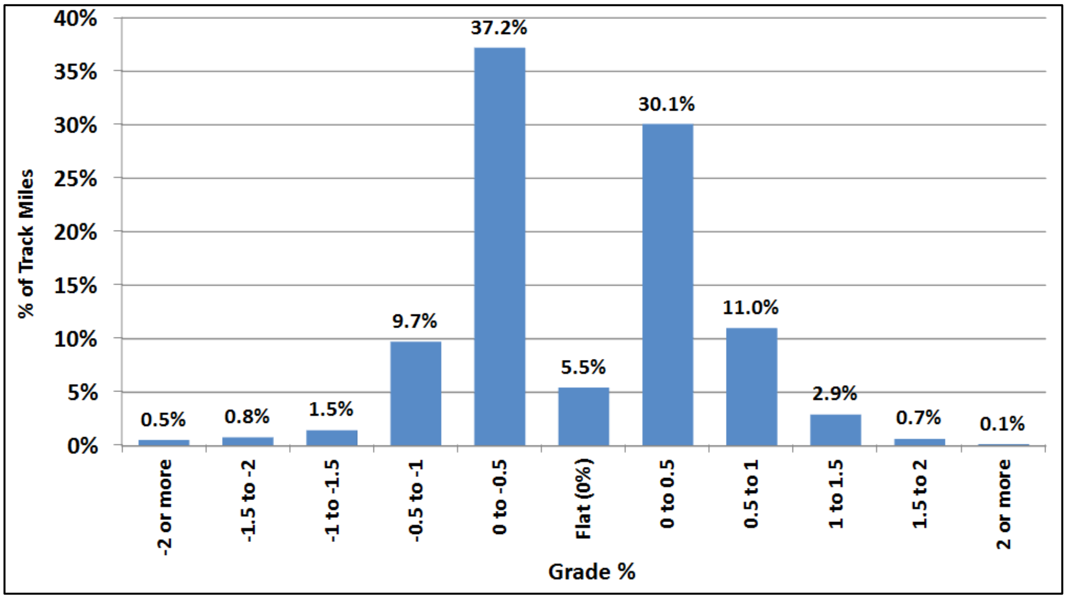

Figure 4. Distribution of main track grade in the simulated mini-network

Figure 5 shows the distribution of the degrees of curvature for the horizontal curves in the main tracks of the mini-network. Approximately 76 percent of the tracks were straight and less than 2 percent of the tracks had curves with more than 3 degrees of curvature. Figure 5 does not show the sign of the curvature (i.e., left- or right-hand curve) since the sign has no impact on train curving resistance.

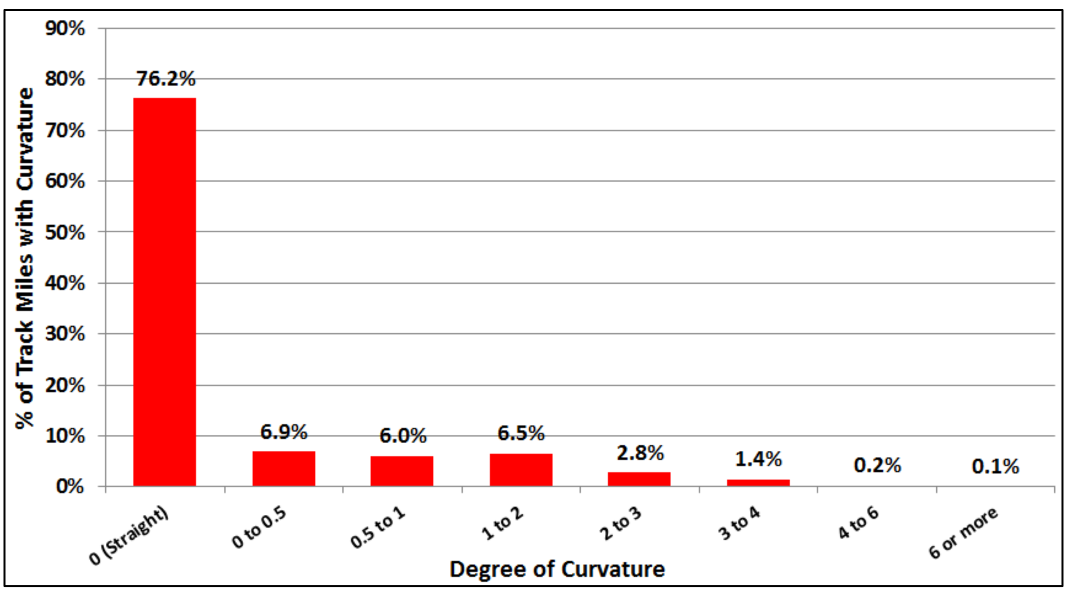

Figure 5. Distribution of main track curvature along the simulated network

2.2 Train Characteristics

Researchers modeled a total of 256 trains in the simulation: 102 freight trains, 66 passenger trains, 56 commuter trains, and 32 HSR. Table 2 summarizes the major attributes of the train types.

Table 2. Summary of mini-network train types

Type of Train	Avg. weight (ton)	Avg. length (ft.)	Number of configurations	Number of trains
Passenger	477	645	3	66
HSR	432	571	1	32
Commuter	248	486	2	56
Freight	8,924	8,120	17	102

Each corridor in the mini-network was assigned appropriate freight train configurations, as detailed in Table 3. The key freight train characteristics were:

- All freight trains were hauled by one of three common freight locomotives operated in the North American rail network: Dash9 (4,400 hp), Dash9 (4,000 hp), or GP38-2 (2,000 hp).
- While most freight trains in the simulation were modeled with Dash9 locomotives, most of the light and local freight trains were hauled by GP38-2 locomotives.
- Three types of freight trains were modeled with DP configurations (i.e., total 31 trains), in which all were powered by Dash9 (4,400 hp) locomotives. All DP trains were long and relatively heavy.

Table 3. Freight train configurations

#	Name	Weight (ton)	Length (ft)	Max Speed (mph)	Type of Loco	# of Loco	DP?	Loco Consist	# of Trains
1	DP-1	17,086	13,065	60	Dash9 (4,400	6	YES	3-X-3	14
2	DP-2	8,543	12,848	60	Dash9 (4,400	3	YES	2-X-1	9
3	NDP-3	11,697	10,952	60	Dash9 (4,400	4	NO	4-X	11
4	NDP-4	6,543	9,239	60	Dash9 (4,400	3	NO	3-X	13
5	H-FR-E2	16,616	12,921	60	Dash9 (4,000	4	YES	2-X-2	6
6	MidFR-	9,808	6,214	60	Dash9 (4,000	2	NO	2-X	2
7	MidFR-	4,808	6,214	60	Dash9 (4,000	2	NO	2-X	3
8	Local1-H	4,726	2,907	50	GP38-2 (2,000	2	NO	2-X	2
9	Local1-L	4,126	2,730	50	GP38-2 (2,000	2	NO	2-X	2
10	Local2-H	3,626	2,743	50	GP38-2 (2,000	2	NO	2-X	10
11	Local2-L	3,026	2,579	50	GP38-2 (2,000	2	NO	2-X	1
12	Man10-H	7,862	4,082	50	Dash9 (4,400	2	NO	2-X	7
13	Man10-L	6,612	3,543	50	Dash9 (4,400	2	NO	2-X	2
14	Man12-H	3,562	7,363	50	Dash9 (4,400	2	NO	2-X	6
15	Man7	9,931	7,123	50	Dash9 (4,400	1	NO	1-X	3
16	Man9-L	7,808	4,442	50	Dash9 (4,000	2	NO	2-X	3
17	Network1	5,862	3,097	50	Dash9 (4,400	2	NO	2-X	8

The braking characteristics of the freight trains were derived from simulations using the Train Energy and Dynamics Simulator (TEDS), an advanced tool for calibrating and analyzing train dynamics and braking performance [17]. The braking curve results from TEDS were converted to OpenTrack format.

The braking curve of a given train can be affected by the following:

- Weight and length of train
- Train configuration (e.g., conventional, DP, or ECP equipped)
- Initial speed before applying brake
- Track gradient
- Deceleration rate (i.e., change of braking force with time)

For example, for a given train with a specific weight, length, and configuration, the braking curve to stop the train (or maintain train speed under a certain threshold) can be different when the brakes are applied on a 1 percent descending grade compared to when they are applied on a 0.5 percent descending grade. Similarly, the braking characteristics (i.e., deceleration rate, propagation delay, and brake efficiency between frequent applications) are different between DP trains and head-end-only power trains. A train with ECP brakes, as explained in Section 1.1, has significantly different brake characteristics compared to the same train with a CBS (head-end only) or a DP train. The difference between a DP and ECP train is smaller than that between an ECP braked train and a conventional head-end powered train.

The difference made by ECP increases as the freight train gets longer and heavier. Appendix A, Section A.1 gives an example comparison of braking curves for ECP trains and conventionally braked trains, as well as an example comparison of results from TEDS and OpenTrack simulations.

2.3 Operating Rules and Train Scheduling Characteristics

Several operating rules and dispatching instructions were implemented in the simulation model to safely operate trains over the mini-network. In summary:

1. All trains had an initial requested schedule with at least an initial departure time from their designated departure location. HSR, commuter, and passenger trains had additional details in their requested schedules, while freight trains had more flexibility in terms of initial train schedules.[6]
2. All train schedules were "conflict-free" in that they departed from their designated origins and arrived at their assigned destinations without any schedule conflict that may have caused a deadlock anywhere throughout the network. Minor conflicts causing a delay at sidings and yard tracks or braking at a signal or any potential stop point were allowed if they did not create any deadlock later in the trip.
3. In the case of a minor conflict between two trains at a stop point or yard, the dispatching right was given to the train with higher priority in the following order:

[6] Freight train initial schedules are assumed with an improvised scheduling approach, similar to the current practice of freight train scheduling in the North American rail network.

    - HSR (highest priority), commuter, passenger, freight (lowest priority)
    - For trains in the same category (e.g., two freight trains), the one with higher delay was given higher priority to depart
4. All trains departed once per day and arrived at designated destinations regardless of how long it took. In other words, a train may have departed on the first day and arrived the next day if the average operating speed of the train was slow or the travel distance was long.
5. No initial delay was assumed for any train at the beginning of simulation.
6. No signaling, grade crossing, or train mechanical failures were assumed throughout the mini-network.[7]
7. All simulations used the same dispatching rules.

Figure 6 shows the schematic map from Figure 2, updated with the number of daily trains that were distributed throughout different sections of the mini-network.

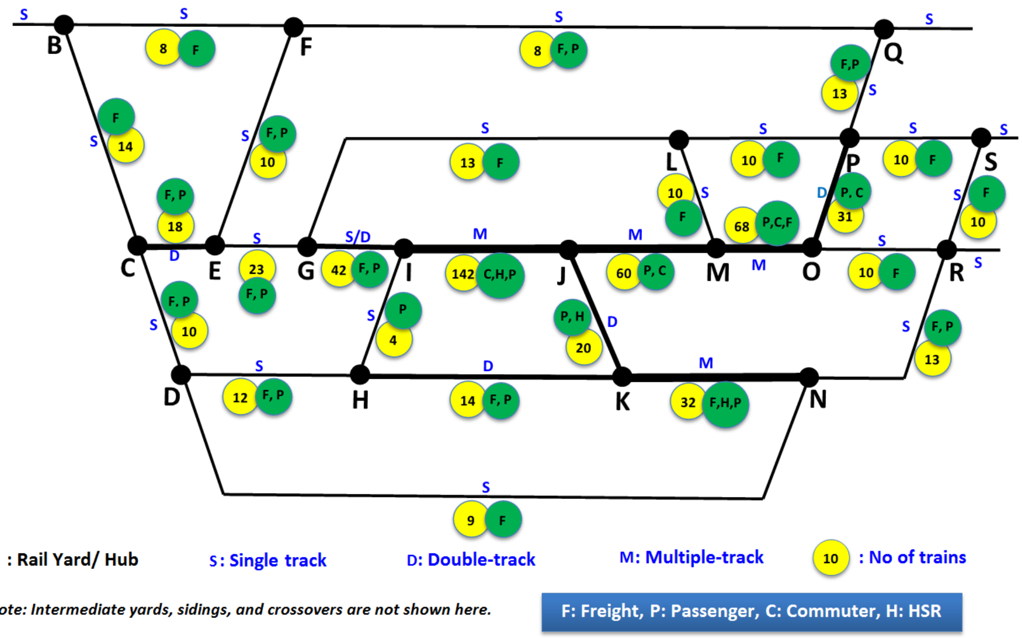

Figure 6. Schematic map of mini-network showing number of daily trains along each section of network in addition to the type of traffic and corridor

Figure 6 shows the central section of the network (I-J-M-O) had more traffic since it had at least double-track sections. Section K-N was also a multi-track corridor, but the estimated capacity of this corridor was lower than the other multi-track sections. This was because it had a mixed traffic of freight, high speed, and passenger trains with significantly different operational speeds,

[7] It is possible to develop a scenario with train mechanical failure, signaling failure, or grade crossing blockage (or any other track-related blockage) through a segment of the network to evaluate the impact of such an incident on network safety and capacity, but such incidents were not modeled in this study.

particularly between freight and HSR trains. The other parts of the network had at least eight trains a day on the single-track sections.[8]

2.4 Signaling Systems

Signaling is a key element of any railroad system that significantly affects the train dispatching rules and capacity limits and controls the safety of train operations. To represent different systems in the U.S. rail network, various signaling systems were implemented throughout the scenarios through combinations of the following signaling systems:

- Automatic block signaling systems with two-aspects (green/red) and three-aspects (green/yellow/red) wayside signals to govern the movement of trains throughout the fixed blocks of the main tracks as well as interlocking areas within the yard limits
- Cab-signaling system governed by track transponders which authorize speed and movement of a train along the fixed blocks
- PTC signaling system which can be identified as an advanced cab-signaling system with a capability of enforcing train braking at a wayside signal if needed
- No dark territory[9] or moving block system[10] was simulated in this study

In scenarios classified under CS, the above-mentioned signaling systems were not evenly distributed throughout the network due to the diversity in traffic types, capacity limits, and operational regimes of each corridor. As a result, the signaling systems developed throughout different parts of the conventional network were as follows:

- 28 percent of tracks equipped with two-aspect signals
- 47 percent of tracks equipped with three-aspect signals
- 13 percent of tracks equipped with regular cab signaling systems (with four-aspect signals)
- 12 percent of tracks equipped with PTC-enforced signaling system (with three- and four-aspect signals)

For scenarios classified under PTC, all trains were controlled by the system throughout the entire network, even for the parts that were originally developed under fixed block systems without any train control enforcement.

All signaling systems used in the study were integrated with the track components (i.e., track segments, switches, and track yards) to provide proper routing alternatives, as required for all defined trains.

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[8] Except for H-I section, 30 miles long, with four passenger trains a day
[9] A territory with no wayside signal between two adjacent yards or sidings
[10] An advanced signaling system in which trains directly communicate with each other without any need of wayside signals or requiring an absolute block system

3. Overview of Mini-network Simulation Results

To investigate the impact of advanced freight train braking systems and advanced signaling systems on network safety and operational performance, seven scenarios were simulated:

Scenario 1 – All freight trains are equipped with a CBS; the network uses a CS system (CBS-CS)

Scenario 2 – All freight trains are equipped with an ABS; the network uses a CS system (ABS-CS)

Scenario 3 – A mix of freight trains with 25 percent ABS and 75 percent CBS; the network uses a CS system (Hyb1-CS)

Scenario 4 – A mix of 50 percent ABS and 50 percent CBS; the network uses a CS system (Hyb2-CS)

Scenario 5 – A mix of 75 percent ABS and 25 percent CBS; the network uses a CS system (Hyb3-CS)

Scenario 6 – All freight trains are equipped with CBS; the network uses a PTC signaling system (CBS-PTC)

Scenario 7 – All freight trains are equipped with an ABS; the network uses a PTC signaling system (ABS-PTC)

All simulation scenarios used the same infrastructure and operating rules. The only difference was the braking characteristics of the freight trains and the signaling system used. Table 4 summarizes the combinations of different freight train braking systems and signaling systems for each scenario analyzed in the study.

Table 4. Summary of network simulation scenarios defined for the study

Scenario #	Freight Braking System	Network Signaling System	Scenario Acronym
1	CBS	Conventional Signal	CBS-CS
2	ABS	Conventional Signal	ABS-CS
3	Hybrid-1	Conventional Signal	Hyb1-CS
4	Hybrid-2	Conventional Signal	Hyb2-CS
5	Hybrid-3	Conventional Signal	Hyb3-CS
6	CBS	PTC	CBS-PTC
7	ABS	PTC	ABS-PTC

The following OpenTrack simulation outputs were used to compare scenarios:

- Overall network velocity and delay
- Average speed and delay for each type of train
- Track and capacity utilization through selected parts of the network
- Safety of operating trains through the network:
    - Number of stops at stations (sidings and yards)
    - Number of braking actions at signals for route reservation

- Number of stops at signals due to unavailable route

Stringline[11] diagrams are one of the best ways to illustrate the movement of trains in a network. In this study, nine different stringline diagrams were defined to cover all 256 trains simulated.

All stringlines shown in this report distinguish the train type by the following colors:

- Blue: freight train
- Gray: passenger train
- Green: commuter train
- Red: HSR train

The following sub-sections summarize the results for each scenario.

3.1 Scenario 1 – Conventional Freight Trains Under CS System

Figure 7 shows the stringline results for section B-C-E-G-I-J-M-O-P of the mini-network under Scenario 1 (CBS-CS). A variety of different trains (e.g., passenger, HSR, commuter, and freight) operated over this section, which comprised 886 miles of tracks.

The legend on the vertical axis indicates the number of tracks. Single-track parts of the corridor also have a gray background across the diagram, while the double- or multi-track sections have a white background.

Figure 7 shows the time horizon extended for almost 2 days of operations because some of the freight trains dispatched in the first day arrived at their designated destinations on the following day. Also, because various sections of the corridor had different traffic congestion levels, some trains (particularly through the I-J-M-O section) experienced delays or speed reductions to avoid any deadlock or major schedule conflicts. More details about train delays are discussed in the following sub-sections.

Figure 8 and Figure 9 show stringline results in two other corridors of the mini-network with approximately 1,565 and 818 miles of track, respectively. These three stringlines do not show every train operated through the entire corridor because some trains had origins or destinations located in other parts of the network.

As shown in Figure 8, two freight trains were simulated for 1,600 miles of travel between rail hubs at Yard B and Yard S, with various stops and meet-passes to allow faster trains (e.g., HSR and passenger trains) to overtake them along intermediate sidings and yards. These two freight trains were among the heaviest type of freight trains (i.e., Type DP-1, as detailed in Table 3) with over 17,000 tons in weight and measuring over 13,000 feet long. Overall, there were 6 freight trains traveling at least 1,000 miles and 22 freight trains traveling between 500 to 1,000 miles of hauling distance throughout different corridors of the mini-network.

[11] A stringline is a distance-time diagram (i.e., train graph) which shows movement and schedule activities of given trains along a given corridor. The horizontal axis of the diagram typically represents time, while the vertical axis shows stop points of trains (stations, sidings, and yards). Each stringline represents one train movement along the corridor in either direction (northbound or southbound).

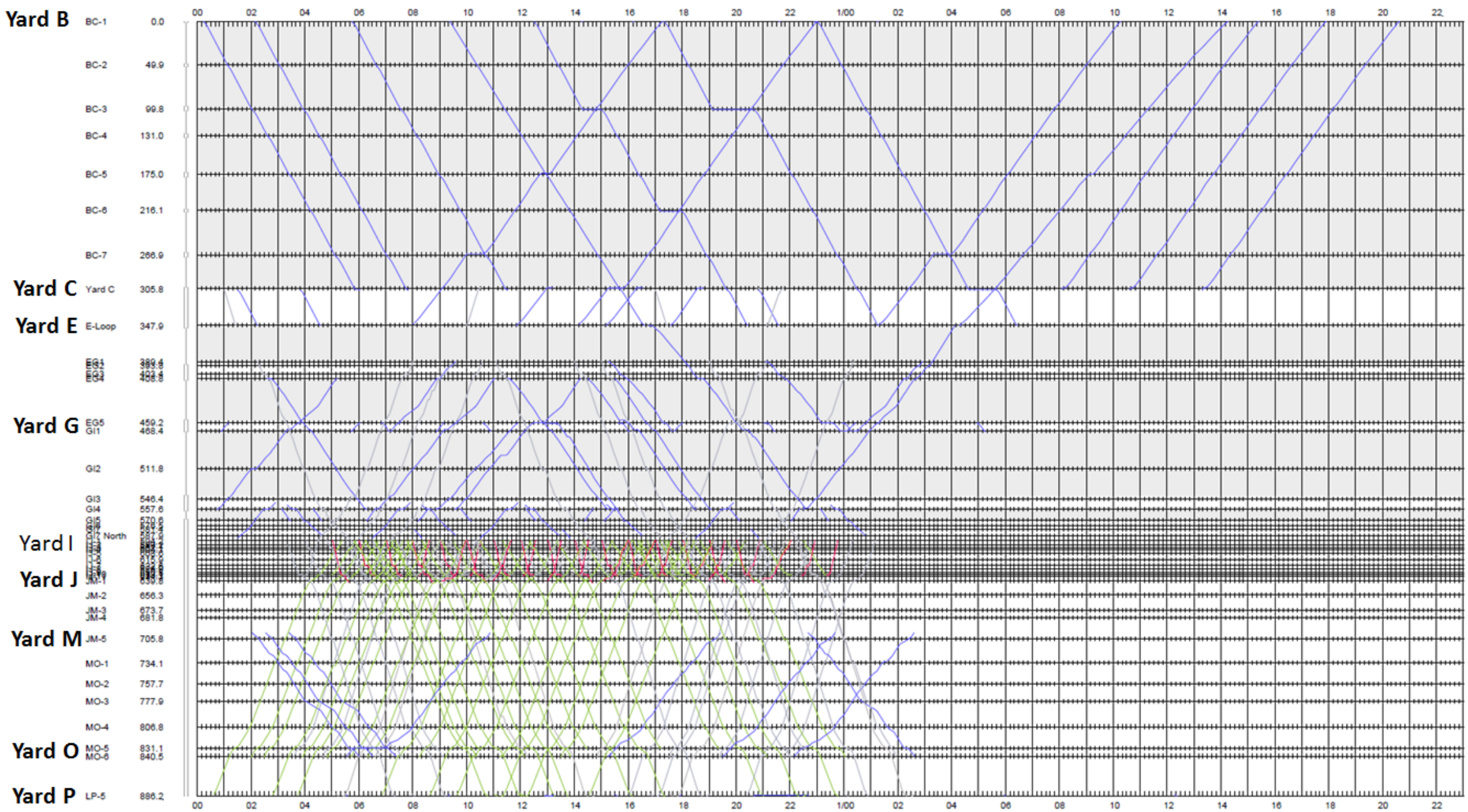

Figure 7. Stringline results for section B-C-E-G-I-J-M-O-P of mini-network in Scenario 1 (CBS-CS)

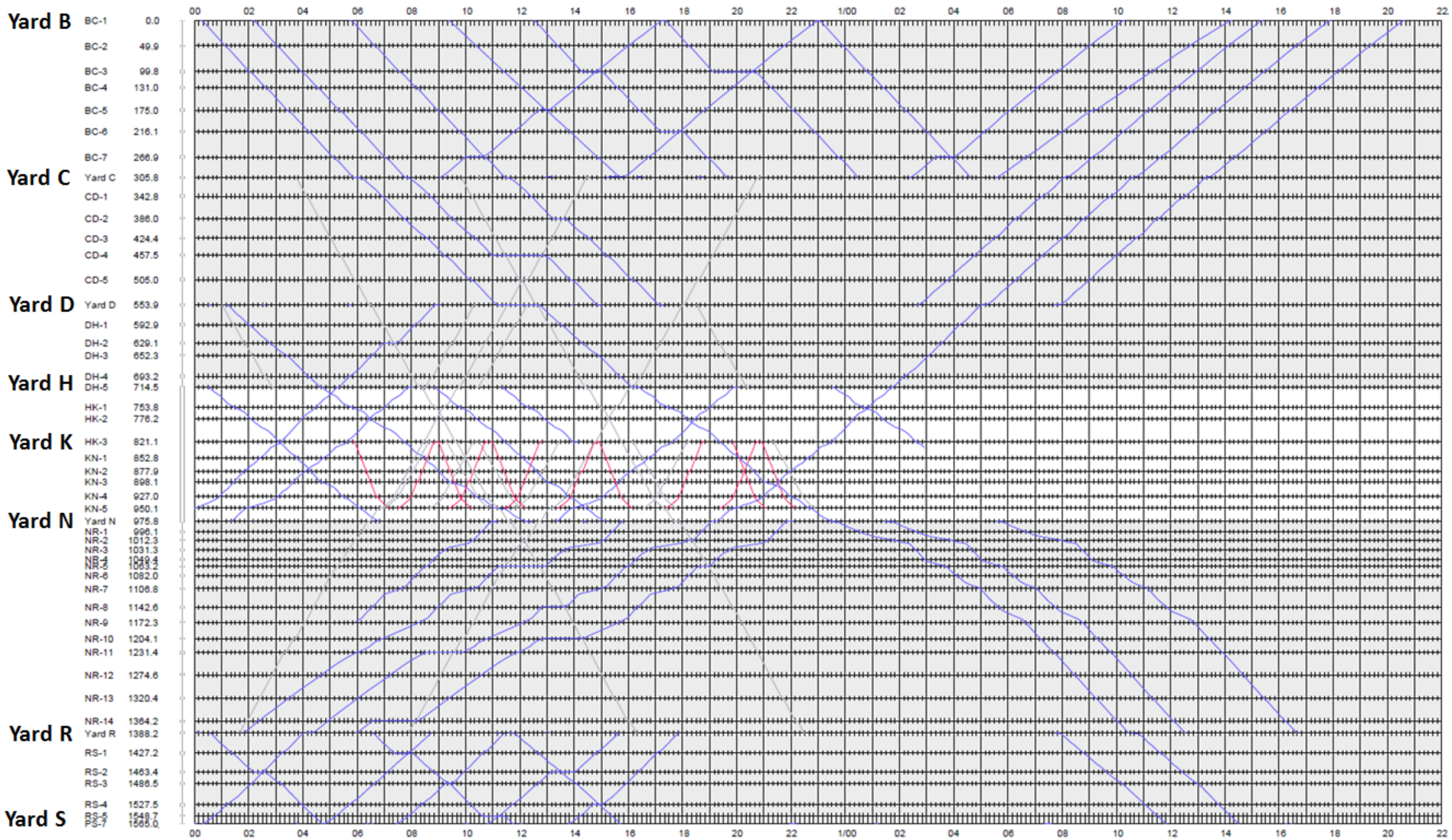

Figure 8. Stringline results for section B-C-D-H-K-N-R-S of mini-network in Scenario 1 (CBS-CS)

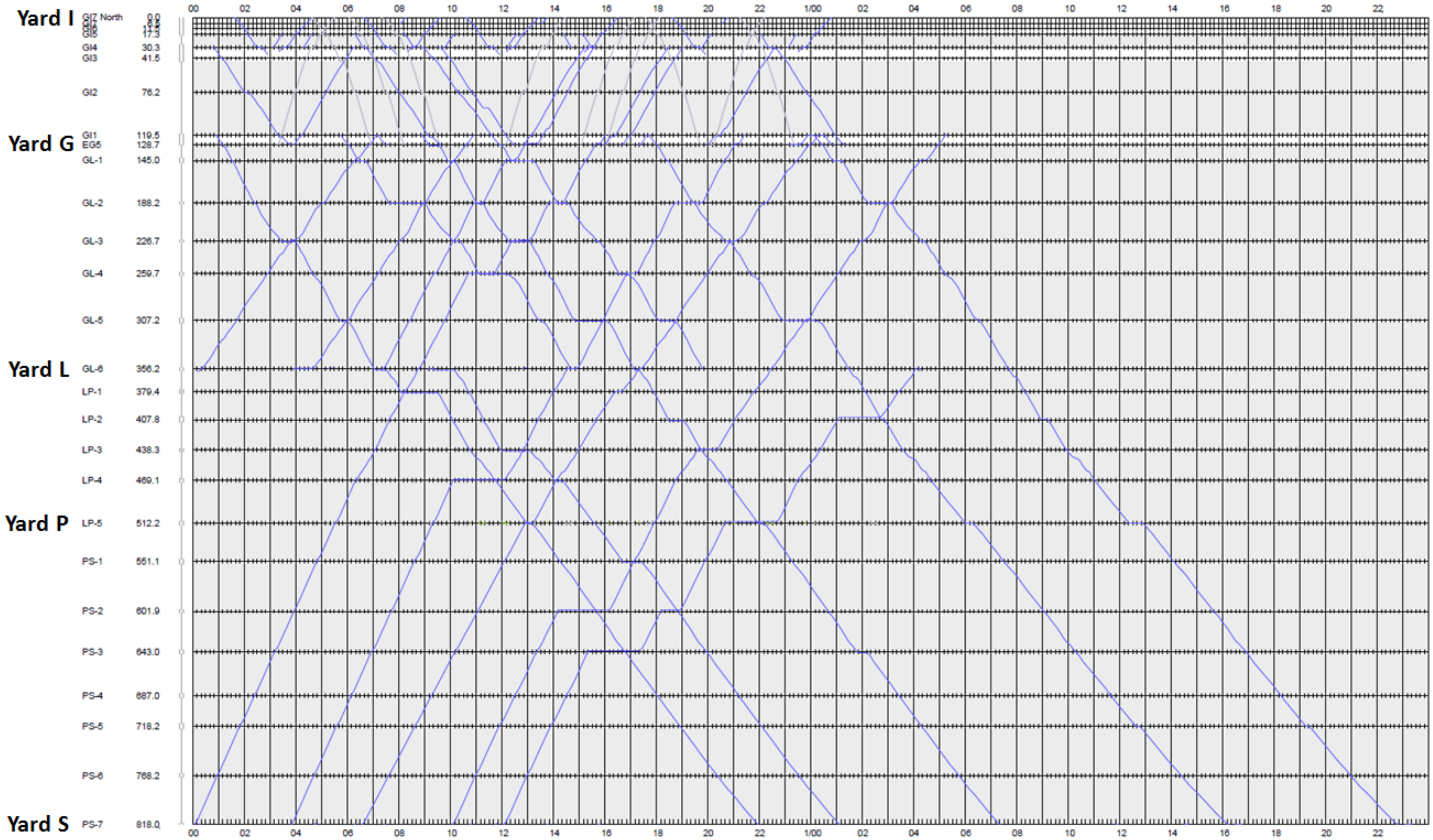

Figure 9. Stringline results for section I-G-L-P-S of mini-network in Scenario 1 (CBS-CS)

As mentioned in the previous section, one of the simulation dispatching rules was to enforce a deadlock-free schedule for all trains during every simulation scenario. However, applying changes in braking system or signaling system characteristics may cause a deadlock throughout the network which should be resolved. In this study, any major train conflicts and deadlocks were resolved by applying one or both of the following techniques:

- Minor adjustments on the initial requested schedules of certain trains as needed
- Additional stop time or stop location for certain trains to provide a proper meet-pass or overtaking alternative

If these techniques could not resolve the major schedule conflicts or deadlock, trains can be removed from the simulation until a conflict-free schedule is achieved throughout the network. In this study no train was removed from the initial schedule.

Figure 10 shows an example of two deadlock incidents observed in the I-G-L-M corridor for Scenario 1.

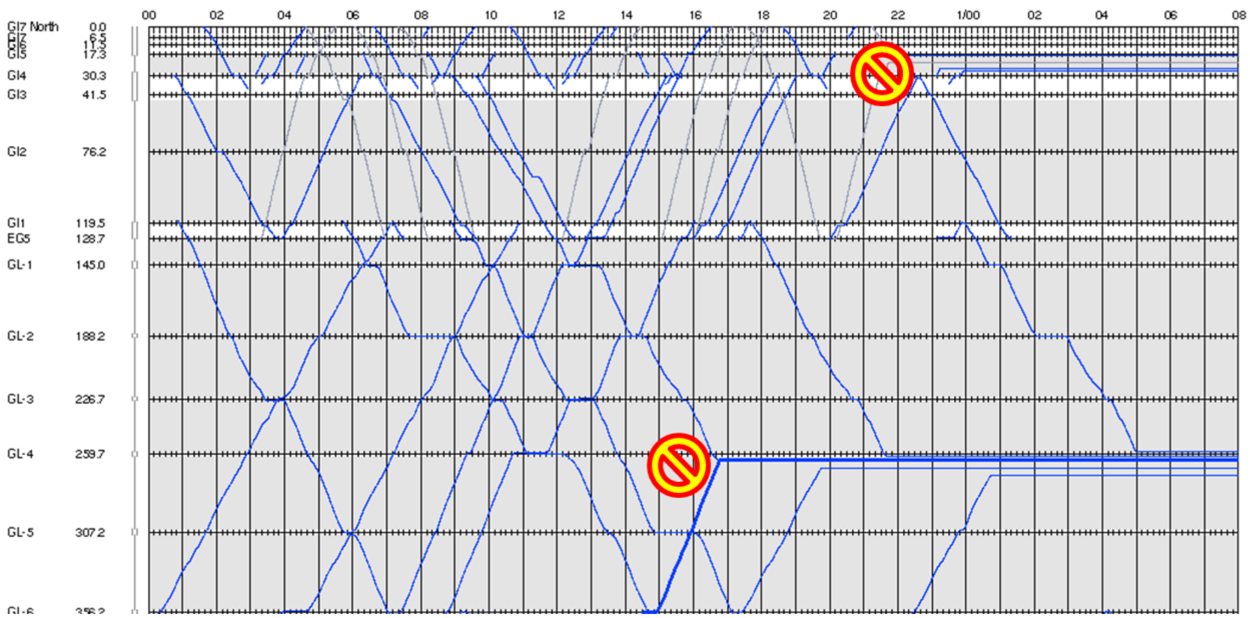

Figure 10. Examples of two deadlocks on the I-G-L-M corridor in Scenario 1 (CBS-CS)

The conflicts shown in Figure 10 were resolved with minor adjustments to the dwell times of the conflicted trains at the stop points prior to the deadlock location. The resulting stringlines are shown in Figure 11.

Stringline results for other trains in this scenario are shown in Appendix A.2. Also, the performances of selected trains are shown in Appendix A.4 in terms of speed profile, track speed limits, tractive effort, acceleration, and track gradients for the entire route.

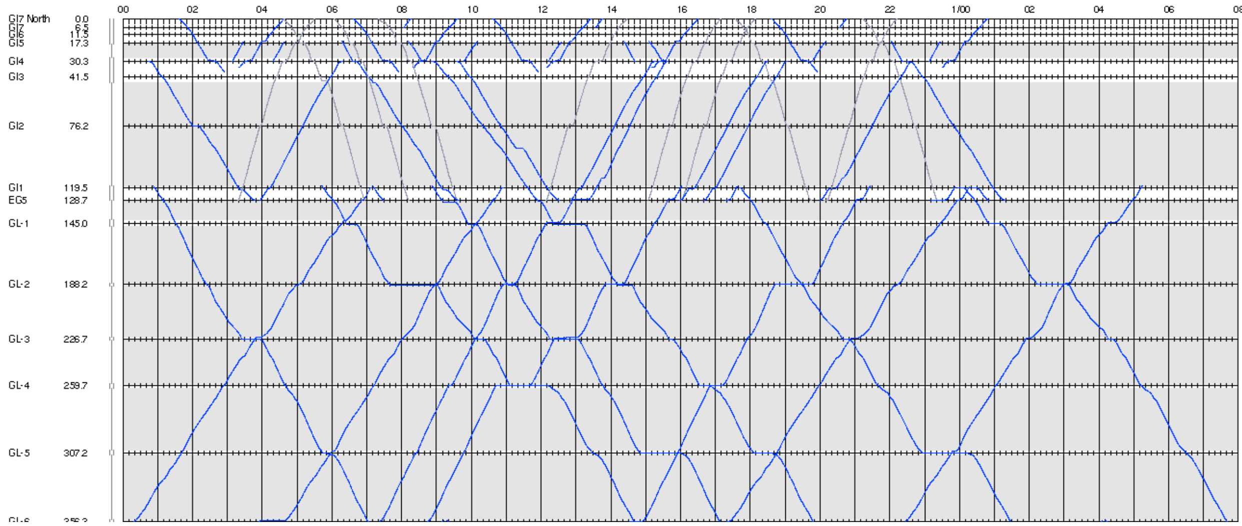

Figure 11. Conflict-free schedule of trains on the I-G-L-M corridor after resolving the deadlocks initially observed when simulating Scenario 1 (CBS-CS)

3.2 Scenario 2 – Advanced Freight Trains Under CS System

Changing the braking system of the freight trains from CBS to ABS was expected to change their train handling and speed profiles.

Figure 12, Figure 13 and Figure 14 show the Scenario 2 stringlines for the same corridors shown in Figure 7 to Figure 9 for Scenario 1. The stringline results for Scenarios 1 and 2 initially look similar. However, a detailed comparison shows certain differences. Scenario 2, with advanced brakes for freight trains, resulted in reduced delay and slightly different train arrival and departure times in certain sidings and yards. Some of these schedule changes are highlighted in Figure 12 to Figure 14 with red circles. Further analysis is provided in Section 4. Appendix A presents the stringline results and performance characteristics for other trains in Scenario 2.

3.3 Scenarios 3, 4, and 5 – Mixed Freight Trains Under CS System

Scenario 3 included a mix of 25 percent of freight trains with advanced brakes and 75 percent with conventional brakes. Figure 15 shows the stringline results for Scenario 3 (Hyb1-CS) on section B-C-E-G-I-J-M-O-P of the mini-network. When comparing this figure against Figure 7 (Scenario 1) and Figure 12 (Scenario 2), some minor deviations can be observed in the train schedules, especially for the freight trains. Relative to Scenario 1, some freight trains arrived at their final destination slightly earlier in this scenario (Figure 15 shows examples highlighted with a red circle). This demonstrates that a combination of mixed conventional and advanced braking systems could provide a conflict-free schedule for all trains. Further analysis of these results is provided in Section 4.

In Scenario 4 (Hyb2-CS), 50 percent of freight trains were equipped with ABS brakes. Figure 16 shows the stringline for Scenario 4 on section B-C-E-G-I-J-M-O-P of the mini-network. When comparing this figure against previous scenarios (Figure 7, Figure 12, and Figure 15) some minor deviations (highlighted with red circles) can be observed in the train schedules, especially for the freight trains. An increase in the amount of freight trains with advanced brakes allowed some trains to arrive at their destination earlier than in Scenario 3, which had fewer trains with ABS brakes.

A similar trend is observed in Scenario 5, Hyb3-CS (Figure 17), with 75 percent of freight trains equipped with ABS compared to Scenario 1 (Figure 7), Scenario 3 (Figure 15), and Scenario 4 (Figure 16) which have more freight trains with CBS systems. In other words, gradually converting freight trains from CBS to ABS may affect train schedules throughout the network because it can relatively improve the performance of freight trains. Further analysis of these results is provided in Section 4.

3.4 Scenario 6 – Conventional Freight Trains Under PTC System

Scenario 6 (CBS-PTC) was developed to demonstrate the impact of PTC signaling systems throughout the entire network with freight trains operating under CBS. Figure 18 shows the stringline results for this scenario on the selected section of the mini-network. When comparing this figure against Figure 7 (Scenario 1), which has the same braking characteristics for freight trains but under CS system, some minor deviations are observed in certain areas (an example is highlighted with a red circle).

Since under a PTC signaling system the approach speed of trains toward the next block can be increased, the occupancy (i.e., reservation) and release times of a fixed block can be performed faster and more reliably than in the CS system. Thus, the overall performance of trains throughout the entire network can be improved in comparison to the CS system. Further analysis of these results is provided in Section 4.

3.5 Scenario 7 – Advanced Freight Trains Under PTC System

Scenario 7 (ABS-PTC) was developed to demonstrate the combined effect of the PTC signaling system, like Scenario 6, with freight trains equipped with ABS instead of conventional brakes. Figure 19 shows train stringlines for this scenario over the selected section of the mini-network. When comparing this scenario against Scenario 2 (Figure 12.) with CS, minor changes in train performance are seen, as highlighted in red circles on Figure 19.

Comparing this scenario against Scenario 6 with conventional freight trains and PTC signaling system (Figure 18) reveals other changes in the train stringlines that come from the differences between freight train braking systems in these two scenarios and are not due to the type of signaling. Two examples of such differences are highlighted on Figure 19 in black circles.

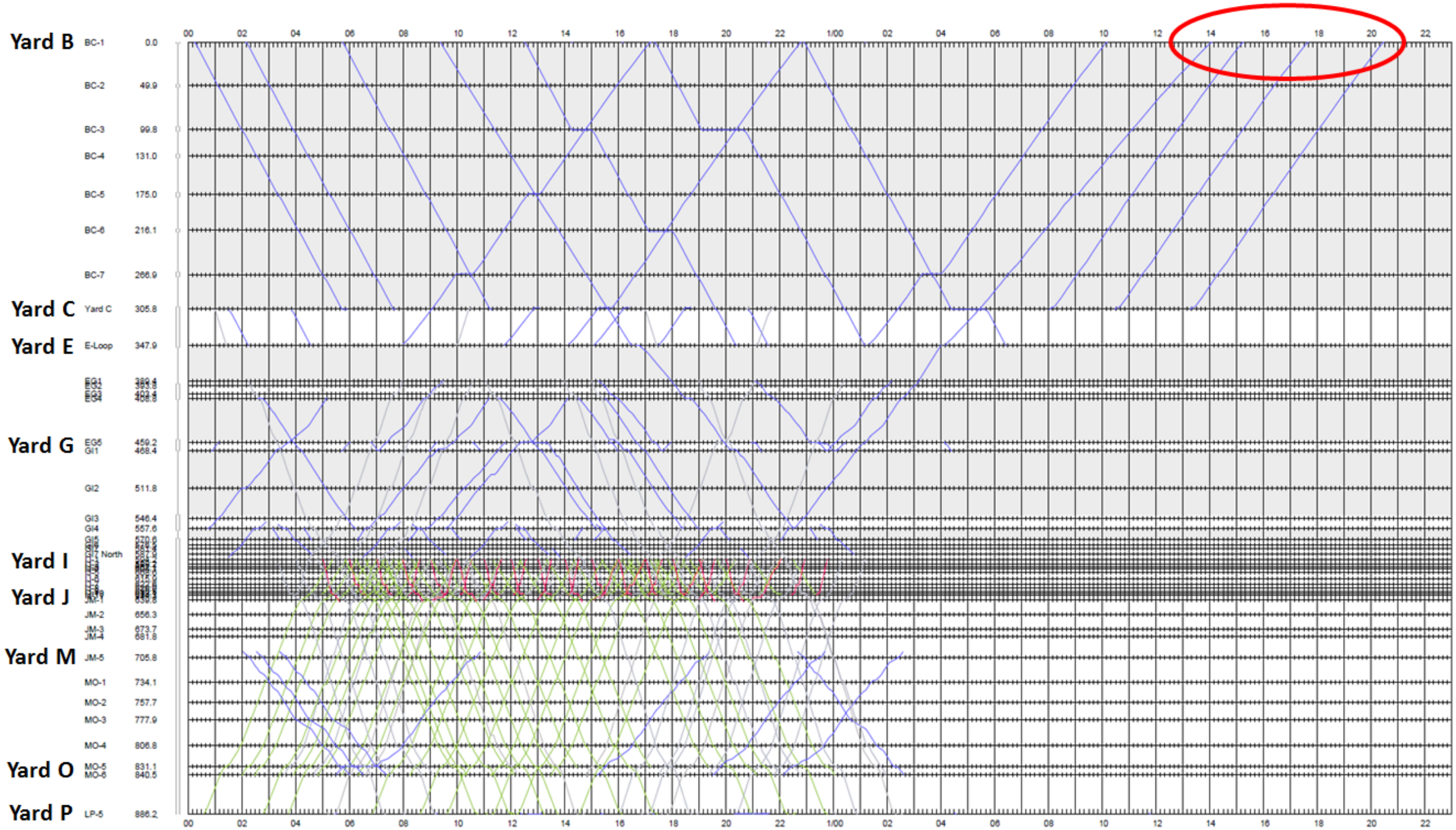

Figure 12. Stringline results for section B-C-E-G-I-J-M-O-P of mini-network in Scenario 2 (ABS-CS)

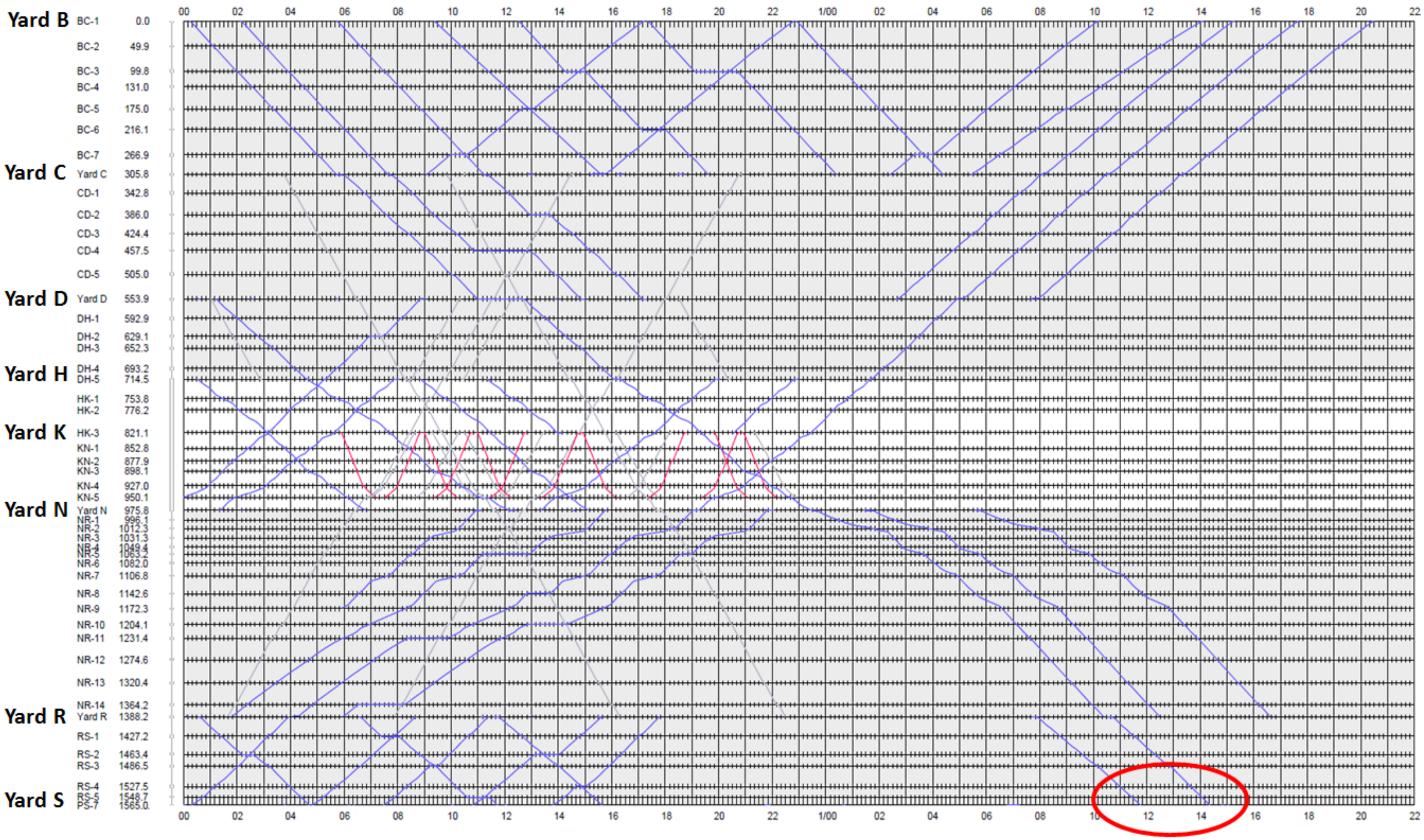

Figure 13. Stringline results for section B-C-D-H-K-N-R-S of mini-network in Scenario 2 (ABS-CS)

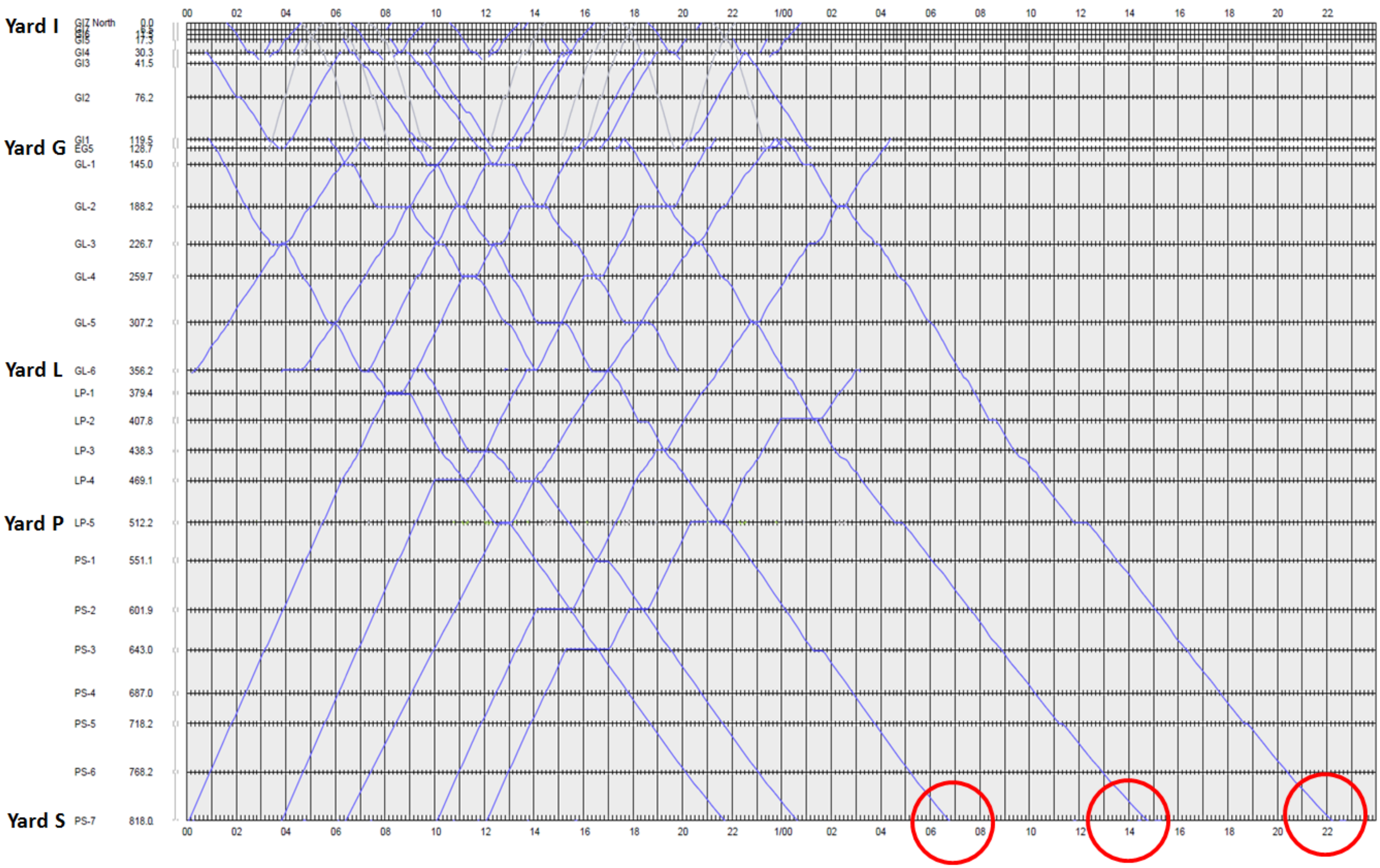

Figure 14. Stringline results for section I-G-L-P-S of mini-network in Scenario 2 (ABS-CS)

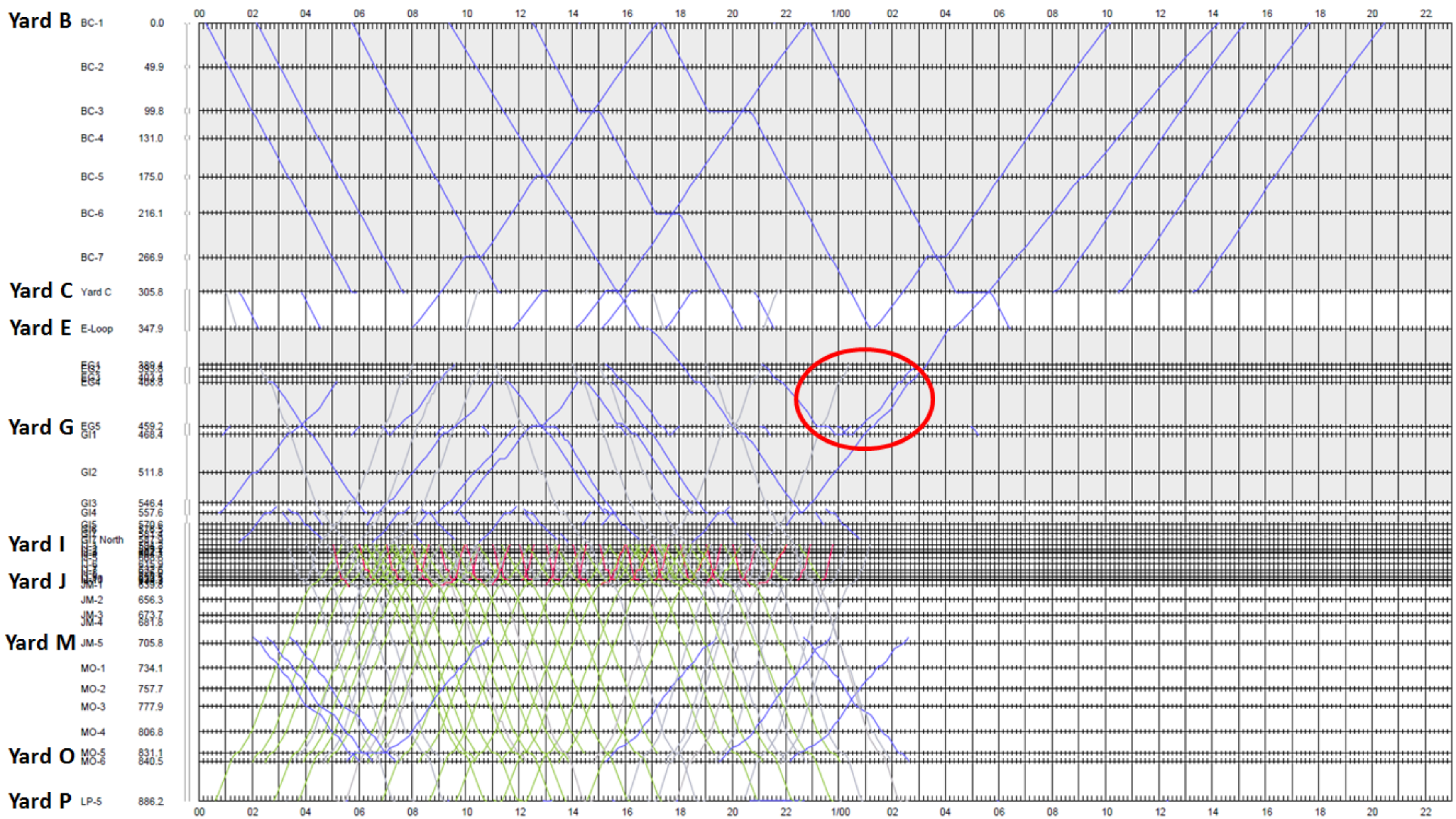

Figure 15. Stringline results for section B-C-E-G-I-J-M-O-P of mini-network in Scenario 3 (Hyb1-CS)

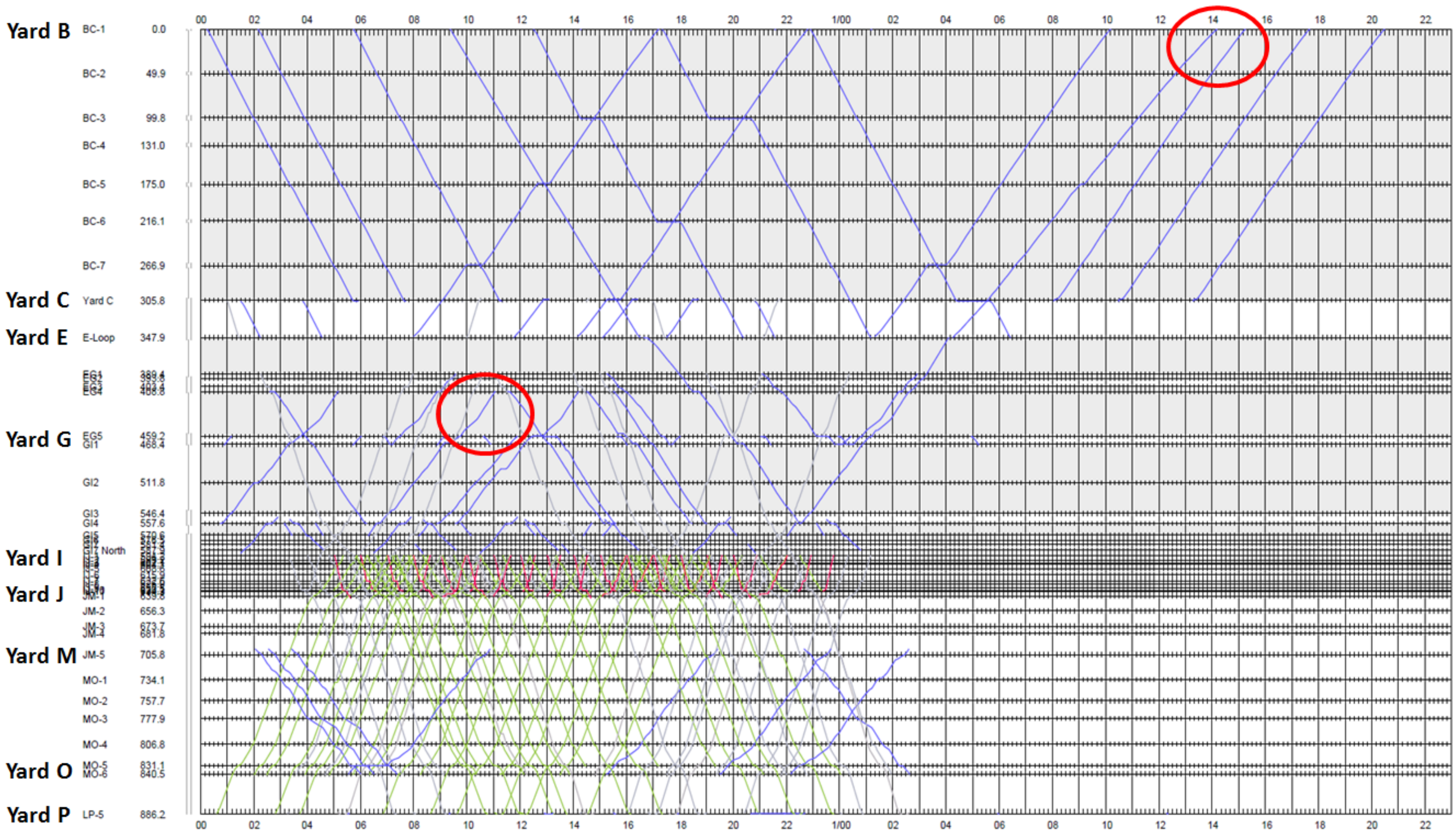

Figure 16. Stringline results for section B-C-E-G-I-J-M-O-P of mini-network in Scenario 4 (Hyb2-CS)

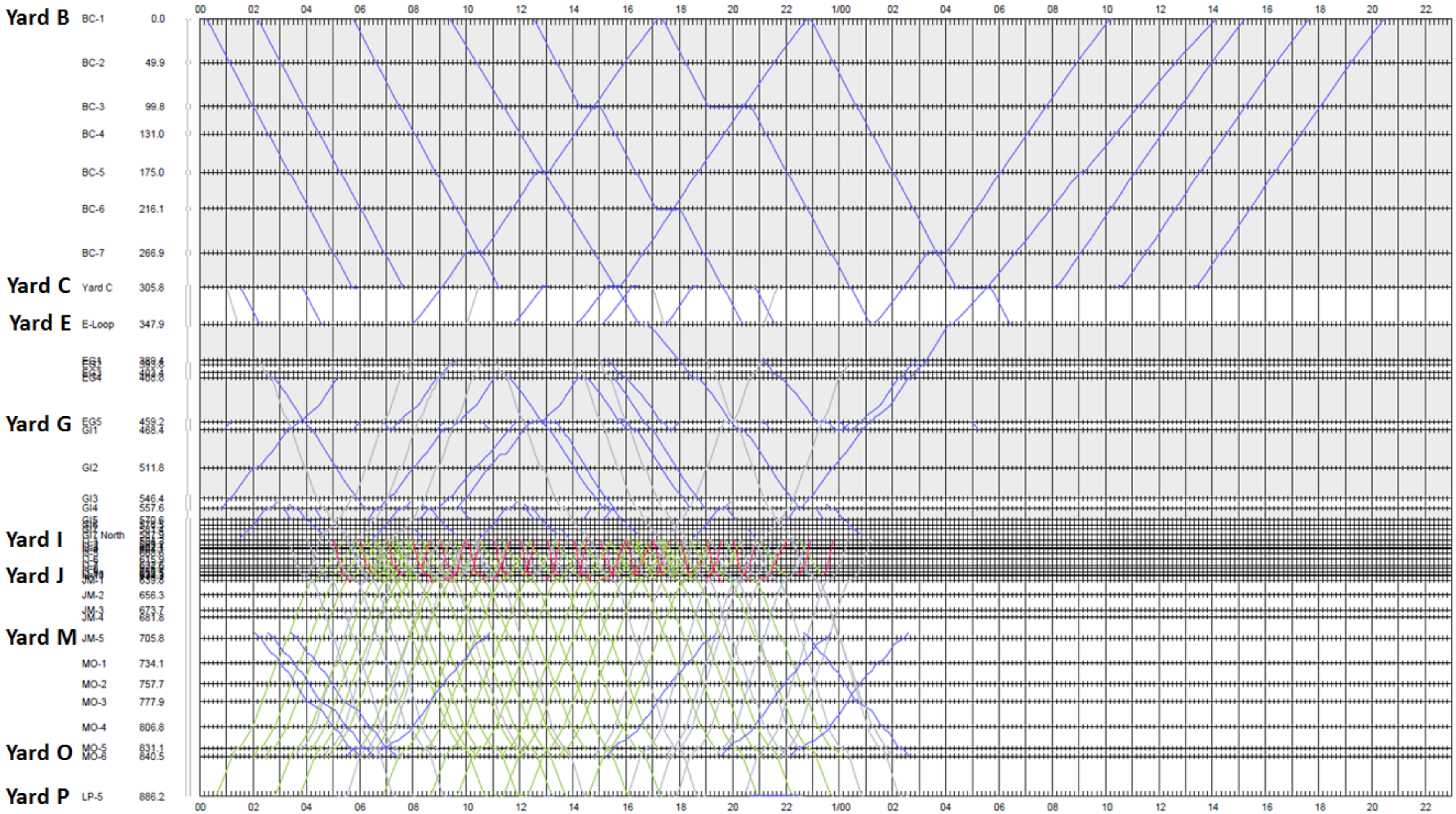

Figure 17. Stringline results for section B-C-E-G-I-J-M-O-P of mini-network in Scenario 5 (Hyb3-CS)

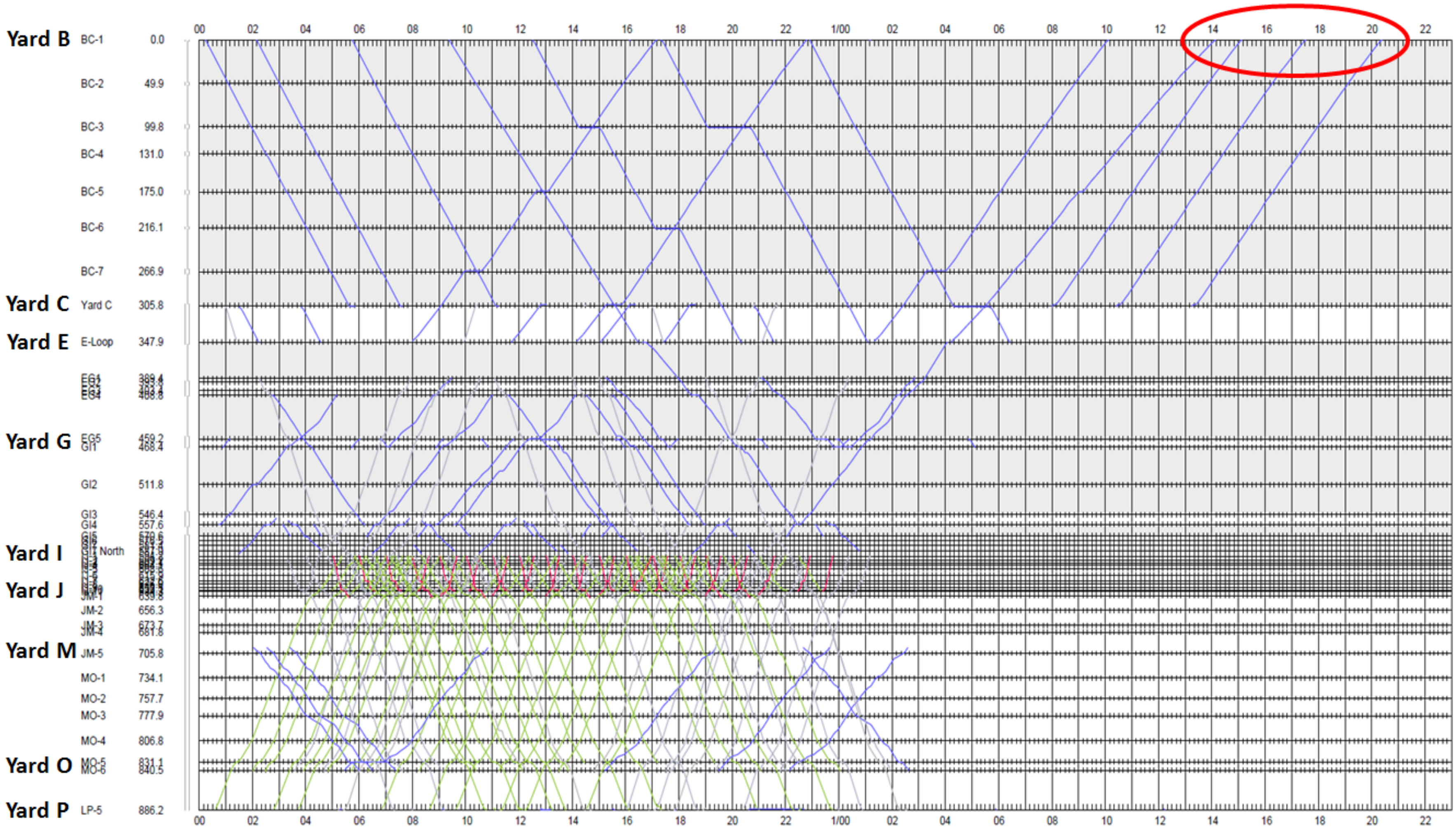

Figure 18. Stringline results for section B-C-E-G-I-J-M-O-P of mini-network in Scenario 6 (CBS-PTC)

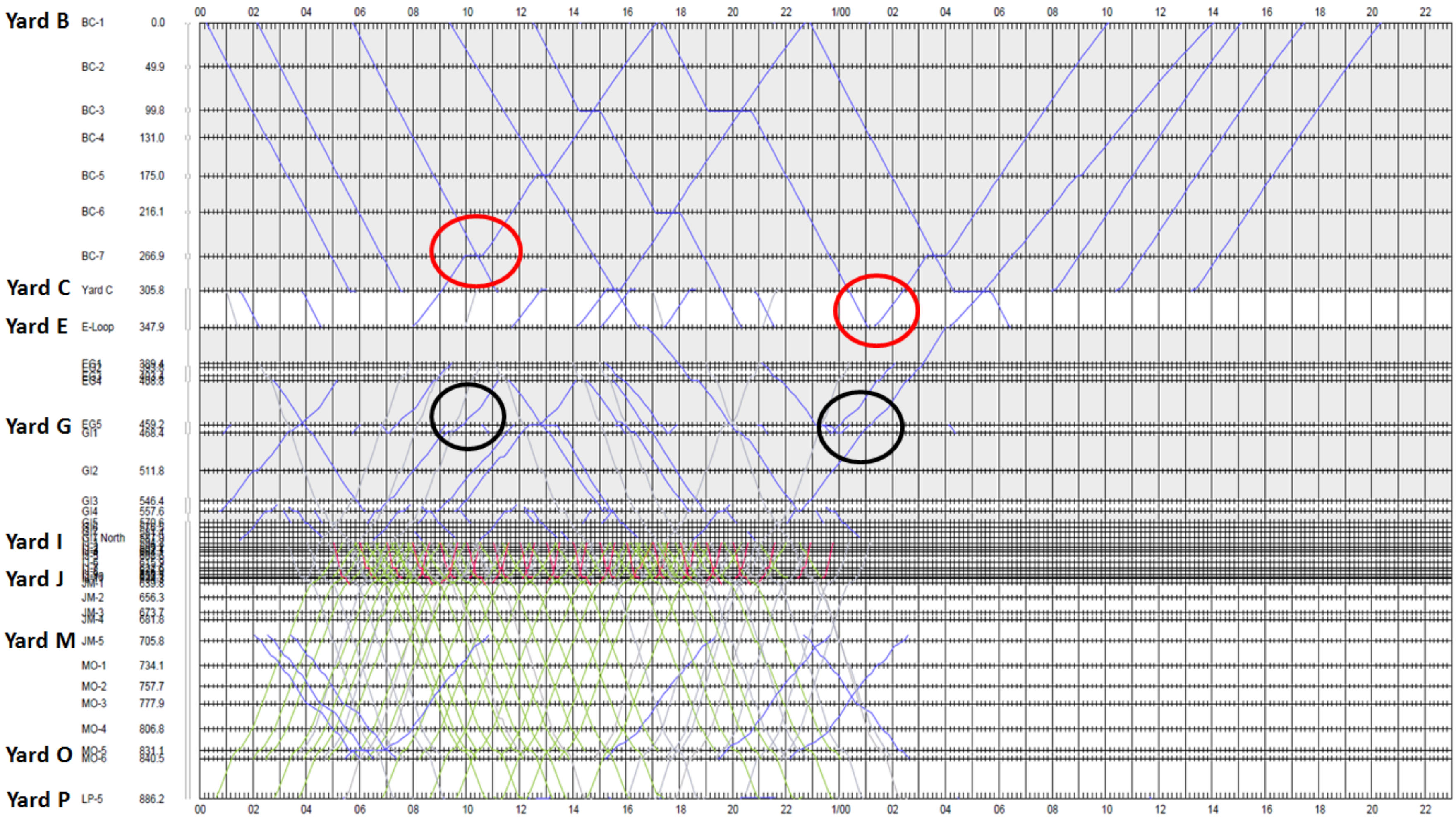

Figure 19. Stringline results for section B-C-E-G-I-J-M-O-P of mini-network in Scenario 7 (ABS-PTC)

4. Analysis of Simulation Results

This section reviews the results of all simulation scenarios from different network safety and operational perspectives based on various performance metrics, as defined below. It also compares different scenarios side-by-side to evaluate any benefits that an advanced train control technology (e.g., PTC) can provide for a given measure of network performance compared to the conventional technologies.

4.1 Review of Performance Metrics and Benchmarks

The following performance metrics were used to compare the results between the different scenarios. Results are presented for the following measures of network safety and operational performance.

- Average delay of all trains in a category
  - Delay is defined as the difference between actual and planned arrival time at any planned stop location. The delay results are also presented as a normalized delay per 100 train-miles. This gives a more direct comparison between different trains and scenarios.
- Network velocity
  - Network velocity is the average speed of all trains in a category weighted by their respective travel distances. This includes a sub-category of velocity that excludes yards, which is essentially considered as a "moving velocity."
- Average station (i.e., yard and siding) stops for all trains in a category
- Average braking at signals for all trains in a category
  - A route braking action at a signal is defined as a brake application for a train due to the signal aspects of following blocks to reserve (i.e., lock) the next available signal block of tracks through the respective route of the train.
- Average signal stops for all trains in a category
  - Signal stops are the number of train stops at signals when the next block is not available (e.g., red signal).
- Track utilization rate
  - The track utilization rate is used for evaluating the capacity and congestion levels of the given network for selected segments of corridors (mainly the potential bottlenecks) in each simulation scenario. Details about track and capacity utilization are discussed in Section 4.2.

Average train delay and network velocity are measures of operational performance. Average station stops can be interpreted differently for freight and passenger trains. Since passenger trains (i.e., commuter and HSR services in this study) have predetermined stop locations in their daily schedules, there should be no difference between simulation scenarios in terms of number of stops for these trains. Additional stops at stations for the passenger services may be required to resolve potential deadlocks. Fewer station stops can also be interpreted negatively when passenger trains are forced occasionally to miss their scheduled stops to avoid potential deadlocks.

For freight trains, most station stops are necessary to resolve potential deadlocks. Thus, a lower average of stops at stations for freight trains indicates less idling time.

High values of average number of route braking at signals indicate increased risk of schedule conflicts. Extreme values can indicate a high risk of train collisions, especially if they coincide with a human error or a signal failure.

Average number of signal stops is a subcategory of average route braking at signals since every train needs to brake to stop at a signal. High values of this metric indicate increased risk of signals being overrun.

Results for network velocity and delay were computed for a sub-category of trains running through single-track segments. The team theorized that many benefits of the newer technologies can be fully realized only on single-track segments of the network, or conversely more applicable for double-track corridors. Such a hypothesis is evaluated in Section 4.3.

Since each individual train has the same route and origin-destination in all scenarios, the main operational characteristics of each train category (i.e., average train-miles and average travelled distance) are the same for all scenarios, as summarized in Table 5. However, other network details can be different in each scenario.

Table 5. Summary of trains' operational parameters through the entire network

Parameter	Freight	Passenger	Commuter	HSR	Total
Number of Trains	102	66	56	32	**256**
Total Train-Miles	38,980	19,865	11,456	3,319	**73,620**
Avg. Distance (miles)	382	301	204	104	**288**

4.2 Overall Analysis of Safety and Operational Performance

4.2.1 Delay Analysis

Figure 20 summarizes the results for network delay for the seven scenarios categorized by type of train. The braking characteristics of freight trains with CBS were expected to have more delays overall than with trains having ABS. The results in Figure 20 show around 28 percent more average delay in arrival time of all trains (330 seconds vs. 257 seconds) for the CBS in comparison to ABS on freight trains. Considering the freight trains only, there was a 37 percent reduction in arrival delay for freight trains with CBS vs. ABS (495 seconds vs. 313 seconds), as shown in Figure 20.

For combined PTC and ABS (Scenario 7), the arrival time delays for freight trains are further reduced to 47 percent (495 seconds vs. 261 seconds).

The hybrid scenarios with an increasing percentage of trains using ABS follow a trend as expected (i.e., a larger reduction in delay). These scenarios show that as the percentage of trains with ABS grows, the benefits from reduced train delay grow as well. Each additional 25 percent of trains equipped with ABS reduces the average delay for all trains by 3–8 percent; while for only freight trains, the reduction is 6–12 percent.

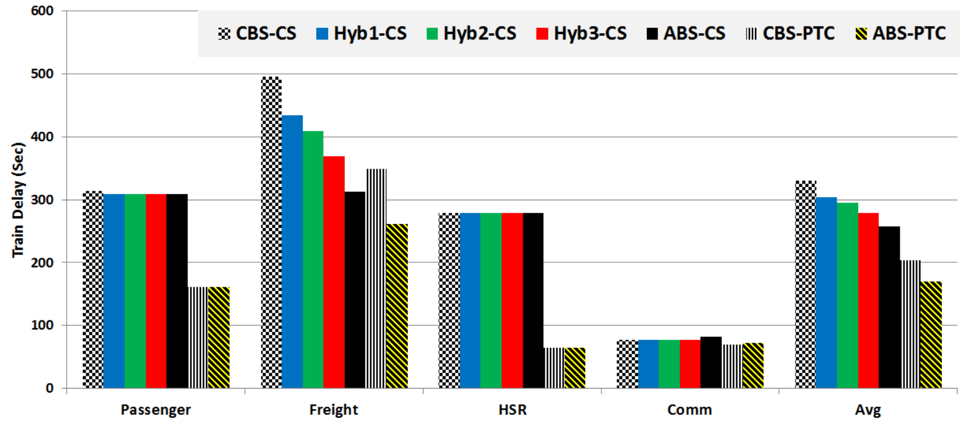

Figure 20. Summary of network delay for all scenarios categorized based on train types

The HSR trains are delayed the same in all CS scenarios. The average delay is relatively high, most likely because the HSR trains were operated through the most congested parts of the network with a high diversity in types of trains (except for freight traffic) sharing the same tracks. The scenarios with PTC reduce delay times by 77 percent for HSR trains.

The passenger trains have approximately 1.5 percent more average delay in Scenario 1 (i.e., CBS for freight trains) compared to the other scenarios with ABS for freight trains. However, scenarios with PTC significantly reduce the delay in arrival time of passenger trains, like what is observed for HSR services, by about 49 percent, as shown in Figure 20.

On the other hand, the commuter trains show minor changes in their arrival time delays for all scenarios. Scenario 2 has a slightly higher average delay, about 6 percent higher, compared to the other scenarios; one explanation for this is the schedule changes required to resolve major conflicts observed when simulating this scenario. (Examples are shown in Figure 10 and Figure 11) Also, as shown in Figure 20, commuter trains have relatively lower delays compared to other types of trains. Therefore, it is reasonable to conclude that deploying new train technologies such as PTC may not provide any additional benefits for commuter services that tend to have lower operational speed and more stops through their daily schedules, compared to passenger and HSR services.

Figure 21 summarizes the results for network delay normalized by 100 train-miles for comparison between different train performances regardless of their travel length. When comparing Figure 21 to Figure 20, a similar trend of delay reduction can be seen for the initial results before normalizing the delays. However, there are certain differences between these two figures:

- The normalized delays of HSR services increases compared to the original values, while they are reduced for other types of trains. This is mainly due to many HSR services with delays traveling at a distance shorter than 100 miles, causing the normalized values of delay to increase accordingly.
- The ratio of delay reduction for PTC was significantly increased from 49 to 76 percent for passenger trains when normalized. This implies that many of those passenger trains, which under PTC scenarios reduced their respective delays, had relatively short travel distances.

- The ratios of delay reduction by applying either ABS or PTC technologies reduce for freight trains when normalized (e.g., 47 percent in initial analysis between Scenarios 1 and 7 reduced to 26 percent). Also, many local freight trains with short travel distances operating through relatively congested segments of the mini-network do not gain any major benefits from these technologies and their delays do not reduce as much as for other freight trains with longer hauls.

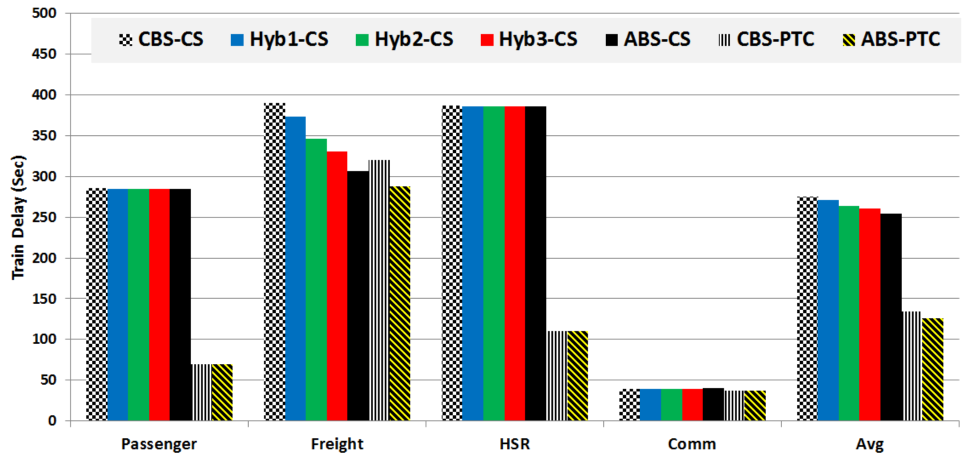

Figure 21. Summary of network delay for all scenarios normalized by 100 train-miles

4.2.2 Network Velocity Analysis

Figure 22 presents the network velocities of all scenarios categorized by type of train. As shown, the network velocities of commuter trains are similar for all scenarios, while for passenger trains the velocity is slightly increased (about 1 percent improvement) under PTC scenarios. For HSR services, network velocity is 3.8 percent higher for scenarios under PTC signaling systems.

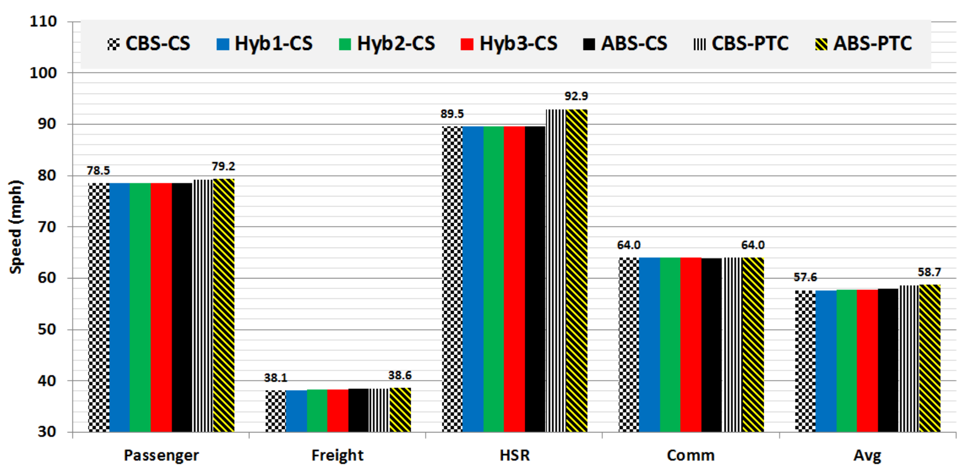

Figure 22. Summary of network velocity categorized based on type of trains

As shown in Figure 22, the network velocity of freight trains with 100 percent ABS (Scenario ABS-CS) is approximately 0.4 mph (slightly over 1 percent) higher than the freight trains with CBS (Scenario CBS-CS). PTC adds 0.26 mph to the CBS trains and 0.11 mph to the ABS trains. Overall, considering all types of trains, the network velocity of Scenario 2 (ABS-CS) is approximately 0.4 percent higher than Scenario 1 (CBS-CS). However, the average network velocity of all trains under PTC signaling systems are about 1 mph higher than under CS (Scenarios 1 to 5), providing about 1.7 percent improvement in network velocity on average for all trains.

Looking strictly at the moving velocity of trains without considering dwell times at sidings and yards, the updated velocities are between 4 to 9 mph higher than the original speeds (Figure 22), depending on the type of train. As shown in Figure 23, PTC adds 0.56 mph to the freight train velocities with CBS and 0.24 mph to the ABS trains; this is nearly double the effect when compared to the initial velocities of freight trains. A similar trend can be seen for the average network moving velocity of trains compared to the initial network velocity, considering all stop times.

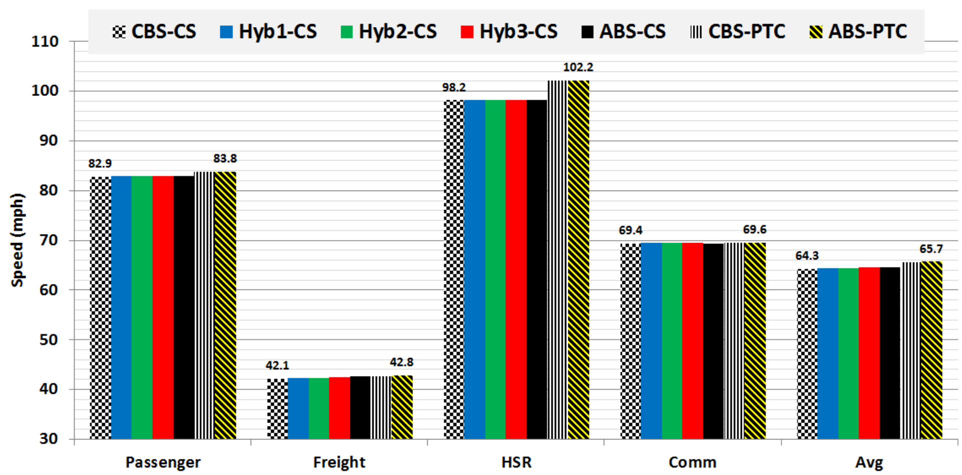

Figure 23. Summary of moving velocity of trains (excluding stop times) categorized based on type of trains

4.2.3 Average Number of Station Stops

Figure 24 shows the average number of station stops for all train types. As illustrated in the figure, all scenarios are essentially the same for each type of train, since there was only a limited number of changes in the stop patterns when simulating each scenario.

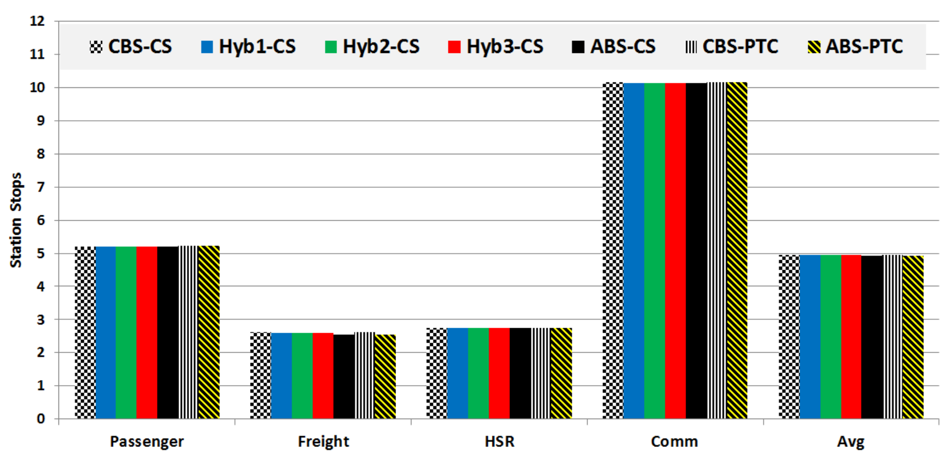

Figure 24. Summary of station stops for all scenarios

4.2.4 Average Number of Braking at Signal

The average number of route braking actions at signals (i.e., to reserve and lock the next block of the assigned route) represents a risk factor for the given train operating regime, since a higher number of braking actions increases the risk of train accidents. As presented in Figure 25, freight trains have almost 18 percent higher braking actions in Scenario 1 (CBS-CS) compared to Scenario 2 (ABS-CS) due to route reservation (i.e., locking) conflicts, especially within the exit and entrance boundaries of stations (i.e., interlocking segments).

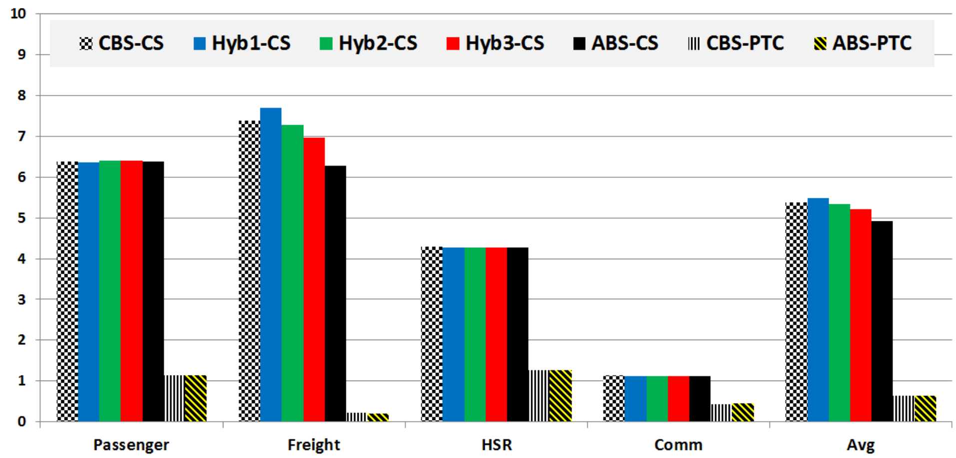

Figure 25. Number of braking actions at signals in all scenarios

As shown in Figure 25, the hybrid scenarios gradually reduce the number of braking actions at signals except in Scenario 3 (Hyb1-CS), with only 25 percent freight trains under ABS, which increased the number of braking actions. Such an increase may highlight the challenges of hybrid operation regimes when only a small portion of freight trains are retrofitted or converted with ABS compared to the condition when all trains are homogenously operated under a CBS system. Other types of trains have a similar number of braking actions at signals under Scenarios 1 to 5.

Figure 25 shows that with the addition of PTC, the average number of braking actions at signals is significantly reduced for all train types. For freight trains using PTC, the average braking at signal is less than 5 percent in scenarios with CS systems. This highlights the efficiency of this system in eliminating unnecessary braking actions and improving network safety.

4.2.5 Number of Stops at Signals

Figure 26 shows that freight, passenger, and HSR services have a higher average number of stops at signals (i.e., about 4 percent higher, respectively) in Scenario 1 (CBS-CS) compared to Scenario 2 (ABS-CS). However, commuter services in Scenario 1 have 5 percent lower average signal stops compared to Scenario 2.

On the other hand, the PTC signaling scenarios significantly reduce the number of signal stops for passenger and HSR trains, like that seen for the number of route braking actions at signals presented in Figure 25. The reduction for commuter trains was smaller but still noticeable, a little over 10 percent.

Freight trains with PTC signaling systems do not see much change to their number of signal stops since these metrics are already at the lowest level compared to other types of trains. This is likely a result of operating freight trains through the parts of the network with low traffic congestion. Thus, the number of necessary stops at the signals due to the traffic congestion is already low for freight trains, and PTC does not provide any additional benefit to reduce the number of stops at signals lower than what is already achieved.

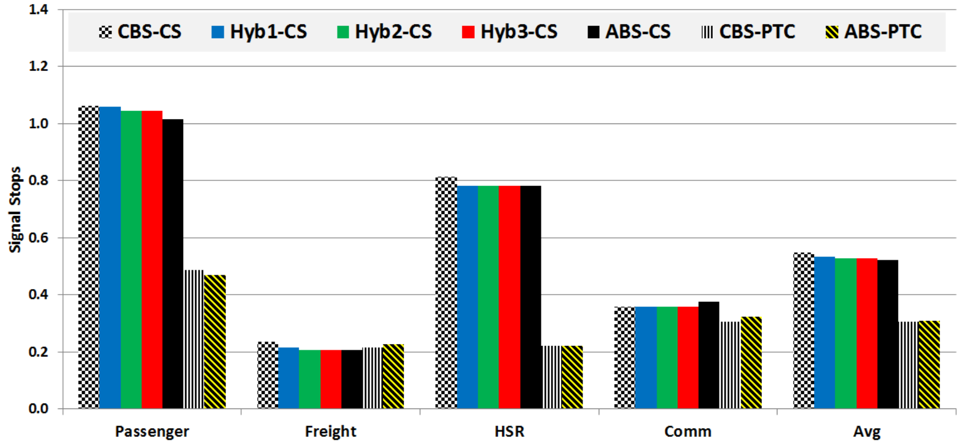

Figure 26. Number of stops at signals for all scenarios

4.2.6 Capacity and Track Utilization Analysis

Track utilization is one of the capacity metrics that shows how long a segment of track (e.g., a signaling block or part of it) is occupied by trains during a certain period (e.g., per hour, per day). It is important to assess the track utilization level at network bottlenecks and sections with a high density of daily traffic. A higher rate of track utilization can demonstrate a higher productivity rate of railroad assets. However, for bottlenecks and critical parts of the network, especially within yard boundaries, a high track utilization rate (usually more than 70 percent [15, 18]) may also increase the risk of train incidents, particularly when PTC systems are not installed through the given corridor.

Figure 27 shows the number of daily trains operated over 74 selected segments of track in different corridors of the mini-network. These segments were selected with lengths from 0.3 miles to approximately 2 miles and were mostly located at the critical parts of different corridors (e.g., part of a long signaling block, a heavy grade, an entrance, or an exit signaling block of a busy yard).

As shown in Figure 27, the number of daily trains varies from 8 to 71 over the selected track segments. All segments with more than 22 daily trains are in corridors with at least 2 main tracks.

After evaluating the number of daily trains and assessing the maximum number of trains passing per hour through each section of track shown in Figure 27, 16 of these segments were selected for further track utilization rates analysis.

Figure 28 illustrates the same number of daily trains for the 16 selected segments with details of track types. As shown in the figure, there are five selected segments which are single-track with heavy grades (over 1.5 percent grade) mostly dedicated to freight trains. The rest of the segments were selected to present a diverse collection of single-, double-, and multi-track sections of network with different types of traffic and congestion levels.

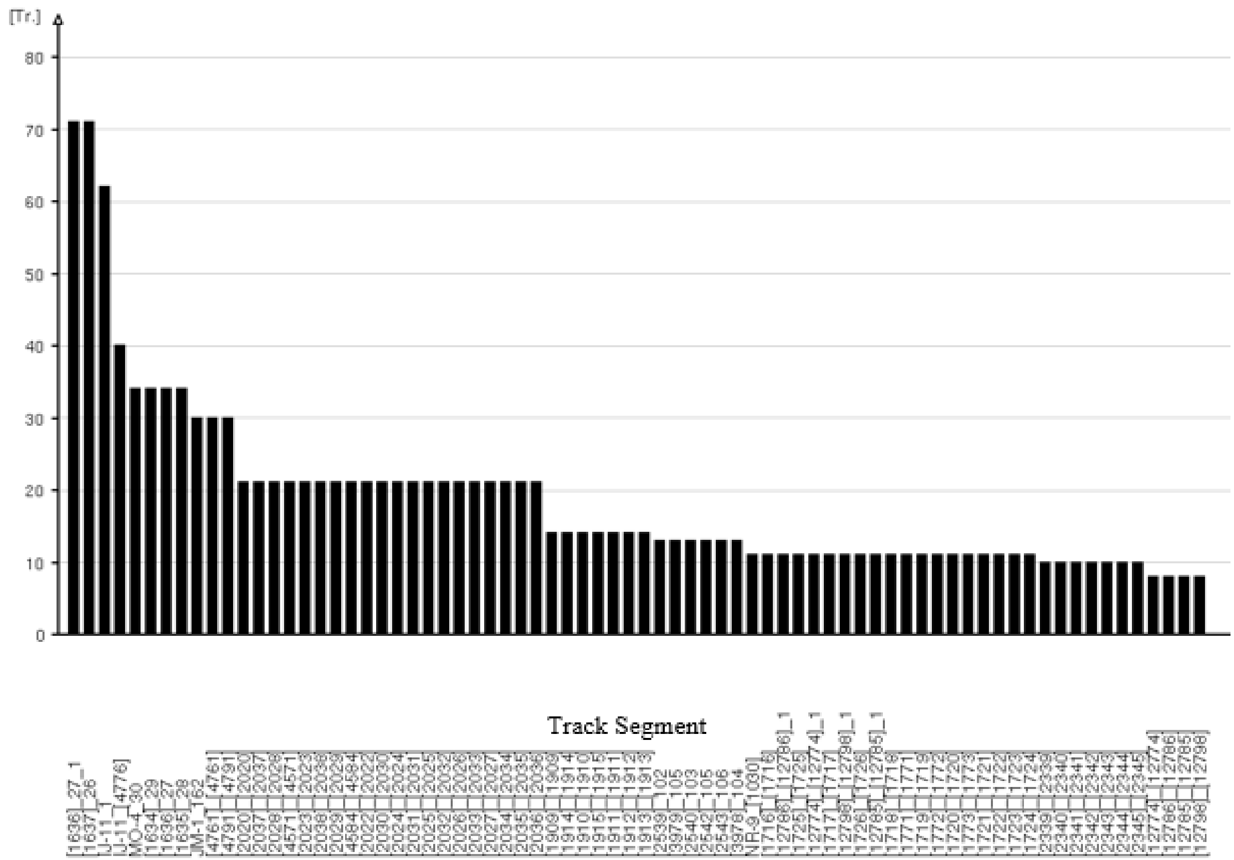

Figure 27. Number of daily trains over selected track segments of the mini-network

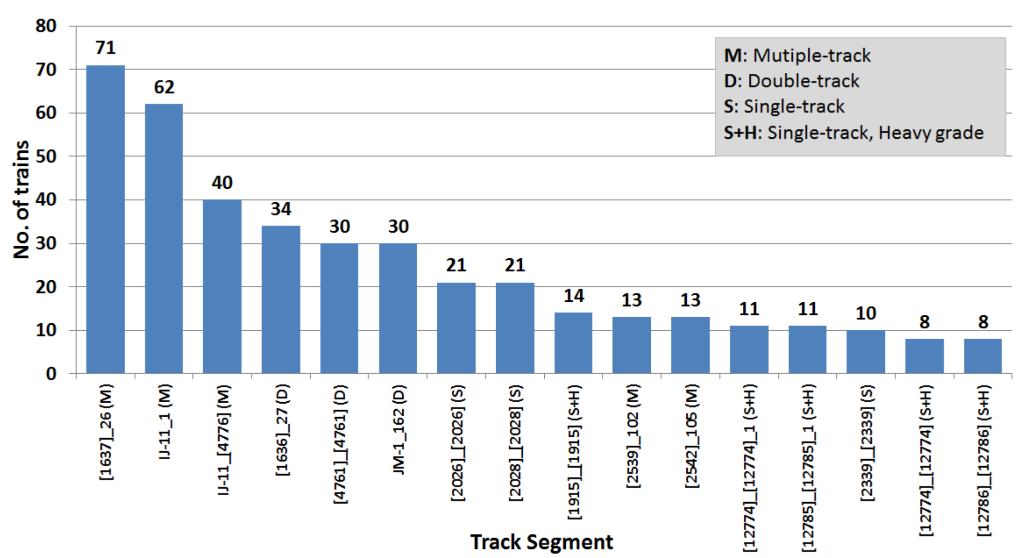

Figure 28. Number of daily trains over selected segments with track details

[Figure 29](#) shows the maximum number of trains per hour over the selected segments for Scenario 1 (CBS-CS), Scenario 2 (ABS-CS), Scenario 6 (CBS-PTC), and Scenario 7 (ABS-PTC).[12] The legends on the figure show the line color for each scenario and type of track segment like that used for Figure 28. As shown in Figure 29, the track segments have a significant range of utilization from one to nine trains per hour. All segments with at least four trains per hour are in the corridors with at least two main tracks.

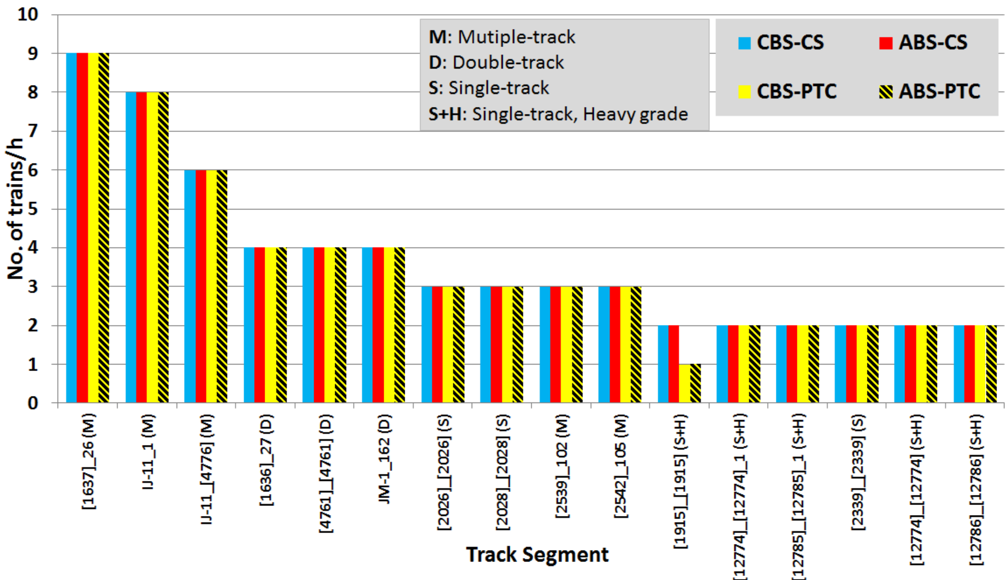

Figure 29. Maximum number of trains/hour over selected segments for all scenarios

All simulation scenarios have the same maximum number of trains per hour for each selected segment, except for one of the single-track segments with heavy grade (shown in Figure 29) that has reduced one train per hour under PTC scenarios. This is mainly achieved due to higher network speed and much lower braking actions observed under PTC scenarios compared to the CS systems.

Figure 30 shows the maximum track utilization rate per hour for different track segments and scenarios. It should be noted that a high track utilization rate can be due to reasons other than a capacity shortage of the given corridor. For example, when a heavy freight train is moving slowly along a long signaling block that includes the track segment with a high utilization rate, the segment is occupied as long as the train does not exit the signaling block.[13]

[12] There was no difference between number of trains in hybrid Scenarios 3 to 5, compared to Scenarios 1 and 2, so these scenarios are not included in the network capacity analysis.

[13] The occupation status of a signaling block and its duration depend on the signaling characteristics (e.g., number of signal aspects, the signal release procedure) and the speed of train moving along the block. The occupation time of a given block can be significantly reduced in advanced signaling systems (e.g., cab-signals and PTC systems).

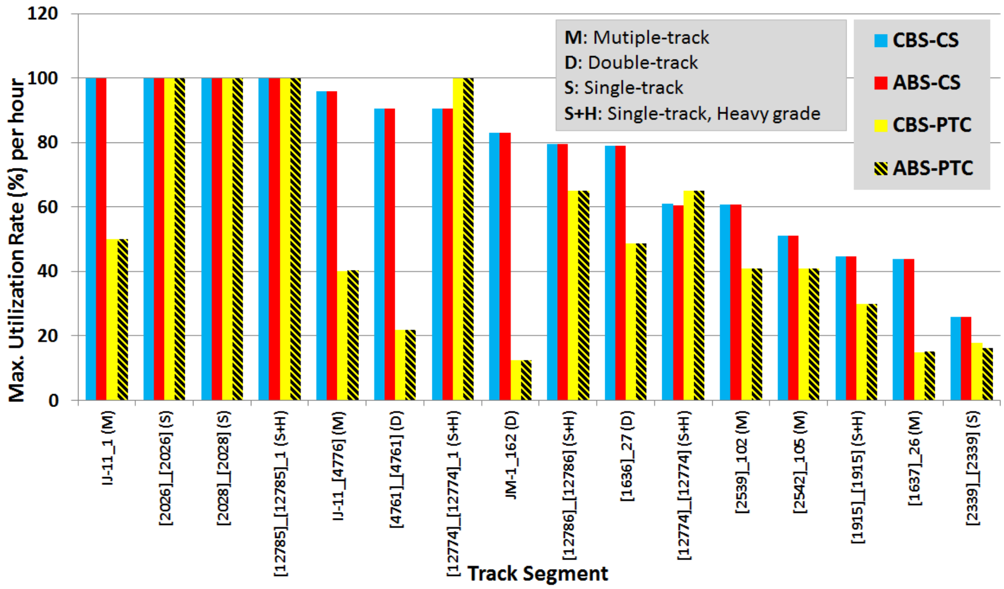

Figure 30. Maximum track utilization rate per hour for selected segments

As shown in Figure 30, there are several segments with the maximum utilization rate of 100 percent in every scenario which may or may not represent a corridor with capacity shortage. Reviewing these segments versus the charts presented in Figure 28 and Figure 29 revealed the following:

- Only one track segment is in a corridor with a high volume of daily traffic (i.e., 62 daily trains). It is one of the track segments in the network with significant capacity shortage and high risk of unsafe operations.
- The other three segments with 100 percent maximum utilization rates are single-track corridors with a maximum number of two and three trains per hour (i.e., 11 and 21 daily trains, respectively). Therefore, the full maximum track utilization rates of these segments are caused by heavy freight trains moving slowly through these segments as part of long signaling blocks.
- The track segment with 71 daily trains (first bar in Figure 28) has a maximum utilization rate of 44 percent, which does not indicate a capacity bottleneck due to the cab signaling system throughout this section and its relatively moderate track grades.

Comparing Scenarios 1 (CBS-CS) and 2 (ABS-CS) in Figure 30 shows that deploying ABS does not have any impact on the maximum track utilization rate, except for a couple of selected segments with less than 2 percent reduction in their maximum track utilization rates. However, PTC scenarios seem to have a much bigger impact on the track utilization rates for different segments due to a PTC signaling system providing an improvement in capacity compared to a CS system.

As shown in Figure 30, there are track segments with a maximum utilization rate of 100 percent under both conventional (Scenarios 1 and 2) and PTC (Scenarios 6 and 7) signaling systems. However, reviewing the type of tracks in these segments shows that all are part of single-track corridors. On the other hand, one of the multi-track segments with 100 percent maximum utilization rate under CS system (first bar of Figure 30, from left) has a significant reduction in its utilization rate under PTC scenarios (50 percent). Reviewing other segments located along double- or multi-track corridors also confirms that PTC had a significant impact on maximum track utilization rates of double- and multi-track corridors, while it may have a minor impact on single-track corridors with high utilization rates. As shown in Figure 30, two of the single-track corridors with more than 60 percent maximum utilization rates under the CS system have even higher utilization rates under the PTC system, indicating that PTC may not provide any additional benefits for a given single-track corridor if it is at or above the utilization rate of 60 percent.

Table 6 summarizes the potential impact of new train control technologies over the track utilization rate of different types of corridors under CS systems.

Table 6. Potential impact of new train technologies on track utilization rate

Type of corridors	ABS for freight trains	PTC systems
Single-Track with heavy grades	No significant impact	Potential improvement if utilization rate is below capacity limit (60%)
Single-Track	No significant impact	Potential improvement if utilization rate is below capacity limit (60%)
Double-Track	No significant impact	Significant improvement especially for directional and dedicated passenger corridors
Multi-Track	No significant impact	Significant improvement especially for directional and dedicated passenger corridors

Overall, the network capacity utilization of each scenario was estimated using the following:

- Number of daily trains
- Type of corridor (e.g., single-, double-, or multi-track corridor)
- Type of signaling system (e.g., wayside, cab signaling, or PTC)
- Impact of maximum track utilization rate per hour for the selected segments

Table 7 compares the capacity utilization of major corridors as well as the entire network between CS systems (Scenarios 1 and 2) against the PTC systems (Scenarios 6 and 7).

Table 7. Network capacity utilization, CS system vs. PTC system

Selected Corridors	Bottleneck	Conventional Signaling	PTC
I-J	I-J	71.0%	42.2%
I-J-M-O	I-J	71.0%	42.2%
J-K-N	J-K	19.6%	12.2%
B-C-D-N	D-N	40.9%	36.8%
C-E-F-Q	E-F	31.8%	25.5%
E-G-I	E-G	100%	83.6%
G-L-M	G-L	53.2%	37.2%
M-O-R	O-R	36.4%	25.5%
O-P-Q	P-Q	47.3%	35.2%
B-F-Q	F-Q	29.1%	24.2%
P-S-R	S-R	36.4%	27.0%
D-N-R	N-R	59.1%	53.2%
Entire Network	**E-G**	**35.6%**	**28.6%**

It should be noted that the capacity of the entire network was estimated using all segments of the network by considering the train-miles of each segment individually. As presented in Table 7, the PTC system reduces the capacity utilization by about 4 percent to approximately 30 percent in comparison to the same corridors under the CS system. Such fluctuation between capacity improvements of different corridors depends on several factors including type of track (i.e., single-, double-, or multi track), type of traffic, operation regime and dispatching pattern, grade magnitude of tracks, type of signaling system, and congestion level along bottlenecks.

Overall, it is estimated that the capacity utilization of the mini-network, considering the weighted average of all corridors, drops from 35.6 percent under the CS system to about 28.6 percent under the PTC system. This reduction in capacity utilization, a 7 percent improvement on average, could be used to introduce additional services, roughly between 10 to 40 new services depending on various criteria such as type of corridor and new services planned to be added.

4.3 Impact of New Technologies over Single-Track Network

This sub-section takes a closer look at the performance metrics for the single-track corridors of the network. More than 80 percent of the national rail network is single-track, and some of the opportunities or challenges of these new train control technologies may only be applicable for double- or multi-track corridors. Figure 31 shows the percentage of train-miles of each type of train that moved through single-track sections. As mentioned in Section 2.1, about 86 percent of the main tracks developed in this study were single-track. Figure 31 shows there was approximately the same percentage of freight train miles on the single-track corridors. Thus, the traffic flow of freight trains was distributed evenly through the mini-network. However, only 41 percent of passenger traffic, 1 percent of commuter services, and no HSR service moved across single-track segments of the network, demonstrating that most of the traffic on single-track segments belonged to freight services.

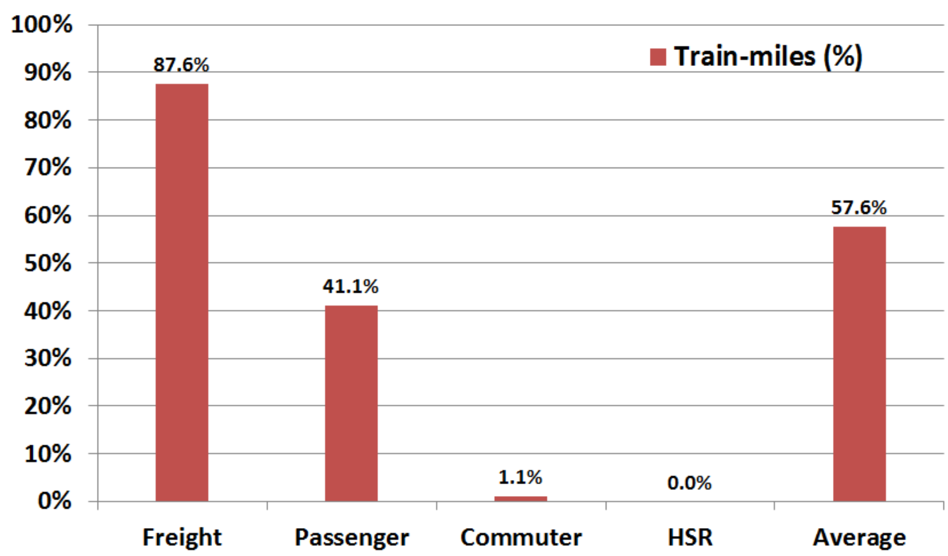

Figure 31. Percentage of each type of train moving through single-track corridors compared to the full mini-network by train-mile

Figure 32 presents the average travel distance and number of trains for each train category that moved only on the single-track corridors in comparison to the full mini-network. As shown in the figure, almost half of all the trains (i.e., mostly freight services) were operated throughout the single-track corridors. As a result, the average travel distance of trains moving through single-track segments are skewed about 20 percent higher than the average travel distance of all trains across the full mini-network.

Since commuter and HSR trains have no major role throughout the single-track corridors, they are not included in the rest of the analysis of this section. Further details about other measures of safety and operational performance affected by single-track operations are presented in the sub-sections below.

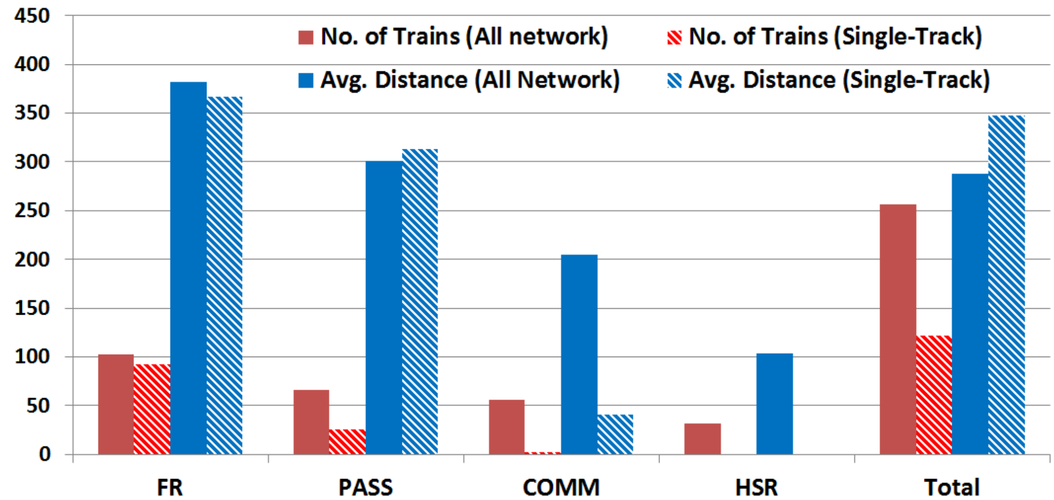

Figure 32. Number of trains and average travel distance of each type of train through the single-track corridors vs. the full mini-network

4.3.1 Train Delay Analysis

Figure 33 shows a comparison between freight and passenger trains delays moving throughout the single-track corridors versus the respective delays through the full mini-network in each scenario.

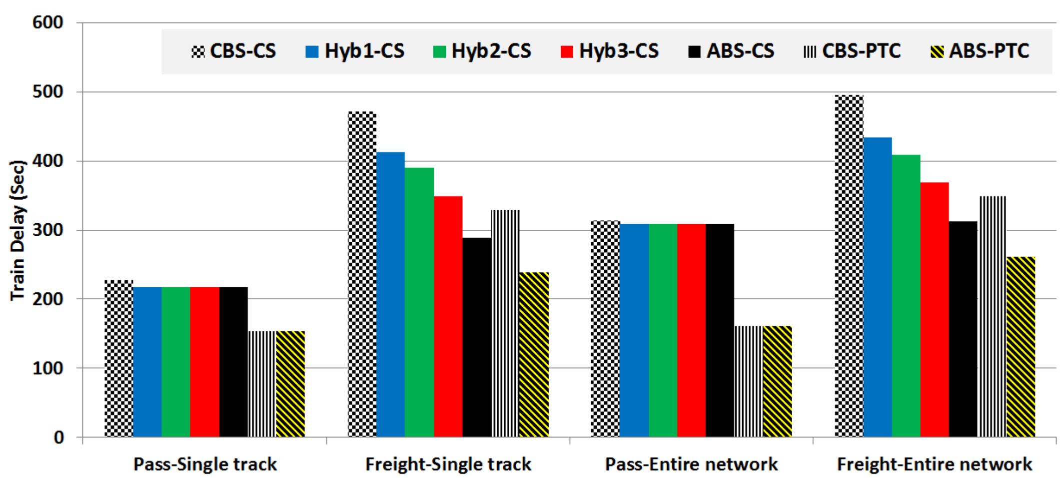

Figure 33. Delay analysis for trains moving through single-track corridors vs. full mini-network for all scenarios

Comparing these two groups of metrics shows the trend of delay reduction observed for the full mini-network is also seen for the single-track corridors for both passenger and freight trains.

However, the ABS system provides slightly more improvement for both passenger and freight trains when compared to the same type of trains through the full mini-network. For example, in the passenger train category, ABS reduces the delay by more than 4 percent, while throughout the full mini-network the reduction is about 1.5 percent.

Under PTC, passenger train delays through the full mini-network are more reduced than when considering only the single-track sections (i.e., 33 percent reduction over the single-track vs. 48 percent through the full mini-network).

4.3.2 Network Velocity

Figure 34 shows that the average velocity for the single-track network is about 10 mph slower in every scenario compared to the full mini-network. This speed reduction in single-track scenarios is due to freight trains being the dominant type of traffic through the single-track corridors with only a few commuter and no HSR services. Thus, as the average velocity of freight trains is much lower than HSR and passenger services, the overall velocity of single-track corridors also is proportionally impacted by freight trains. When comparing the amount of increase in network velocity based on advanced train control technologies, ABS systems provide more benefit for the single-track sections compared to the full mini-network (i.e., 0.8 percent increase in single-track vs. 0.5 percent through the full mini-network). However, when PTC is implemented, the analysis shows the full mini-network gains increase in network velocity (1.7 percent) more in comparison to the single-track corridors (1.3 percent).

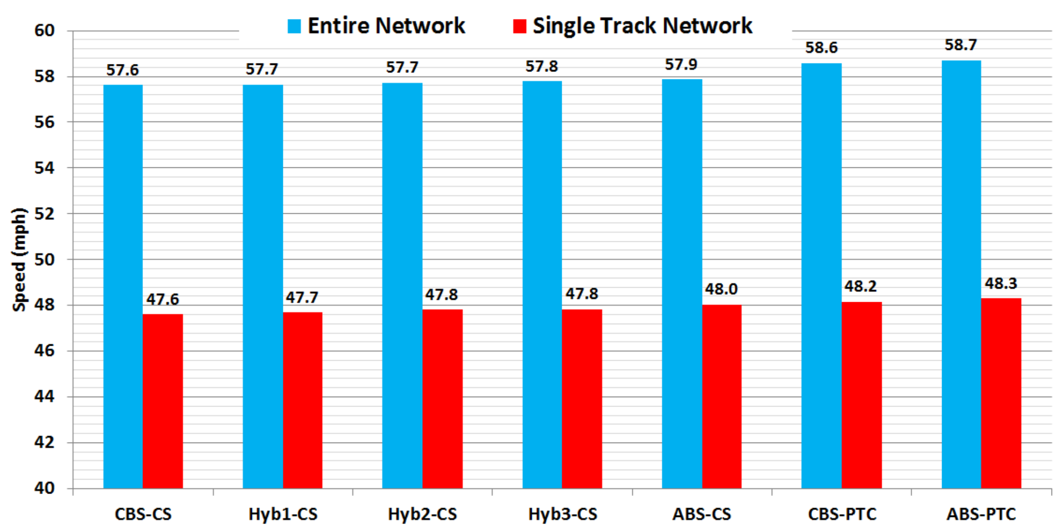

Figure 34. Network velocity, single-track vs. full mini-network

4.3.3 Number of Station Stops

Similar to what was observed in Section 4.3.2 for the full mini-network, none of the train control technologies have any significant impact on the number of station stops for any type of trains throughout the single-track corridors.

4.3.4 Braking Actions at Signal

Figure 35 compares the number of braking actions at signals (i.e., for route reservation) for freight and passenger trains operating only on single-track corridors with those operated over the full mini-network.

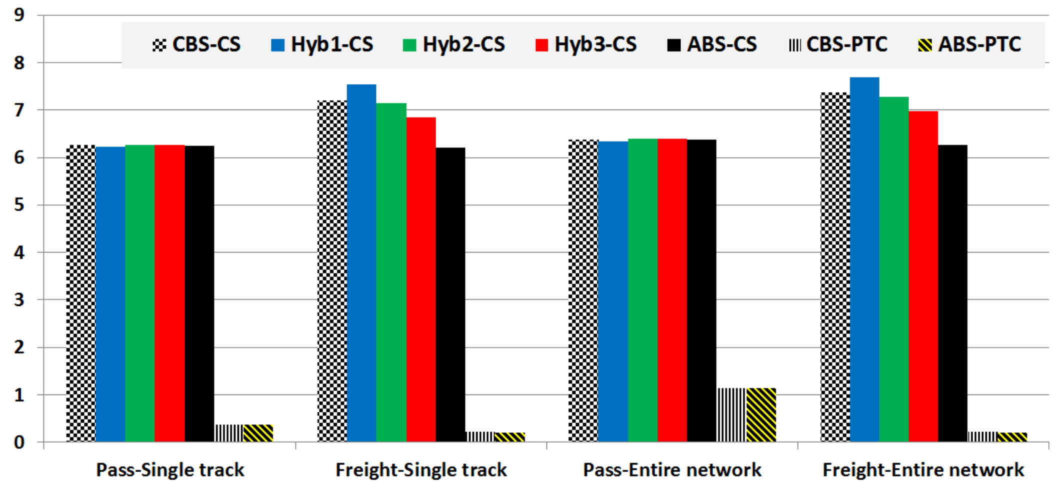

Figure 35. Number of braking at signals for trains moving through single-track corridors vs. full mini-network

Based on results presented in Figure 35, a similar trend between single-track and full mini-network values is seen for both freight and passenger trains, for each scenario side-by-side. The amount of improvement for freight trains through the single-track corridors is the same as for the full mini-network when comparing ABS or PTC technologies to conventional systems.

However, for passenger trains, the ABS system provides slightly more improvement when compared to the full mini-network outcomes. Also, in terms of PTC impact on the passenger trains, there is a larger reduction in braking actions observed through the single-track corridors in comparison to the full mini-network (i.e., 94 percent reduction over the single-track, vs. 82 percent through the full mini-network).

4.3.5 Number of Stops at Signals

The number of stops at signals through the single-track corridors are compared to the entire network in Figure 36. As presented in this figure, the numbers of stops at signals for freight trains through the single-track corridors are almost the same as for the full mini-network. This means almost all freight train stops at signals occurred in the single-track corridors and not across the double- or multi-track sections, though few freight trains were operated over the multi-track sections.

For passenger trains on the other hand, there is a major reduction in number of stops at signals over the single-track corridors compared to the full mini-network, meaning that most of the stops occurred along double- and multi-track corridors. This is most likely due to more congestion observed through multi-track sections, while considering the fact that only 41 percent of passenger trains moved through the single-track sections. Nevertheless, the impact of PTC technology on passenger trains along the double- or multi-track corridors seems to be more beneficial when comparing the percentage of reduction between the full mini-network and the single-track corridors (i.e., 55 percent vs. 22 percent, respectively).

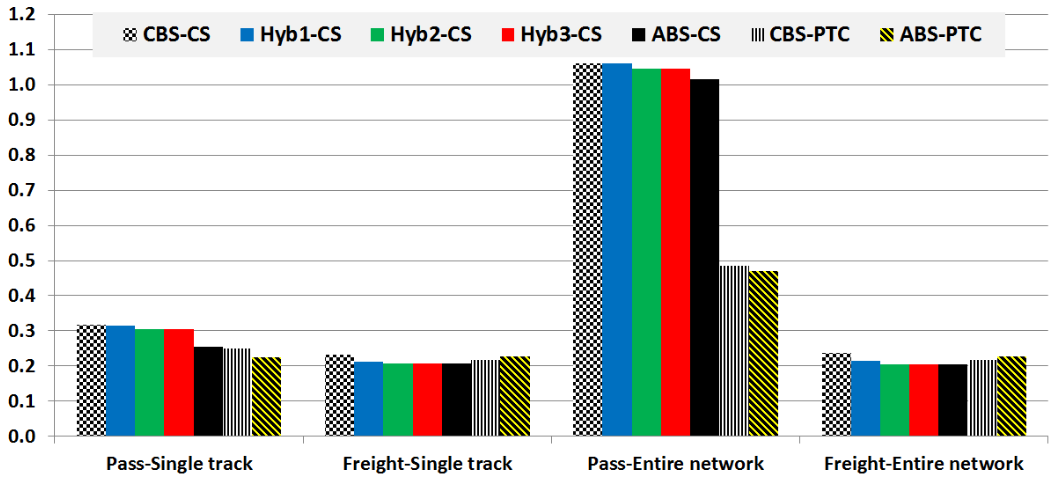

Figure 36. Number of stops at signals for trains moving through single-track corridors vs. full mini-network

4.3.6 Capacity and Track Utilization

As explained in Section 4.2.6, track utilization analysis was conducted using selected segments of tracks throughout single-, double-, and multi-track corridors. Thus, in this section, only those segments located through single-track corridors are briefly analyzed in terms of track and capacity utilization rates. Figure 37 presents the number of daily trains over selected single-track segments of the network.

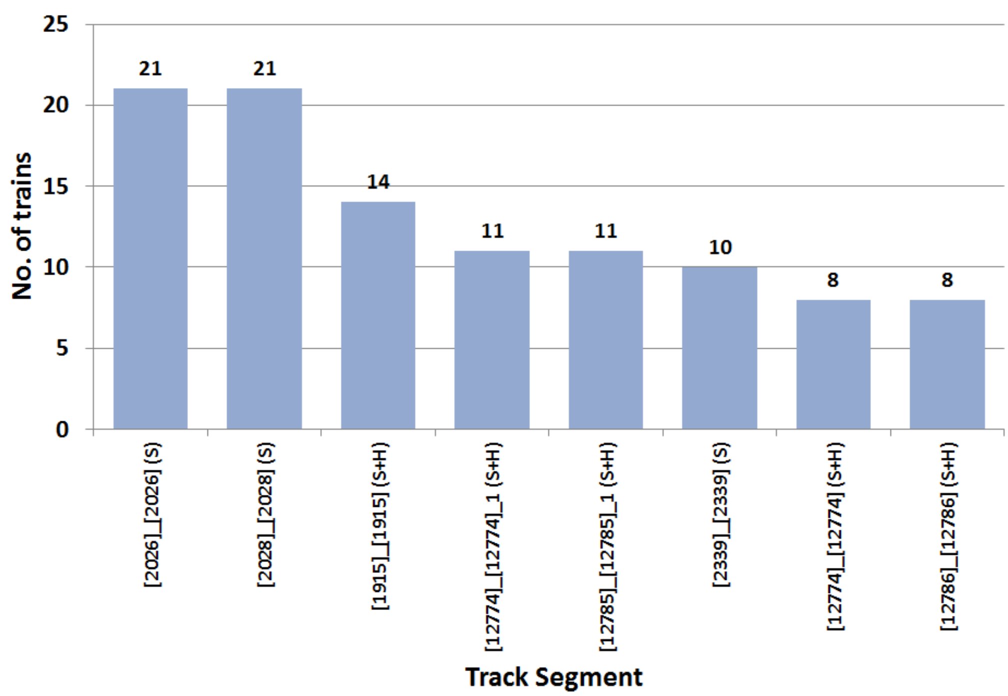

Figure 37. Number of daily trains observed for the selected single-track segments of the network

As shown in the figure, there are a few corridors with a maximum number of 21 daily trains which is close to the upper threshold of capacity limit for a single-track corridor with a reasonable level of service. Also, it should be noted that those segments with 21 daily trains were not among the corridors with heavy grades. As presented in Figure 37, the corridors labeled with "S+H," have a maximum number of 14 daily trains, which is about 33 percent lower than what is observed in other single-track corridors with lighter track grades.

Figure 38 presents the maximum number of trains per hour that passed through the selected segments for all scenarios. As shown, PTC reduces the number of trains per hour for one of the single-track corridors with heavy grades. Such reduction in number of hourly trains is achieved without changing the schedule of trains or removing any service from the simulation. Further review confirmed that PTC slightly increases the speed of some trains operating along the given corridor. This increases the headway between two adjacent trains following each other to slightly longer than an hour, which results in one less train during a 1-hour period.

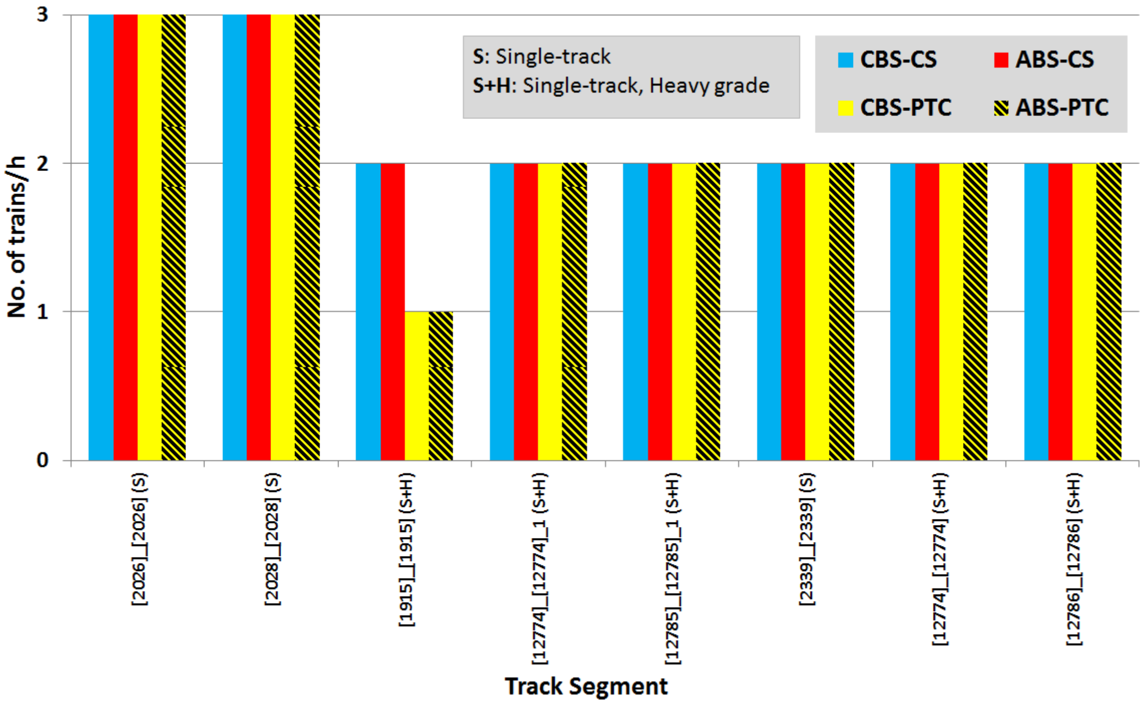

Figure 38. Maximum number of trains per hour for the selected single-track segments of network

Figure 39 presents the maximum utilization rate of single-track corridors in an hour. As mentioned earlier, ABS has minor or no impact on the track utilization rate, while PTC is particularly effective at reducing the track utilization rates for segments of single-track corridors with utilization rates below 60 percent. Above that limit, PTC may not be efficient enough to improve the utilization rate. It should be noted that, under certain conditions, PTC may even increase track utilization for some of the single-track segments with very high utilization rates.

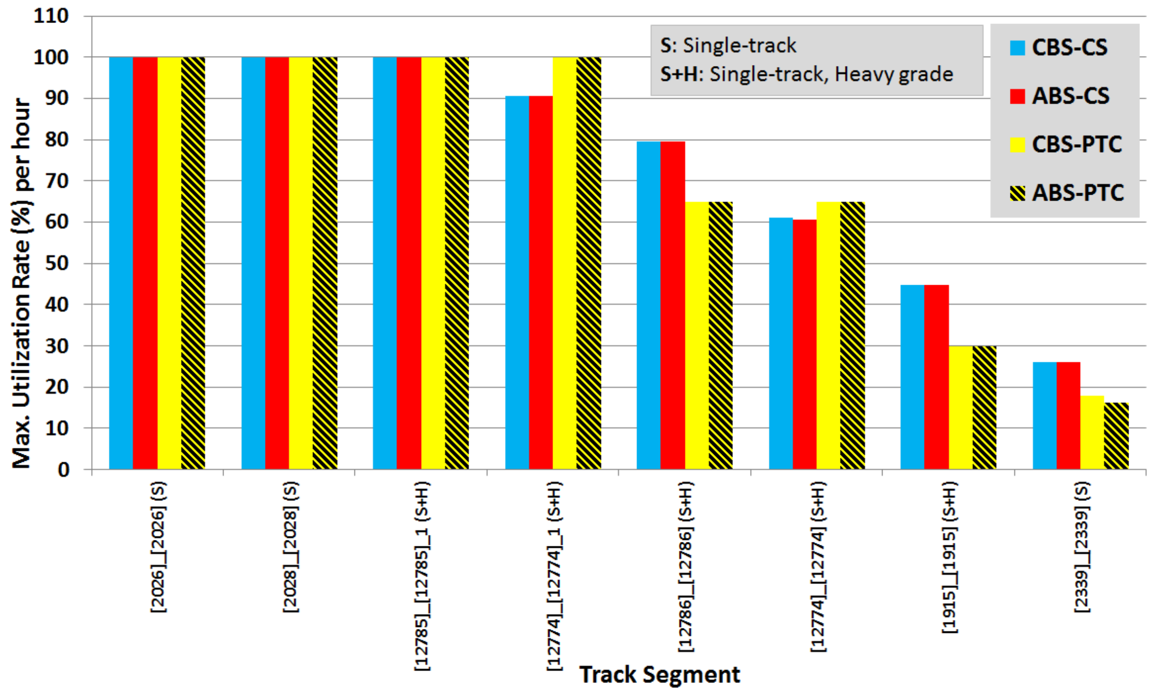

Figure 39. Maximum utilization rate (%) per hour for the selected single-track segments of network

A comparison of the capacity utilization of single-track corridors between CS vs. PTC systems is shown in Table 8. As presented in this table, capacity utilization reduction due to applying PTC varies between 4 percent to approximately 17 percent, in comparison to the same corridors under a CS system. The range of reduction in capacity utilization through single-track corridors is certainly lower than the amount of improvement observed through the full mini-network (Table 7) since PTC has a higher impact on improving capacity through double- and multi-track corridors. As a result, the capacity of the full mini-network when considering only single-track corridors is reduced from 39.9 to 32.4 percent using a PTC signaling system, compared to a reduction from 35.6 to 28.6 percent when considering the full mini-network including double- and multi-track corridors.

Table 8. Capacity utilization of single-track corridors, conventional vs. PTC system

Selected Corridors	Bottleneck	Conventional Signaling	PTC
B-C-D-N	D-N	40.9%	36.8%
C-E-F-Q	E-F	31.8%	25.5%
E-G-I	E-G	100%	83.6%
G-L-M	G-L	53.2%	37.2%
M-O-R	O-R	36.4%	25.5%
O-P-Q	P-Q	47.3%	35.2%
B-F-Q	F-Q	29.1%	24.2%
P-S-R	S-R	36.4%	27.0%
D-N-R	N-R	59.1%	53.2%
Single-Track Network	**E-G**	**39.9%**	**32.4%**

4.4 Side-by-Side Review of Scenarios

4.4.1 Scenario 1 (CBS-CS) vs. Scenario 2 (ABS-CS)

This section compares Scenario 1 (CBS-CS) and Scenario 2 (ABS-CS) under CS systems to assess any major impact in safety and operational performance from advanced braking technologies in freight trains. The analysis of station stops is not included in this comparison as no significant differences were observed between any of the scenarios in this study (Sections 4.2.3 and 4.3.3).

Figure 40 summarizes the relative percentage of improvement for different performance metrics between Scenarios 1 and 2.

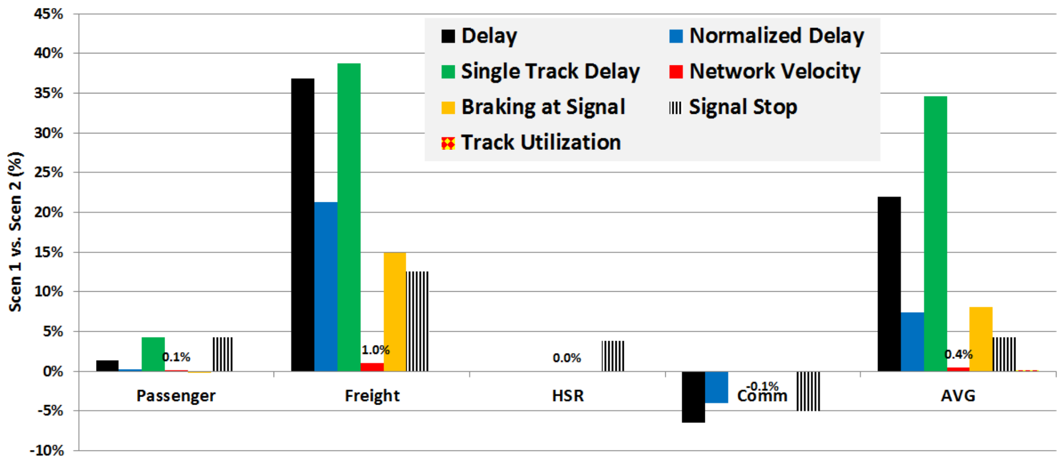

Figure 40. Relative improvement between Scenarios 1 (CBS-CS) and 2 (ABS-CS)

The percentage of relative improvement of a given metric is positive if ABS technology (Scenario 2) improves the respective metric compared to CBS (Scenario 1). Also, a metric with a negative value (e.g., delay of commuter services) means applying the technology reduced performance compared to the initial scenario (in this case Scenario 1).

As shown in Figure 40, except for commuter trains, the ABS system either maintains or improves the performance metrics, particularly the delay, signal stops, and number of braking actions of freight trains at signals. On average, and considering all types of trains, all metrics either slightly improve or remain relatively unaffected (e.g., network velocity with only 0.4 percent improvement), with the emphasis on the fact that freight trains are the major beneficiary of ABS technology followed by passenger trains.

4.4.2 Scenario 1 (CBS-CS) vs. Scenario 6 (CBS-PTC)

This sub-section compares Scenario 1 (CBS-CS) with Scenario 6 (CBS-PTC) to assess any major impact that PTC technology provides without applying any changes in freight train braking systems. Figure 41 summarizes the relative percentage of improvement for different performance metrics between Scenarios 1 and 6.

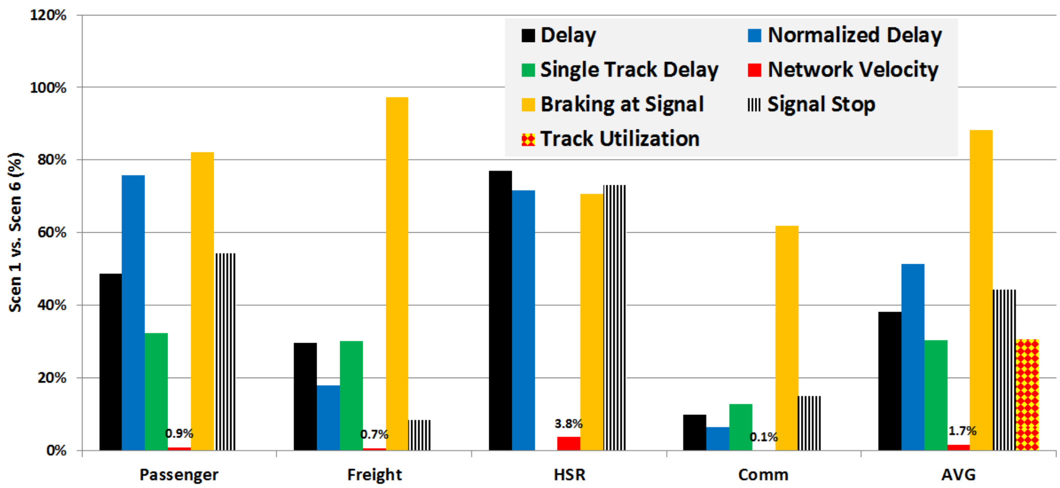

Figure 41. Relative improvement between Scenarios 1 (CBS-CS) and 6 (CBS-PTC)

As shown in Figure 41, in most cases, the PTC system significantly improves performance, particularly for braking at signals, delay, and signal stops for passenger and HSR services.

For example, the values of braking at signals for different types of trains are improved between 62 percent (commuter) to 97 percent (freight) with an average value of 88 percent improvement across all trains. Also, the average number of stops at signals and train delay (i.e., normalized delay) are significantly improved by 44 and 51 percent, respectively.

Network velocity is another index which improves (by 1.7 percent on average), particularly for HSR and passenger trains with 3.8 and 0.9 percent improvement, respectively.

Also, the maximum track utilization rate of the critical segments of the network discussed in the previous section is also improved by an average of approximately 30 percent compared to the CS system. Such improvement in maximum track utilization rate is a good indicator of improving capacity limits which could be used for additional services.

4.4.3 Scenario 2 (ABS-CS) vs. Scenario 7 (ABS-PTC)

Scenario 2 (ABS-CS) and Scenario 7 (ABS-PTC) are compared in this section to assess any major impact that PTC technology may have when freight train braking systems are already upgraded with advanced technologies. Figure 42 summarizes the relative percentage of improvement for different performance metrics between Scenarios 2 and 7.

An improvement like the one in Section 4.4.2 is also observed between Scenario 2 and Scenario 7. In other words, PTC has a similar impact on different measures of network safety and operational performance whether freight trains are equipped with advanced braking technologies or not. Comparing Figure 41 to Figure 42 shows the relative improvement between Scenario 1 and Scenario 6 (Figure 41) is slightly higher than the relative improvement observed between Scenario 2 and Scenario 7 for some of the performance metrics. Such a minor difference between the results is most likely due to Scenarios 2 and 7 improving in some of the safety and operational performance metrics compared to Scenario 1 by deploying ABS for freight trains. More discussion is included in Section 4.4.4.

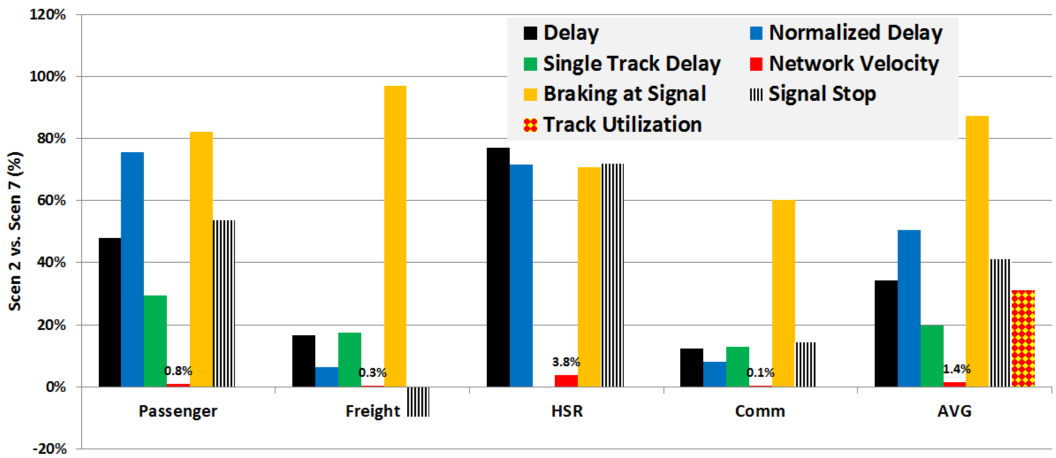

Figure 42. Relative improvement between Scenarios 2 (ABS-CS) and 7 (ABS-PTC)

4.4.4 Scenario 6 (CBS-PTC) vs. Scenario 7 (ABS-PTC)

The results of Scenarios 6 and 7 are compared side-by-side to evaluate whether there are any additional benefits that can be obtained by deploying ABS in the freight trains when the PTC system is already implemented on the network. Figure 43 summarizes the relative percentage of improvement for different performance metrics between Scenarios 6 and 7.

As shown in Figure 43, there are certain additional benefits that ABS on freight trains can produce mostly by reducing the delay (especially for local trains moving through congested single-track corridors) as well as increasing the network velocity of freight trains. On the other hand, no significant improvement is observed for passenger and HSR services. Some of the commuter train values (e.g., delay, braking actions at signals, and signal stops) dropped to 5 percent lower than their respective metrics in Scenario 6.

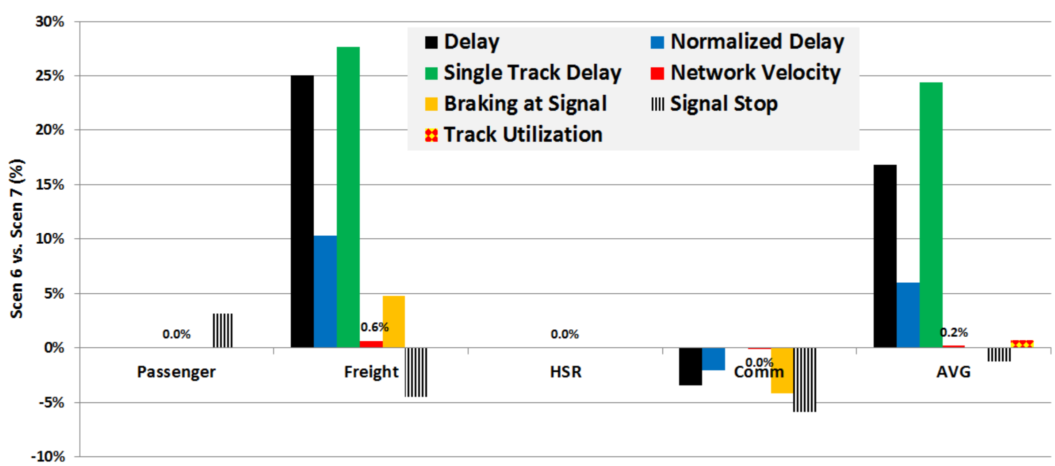

Figure 43. Relative improvement between Scenarios 6 (CBS-PTC) and 7 (ABS-PTC)

4.4.5 Scenario 1 (CBS-CS) vs. Scenario 7 (ABS-PTC)

The comparison between Scenarios 1 and 7 demonstrates how much improvement can be provided if both advanced train control technologies (ABS and PTC) are implemented through the network (represented by Scenario 7), in comparison to conventional braking and signaling systems (represented by Scenario 1). Figure 44 summarizes the percentage of improvement between Scenarios 1 and 7 for various performance metrics.

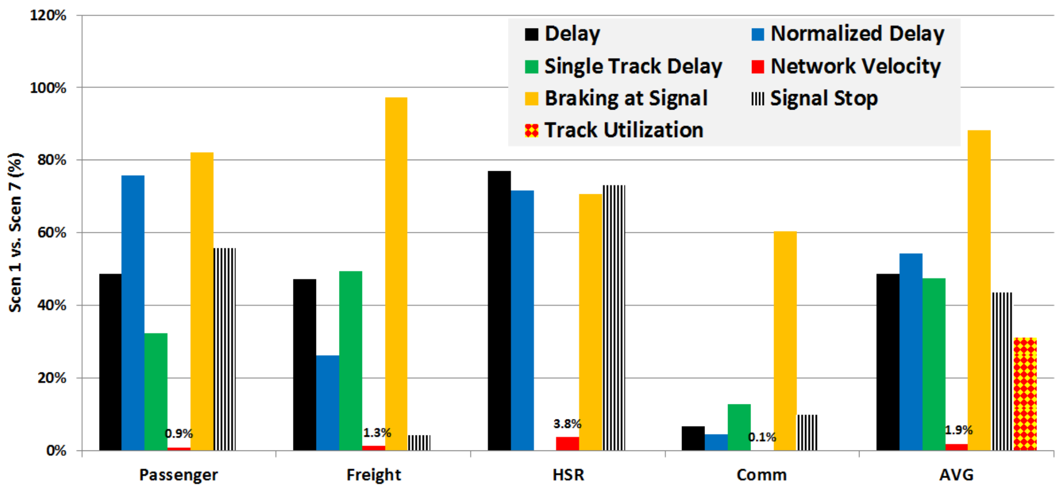

Figure 44. Relative improvement between Scenarios 1 (CBS-CS) and 7 (ABS-PTC)

As shown in this figure, all measures of safety and operational performance have improved and are higher than any other scenarios compared side-by-side. In other words, a combination of ABS and PTC systems provides the highest degree of improvement in different areas, as shown below:

- Reducing trains delay by about 48 percent
- Increasing network velocity by 1.9 percent
- Reducing number of braking at signals by about 88 percent
- Reducing number of signal stops by 44 percent
- Reducing the maximum track utilization rate by 31 percent

4.5 Summary of Simulation Results

This section reviews the results of the simulation scenarios in terms of different safety and operational performance metrics. A summary of relative improvement due to advanced train control technologies (i.e., ABS and PTC) for the scenarios in this study, except the hybrid scenarios, is illustrated in Figure 45, considering the average of all types of trains in each scenario and for each performance metric.

Based on the analysis of results in this section, ABS improves the performance of freight trains particularly in terms of delay, braking actions at signals, and signal stops, although it may not have any major impact on other performance metrics. The PTC system has a beneficial impact on almost every type of train for every performance metric.

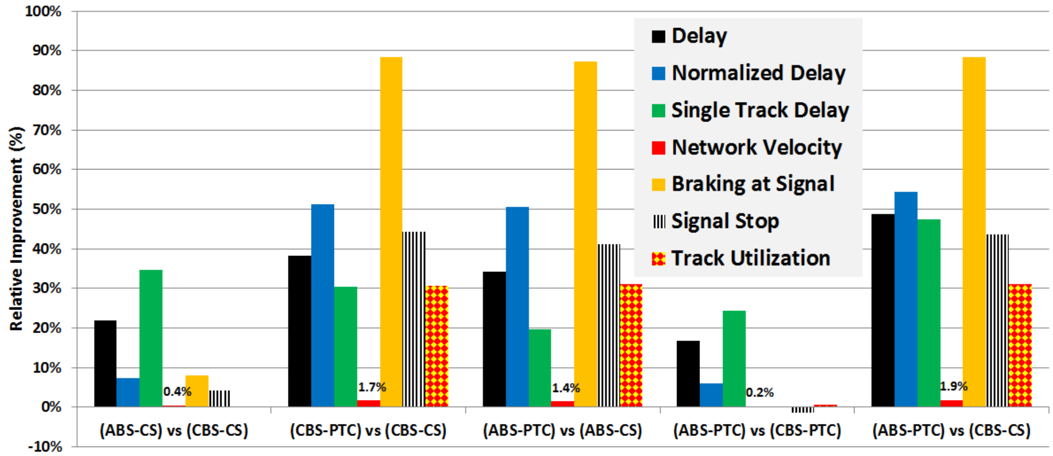

Figure 45. Comparing relative improvement of all major scenarios side-by-side for different performance metrics

Table 9 summarizes the impact of each technology on the performance metrics using a quantitative scoring approach on a scale of 0–5, 0 being below 1 percent and 5 being between 80–100 percent. The value of each cell in the 2nd and 3rd columns in Table 9 presents the average percentage of impact on all type of trains combined, but some cells may have a particular score for a specific type of train or specific type of corridor if significantly different from the average score.

Table 9. Degree of impacts caused by ABS or PTC systems on different measures of safety and operational performance

Metric	ABS for freight trains	PTC systems
Delay (Normalized)	1 (2 for freight trains)	3 (4 for HSR and passenger trains)
Network Velocity	0 (1 for freight trains)	1 (0 for freight, commuter, and passenger trains)
Safety (Braking at signal)	1	5 (4 for HSR and commuter trains)
Safety (Signal Stops)	1	3 (4 for HSR trains)
Capacity & Track Utilization Rate	0	1–2 (2–3 for multi tracks and passenger oriented corridors)

Scale: *0 (less than 1 percent impact), 1(1–19 percent), 2(20–39 percent), 3(40–59 percent), 4(60–79 percent), 5(80–99 percent impact)*

Details of the impact of these advanced train control technologies over the respective safety and operational performance metrics can be summarized as follows:

- Delay
  - ABS, when used instead of CBS, reduces delays for freight trains.
  - PTC systems have a significant impact on reducing the delay for HSR and passenger trains (about 50 to 75 percent reduction, compared to CS systems), but the impact is lower for freight and commuter trains (about 15 to 30 percent reduction in delay).

- Network Velocity
    - All train control technologies improve the network velocity in all scenarios, but freight and HSR trains benefit more from ABS and PTC, respectively, than do passenger and commuter trains.
    - Overall, ABS increases network velocity by 0.3 mph (0.5 percent), while PTC increases network velocity by 1 mph (1.7 percent), and notably even higher for HSR trains (3.4 mph higher).
    - Since most of the traffic along single-track corridors belongs to freight trains, ABS is able to increase the network velocity through single tracks by about 0.8 percent (versus 0.5 percent for the entire network), while PTC only improves speed by 1.3 percent for single tracks (versus 1.7 percent improvement through the full mini-network).
- Braking at Signals
    - ABS reduces the number of brake applications at signals for freight trains (15 percent) but no improvement is observed for other types of trains.
    - PTC significantly reduces the amount of braking at signals (about 88 percent on average), particularly for freight (over 95 percent) and passenger trains (about 82 percent).
- Stops at Signals
    - The number of stops at signals in freight trains with ABS is slightly lower than those with CBS (about 12 percent improvement), but for other types of trains there is no major improvement observed.
    - PTC reduces the number of stops at signals significantly; by about 73 and 54 percent for HSR and passenger trains, respectively. However, it has less impact on commuter and freight trains, reducing stops at signals by only 15 and 8 percent, respectively.
- Capacity and Track Utilization Rate
    - No significant benefit is observed in capacity and track utilization rates when freight trains are equipped with ABS.
    - PTC improves the maximum track utilization rate on most of the network corridors by approximately 30 percent, especially through double- and multi-track corridors with more passenger and commuter services than freight trains (up to approximately 80 percent reduction in maximum track utilization rates for these corridors).
    - PTC reduces the capacity utilization of different corridors between 4 percent to approximately 30 percent compared to CS systems, with average capacity improvement of approximately 7 percent throughout the mini-network. This could aid in adding additional services.

5. Scaling the Mini-Network Results to the National Network

Section 4 discussed the safety and operational performance impacts of applying advanced train control technologies on a mini-network comprising approximately 5,000 miles of main tracks (over 6,000 miles including multi-track segments) with 256 daily trains, including 102 freight trains. This section suggests a method for scaling the mini-network results to the full U.S. rail network based on available information or interpreted data and engineering judgment.

Three major scenarios of applying advanced train control technologies (i.e., ABS, PTC, and combined ABS-PTC) are used in this section to evaluate potential improvements to the national rail network.

5.1 Scaling Factors

Although multiple parameters and variables can affect network operational safety and operational performance, the proposed method addresses those that are significant and can be scaled. These parameters are listed in Table 10. Most of the data for the U.S. rail network was taken from 2018 Railroad Facts published by AAR [19].

Table 10. Parameters used to scale the Mini-network results to the U.S. network

Parameter	Mini-network	U.S. rail network	Notes
Length of main tracks (miles)	5,000	138,000 [1]	[1]: Railroad Facts [19]
Annual train-miles	13.4 million [2]	529.2 million [3]	[2]: Assuming 2 days travel cycle, on average, for the trains of study, [3]: AAR [19] and BTS data [20]
Number of sidings and yards	150	4,600 [4]	[4]: Estimated based on 30 miles average distance between sidings and yards throughout the U.S. rail network
% of congested corridors	36% [5]	21% [6]	[5]: Estimated through the study for CS system, [6]: AAR's study on freight network capacity [13]
Age of freight cars	New	~20 years [7]	[7]: Based on AAR data [21]

5.1.1 Length of Main Tracks

Comparing the nearly 138,000 miles of main tracks in the U.S., which includes Class I railroads and all shortline railroads, to the 5,000 miles of main tracks in the mini-network of this study shows a scaling up factor of 27.6. However, when analyzing network safety and operational performance, the impact of track length cannot be assumed to be linear and should be justified with due consideration of the other parameters in Table 10. This is explained in detail in Sections 5.2 through 5.4.

5.1.2 Annual Train-miles

Total train-miles per year is a measure of how extensively all trains travel in a given network. The value of train-miles for the mini-network (13.4 million) was calculated using a 2-day travel cycle of all 256 trains for one year. The total train-miles for the national rail network (529.2 million) was calculated using 465.3 million train-miles for freight trains [19] plus 32.1 million train-miles of Amtrak and 31.8 million train-miles of commuter rail services. This information was extracted from 2019 data provided by the Bureau of Transportation Statistics [20], assuming 200 and 400 passengers in each Amtrak and commuter train, respectively.

Comparison of the annual train-miles between mini-network and national network shows a scaling factor of 39.5.

5.1.3 Number of Sidings and Yards

There is no data publicly available on the number of rail sidings in the U.S. rail network. Assuming an average distance of 30 miles between two adjacent sidings or yards through the entire 138,000 miles of the U.S. rail network, it was estimated that nearly 4,600 rail sidings and yards are in operation. Comparing this to the 150 sidings and yards in the mini-network shows a scaling up factor of 30.7.

5.1.4 Proportion of Network with Congested Traffic

This parameter emphasizes the role of traffic density and network congestion on safety and operations for a regional territory, if not for the entire network. Based on the capacity and track utilization analysis conducted in this study, the overall capacity utilization of the mini-network was about 36 percent for conventional braking and signaling systems.

According to a study of freight network capacity conducted by AAR [13], nearly 13 percent of the U.S. rail network, without considering passenger and commuter services, was at or above 70 percent capacity limit in the year 2005. The same report predicts 55 percent of the rail network above 70 percent capacity limit in the year 2035. Using linear projection, in the year 2020 the rail network should experience roughly 21 percent congestion. Thus, the scale factor for this parameter was estimated to be 0.58 (21 percent divided by 36 percent) for traffic congestion level between the mini-network and the U.S. rail network.

5.1.5 Age of Freight Cars

All trains in this study were modeled to operate without any mechanical or brake defects affecting train performance. However, in practice the efficiency of braking systems reduces with age, even when equipped with advanced braking components.

The efficiency of braking components, including rigging and brake valves, may reduce to approximately 90 percent of the initial braking ratio after about 240,000 miles of service [22, 23], although many braking components (e.g., brake valves and brake shoes) are maintained and refurbished on a schedule. In 2017, there were 1.66 million freight cars in service operating approximately 34,065 million car-miles [19]. Thus, the average annual mileage of a car was estimated to be around 20,522 miles for a given year. This implies that a given car may take about 11.6 years to reach the benchmark of 240,000 miles of service.

According to AAR, the average age of freight cars in the current U.S. rail network is 20 years [19]. Based on the braking data, it may be concluded that most of the U.S. freight car fleet with an average age of 20 years of service has a 90 percent brake efficiency compared to the new cars simulated in this study. Thus, the scaling factor for the age of freight cars was estimated to be 1/0.9 = 1.1.

Table 11 summarizes the scaling factors for the network parameters analyzed in this study. An analytical approach for combining these factors is discussed in the following sub-section.

Table 11. Estimated factors to scale the mini-network results to the U.S. rail network

Parameter	Study network	U.S. rail network	Scaling Factor
Length of main tracks (miles)	5,000	138,000	27.6
Annual freight train-miles	13.4 million	529.2 million	39.5
Number of sidings and yards	150	4,600	30.7
% of congested corridors	36%	21%	0.58
Age of freight cars	New	~20 years	1.1

5.2 Network Scaling Formulation

As explained in Section 4, five measures of safety and operational performance were used to assess the benefits of advanced train control technologies (Scenarios 2, 6, and 7) against conventional braking and signaling systems (Scenario 1). These performance metrics were also used to estimate the benefits for the full U.S. rail network.

A summary of the metrics and respective percent improvements observed between Scenarios 1 and 2 (CBS vs. ABS) for the mini-network are:

- **Network delay:** 22 percent improvement for Scenario 2
- **Network velocity:** 0.4 percent improvement for Scenario 2
- **Network capacity utilization:** 0.2 percent improvement for scenario 2
- **Braking at signals:** 8 percent improvement for Scenario 2
- **Number of stops at signals:** 4 percent improvement for Scenario 2

To estimate the level of improvement using each advanced train control technology, an analytical model was developed in this study to apply findings from mini-network simulations to the national rail network.

Equation 1 is the main formula for this analytical model that estimates any improvement projected for the national rail network:

$$Y_{jk} = M_{jk} \,.\, Y'_{jk} \qquad j \in (2,6,7)\ ;\ k \in (1,2,3,4,5) \qquad \text{Eq. 1}$$

Where;

- J = Scenario of applying advanced train control technologies (2 = "ABS," 6 = "PTC," 7 = "ABS-PTC")
- k = Safety and operational performance metric (e.g., network delay and network velocity)
- M_{jk} = Estimated "impact factor" for the specific metric "k" as a result of implementing scenario "j"
- Y_{jk} = Estimated improvement (percentage) in specific metric "k" as a result of implementing scenario "j" in the national rail network
- Y'_{jk} = The simulated improvement (percentage) in specific metric "k" as a result of implementing scenario "j" in the mini-network

The impact factor M_{jk} combines the five scaling factors described in Section 5.1 in a unique way for each safety and operational performance metric "k" over each scenario "j", as shown in Equation 2:

$$M_{jk} = \sum_{i=1}^{5} (A_{jki} \, . \, X_i^{P_{ji}}) \qquad j \in (2,6,7) \; ; \; k \in (1,2,3,4,5)$$

Eq. 2

Where:

- X_i = The set of scaling factors for the five network performance metrics relating the simulated network to the target network (i.e., $X_1 = 27.6$, $X_2 = 39.5$, $X_3 = 30.7$, $X_4 = 0.58$, $X_5 = 1.1$)
- P_{ji} = Impact power for scaling factor X_i in scenario "j"
- A_{jki} = A weighting factor for scaling factor X_i calibrated for each metric "k" in each scenario "j" where:

$$\Sigma_i A_{jki} = 1 \; for\ each\ (j, k)\ combination \qquad \text{Eq. 3}$$

Equation 2 shows that the five scaling factors, X_i, can be weighted differently for each safety and operational performance metric "k" and scenario "j." It also shows the impact of the scaling factors is not assumed to be linear. For example, as shown in Equation 4, Equation 2 is calibrated for Scenario 2 (applying ABS on freight trains) using different P_{ji} values.

$$M_{2k} = \left(A_{2k1}.X_1^{1/3} + A_{2k2}.X_2^{1/3} + A_{2k3}.X_3^{1/3} + A_{2k4}.X_4 + A_{2k5}.X_5^{1/2} \right)$$

Eq. 4

It should be mentioned that the impact power (P_{ji}) and the weighting factors (A_{jki}) in Equation 2 were calibrated through the following constraints using engineering judgement and a heuristic approach derived from dozens of simulated scenarios over different sample sizes of networks and corridors:

- If the characteristics of the national (i.e., target) network are the same as those for the mini-network (all $X_i = 1$) then the estimated improvement percentage for each safety and operational performance metric in each scenario must be identical between the national and the simulated networks ($M_{jk} = 1$ and $Y_{jk} = Y'_{jk}$).
- Under no condition can the value of any M_{jk} be more than 3 (e.g., $Y_{2\,1} \leq 3Y'_{2\,1}$).
- Under no condition can the value of any Y_{jk} be more than 1 (maximum of 100 percent improvement for each metric in the national network).[14]
- Under no condition can the value of one individual component of Equation 2 exceed the value of the other components combined; otherwise, it would be an indication of a calibration error. The constraint shown in Equation 5 shows an example of evaluating Equation 2 during calibration of the weighting factors for Scenario 2.

[14] In theory, the projected improvement for a target network can be higher than 100 percent. However, for the reported analyses in this study, an upper threshold of 100 percent was used based on the simulations conducted on the mini-network under advanced train control technologies.

$$(\text{e.g. } A_{2k1}.X_1^{1/3} \leq A_{2k2}.X_2^{1/3} + A_{2k3}.X_3^{1/3} + A_{2k4}.X_4 + A_{2k5}.X_5^{1/2}) \qquad \text{Eq. 5}$$

5.3 Estimating Weighting Factors

Each safety and operational performance metric (k) can be affected differently when computing its network impact factor (M_{jk}) for a given scenario from a specific network-related characteristic (i). For example, when analyzing network delay, the scaling factor of each network parameter can be weighed uniformly ($A_{j1i} = 0.20$), but for evaluating the braking actions at signals (i.e., for route reservation), the scaling factor for network congestion level may have higher weight compared to the total length of the tracks over the network (e.g., $A_{j41} = 0.15$; $A_{j44} = 0.30$).

This section presents the estimated weighting factors for each scenario (i.e., advanced train control technologies), which may be different when evaluated for a given safety and operational performance metric (k) based on given network characteristics (i).

Table 12 lists the weighting factors for each combination of safety and operational performance metric and network scaling factor for Scenario 2 (ABS). As shown in Table 12, the scaling factors for congestion level have been given higher weights, particularly for the capacity utilization metric, since a congested network can rapidly degrade safety and operational performance, and the length of tracks has the lowest weight compared to the other parameters.

Table 12. Estimated weighting for each network scaling factor (*i*) customized for each performance metric (*k*) based on ABS (Scenario 2)

	Network Parameter Scaling Factor (i)					
Safety and Operational Performance Metric (k)	Length of tracks (i=1)	Train-miles (i=2)	Number of sidings (i=3)	Congestion level (i=4)	Fleet age (i=5)	Total
Network Delay (k=1)	0.2	0.1	0.1	0.3	0.3	1
Network Velocity (k=2)	0.15	0.15	0.15	0.3	0.25	1
Capacity Utilization (k=3)	0.1	0.1	0.2	0.5	0.1	1
Braking at Signal (k=4)	0.15	0.2	0.2	0.3	0.15	1
Number of Signal Stops (k=5)	0.15	0.2	0.2	0.3	0.15	1
Impact Power (P_{2i})	1/3	1/3	1/3	1	1/2	

Table 13 lists the weighting factors for each combination of performance metric and scaling factor estimated in Scenario 6 (i.e., applying PTC).

Table 13. Estimated weighting for each network scaling factor (*i*) customized for each performance metric (*k*) assuming PTC systems (Scenario 6)

	Network Parameter Scaling Factor (i)					
Safety and Operational Performance Metric (k)	Length of tracks (i=1)	Train-miles (i=2)	Number of sidings (i=3)	Congestion level (i=4)	Fleet age (i=5)	Total
Network Delay (k=1)	0.1	0.1	0.1	0.4	0.3	1
Network Velocity (k=2)	0.2	0.2	0.1	0.3	0.2	1
Capacity Utilization (k=3)	0.1	0.1	0.2	0.5	0.1	1
Braking at Signal (k=4)	0.05	0.05	0.15	0.6	0.15	1
Number of Signal Stops (k=5)	0.15	0.15	0.1	0.5	0.1	1
Impact Power (P_{6i})	1/3	1/3	1/4	2	1	

Similar to the weighting factors estimated for Scenario 2 (Table 12), the weighting factors estimated for Scenario 6 (Table 13) have slightly higher values for congestion level, since the results of simulation in Scenario 6 demonstrate that PTC has a high impact on network velocity and capacity utilization rates throughout congested parts of the network, particularly along multi-track corridors. The respective impact powers of this scenario (P_{6i}) were also updated to address the impact of congestion and fleet age.

Table 14 lists the weighting factors for each combination of safety and operational performance metric and scaling factor estimated in Scenario 7 (i.e., applying ABS and PTC systems together). It should be highlighted that the weighting factors estimated for Scenario 7 (ABS-PTC) were picked from the safety and operational performance metrics of Scenario 2 (ABS) and Scenario 6 (PTC) in a way that reflects the higher impact weight they individually imposed over each safety and operational performance metric (*k*) as discussed in this section. For example, in terms of weighting factors for braking actions at signals (*k*=4), PTC has a much higher impact than ABS technology; thus, the respective metrics estimated for Scenario 6 (Table 13) also were used for Scenario 7. However, for network delay weighting factors (*k*=1), the same estimated values for the ABS system (i.e., first row of Table 12) were used for Scenario 7 (Table 14).

Table 14. Estimated weighting for each network scaling factor (*i*) customized for each performance metric (*k*) assuming ABS-PTC systems (Scenario 7)

	Network Parameter Scaling Factor (i)					
Safety and Operational Performance Metric (k)	Length of tracks (i=1)	Train-miles (i=2)	Number of sidings (i=3)	Congestion level (i=4)	Fleet age (i=5)	Total
Network Delay (k=1)	0.2	0.1	0.1	0.3	0.3	1
Network Velocity (k=2)	0.1	0.2	0.15	0.3	0.25	1
Capacity Utilization (k=3)	0.1	0.1	0.2	0.5	0.1	1
Braking at Signal (k=4)	0.05	0.05	0.15	0.6	0.15	1
Number of Signal Stops (k=5)	0.15	0.15	0.1	0.5	0.1	1
Impact Power (P_{7i})	1/3	1/3	1/4	2	1	

5.4 Estimating Improvement Over the National Network

The weighting factors and impact powers estimated in Section 5.3 were used in Equations 1 to 3, and used as the constraints presented in Section 5.2 to assess the improvement in safety and operational performance metrics expected for each scenario when applying advanced train control technologies. Table 15 presents the estimated improvement percentage for each safety and operational performance metric on the U.S. rail network based on assuming deployment of ABS on freight trains.

Table 15. Estimated improvement over the U.S. rail network, as a result of deploying ABS for freight trains (Scenario 2)

Safety and Operational Performance Metric (*k*)	Improvement over the Mini-Network (Y'_{2K})	M_{2k}	Estimated Improvement over the National Network (Y_{2k})
Network Delay (*k*=1)	22%	1.75	38.4%
Network Velocity (*k*=2)	0.4%	1.87	0.7%
Capacity Utilization (*k*=3)	0.2%	1.66	0.3%
Braking at Signal (*k*=4)	8%	2.09	16.7%
Number of Signal Stops (*k*=5)	4%	2.09	8.4%

As expected, the biggest improvement over the U.S. rail network when upgrading braking systems on freight trains is a reduction in network delay of 38.4 percent followed by an estimated reduction in the number of braking actions at signals of 16.7 percent and a reduction in unnecessary signal stops of 8.4 percent. The other two metrics, increasing network velocity and reduction in network capacity utilization, have minor estimated improvements (0.7 and 0.3 percent, respectively) when implementing ABS technology on freight trains.

Table 16 presents the estimated improvement percentage for each safety and operational performance metric based on assuming deployment of PTC systems throughout the national rail network.

Table 16. Estimated improvement over the U.S. rail network, as a result of deploying PTC system (Scenario 6)

Safety and Operational Performance Metric (k)	Improvement over the Mini-Network (Y'_{6K})	M_{6k}	Estimated Improvement over the National Network (Y_{6k})
Network Delay (k=1)	38%	1.34	51.0%
Network Velocity (k=2)	1.7%	1.84	3.1%
Capacity Utilization (k=3)	7.0%	1.39	9.7%
Braking at Signal (k=4)	88%	1.04	91.6%
Number of Signal Stops (k=5)	44%	1.48	65.0%

As shown in Table 16, implementing the PTC system throughout the entire national rail network can improve all measures of network safety and operational performance. It can particularly reduce braking at signals (i.e., passing through the wayside signals) and the number of stops at signals by a significant percentage compared to the scenario of operating trains under a CS system (Scenario 1). In addition, it could also increase network velocity by 3 percent, lower capacity utilization by approximately 10 percent, and reduce network delay by 51 percent.

Table 17 presents the estimated improvement percentage for each safety and operational performance metric based on assuming deployment of both ABS and PTC systems throughout the national rail network.

Table 17. Estimated improvement over the U.S. rail network as a result of deploying ABS and PTC systems (Scenario 7)

Safety and Operational Performance Metric (k)	Improvement over the Simulated Network (Y'_{7K})	M_{7k}	Estimated Improvement over the National Network (Y_{7k})
Network Delay (k=1)	49%	1.61	79.0%
Network Velocity (k=2)	1.9%	1.71	3.3%
Capacity Utilization (k=3)	7.2%	1.39	10.0%
Braking at Signal (k=4)	88%	1.04	91.6%
Number of Signal Stops (k=5)	44%	1.48	65.0%

As presented in Table 17 and Figure 46, the estimated improvement over the national rail network assuming deployment of both ABS and PTC systems is the combination of improvement provided by each system individually.

Reviewing outcomes of Scenario 7 (ABS-PTC) side-by-side against the two scenarios in which they are deployed individually, as shown in Figure 46, confirms that delay throughout the national rail network could be significantly reduced by 41 and 28 percent compared to Scenarios 2 (ABS) and 6 (PTC), respectively.

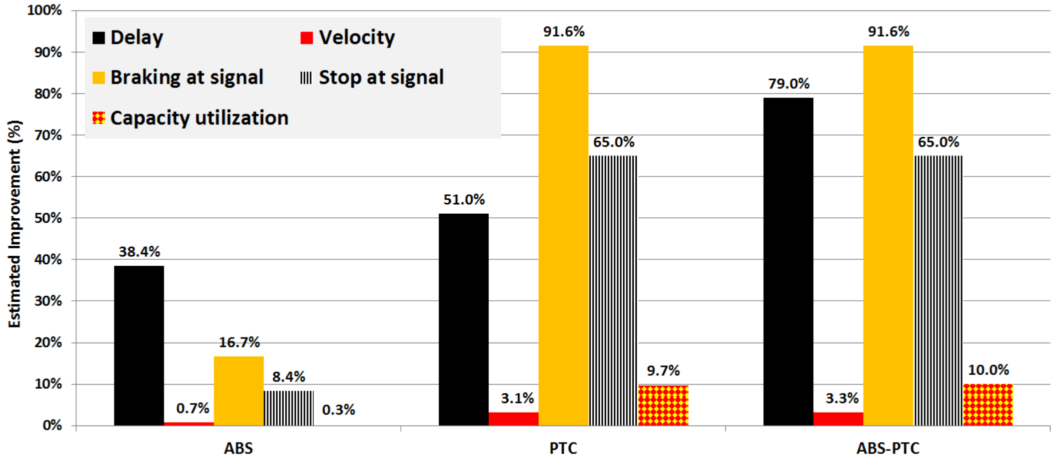

Figure 46. Estimated improvement of network performance metrics over the national rail network assuming ABS, PTC, and ABS-PTC scenarios

Similar patterns can be seen for capacity utilization, route braking, and stops at signals when compared with Scenario 2 (ABS), but little improvement is seen when compared to deploying only PTC (Scenario 6). Also, network velocity is estimated to improve by 0.7 percent with ABS and 3.3 percent under combined ABS and PTC systems, but as explained earlier, the improvement is derived mostly from use of the PTC system.

6. Conclusion

Over the last two decades major technology initiatives in the railroad industry have improved the safety and operational performance of freight trains and other trains. Advanced train control technologies such as ABS for freight trains and PTC systems not only improve safety, but may also enhance the performance of operating trains in the network.

This study evaluated the impact of applying advanced train control technologies (i.e., ABS and PTC systems) on the safety and operational performance of the U.S. rail network using a benchmark mini-network simulation approach. The research team developed a hypothetical mini-network and simulated various traffic mixes on corridors similar to North American rail network operations.

The team modeled about 5,000 miles of main tracks in the simulator. However, considering parts of the network with double- and multi-track segments, as well as additional tracks along 150 sidings and yards in the mini-network, approximately 6,200 miles of tracks were built for simulation purposes. A total of 256 daily trains, a mix of intercity passenger, commuter, HSR, and freight services, were scheduled in the mini-network, including 102 daily freight trains in 17 different configurations.

Seven scenarios were simulated in the study to analyze the safety and operational performance impact of deploying advanced train control technologies over the network.

- Scenario 1
  - All freight trains are equipped with a CBS; the network uses a CS system (CBS-CS)
- Scenario 2
  - All freight trains are equipped with an ABS; the network uses a CS system (ABS-CS)
- Scenarios 3–5
  - A mix of freight trains with combination of ABS and CBS systems; the network uses a CS system (Hyb-CS)
- Scenario 6
  - All freight trains are equipped with CBS; the network uses PTC signaling system (CBS-PTC)
- Scenario 7
  - All freight trains are equipped with an ABS; the network uses PTC signaling system (ABS-PTC)

All scenarios were simulated using the same assumptions and network model characteristics except for the braking characteristics of freight trains and the signaling systems of the corridors, depending on the scenario. All train schedules were made “conflict-free,” meaning that they departed from their designated origins and arrived at their assigned destinations without any schedule conflict that could cause a deadlock anywhere in the network.

The team analyzed several safety and operational performance metrics, including network delay, network velocity, maximum track utilization and capacity utilization rates, number of stops at stations, number of braking at signals (i.e., braking actions for route reservations), and number of stops at signals.

Based on the results of the study, researchers concluded that ABS would mostly improve the performance of freight trains, particularly in terms of delay, braking at signals, and signal stops, while it may not have any major impact on other train performance metrics. The team also found that PTC may have a more beneficial impact on almost every type of train and for every performance metric except for the number of station stops, a metric associated more with the prescribed stops for trains.

For example, ABS could increase network velocity throughout the mini-network by 0.3 mph (0.5 percent), while PTC could increase network velocity by 1 mph (1.7 percent), and notably higher for HSR trains (3.4 mph).

PTC systems could also significantly reduce the amount of braking at signals (about 88 percent on average) particularly for freight (over 95 percent) and passenger trains (about 82 percent). In addition, PTC could significantly reduce the number of stops at signals for HSR (about 73 percent) and passenger trains (about 54 percent).

No significant benefit was observed in capacity and track utilization rates when equipping freight trains with ABS systems. However, PTC could improve the maximum track utilization rate of most of the network corridors by approximately 30 percent on average, especially through double- and multi-track corridors, with an average reduction of 7 percent in capacity utilization throughout the mini-network.

The results of the simulation scenarios on the mini-network were then extrapolated to the size of the U.S. rail network using the following scaling factors:

- Total length of tracks
- Train-miles
- Number of sidings and yards
- Congestion level of network
- Age of freight fleet

The weighting of these factors was adjusted to suit each of the five safety and operational performance metrics depending on which train control technology was deployed (e.g., ABS, PTC, or combined ABS-PTC). Scaling the results from the mini-network to the size of the national rail network showed similar improvements using advanced train control technologies compared to conventional braking and signaling systems.

The biggest improvement for freight trains using ABS was a reduction in network delay of 38.4 percent, followed by a reduction in braking at signals (i.e., braking actions for route reservation) of 16.7 percent and a reduction in unnecessary signal stops of 8.4 percent.

However, PTC implementation throughout the national rail network was shown to improve all measures of network safety and operational performance discussed in this study, particularly by reducing braking at signals by 91.6 percent and signal stops by 65 percent compared to operating trains under a CS system (Scenario 1). In addition, PTC can increase network velocity by 3 percent, lower capacity utilization by 9.7 percent, and reduce network delay by 51 percent.

Deploying both ABS and PTC systems together could reduce the national network delay by 79 percent. However, other metrics may see little improvement beyond the benefits provided by deploying the PTC system alone.

Based on analysis of the study results, the following topics are suggested for further extension of the research.

- Analyzing safety and operational performance of trains operating under a future phase of the PTC system (i.e., moving block systems) versus PTC or a mixed operation regime (i.e., trains with moving block technologies and trains with a CS system operating through the same corridor)
- Investigating the impact of implementing a future phase of the PTC system (i.e., moving block systems) over corridors with no wayside signals (i.e., dark territory regime), and assessing challenges and benefits of converting corridors from dark territory directly to a corridor under a moving block operating regime
- Sensitivity analysis of various assumptions and calibration parameters on the mini-network and re-assessment of the results for the national network to see what criteria may provide a higher impact if the assumptions change
- Studying additional services that can be added to an existing network when improving capacity utilization rates by upgrading it with advanced train control technologies (e.g., PTC or moving block signaling systems)

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Abbreviations and Acronyms

ACRONYM	DEFINITION
ABS	Advanced Braking System
AAR	Association of American Railroads
BTS	Bureau of Transportation Statistics
CBS	Conventional Braking System
CS	Conventional Signal
DP	Distributed Power
ECP	Electronically Controlled Pneumatic
FRA	Federal Railroad Administration
HSR	High-speed Rail
Loco	Locomotive
MGT	Million Gross Ton
PTC	Positive Train Control
RSIA	Rail Safety Improvement Act
SA	Sharma & Associates
TEDS	Train Energy and Dynamics Simulator

Appendix A.
Results of the Simulated Scenarios

A.1 Simulation Characteristics and Validation Comparison

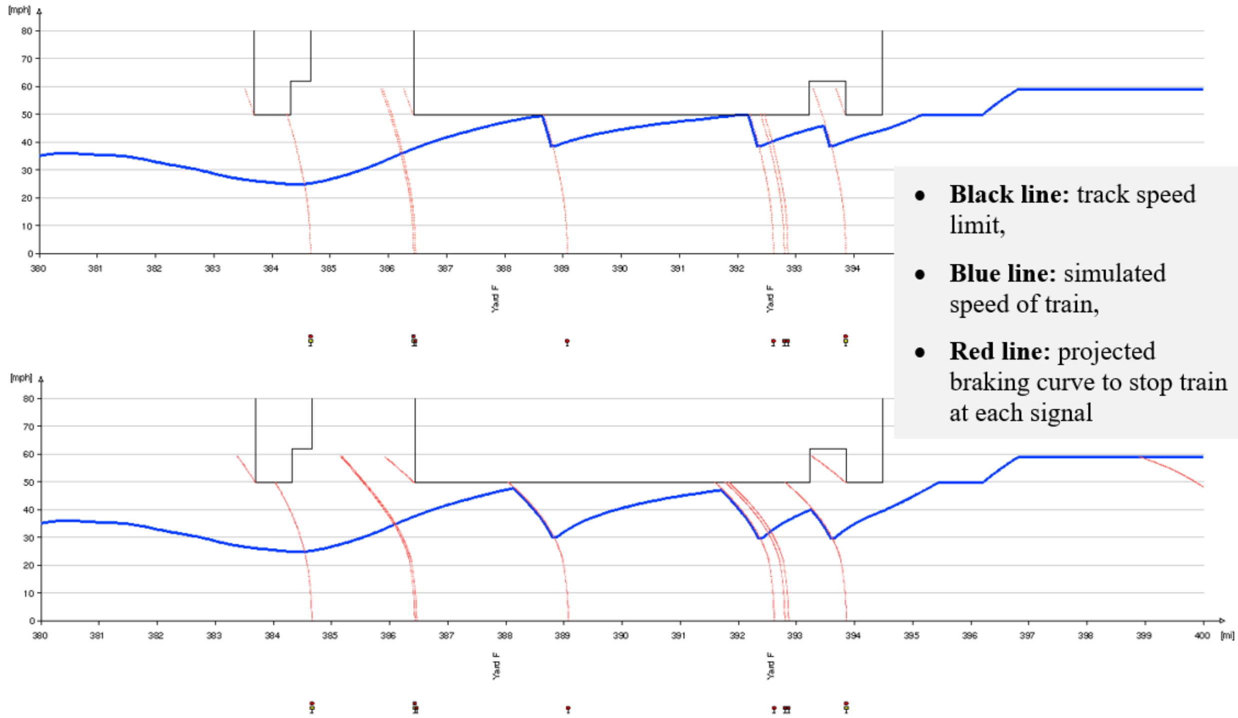

Figure A-1. Speed profile of a sample freight train with ABS braking characteristics (top figure) against its simulated operations under conventional braking characteristics (bottom figure)

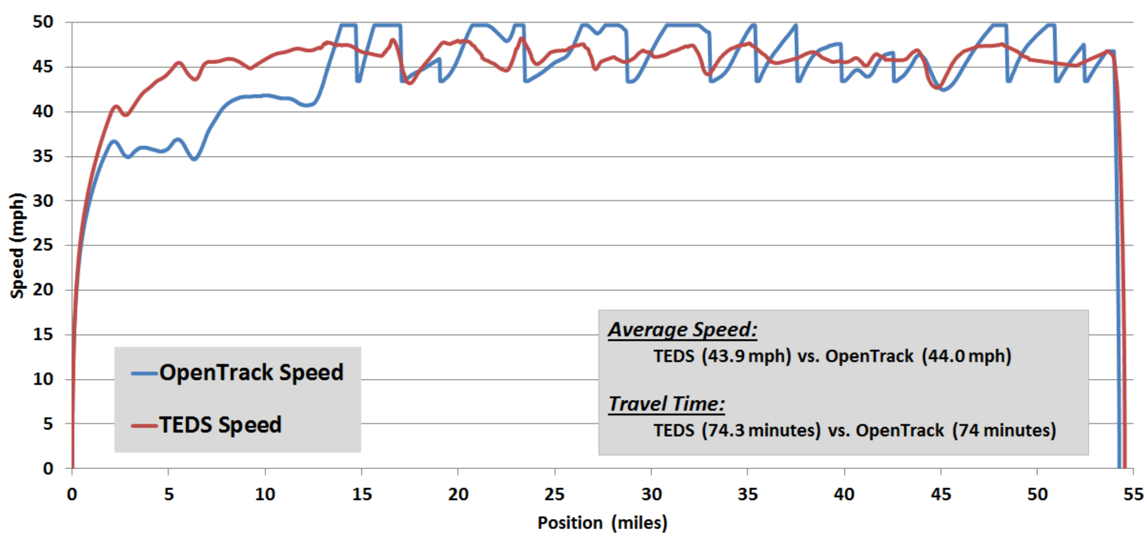

Figure A-2. Comparison between speed profiles of a train simulated in OpenTrack (blue) and speed profile of the same train simulated in TEDS (red)

A.2 Additional Stringline Diagrams for Scenario 1

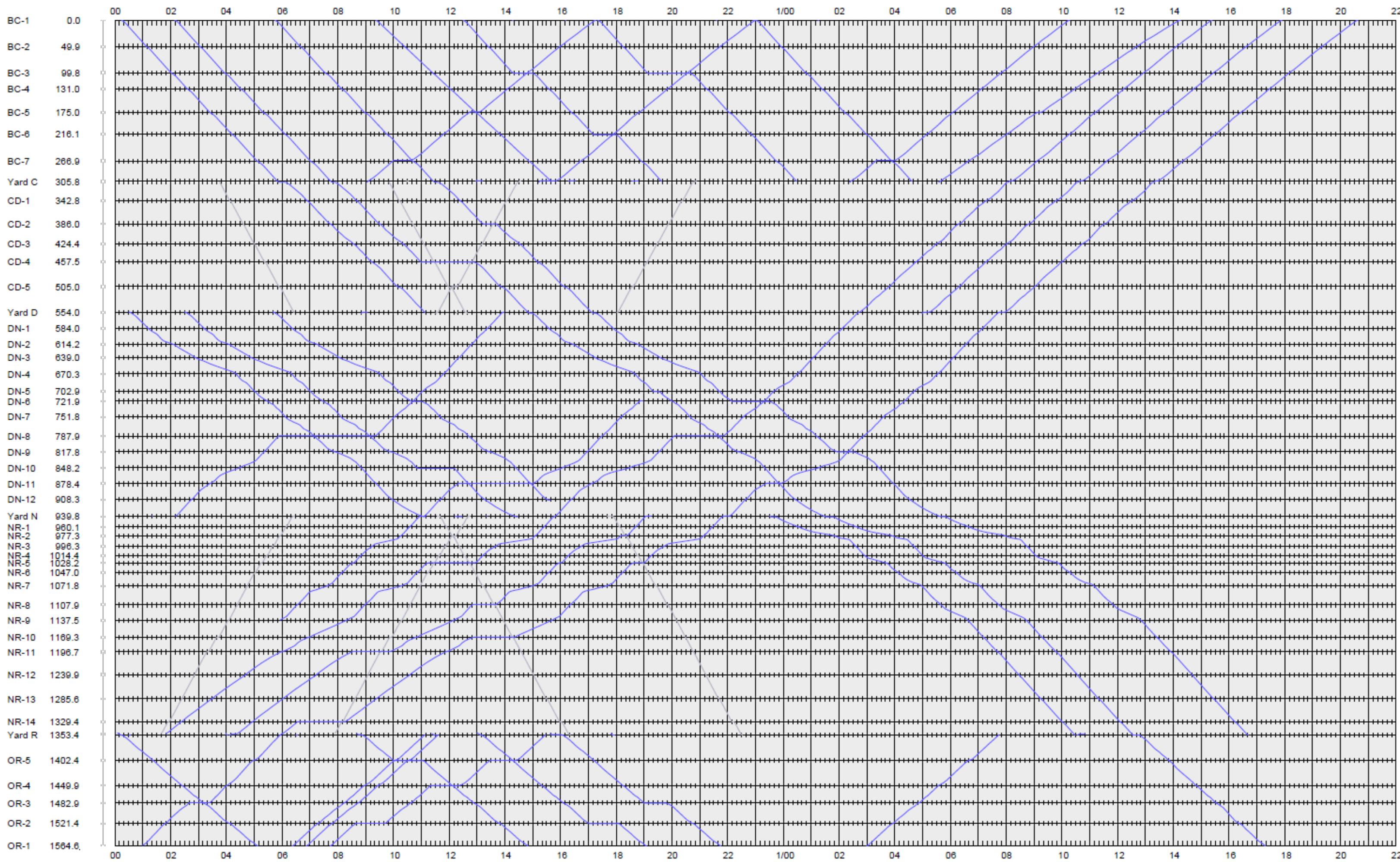

Figure A-3. Stringline results for section B-C-D-N-R-O assuming CBS for freight trains with CS systems

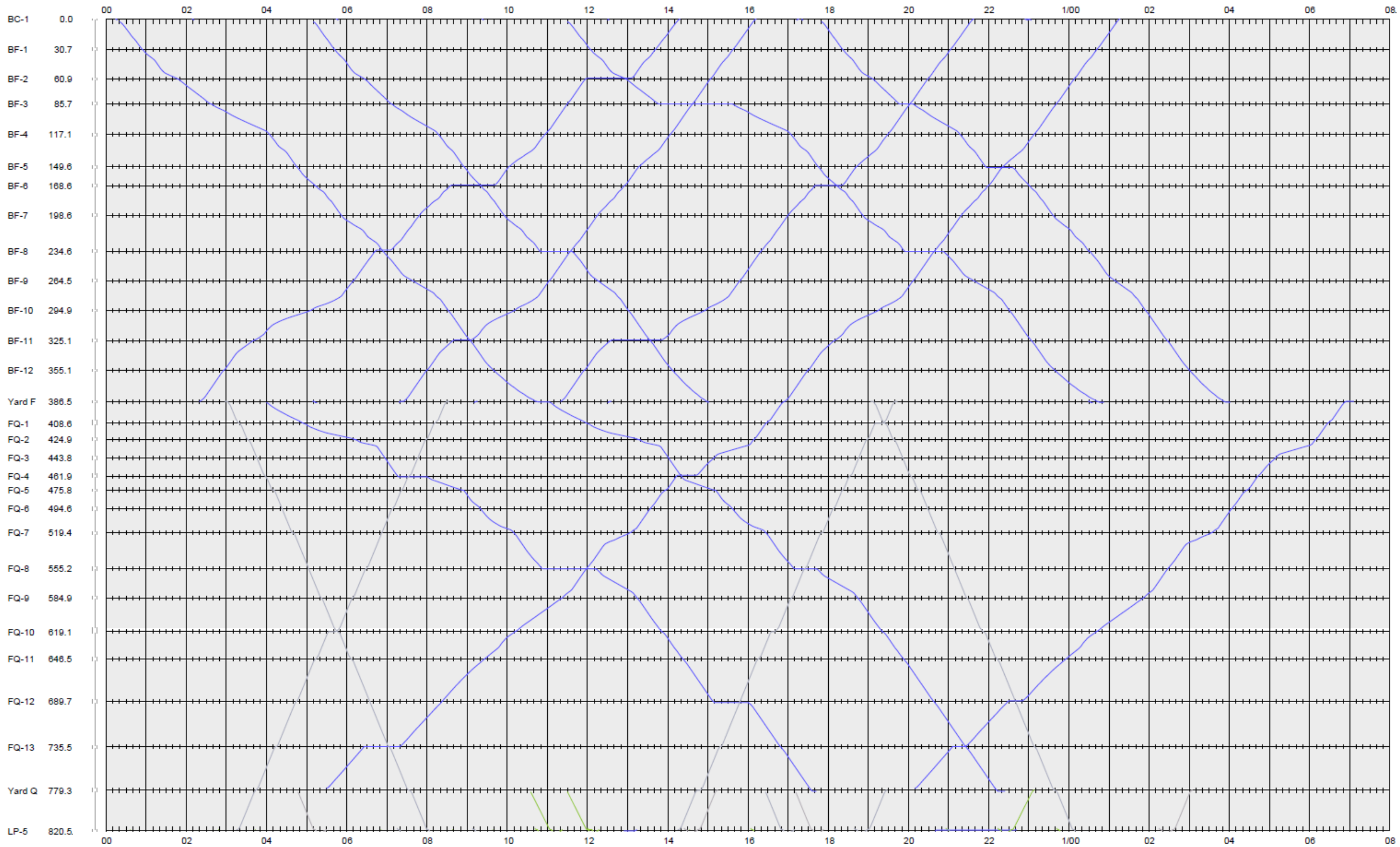

Figure A-4. Stringline results for section B-F-Q-P assuming CBS for freight trains with CS systems

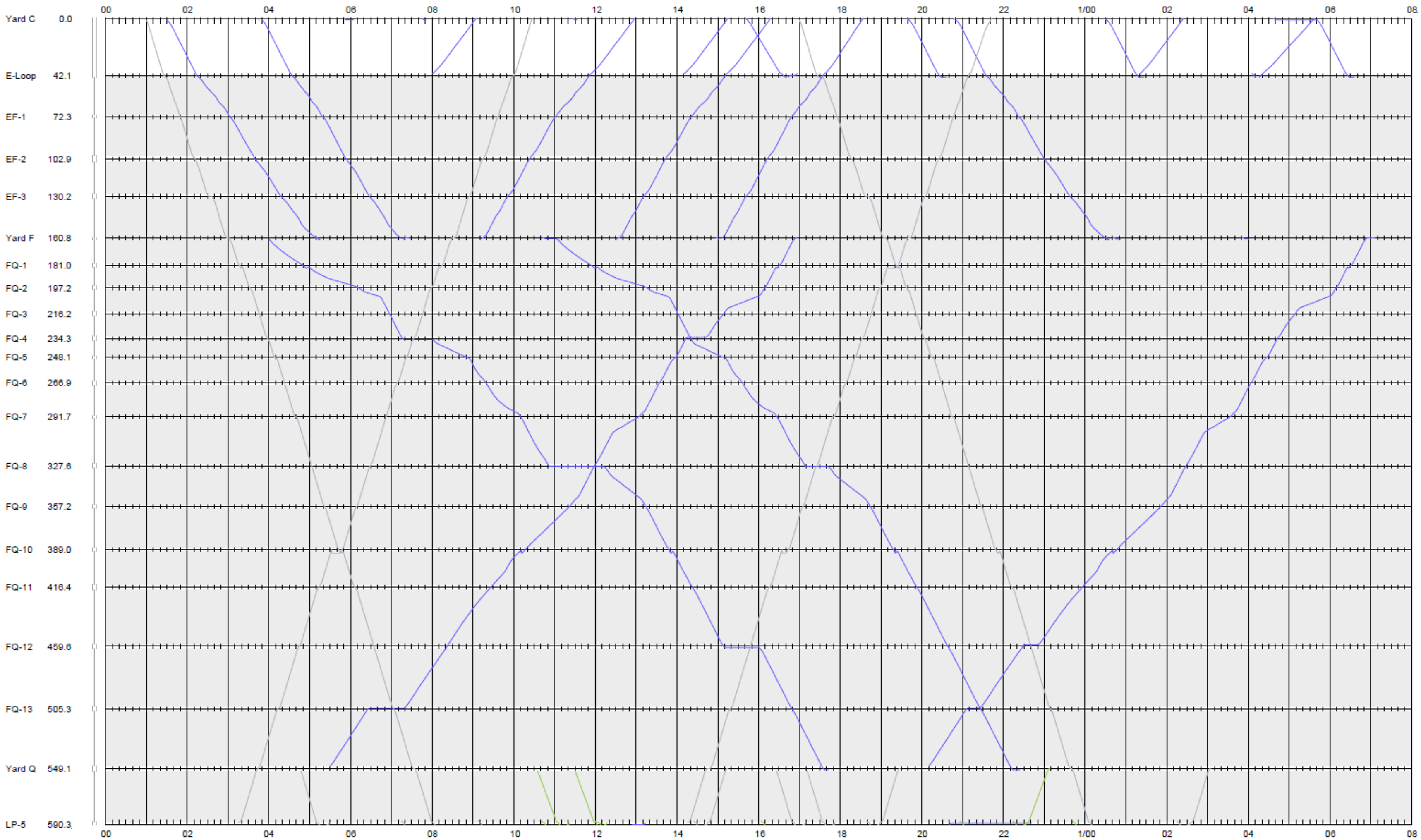

Figure A-5. Stringline results for section C-E-F-Q-P assuming CBS for freight trains with CS systems

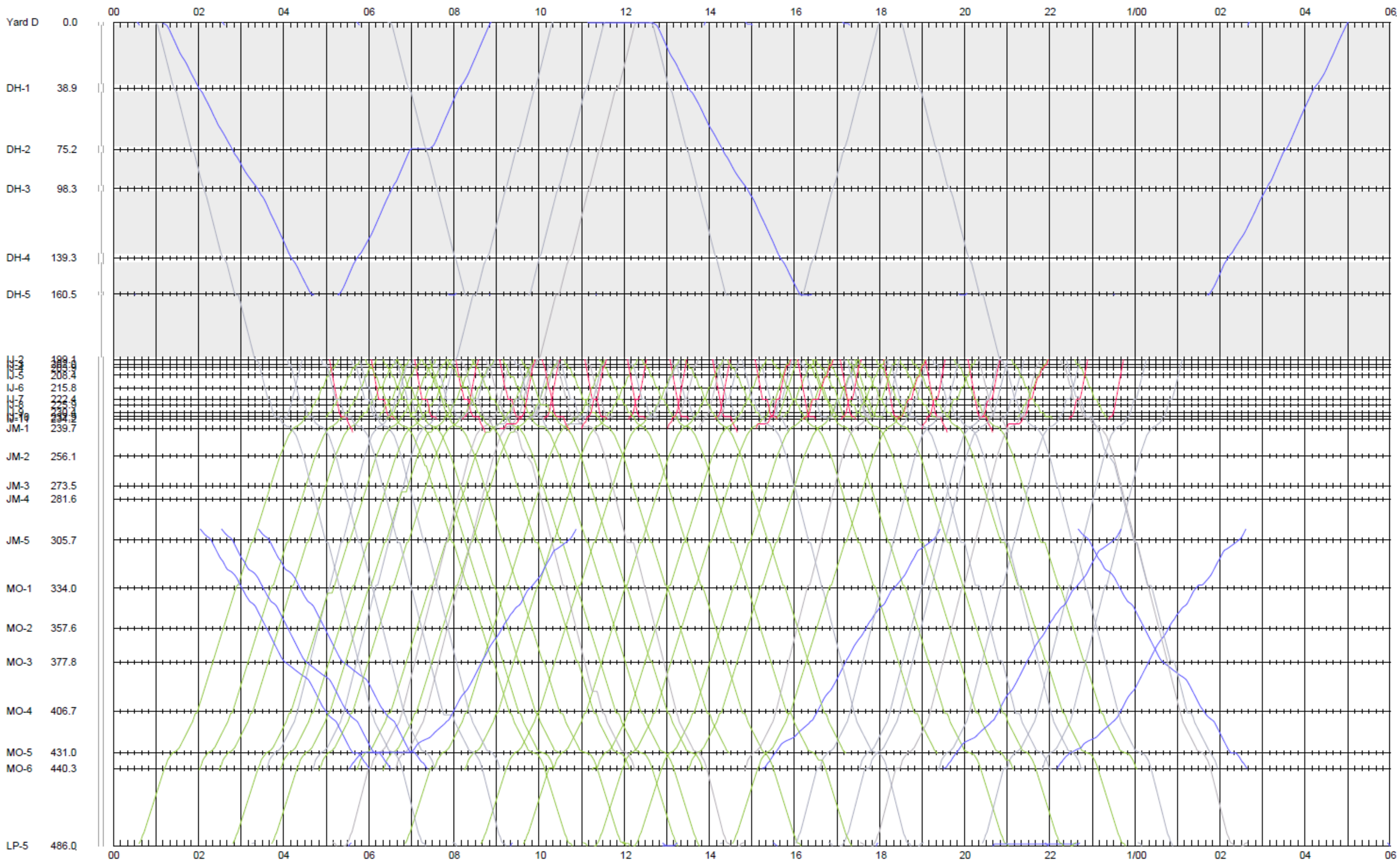

Figure A-6. Stringline results for section D-H-I-J-M-O-P assuming CBS for freight trains with CS systems

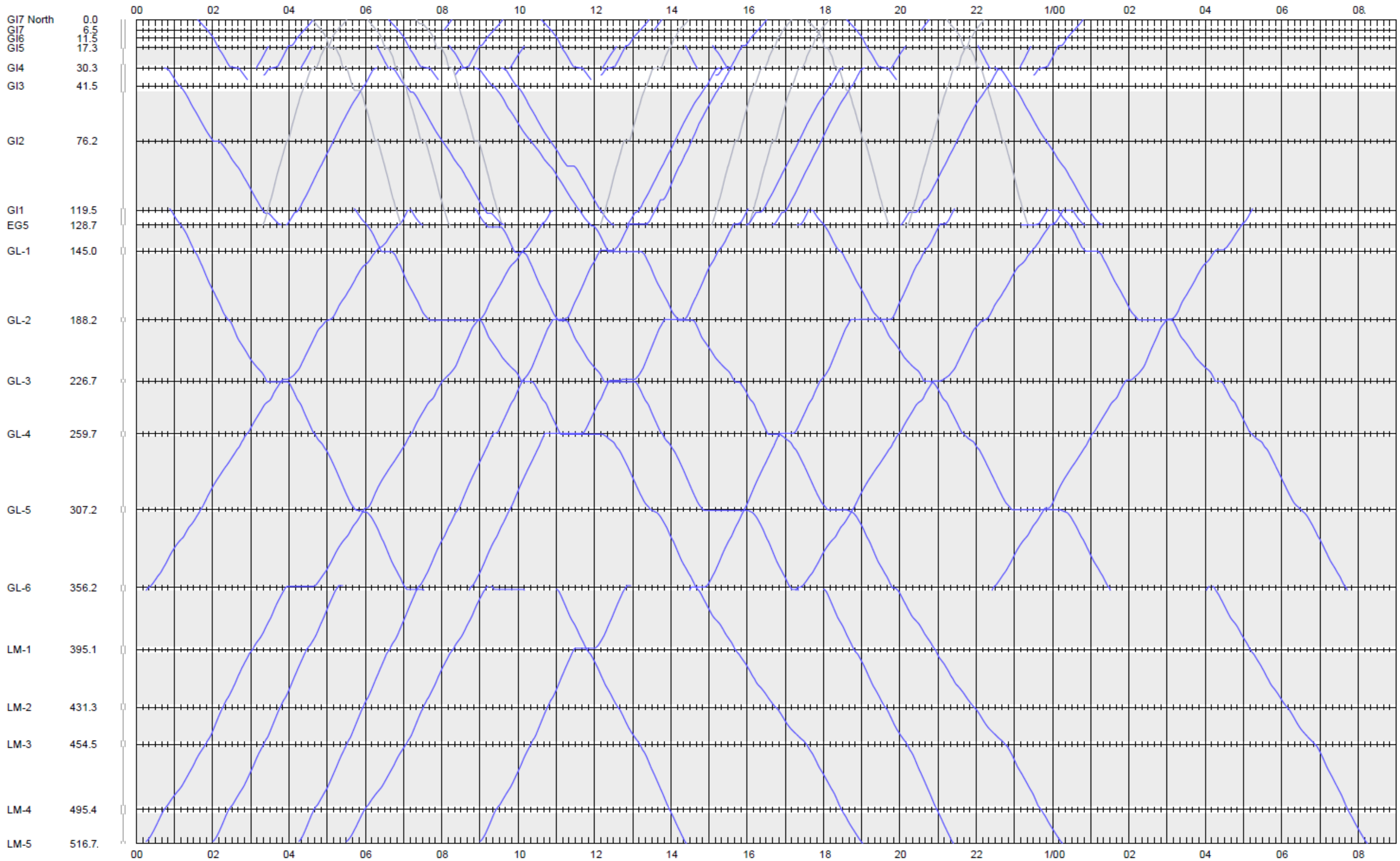

Figure A-7. Stringline results for section I-G-L-M assuming CBS for freight trains with CS systems

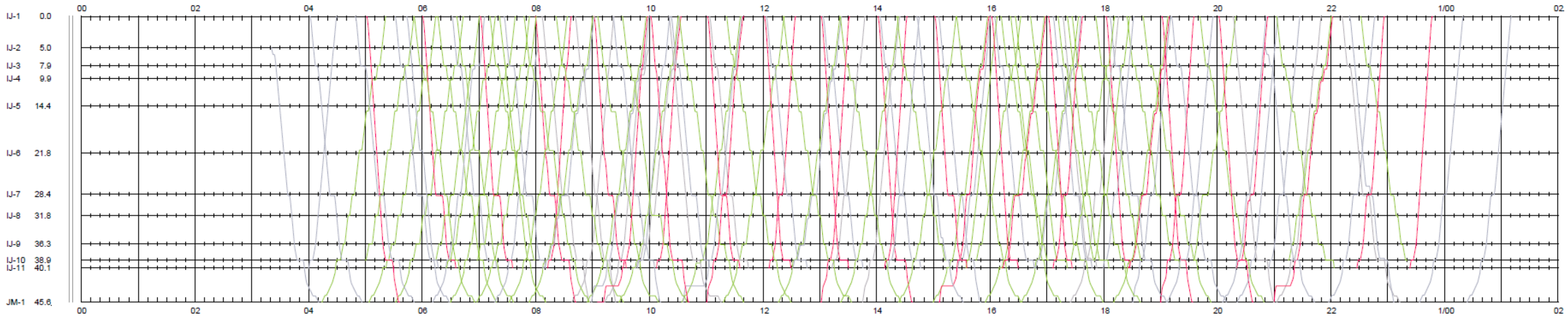

Figure A-8. Stringline results for section I-J assuming CBS for freight trains with CS systems

A.3 Additional Stringline Diagrams for Scenario 2

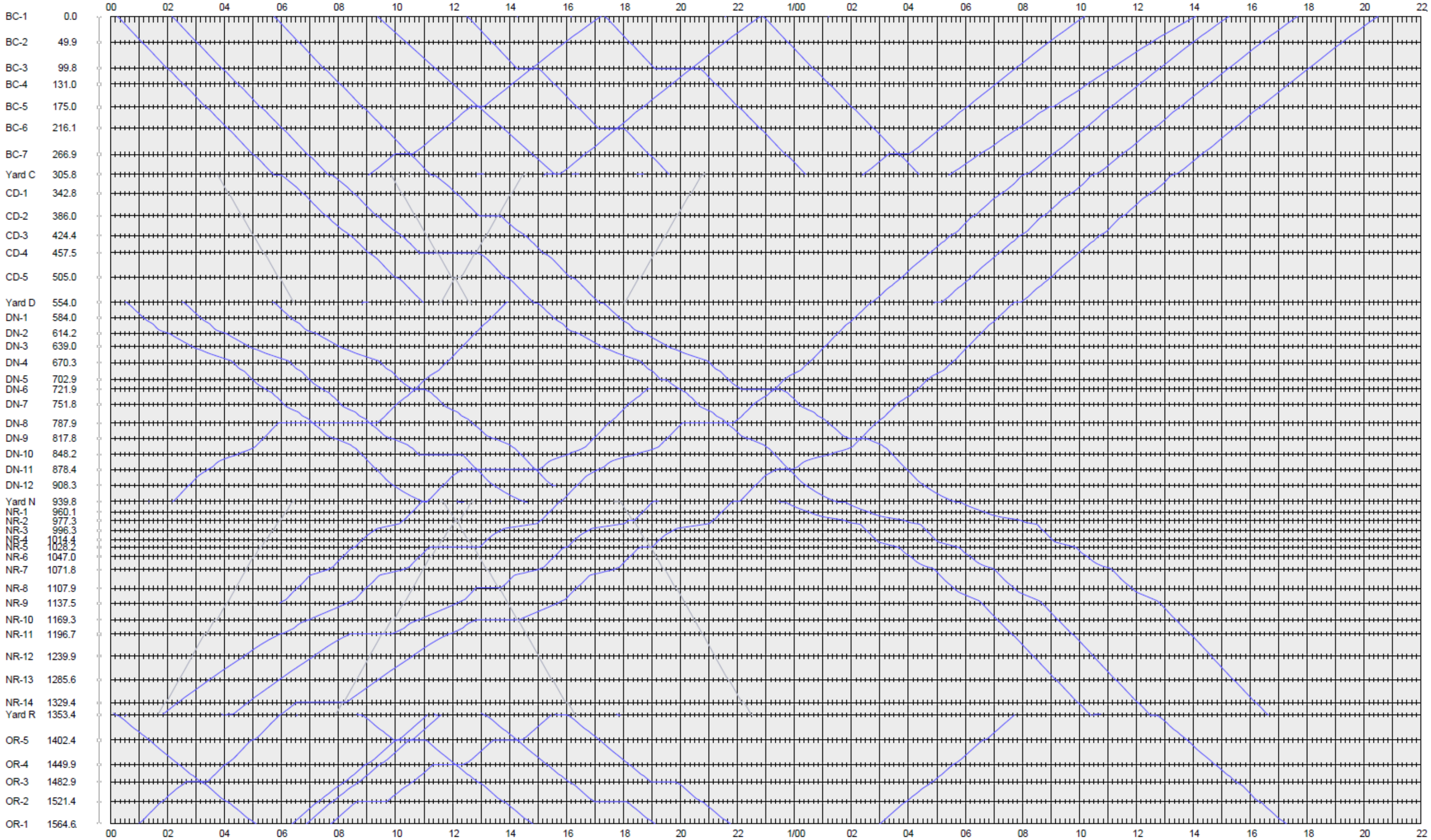

Figure A-9. Stringline results for Scenario 2 on section B-C-D-N-R-O assuming ABS for freight trains with CS systems

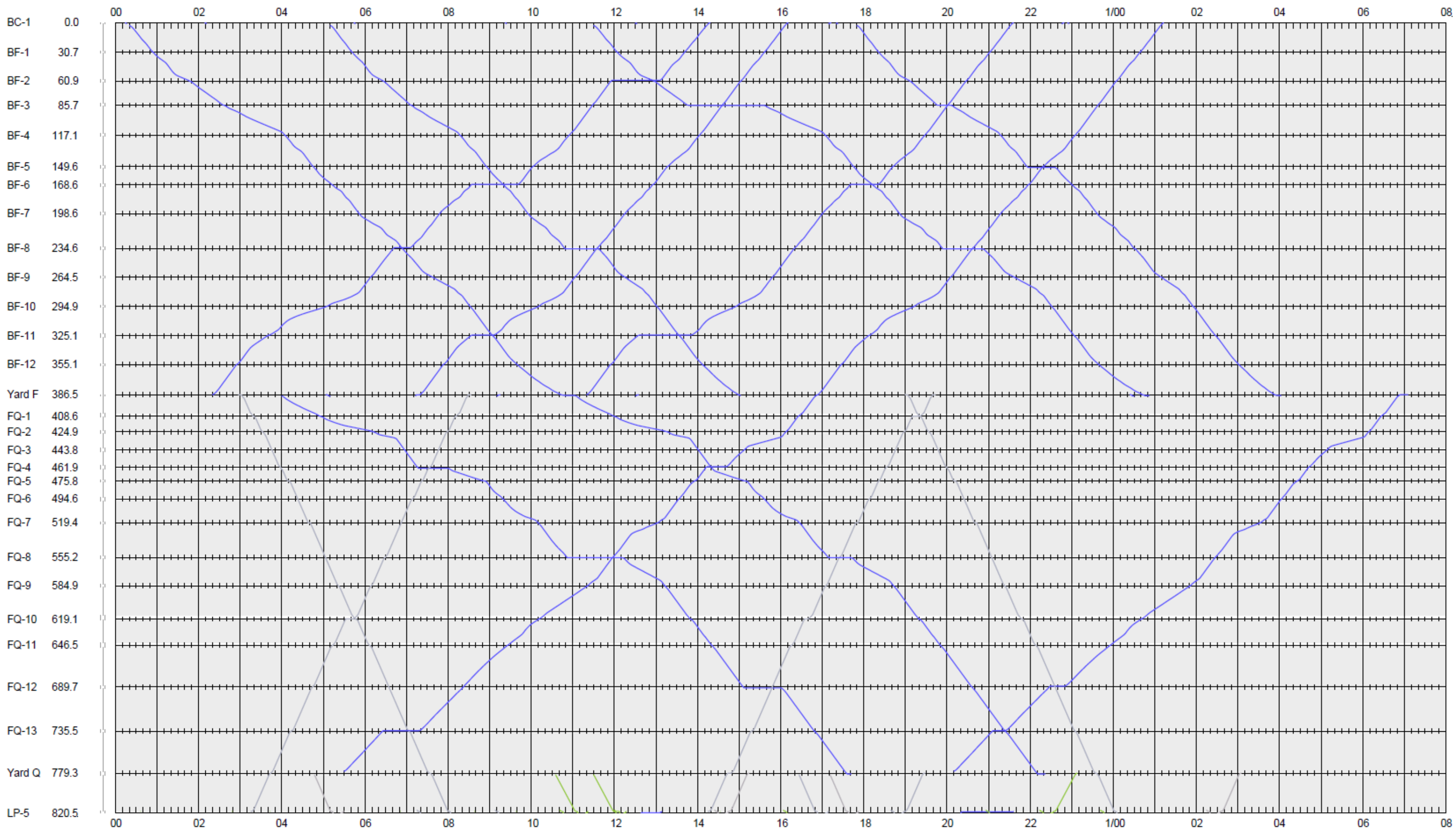

Figure A-10. Stringline results for Scenario 2 on section B-F-Q-P assuming ABS for freight trains with CS systems

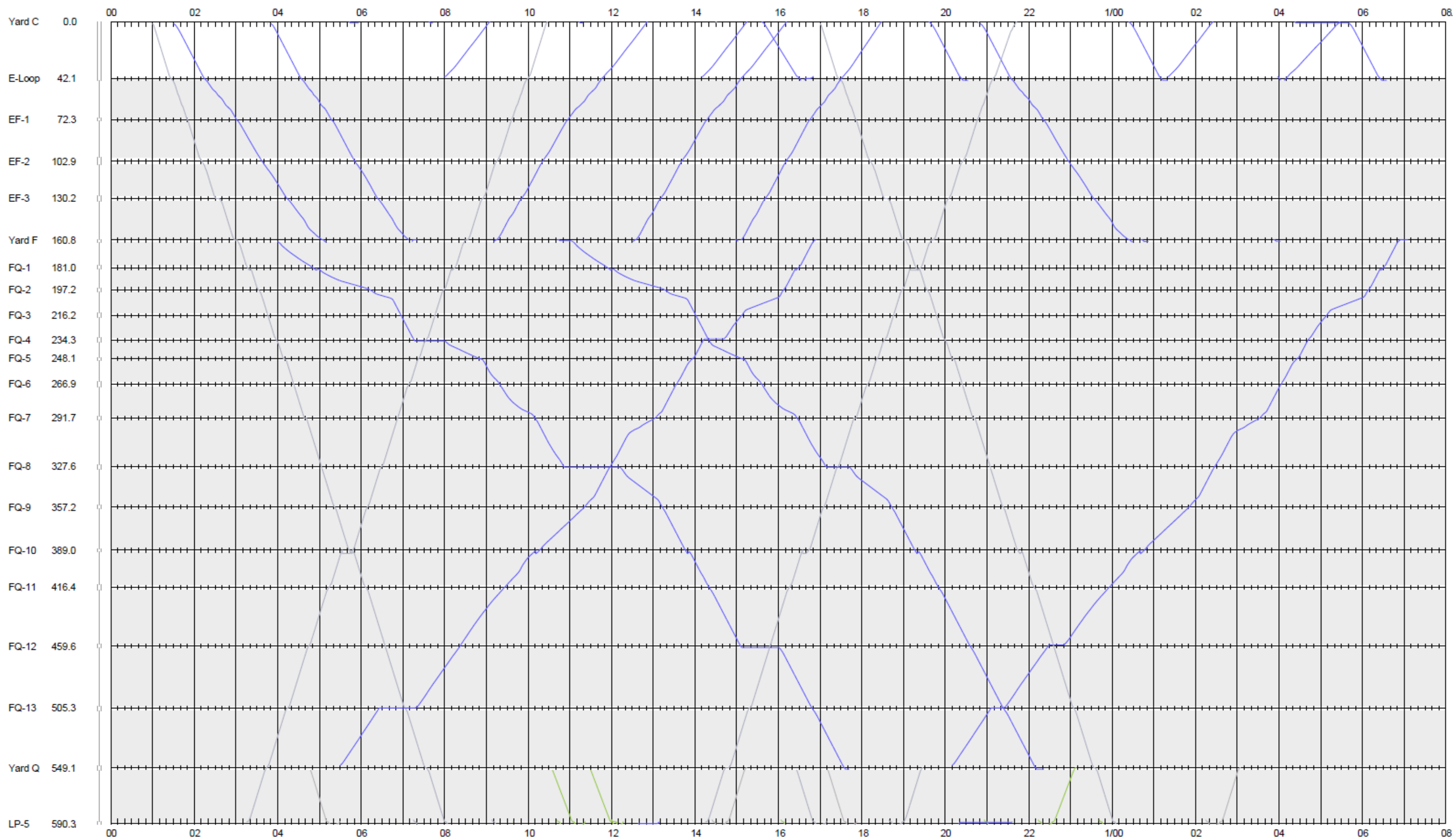

Figure A-11. Stringline results for Scenario 2 on section C-E-F-Q-P assuming ABS for freight trains with CS systems

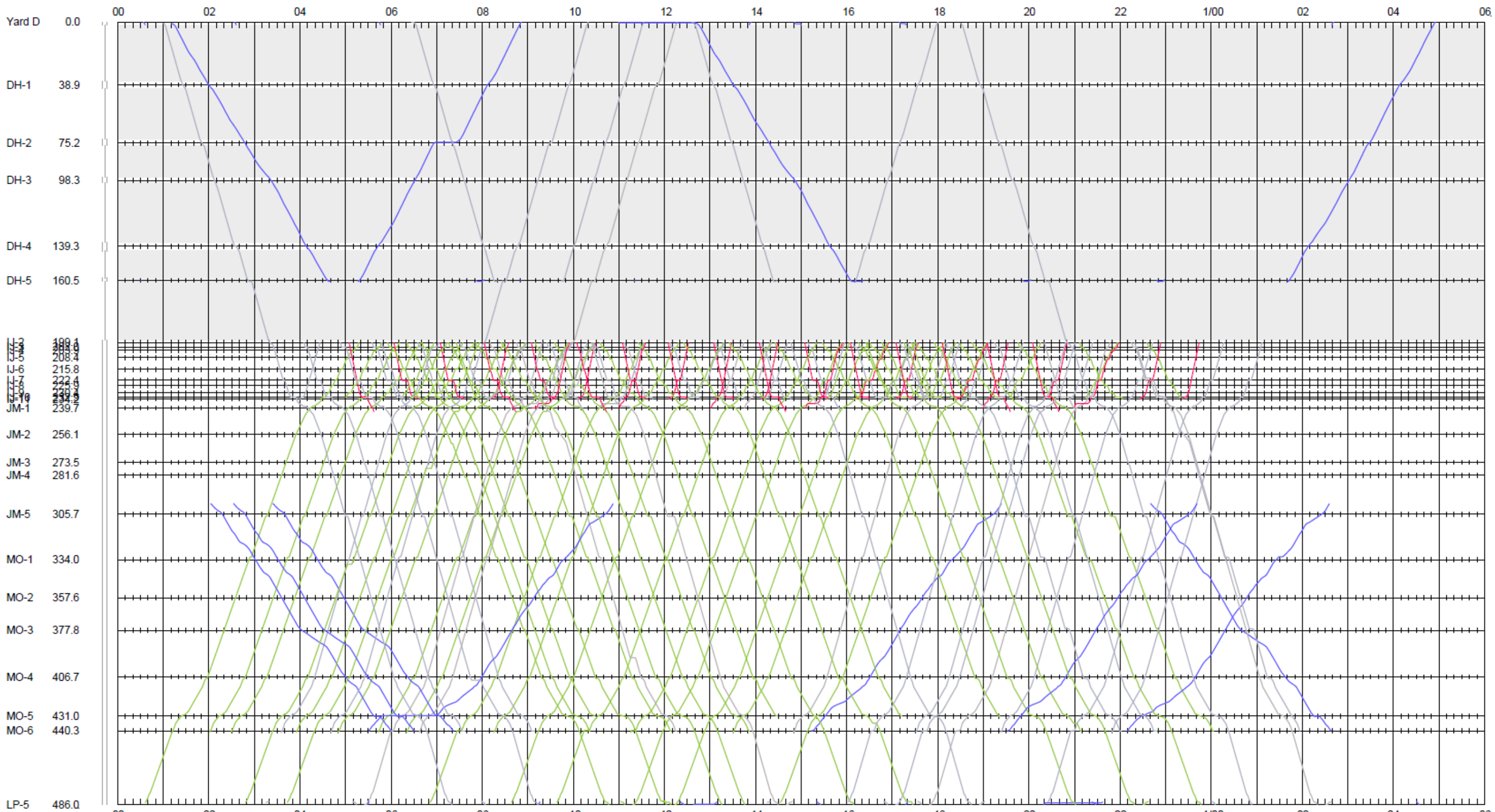

Figure A-12. Stringline results for Scenario 2 on section D-H-I-J-M-O-P assuming ABS for freight trains with CS systems

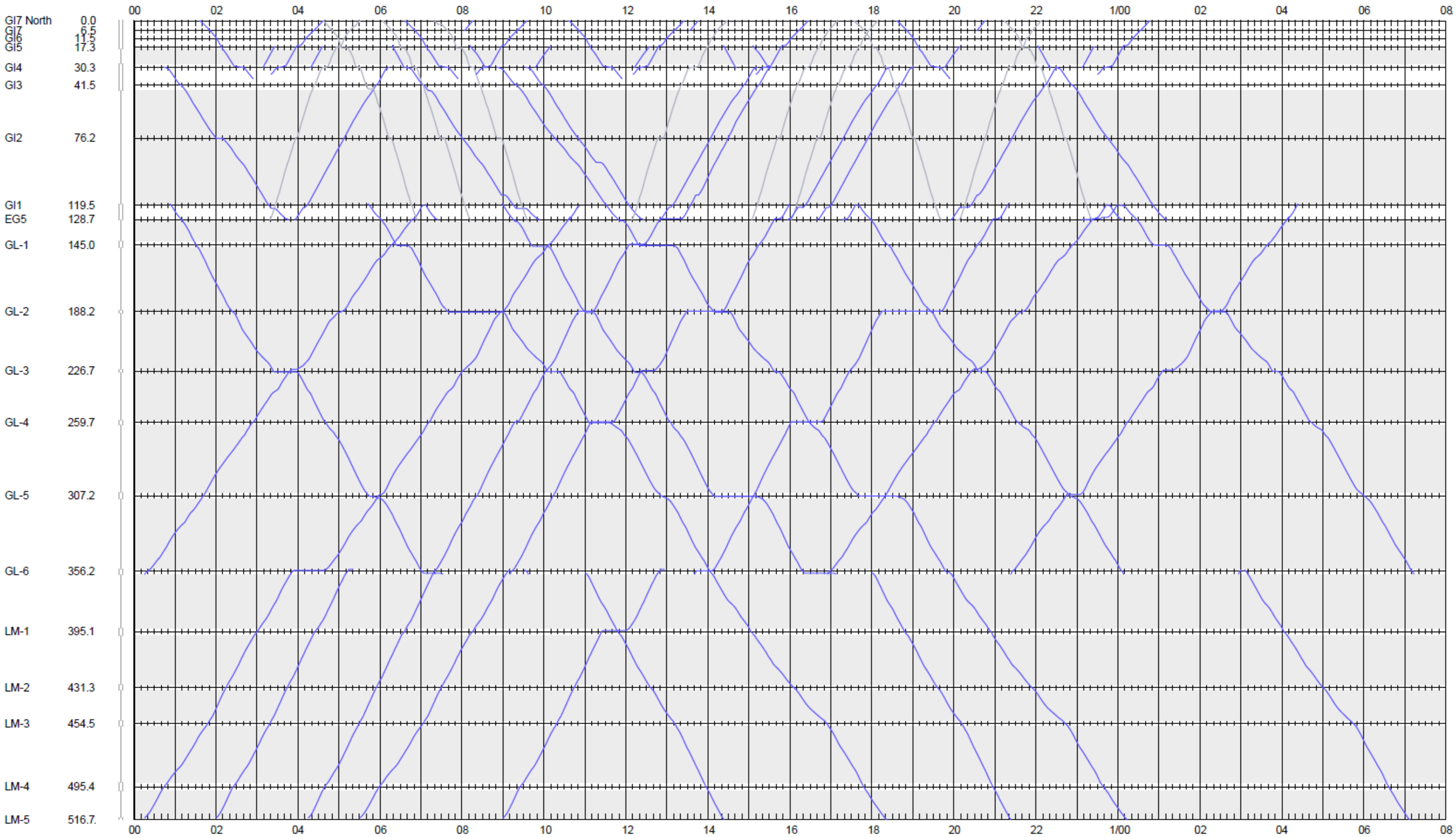

Figure A-13. Stringline results for Scenario 2 on section I-G-L-M assuming ABS for freight trains with CS systems

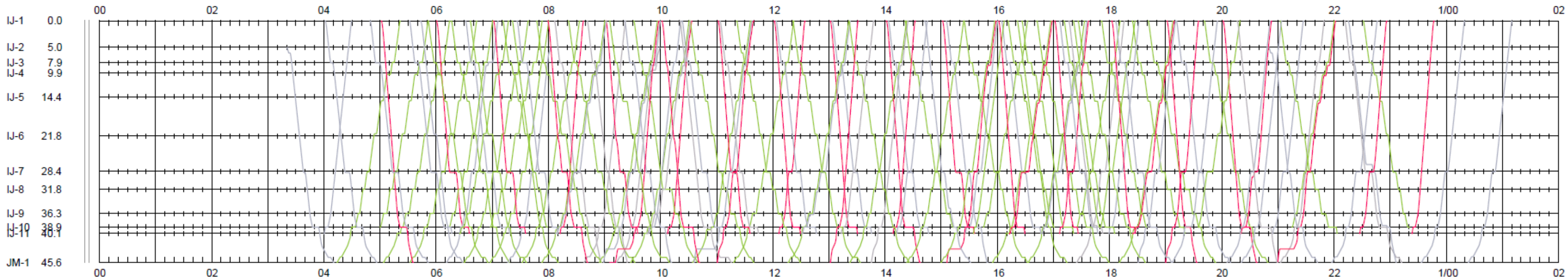

Figure A-14. Stringline results for Scenario 2 on section I-J assuming ABS for freight trains with CS systems

A.4 Additional Stringline Diagrams for Scenario 6

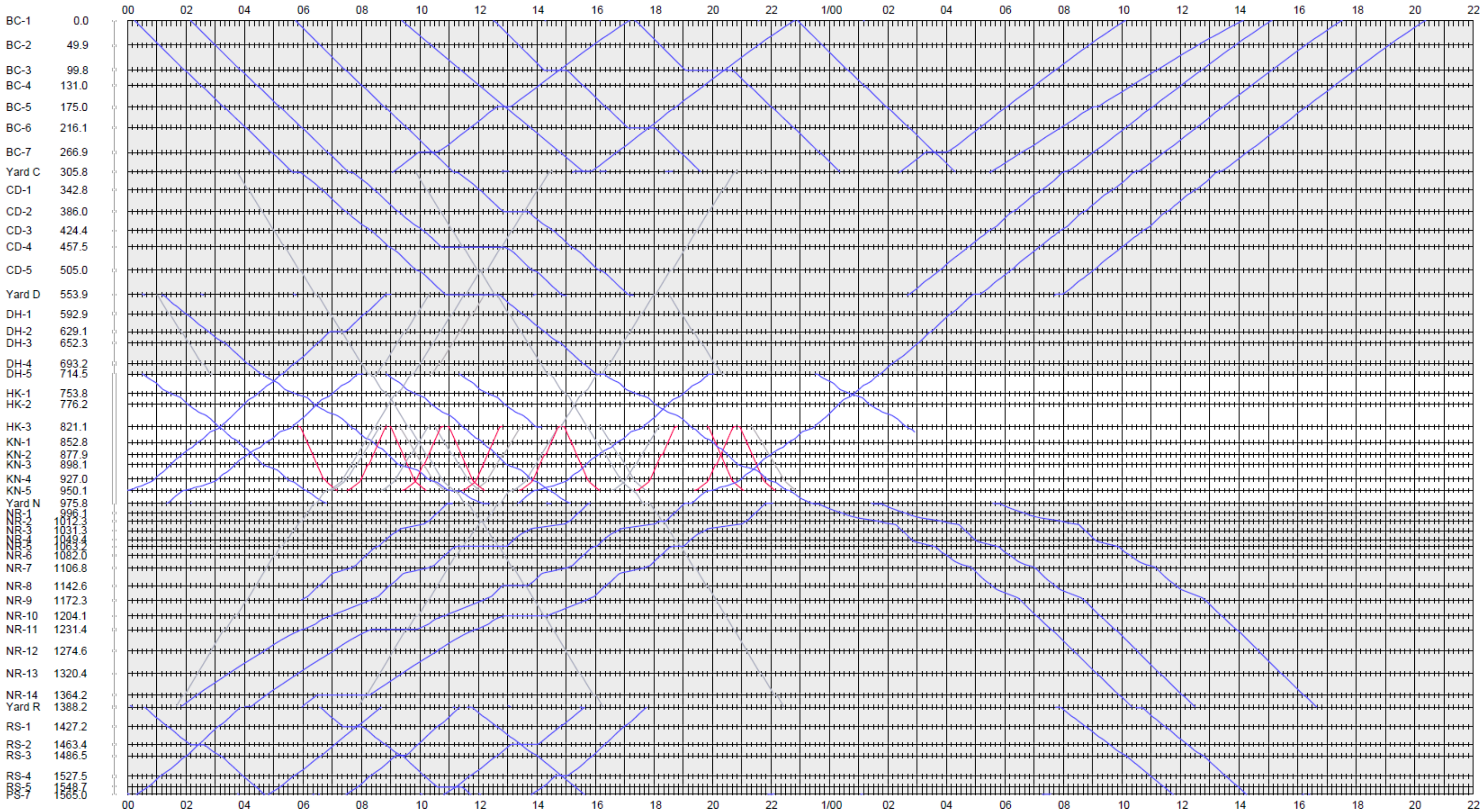

Figure A-15. Stringline results for Scenario 6 on section B-C-D-H-K-N-R-S assuming CBS for freight trains and PTC signaling system

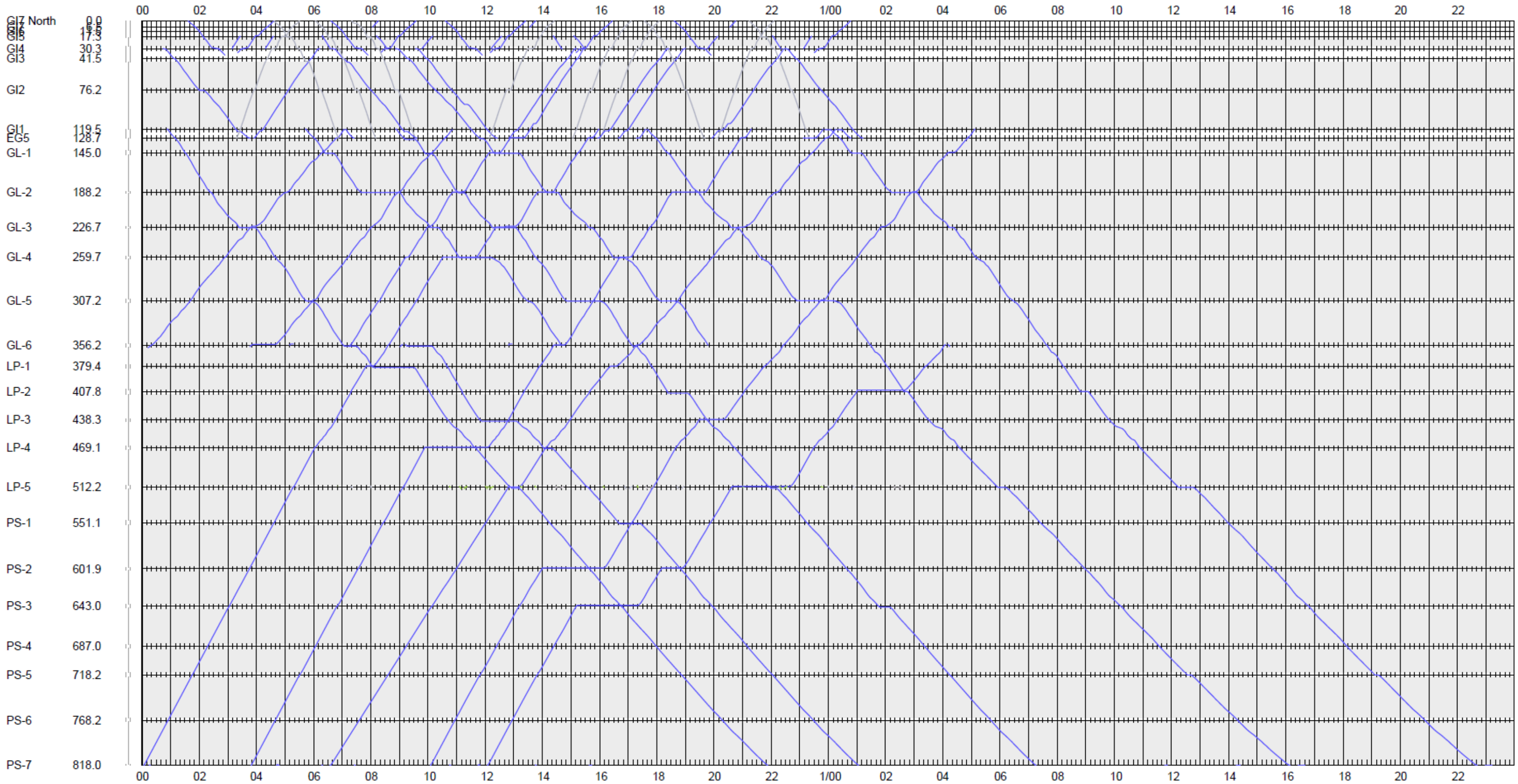

Figure A-16. Stringline results for Scenario 6 on section I-G-L-P-S assuming CBS for freight trains and PTC signaling system

A.5 Additional Stringline Diagrams for Scenario 7

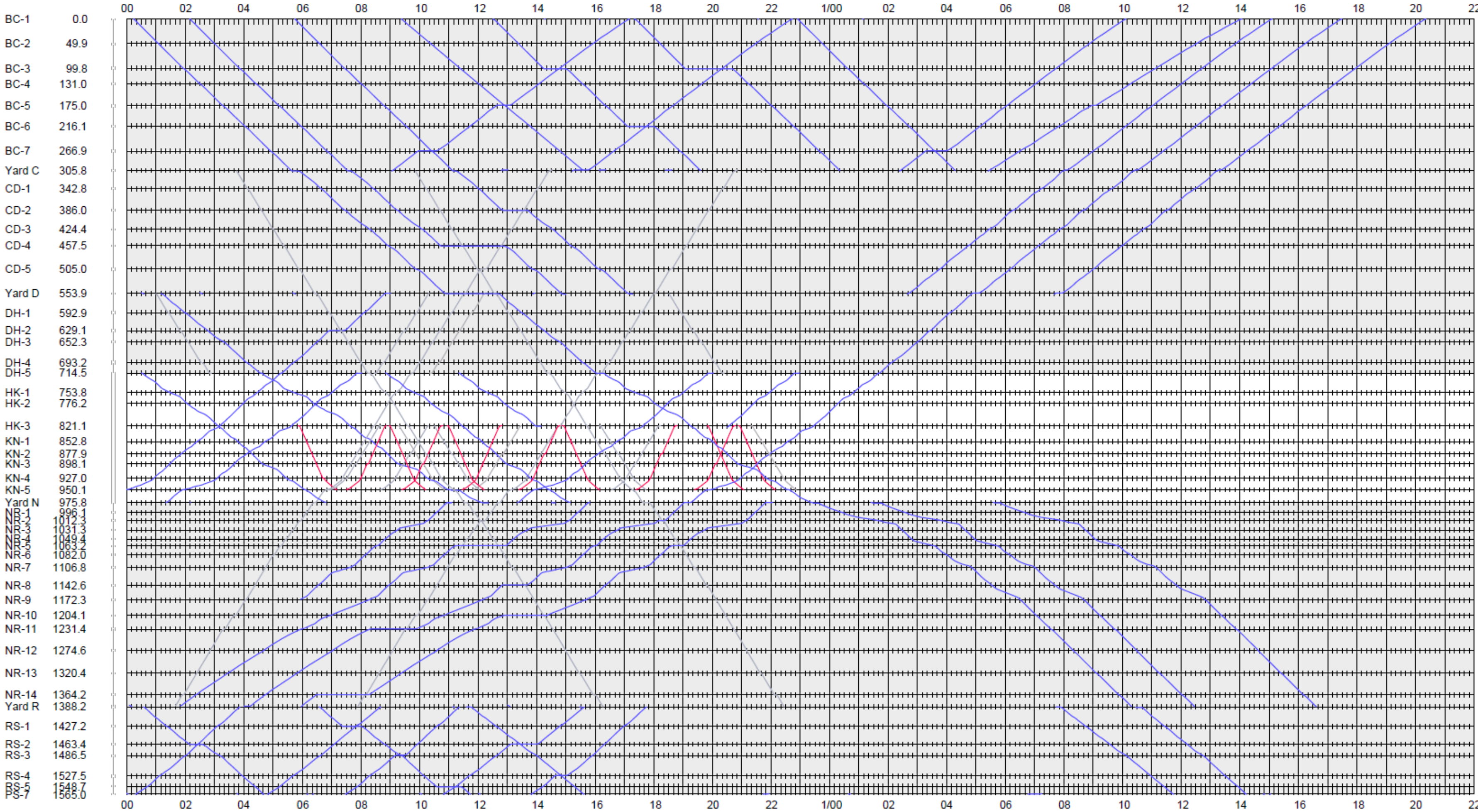

Figure A-17. Stringline results for Scenario 7 on section B-C-D-H-K-N-R-S assuming ABS for freight trains and PTC signaling system

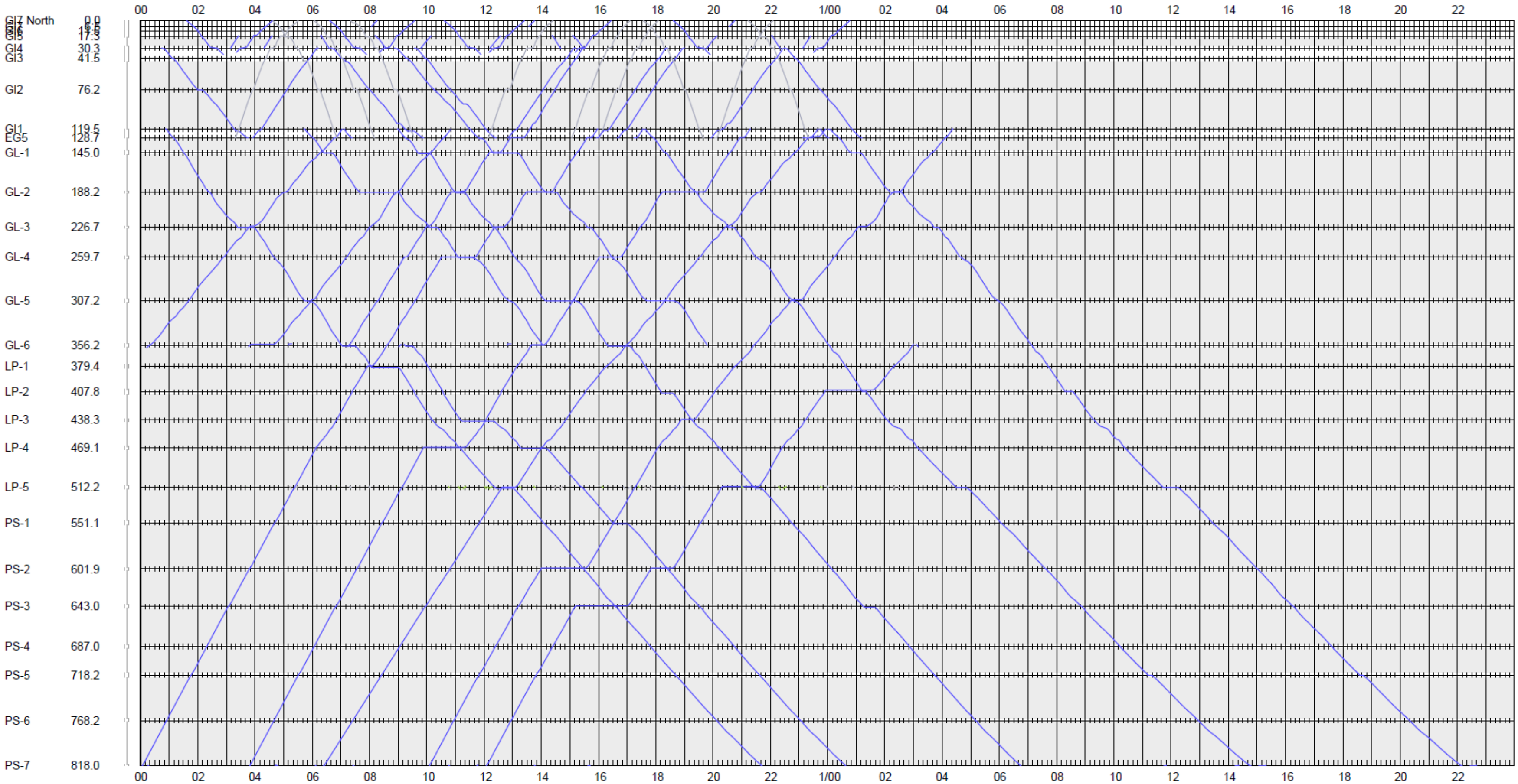

Figure A-18. Stringline results for Scenario 7 on section I-G-L-P-S assuming ABS for freight trains and PTC signaling system

A.6 Performance Plots for Selected Trains

A.6.1 A Freight Train with CBS and CS System

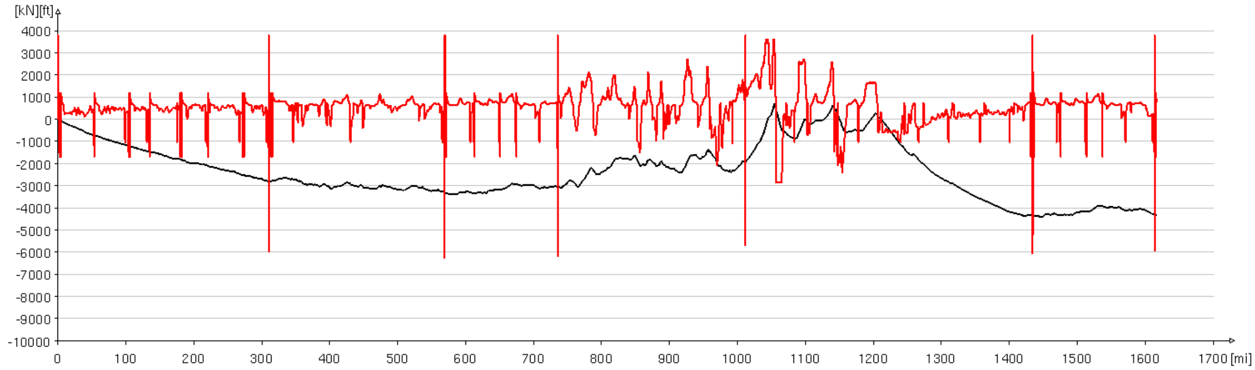

Figure A-19. Track elevation (black line) and tractive effort (red line) of simulated freight train "UnitDP1-020-1" with CBS and CS system

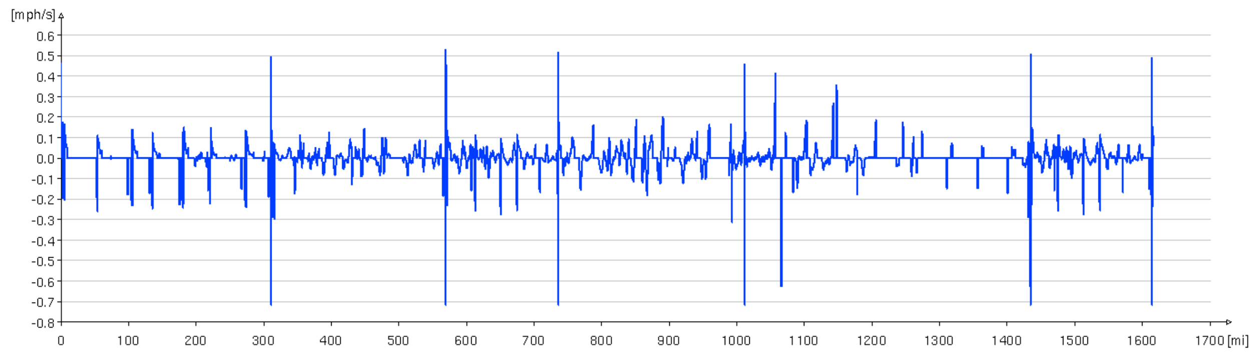

Figure A-20. Acceleration profile of simulated freight train "UnitDP1-020-1" with CBS and CS system

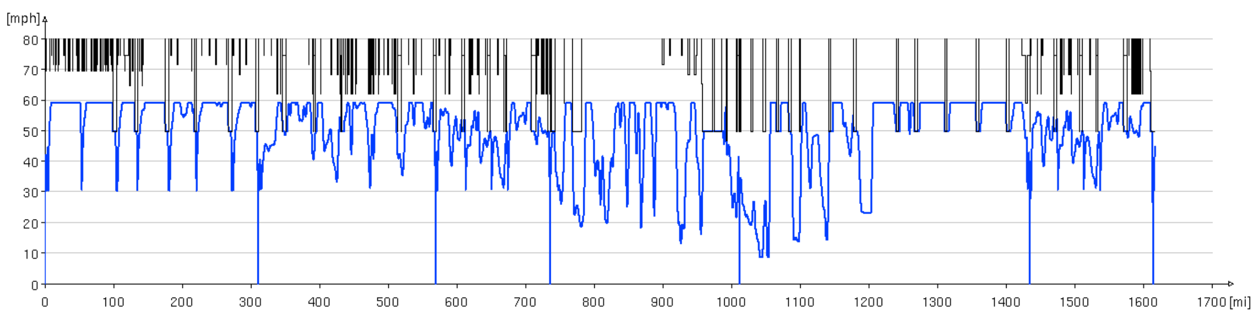

Figure A-21. Speed profile (blue line) and track speed limit (black line) of simulated freight train "UnitDP1-020-1" with CBS and CS system

A.6.2 A Freight Train with CBS and PTC Signaling System

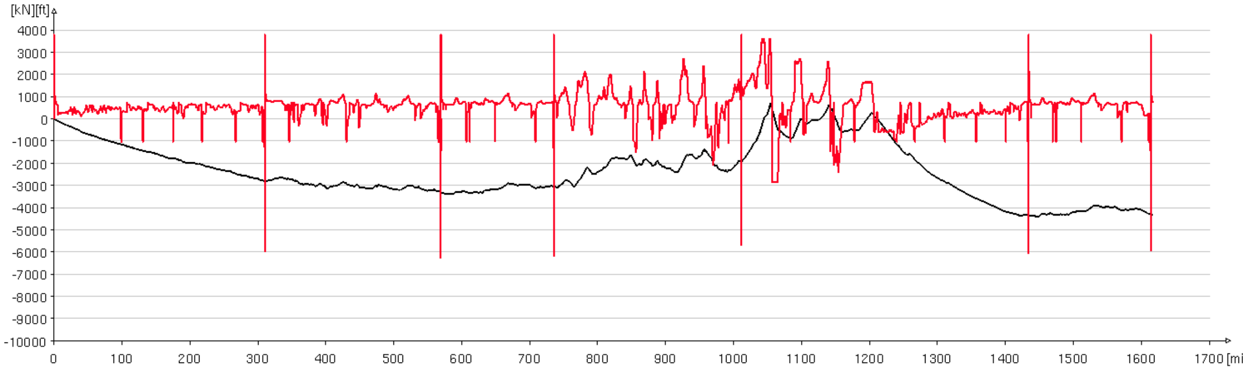

Figure A-22. Track elevation (black line) and tractive effort (red line) of simulated freight train "UnitDP1-020-1" with CBS and PTC signaling system

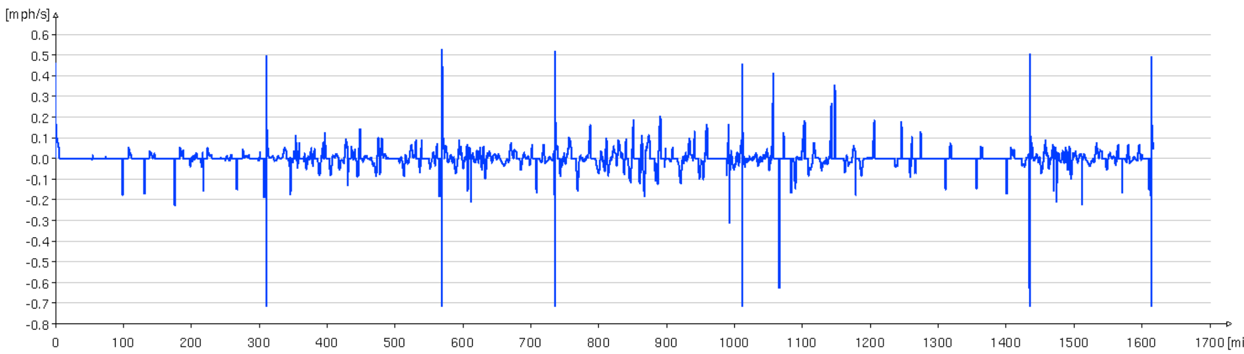

Figure A-23. Acceleration profile of simulated freight train "UnitDP1-020-1" with CBS and PTC signaling system

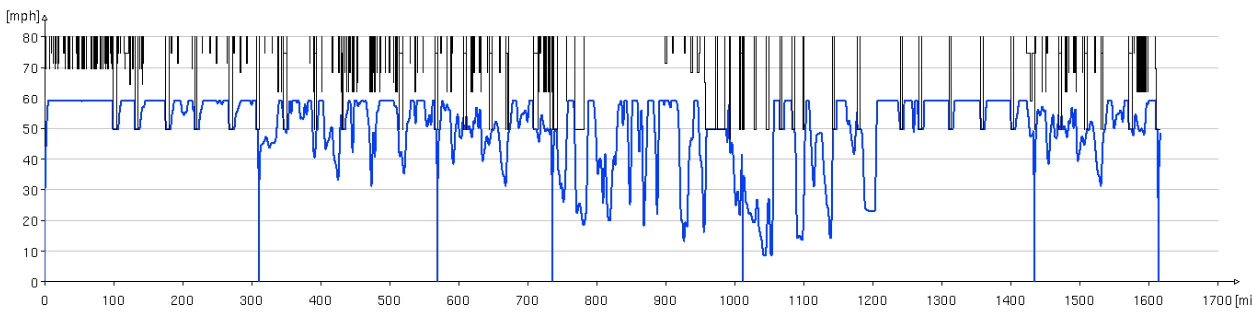

Figure A-24. Speed profile (blue line) and track speed limit (black line) of simulated freight train "UnitDP1-020-1" with CBS and PTC signaling system

A.6.3 A Freight Train with ABS and CS System

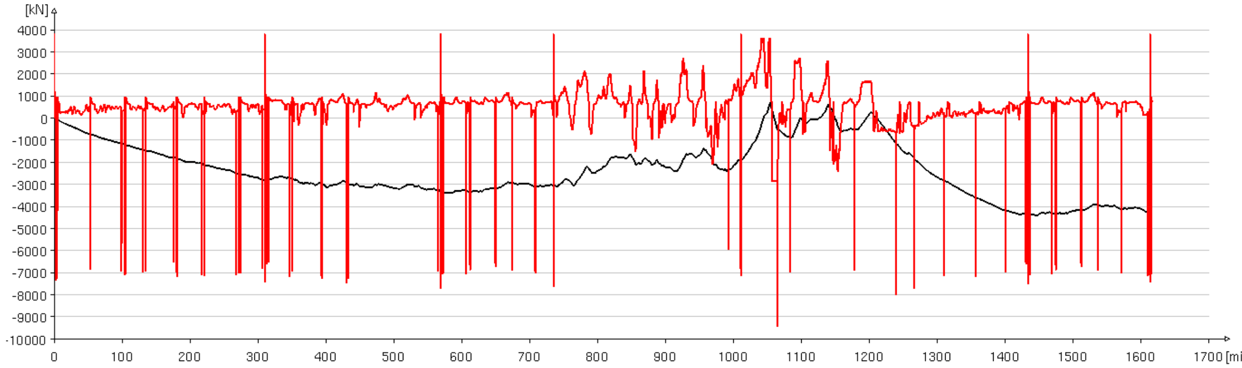

Figure A-25. Track elevation (black line) and tractive effort (red line) of simulated freight train "UnitDP1-020-1" with ABS and CS system

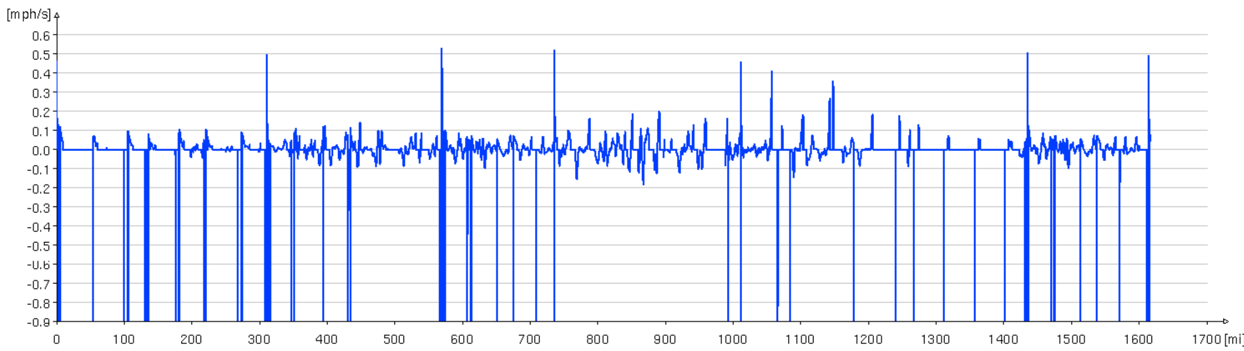

Figure A-26. Acceleration profile of simulated freight train "UnitDP1-020-1" with ABS and CS system

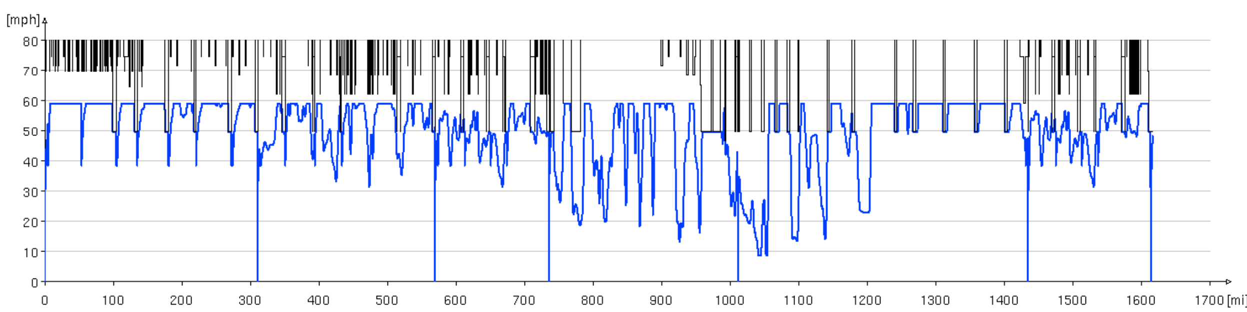

Figure A-27. Speed profile (blue line) and track speed limit (black line) of simulated freight train "UnitDP1-020-1" with ABS and CS system

A.6.4 A Freight Train with ABS and PTC Signaling System

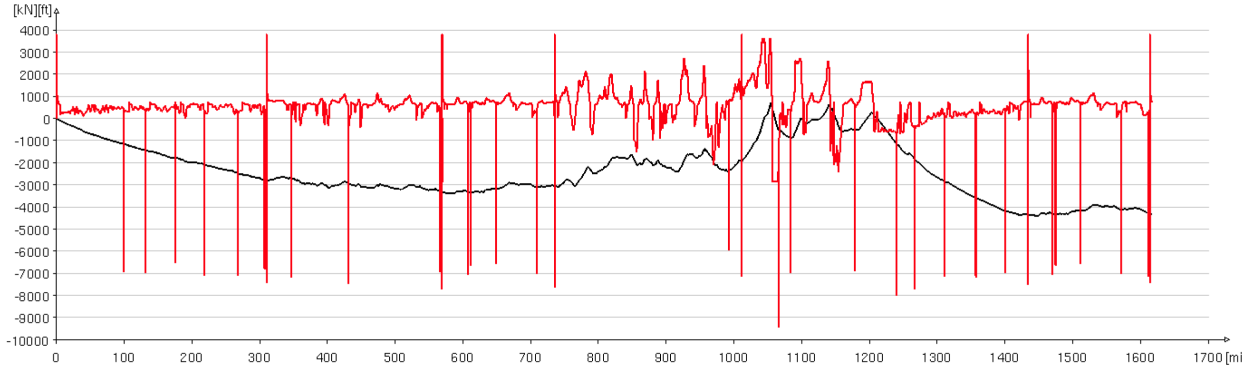

Figure A-28. Track elevation (black line) and tractive effort (red line) of simulated freight train "UnitDP1-020-1" with ABS and PTC signaling system

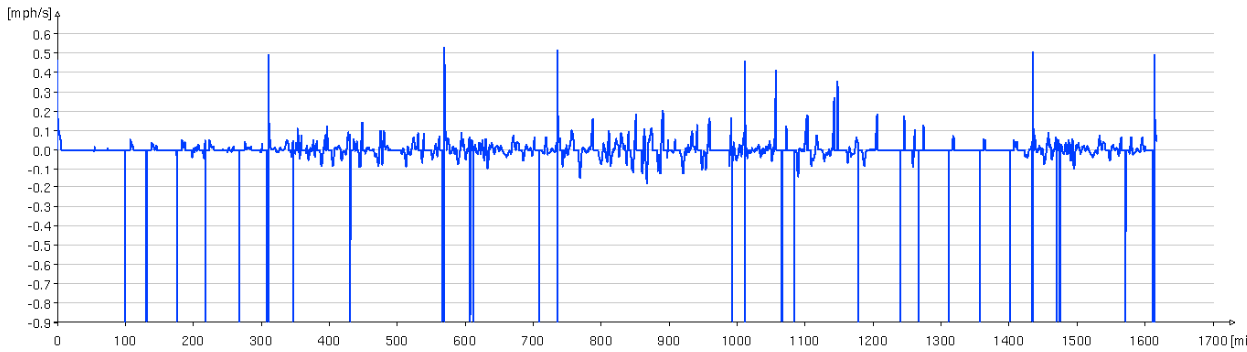

Figure A-29. Acceleration profile of simulated freight train "UnitDP1-020-1" with ABS and PTC signaling system

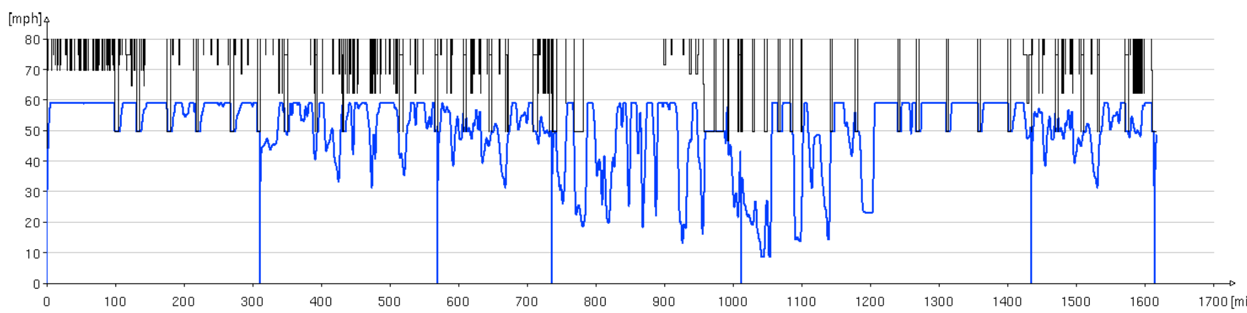

Figure A-30. Speed profile (blue line) and track speed limit (black line) of simulated freight train "UnitDP1-020-1" with ABS and PTC signaling system

A.6.5 A Passenger Train with CS System

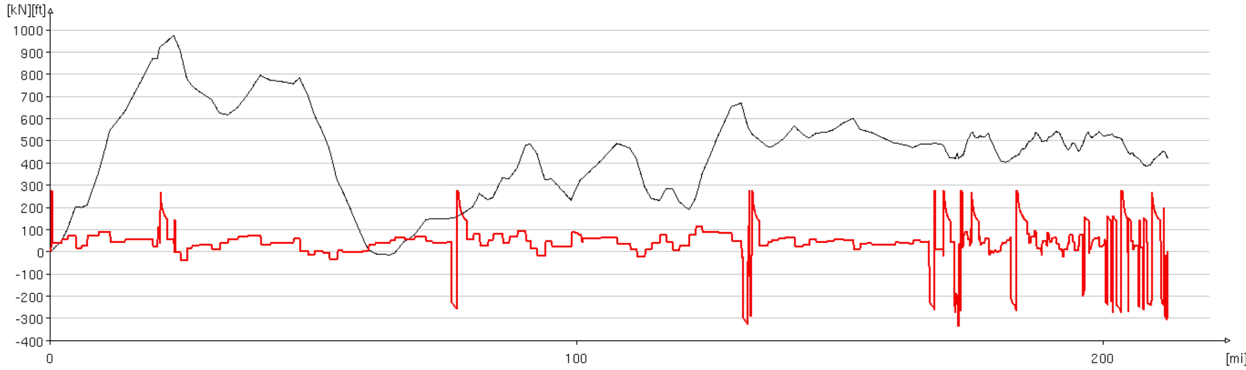

Figure A-31. Track elevation (black line) and tractive effort (red line) of simulated passenger train "Reg 185_KN" with CS system

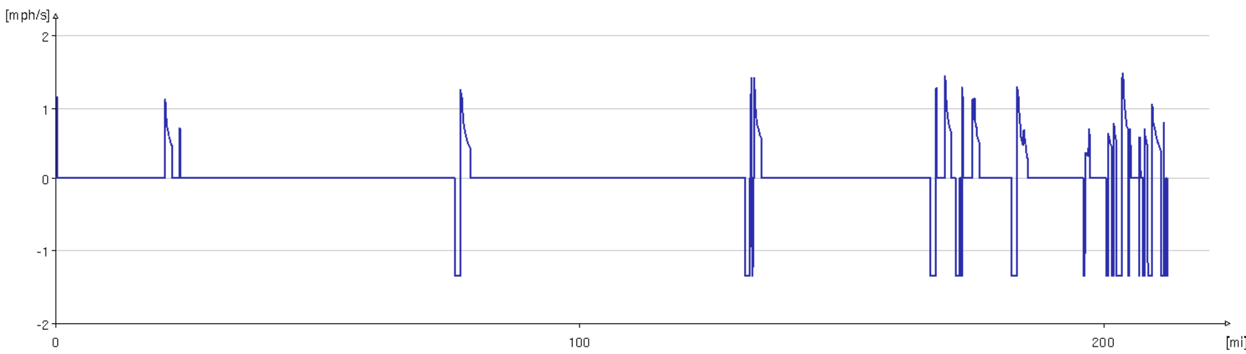

Figure A-32. Acceleration profile of simulated passenger train "Reg 185_KN" with CS system

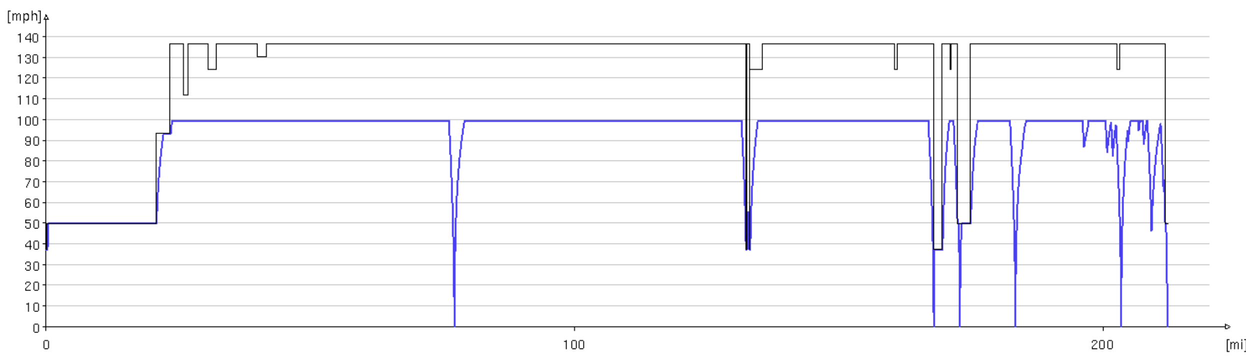

Figure A-33. Speed profile (blue line) and track speed limit (black line) of simulated passenger train "Reg 185_KN" with CS system

A.6.6 A Passenger Train with PTC Signaling System

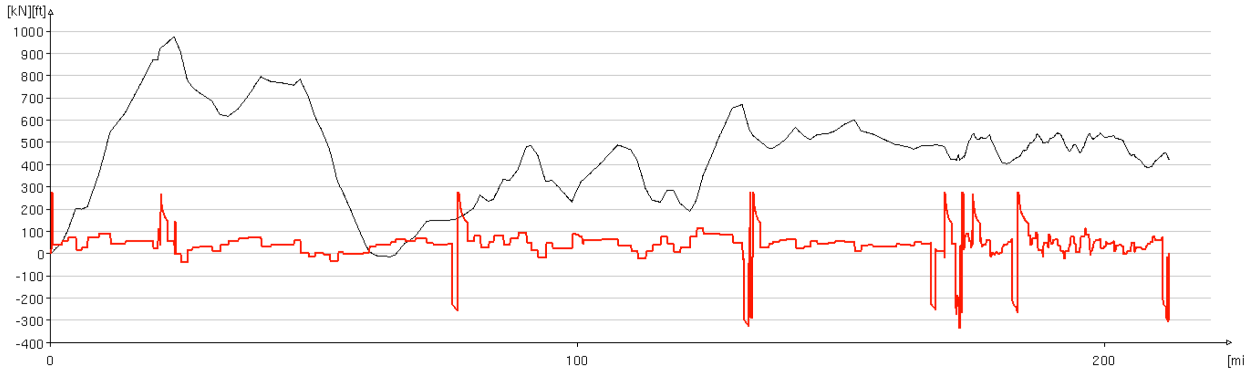

Figure A-34. Track elevation (black line) and tractive effort (red line) of simulated passenger train "Reg 185_KN" with PTC signaling system

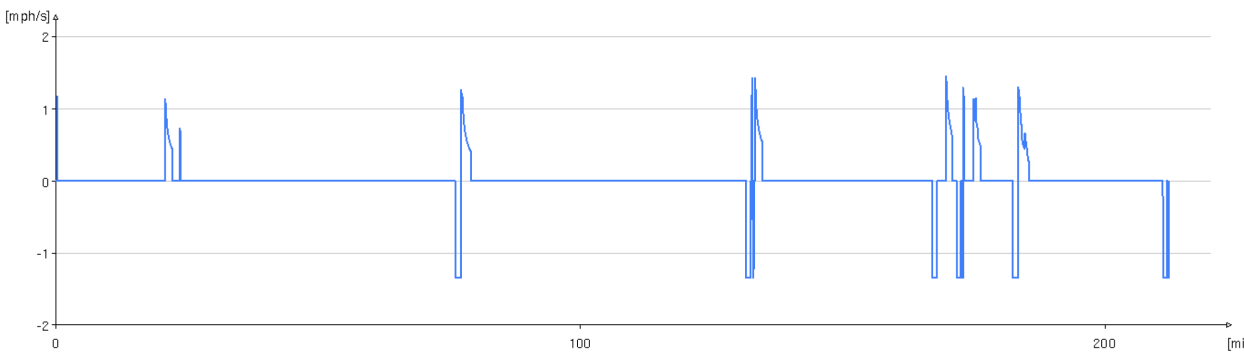

Figure A-35. Acceleration profile of simulated passenger train "Reg 185_KN" with PTC signaling system

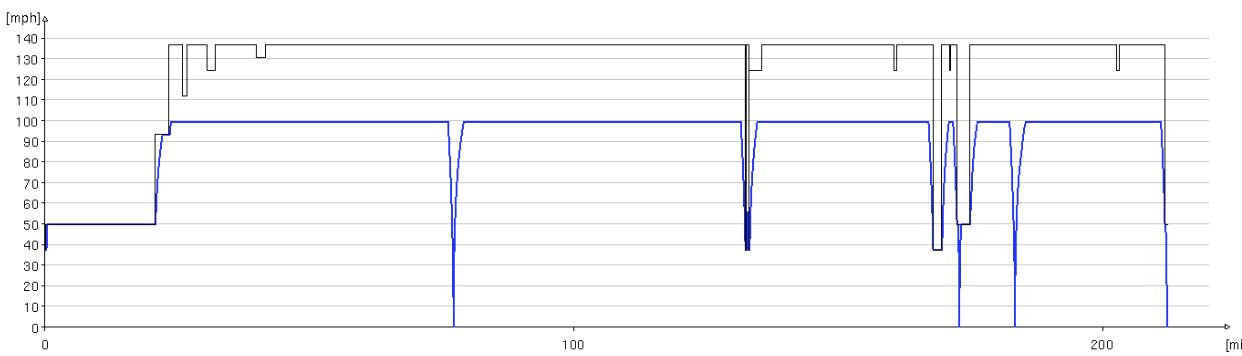

Figure A-36. Speed profile (blue line) and track speed limit (black line) of simulated passenger train "Reg 185_KN" with PTC signaling system

A.6.7 A Commuter Train with CS System

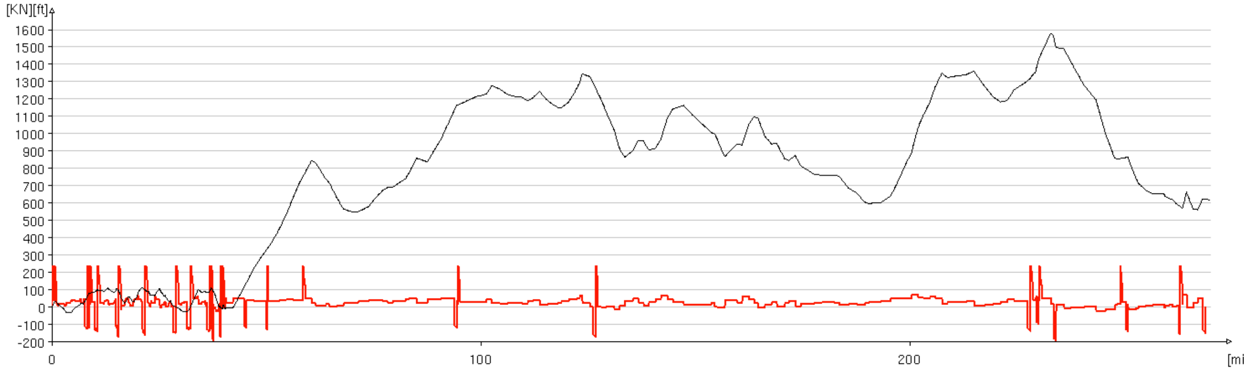

Figure A-37. Track elevation (black line) and tractive effort (red line) of simulated commuter train "Comm_634_J" with CS system

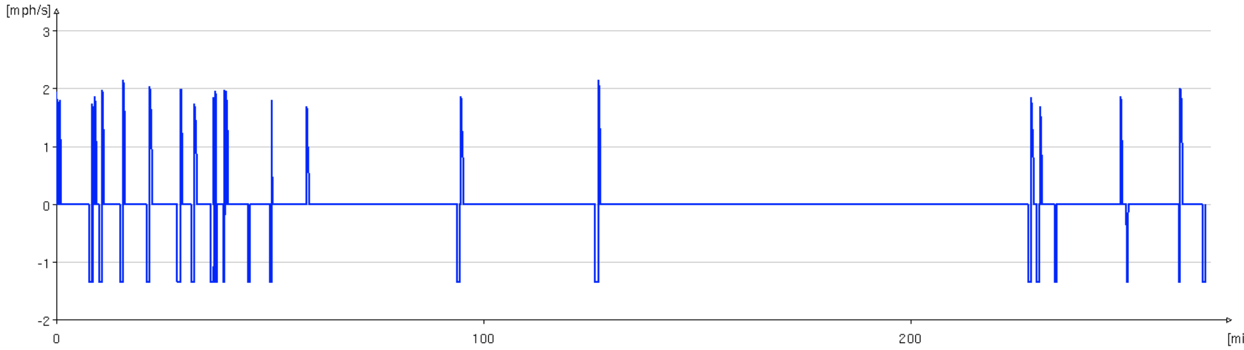

Figure A-38. Acceleration profile of simulated commuter train "Comm_634_J" with CS system

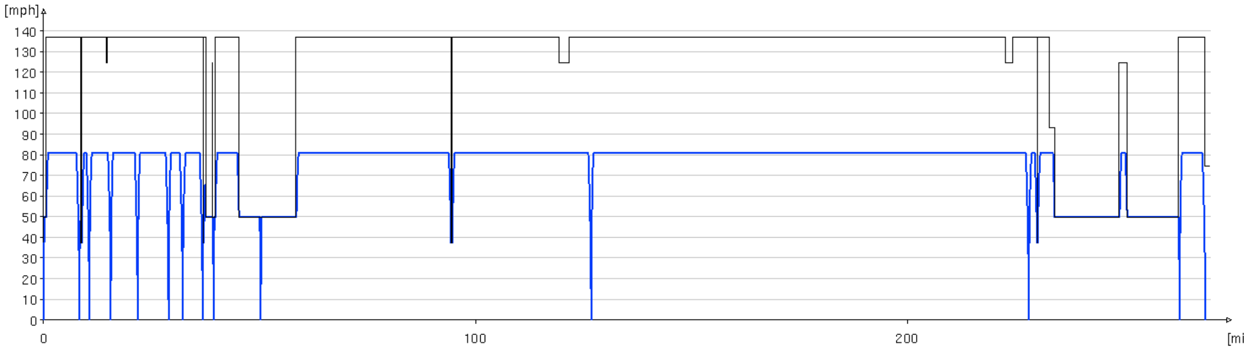

Figure A-39. Speed profile (blue line) and track speed limit (black line) of simulated commuter train "Comm_634_J" with CS system

A.6.8 A Commuter Train with PTC Signaling System

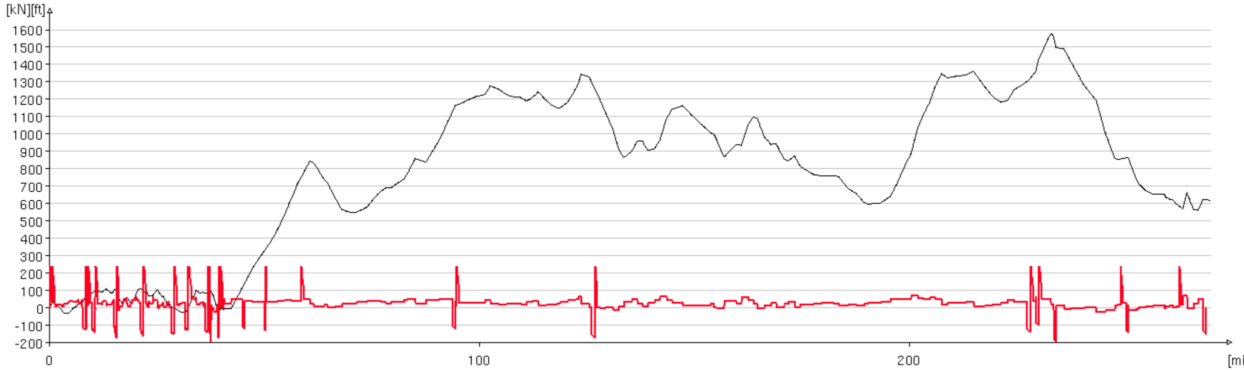

Figure A-40. Track elevation (black line) and tractive effort (red line) of simulated commuter train "Comm_634_J" with PTC signaling system

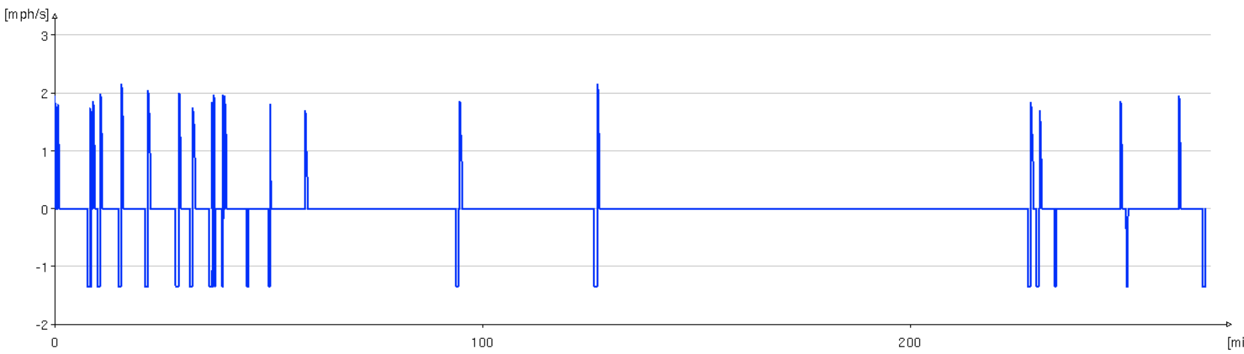

Figure A-41. Acceleration profile of simulated commuter train "Comm_634_J" with PTC signaling system

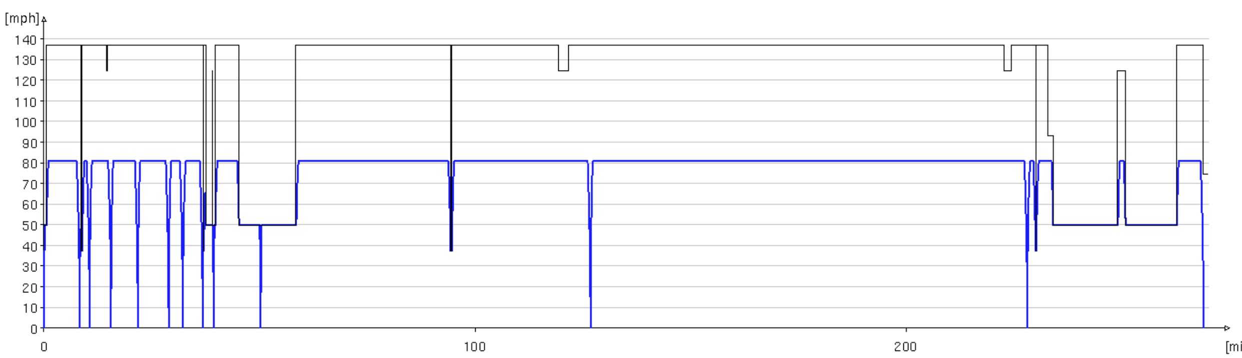

Figure A-42. Speed profile (blue line) and track speed limit (black line) of simulated commuter train "Comm_634_J" with PTC signaling system

A.6.9 A HSR Train with CS System

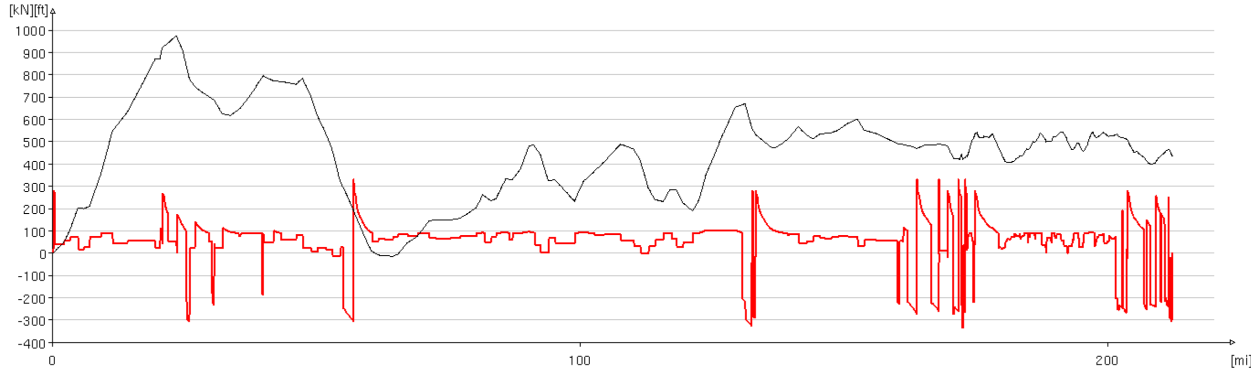

Figure A-43. Track elevation (black line) and tractive effort (red line) of simulated HSR train "HSR2107_KN" with CS system

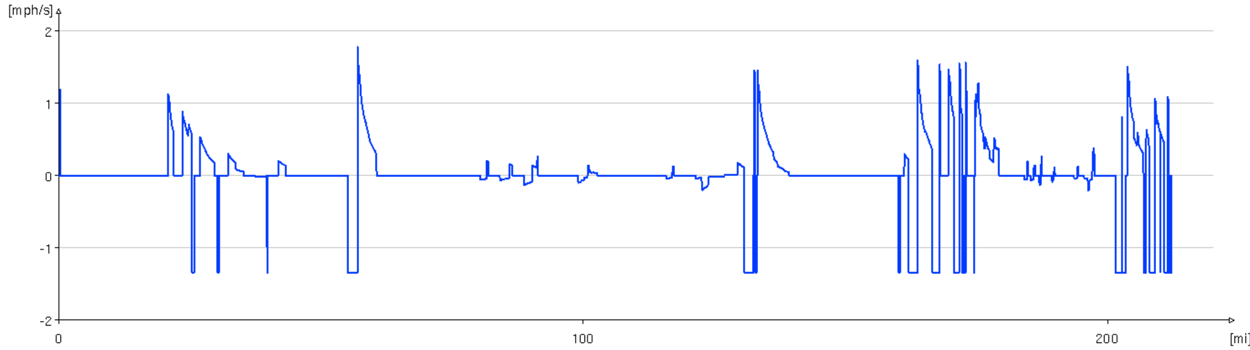

Figure A-44. Acceleration profile of simulated HSR train "HSR2107_KN" with CS system

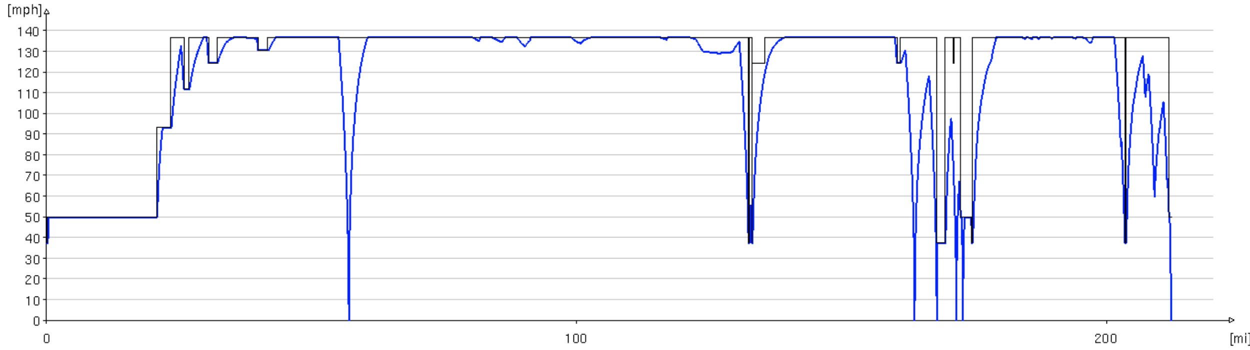

Figure A-45. Speed profile (blue line) and track speed limit (black line) of simulated HSR train "HSR2107_KN" with CS system

A.6.10 A HSR Train with PTC Signaling System

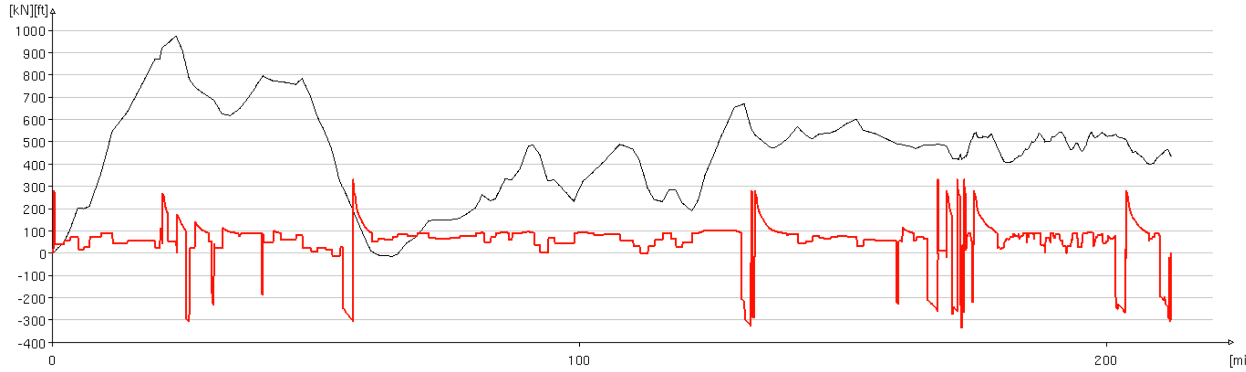

Figure A-46. Track elevation (black line) and tractive effort (red line) of simulated HSR train "HSR2107_KN" with PTC signaling system

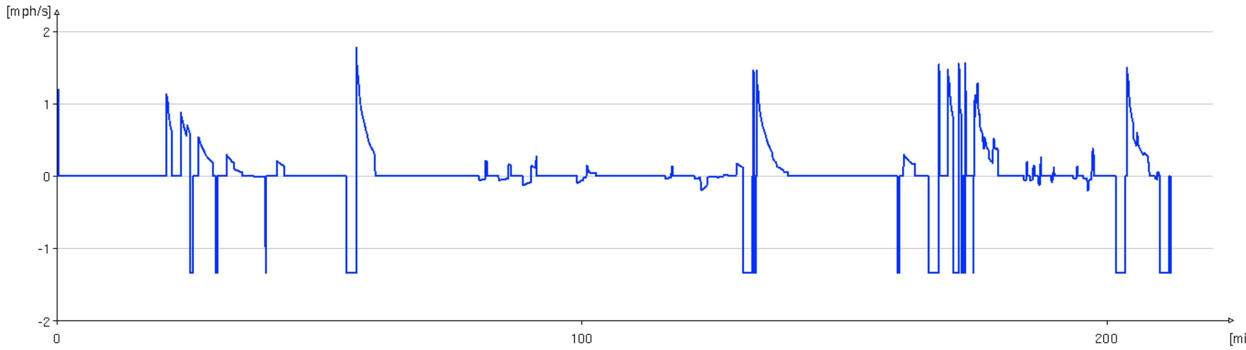

Figure A-47. Acceleration profile of simulated HSR train "HSR2107_KN" with PTC signaling system

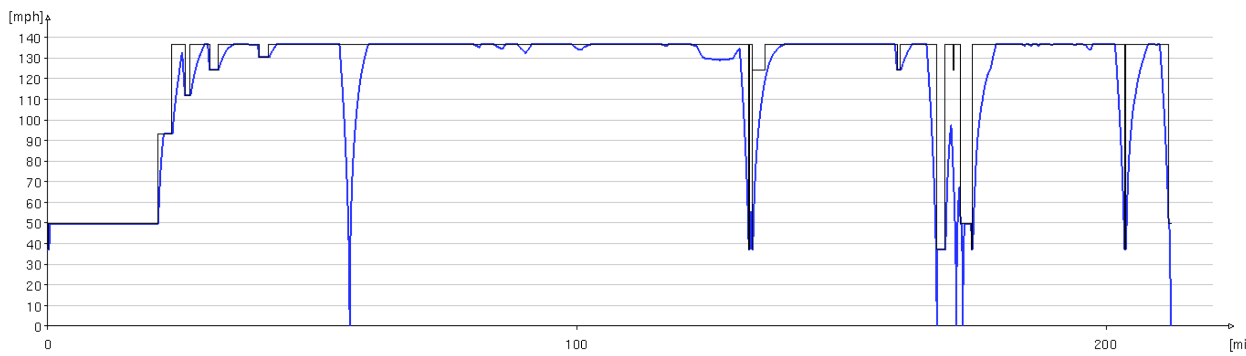

Figure A-48. Speed profile (blue line) and track speed limit (black line) of simulated HSR train "HSR2107_KN" with PTC signaling system