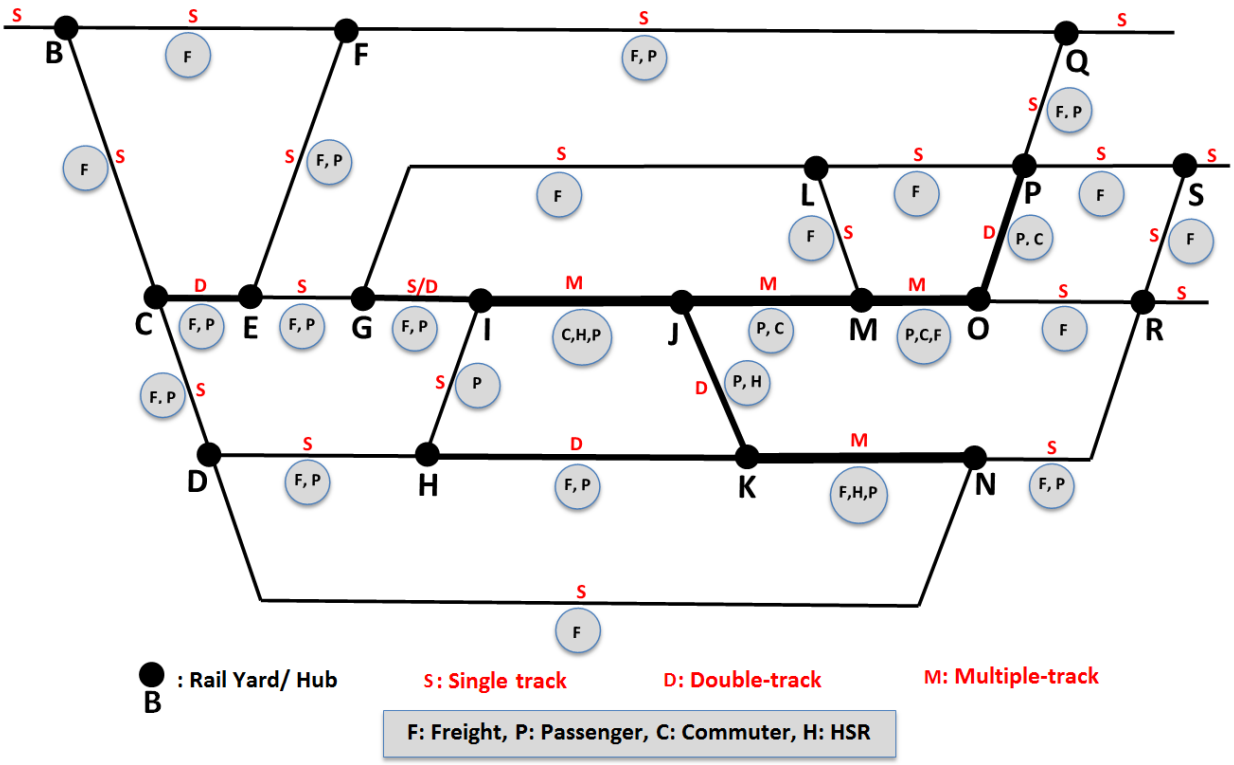
U.S. Department of Transportation
Federal Railroad Administration

Office of Research, Development and Technology
Washington, DC 20590

Impact of an Advanced Braking System over Rail Network Operational Parameters



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The Federal Railroad Administration (FRA) contracted with Sharma & Associates (SA) to evaluate the impact of implementing an advanced braking system (e.g., Electronically Controlled Pneumatic (ECP) brakes) on freight trains in the U.S. rail network. The research team used a mini-network to simulate the effects of the braking system on network operation performance parameters and scaled the mini-network results to the full size of the U.S. freight network.

The results showed improvement in network capacity and safety parameters using advanced braking systems on freight trains. Researchers observed the highest degree of improvement in reducing the amount of network delay by 41.1 percent, while results were lower for route reservation at signals (24.3 percent reduction) and the number of unnecessary stops at signals (4.4 percent reduction). The team noticed only minor improvement in increasing network velocity (0.8 percent) and number of station stops (0.5 percent), though the operational and financial impacts of these enhancements are not negligible.

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Executive Summary

The Federal Railroad Administration (FRA) contracted with Sharma & Associates to evaluate the impact of implementing an advanced braking system (e.g., Electronically Controlled Pneumatic (ECP) brakes) on freight trains in the U.S. rail network. The research team used a mini-network to simulate the effects of the braking system on network operation performance parameters and scaled the mini-network results to the full size of the U.S. freight network.

The results showed improvement in network capacity and safety parameters using advanced braking systems on freight trains. Researchers observed the highest degree of improvement in reducing the amount of network delay by 41.1 percent, while results were lower for route reservation at signals (24.3 percent reduction) and number of unnecessary stops at signals (4.4 percent reduction). The team saw only minor improvement in increasing network velocity (0.8 percent) and number of station stops (0.5 percent), though the operational and financial impacts of these enhancements are not negligible.

The research team used OpenTrack®, a widely used network simulation software, to design a hypothetical mini-network comprised of nearly 5,000 miles of mainline tracks and 150 sidings/yards with characteristics similar to the North American rail network.

The team simulated traffic using 232 daily trains with a mix of intercity passenger, commuter, high-speed rail (HSR), and freight services. The simulation included 78 daily freight trains representative of 17 different train configurations, such as head-end power and distributed power, number of total locomotives, train tonnage, and length.

Researchers then developed three simulation scenarios over the hypothetical mini-network to analyze the impact of deploying an advanced braking system for freight trains over the network capacity and safety features. The team simulated all three scenarios using the same assumptions and network model characteristics except for the braking characteristics of freight trains.

Finally, the team extended the results of the simulation scenarios conducted over the benchmark network to the real size of the U.S. rail network, assuming certain expansion parameters and impact factors such as total length of tracks, freight train-miles, number of siding/yards, congestion level, and age of fleets.

When the research team compared the results of Scenarios 1 and 2, they concluded the first scenario (i.e., freight trains with ECP braking system) provided much better results in terms of network delay and number of braking actions for route reservations, with approximately 22 percent and 11 percent improvement, respectively. Researchers also observed a reduction in the number of unnecessary stops at signals (about 2 percent) in Scenario 1, but the improvement of network velocity and number of stops at stations was less than 1 percent over Scenario 2.

When evaluating the results of Scenario 3 (with mixed conventional and ECP freight trains) in comparison to the other two scenarios, the team concluded that gradually retrofitting the brake systems of freight trains can relatively improve the results of train delays and the number of unnecessary stops at signals. However, it may not provide any major improvements in terms of other network capacity and safety features unless the entire freight fleet (or at least a major portion of it) are retrofitted with advanced braking systems. It should be noted that the team observed no difference in terms of track utilization rates between the scenarios of this study.

1. Introduction

The Federal Railroad Administration (FRA) contracted with Sharma & Associates to evaluate the impact of implementing an advanced braking system (e.g., Electronically Controlled Pneumatic (ECP) brakes) on freight trains in the U.S. rail network. The research team used a mini-network to simulate the effects of the braking system on network operation performance parameters and scaled the mini-network results to the full size of the U.S. freight network.

1.1 Background

FRA's Railroad Policy and Development (RPD) program seeks to ensure the safe, efficient, and reliable movement of people and goods by rail transportation through basic and applied research and development of innovative solutions and technology implementation.

Technology implementations may be driven by a variety of safety and efficiency needs. While some of the technologies' safety benefits and costs might be readily quantifiable, the upsides or downsides of the technologies' implementation on network risk and capacity are not quantified reliably, but nonetheless are crucial for acceptance and implementation.

Over the last decades, there have been major technology initiatives in the railroad industry to improve the operational safety as well as performance of freight rail equipment in shared corridors. Among these, two major technologies have been in public discussion: Electronically Controlled Pneumatic (ECP) brakes and Positive Train Control (PTC) [1]. The ECP system has been under development and evaluation for a longer period than the PTC system and has reached a maturation level where it has been tested by several railroads in North American and deployed by some major railroads across the world [2, 3, 4, 5, 6].

1.1.1 Conventional Braking System

Freight car braking systems use compressed air stored in a local reservoir on each car to produce the necessary application force between the brake shoe and wheel, resulting in train braking. This air is generated by a locomotive compressor and sent 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 also transmitted through the brake pipe by reducing or increasing the pressure in the pipe. The pneumatic brakes are relatively sophisticated and have evolved since their inception nearly 150 years ago with continuous, incremental improvements to increase the signal propagation speed. Features such as accelerated service release (introduced in the ABD valve) and accelerated application (ABDW and ABDX valves by Wabtec and DB-60 valves by Knorr) have provided steady improvements in the air brake system response.

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

1.1.2 ECP Braking System

ECP brakes, a relatively new system, also use compressed air delivered via the brake pipe and stored locally to provide the brake actuation force. The essential difference, however, is that electronic signaling and control is used instead of a pneumatic signal to control ECP brakes. In place of the pneumatic control valve, the car control device (CCD), an electronic processor responding to digital commands, directly controls the brake cylinder pressure at each car. Digital brake command signals and power to operate the CCDs originate at the lead locomotive and are conveyed to each car via an electric cable running the length of the train (i.e., the ECP trainline).

Signal propagation with ECP brakes is essentially instantaneous; a braking command issued from the lead locomotive is received at each vehicle in the train simultaneously. In addition, since the CCD at each car uses closed-loop feedback to control its brake cylinder pressure, the braking force build-up at each car is relatively uniform, thereby minimizing inter-car coupler forces from the disparate braking rates between cars. Unlike conventional pneumatic brakes, ECP brakes can be released in gradual steps. Since the brake pipe is not used to convey braking signals, the car reservoirs are continuously charged whether the brakes are applied or not, and both ECP reservoirs are always connected. These characteristics make ECP brakes much more controllable than the conventional pneumatic system. The ECP system includes the following advantages:

- Permits faster and shorter stops, as well as quicker returns to operating speed after stopping
- Reduces or eliminates the need for cycle braking and power braking practices, thereby improving fuel efficiency
- Provides more intuitive operation
- Reduces training requirements for new engineers

ECP brake operation derived from the uniformity of braking rates and consequent minimization of coupler forces throughout the train also provides benefits such as enhanced safety against derailments, fatigue life extension of structural components, and reduced pile-up damage resulting from derailment with train separation.

1.2 Objectives

The goal of this study was to develop a “mini-network” with representative characteristics of the North American rail system to analyze the possible benefit of operating freight trains with advanced braking systems (e.g., ECP) over conventional braking systems in terms of network capacity parameters and safety indices. The results of the hypothetical mini-network were eventually extended to the U.S. rail network for further advanced analysis.

1.3 Overall Approach

To conduct the proposed study, the research team used a network simulation tool capable of modeling conventional and ECP braking systems, as well as various types of signaling systems. The team selected OpenTrack®, a widely used network simulation software, to evaluate network velocity and capacity characteristics in a hypothetical mini-network with over 5,000 miles of tracks.

Researchers analyzed several parameters relating to capacity and network, including train delay, train conflicts, train speed, network velocity, track utilization level, number of meet-passes and stops, safety, and accident mitigation levels.

The team planned three simulation scenarios on various types of corridors, including mixed freight and passenger traffic. It should be noted that shared-use corridors with congested freight and passenger traffic may have a higher risk of accidents particularly when service disruptions occur [7, 8]. Therefore, any solution that would increase the capacity, service reliability, and train handling along these corridors, including ECP or Distributed Power (DP) technologies, could provide more headway between train arrival and departure times, and eventually reduce the risk of train accidents [9].

The simulation scenarios conducted in this study were:

- **Scenario 1:** freight trains with an advanced braking system (e.g., ECP)
- **Scenario 2:** freight trains with conventional braking systems comprised of a head end power consist and trains with distributed power
- **Scenario 3:** mixed advanced/conventional practices (i.e., 50 percent freight trains with ECP brake system)

In all the scenarios, the team kept the train configuration and braking characteristics of passenger, commuter, and high-speed rail (HSR) trains the same, as the focus of this study was to analyze the impact of freight train brake characteristics over the network capacity and safety indices. Each simulation scenario contained the same assumptions and input models in terms of trains, infrastructure, train routes, dispatching rules, initial train schedules, signaling characteristics, etc. The only differences were the braking characteristics of freight trains.

1.4 Report Structure

This report is structured based on the following sections:

- Section 2 explains simulation assumptions and input models, including the details of tracks, yards/sidings, signals, traffic specifications, train details, dispatching, and operations rules.
- Section 3 reviews simulation results in terms of final train schedules and examines any major differences between the train schedules resulting from operating freight trains with different braking systems.
- Section 4 provides additional details of the simulation results and compares the selected scenarios in terms of train performance (e.g., speed and delay), overall network velocity, network delays, train miles, track utilization levels for critical sections of network, and safety/risk indices of train operations (e.g., number of meet-pass, number of train stops at the signals, and number of unnecessary braking actions).
- Section 5 expands the mini network simulation scenario results to the real size of the U.S. rail network, considering important parameters and assumptions for evaluating the impact of advanced braking systems on freight trains over the network-related characteristics.
- Section 6 summarizes the findings and results of this study.

- Appendix A presents additional simulation model details assumptions, and scenario results used in this study.

2. Network Simulation Input and Assumptions

A rail network simulation is a complex analysis that requires addressing and incorporating various aspects of a railroad system (e.g., network infrastructure, rolling stock, train signaling, and operation details) for the results of the simulation to be acceptable and representative of the existing operating practices.

The research team selected OpenTrack for this study, one of the most trusted rail network simulators. OpenTrack has been deployed by private and public entities around the world (e.g., rail operators, suppliers, government entities, and academia) for simulating the effects of the relevant parameters on network safety and capacity.

The simulation scope parameters for this study were developed in OpenTrack based on the following operations components:

- **Network topology**
  - Single track, double-track, and multiple-track corridors with a variety of track chart characteristics like North American rail practices in terms of grades, curvatures, yards/siding specifications, and complexity in corridor connectivity level
- **Train types**
  - Passenger trains, including intercity, commuter, and HSR trains, as well as various types and configurations of freight trains including local, intermodal, unit (very long trains), and distributed power trains
- **Operating practices**
  - Corridors under dedicated passenger traffic, dedicated freight traffic, and shared-use corridors
- **Braking systems**
  - Freight trains with conventional braking systems (lower deceleration rates due to propagation delay in air brake system, and longer waiting time between release and reapplying brakes), DP freight trains with sharper deceleration rates and less waiting time between brake applications, advanced braking system (e.g. ECP) with much sharper deceleration rates and minimum delay between brake applications compared to conventional freight trains, and different train weights, lengths, and configurations
- **Types of signaling systems**
  - Different conventional signaling systems (a wayside or cab signaling system with two, three, and four aspect signals) and the current PTC signaling system for certain parts of the network, depending on the traffic congestion level

Details of the parameters represented and used in OpenTrack are explained in the following subsections. Further details on the steps and requirements for developing a network simulation study may be found in reference works such as Pachl, 2002 [10], Pouryousef, et al, 2015 [7], Cambridge Systematics, 2007 [11], and Hansen & Pachl, 2008 [12].

2.1 Network Infrastructure and Corridors Characteristics

The U.S. rail network is comprised of approximately 140,000 miles of tracks, in which most of the rail corridors are single track and certain territories are double and multiple track corridors to handle higher volumes of daily traffic [7]. Track gradients and horizontal curves are among the main components of track charts and should be modeled in the simulator since they affect the total train resistance and the traction power required for the train to achieve and maintain the desired operating speed.

Although it is difficult to build a simulation network study for a one as large and complex as the U.S. rail network, the modeled network should include its major characteristics in terms of infrastructure, signaling, train operations, and rolling stock.

Therefore, the mini-network of this study was developed to represent the main backbone of the U.S. rail network, including more single-track corridors than double and multiple-track segments. Other network characteristics of the U.S. rail system were also incorporated in building the mini-network.

Figure 1 shows a schematic map of the mini-network modeled in this study. The parameters of the network are presented in this schematic map, including:

- main yards/rail hubs shown in nodes (e.g., B, C, D)
- main line tracks shown in the links (e.g., B-C, B-F)
- type of traffic (freight, passenger, commuter, and HSR)
- type of corridors (single, double, and multiple-track segments)
- length of each segment between each of two rail yards (in miles)

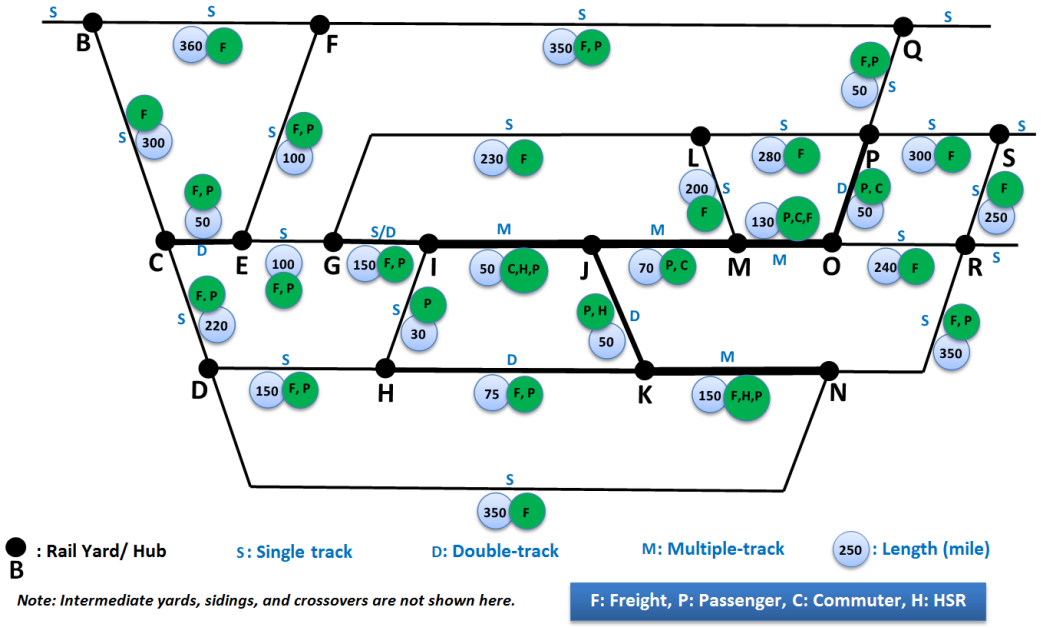


Figure 1. Mini-network showing main rail hubs, tracks, length of tracks, traffic, and corridor types

Figure 2 shows a screenshot of Yard P and its two adjacent sidings which the team built in OpenTrack format. Comparing Figure 2 with the respective part of Figure 1 (segments around Yard P) shows no obvious similarities between the track layouts in these two figures. However, the connectivity and main track layout between different corridors, type of tracks, and type of traffic (Figure 2) match with the ones presented in the schematic map (Figure 1).

Also, as shown in Figure 2, tracks can be developed horizontally or vertically, as the details of each piece of track (e.g., grade, length, curvature, tunnel, grade crossing, mile post, speed limit, etc.) are encoded through each link or node of the track file. Thus, the simulator can calculate train resistance, tractive effort, train speed, acceleration/deceleration, and other train performance parameters regardless of the scale and shape of the links, though it requires a consistent format when building the infrastructure model.

Note: the mini-network map depicted in Figure 2 was developed for illustration purposes only and was not used in the study. The simulation model requires much more detail on the track, yards, and signaling components which were mostly extracted from real track data, including grades, curvatures, and yard/siding locations. The map also does not show the intermediate yards/sidings, nor all the details of the connections, signals, etc. built in OpenTrack as it would be difficult to depict all infrastructural details and track layouts of the network in a single frame.

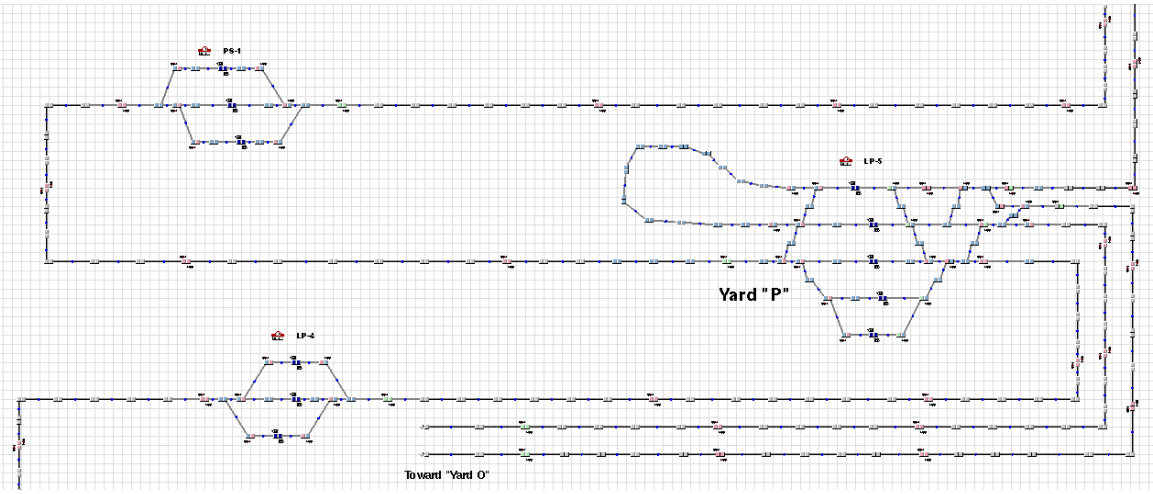


Figure 2. Infrastructure details example in OpenTrack, representing Yard P and two adjacent sidings, with intra-sidings and external network connections around Yard P

Generally speaking, commuter and high speed trains are operated within the central parts of a network with either double or triple-track segments, which have the highest traffic congestion; freight trains do not typically operate along these segments (Figure 1). However, there are certain parts of the network (M-O and K-N) in which the freight trains share the main tracks with commuter and HSR traffic. In addition, there are various segments of the network in which both intercity passenger and freight trains share the tracks, while certain corridors (mostly single-track segments) may be dedicated to only freight traffic.

Overall, the research team modeled more than 4,880 miles of mainline tracks. However, including the parts of the network with double and multiple-track segments as well as considering the length of yards and siding tracks, the team built approximately 6,230 miles of track into the network.

Table 1 summarizes major details of the network developed for the study. As shown in Figure 1 and also presented in Table 1, the majority of the network segments/corridors are single tracks, similar to the existing U.S. rail network.

Table 1. Summary of primary specifications of mini-network infrastructure developed for the simulation

Parameter	Value	Note
Length of corridors	~ 4887 miles	Only main tracks
Length of all tracks	~ 6,234 miles	Including 2nd and 3rd tracks, plus yard/siding tracks
No. of yards/sidings	150	
No. of switches	758	Including crossovers and crossings
No. of signals	1,782	Including signals along main tracks, yards, and transponders
Length of horizontal curves	~ 1,162 miles	

Figure 3 shows the distribution of the main track grades of the simulated network. As shown in the figure, about 72 percent of the grades were within the range of 0 to 0.5 percent, while approximately 20 percent of the grades were distributed within the range of 0.5 to 1 percent. About 5 percent of tracks had grades within 1 to 1.5 percent and less than 3 percent of the network tracks had grades more than 1.5 percent.

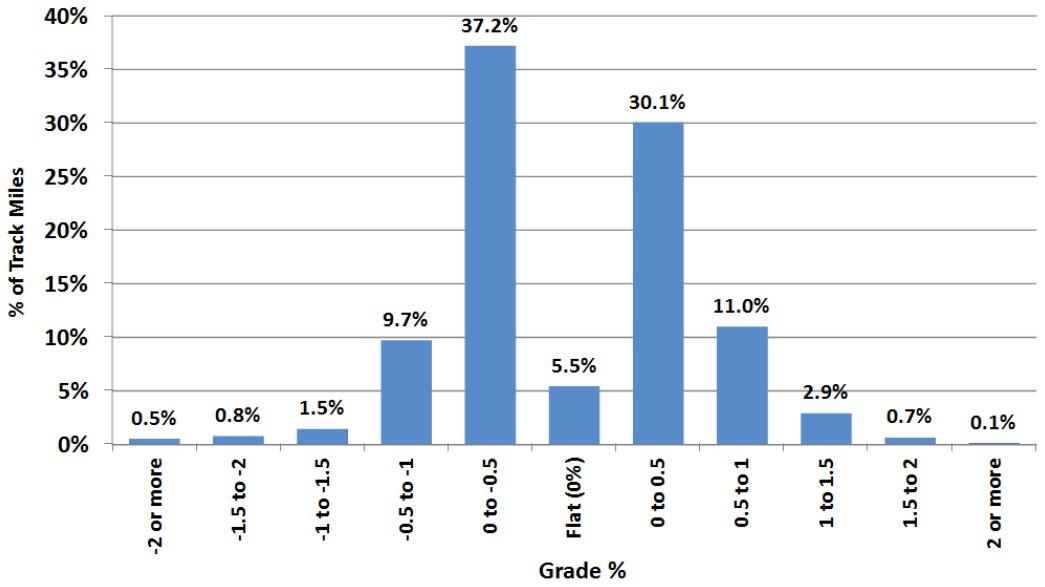


Figure 3. Distribution of main track grade in the simulated mini-network

Figure 4 shows the distribution of the degree of curvature for the horizontal curves on the main tracks of the network. As shown in the figure, about 76 percent of the network tracks were straight (i.e., no horizontal curve) while approximately 13 percent of the network had curves with degree of curvature less than 1. About 9 percent of the tracks had horizontal curves with 1 to 3 degrees of curvature, and only less than 2 percent of the tracks had curves of more than 3

degrees. For illustration purposes, the curve distribution shown in Figure 4 is for the magnitude of the curvature and not the nature (i.e., left or right hand curve) since the sign of the curves has no impact on train curving resistance.

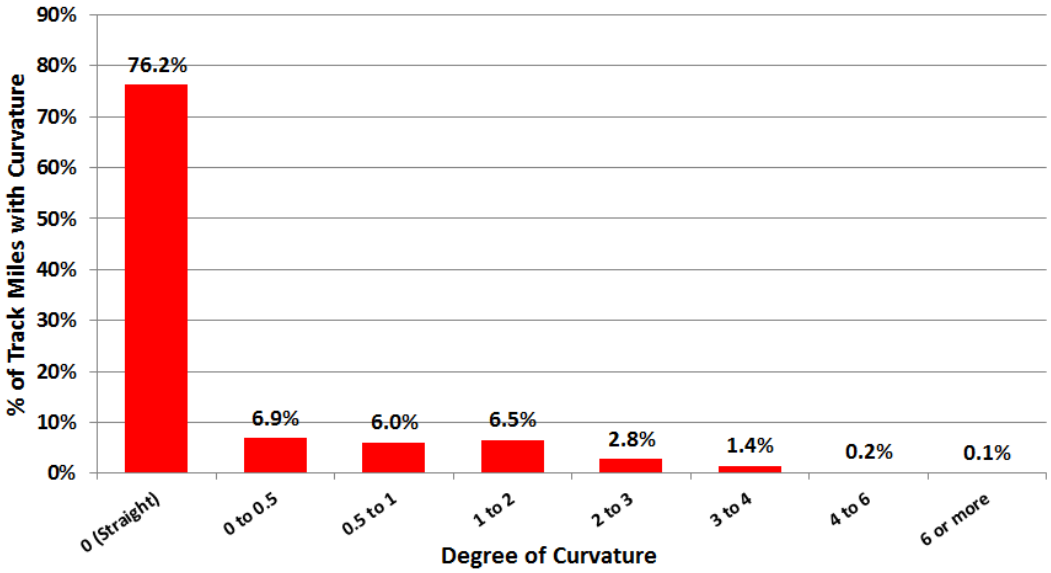


Figure 4. Distribution of main track curvature along the simulated network

2.2 Trains Characteristics

The team modeled a total of 232 trains (78 freight, 66 passenger, 56 commuter, and 32 HSR). Table 2 summarizes major attributes of the train types.

Table 2. Summary of train types developed for the simulation purposes

Type of Train	Avg. weight (ton)	Avg. length (ft.)	No. of configurations	No. of trains
Passenger	477	645	3	66
HSR	432	571	1	32
Commuter	248	486	2	56
Freight	7982	6994	17	78

Since the focus of this research was on freight trains and how different braking systems may affect network capacity and safety features of the entire network, more details about freight train configurations are summarized in Table 3. Researchers modeled varieties of train configurations depending on the territory/corridor in which the train was assigned to be operated. Below is a list of freight trains characteristics that are worth highlighting.

- All freight trains were hauled by one of three popular freight locomotives available in the North American rail network: Dash9 (4400 hp), Dash9 (4000 hp), or GP38-2 (2000 hp).
- While most freight trains in the simulation were modeled by either Dash9 locomotives, most of the light and local freight trains were powered by GP38-2 locomotives.
- Three types of freight trains were modeled with DP configurations (15 trains total) and all were powered by Dash9 (4400 hp) locomotives. All DP trains were long and relatively heavy.

Table 3. Details of freight trains simulated in the study

No.	Name	Weight (ton)	Length (ft.)	Max speed (mph)	Type of Loco	No. of Loco	DP?	Loco Consist	No. of Trains
1	DP-1	17086	13065	60	Dash9 (4400 hp)	6	YES	3-X-3	5
2	DP-2	8543	12848	60	Dash9 (4400 hp)	3	YES	2-X-1	4
3	NDP-3	11697	10952	60	Dash9 (4400 hp)	4	NO	4-X	6
4	NDP-4	6543	9239	60	Dash9 (4400 hp)	3	NO	3-X	8
5	H-FR-E2	16616	12921	60	Dash9 (4000 hp)	4	YES	2-X-2	6
6	MidFR-E1	9808	6214	60	Dash9 (4000 hp)	2	NO	2-X	2
7	MidFR-W1	4808	6214	60	Dash9 (4000 hp)	2	NO	2-X	3
8	Local1-H	4726	2907	50	GP38-2 (2000 hp)	2	NO	2-X	2
9	Local1-L	4126	2730	50	GP38-2 (2000 hp)	2	NO	2-X	2
10	Local2-H	3626	2743	50	GP38-2 (2000 hp)	2	NO	2-X	10
11	Local2-L	3026	2579	50	GP38-2 (2000 hp)	2	NO	2-X	1
12	Man10-H	7862	4082	50	Dash9 (4400 hp)	2	NO	2-X	7
13	Man10-L	6612	3543	50	Dash9 (4400 hp)	2	NO	2-X	2
14	Man12-H	3562	7363	50	Dash9 (4400 hp)	2	NO	2-X	6
15	Man7	9931	7123	50	Dash9 (4400 hp)	1	NO	1-X	3
16	Man9-L	7808	4442	50	Dash9 (4000 hp)	2	NO	2-X	3
17	Network1	5862	3097	50	Dash9 (4400 hp)	2	NO	2-X	8

The team modeled the braking characteristics of the freight trains using a comparison-based approach by simulating the same train type in TEDS[1] as an advanced tool for calibrating and analyzing the train dynamics and braking performance of trains. Researchers then extracted the results of the TEDS simulations as a benchmark of braking curve characteristics and converted them to OpenTrack format. It should be noted that the train braking curve of a given train can be affected by the following criteria and parameters:

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

As an example, for a given train with a specific weight, length, and configuration, the braking curve to stop the train (i.e., maintain train speed under a certain threshold) can be different when the train applies brakes on a 1 percent descending grade compared to when it applies brakes over a 0.5 percent descending grade. Similarly, the brake characteristics (e.g., deceleration rate, propagation delay, or brake efficiency between frequent applications) are different between a DP train and head-end only power trains. An ECP train, as explained previously, has more significant differences in terms of brake characteristics compared to the same train with a

[1] Train Energy and Dynamics Simulator (TEDS), a simulation tool that was developed by the Federal Railroad Administration (FRA) [16].

conventional brake system (head-end only) or even a DP train. Also, the difference between a DP and ECP train is smaller than that between an ECP train and a conventional head-end power train.

It should be noted that the longer and heavier a freight train, the more deviation between the brake efficiency of an ECP train versus a conventional configuration of a train with head-end only locomotives. Appendix A includes some of the braking curves of an ECP train compared against a configuration using conventional brakes. Researchers used the simulation results of operating a given train on a given corridor in both TEDS and OpenTrack to compare and validate the simulation model in OpenTrack. These results are also shown in Appendix A.

2.3 Operating Rules and Train Scheduling Characteristics

The research team used several operating rules and dispatching instructions in the simulation model to safely operate trains over the network. These rules are summarized below:

1. All trains had an initial requested schedule with at least an initial departure time from its designated departure location. HSR, commuter, and passenger trains may have had additional details in their requested schedules, while freight trains may have had more flexibility (freedom) in terms of initial train schedules[2].
2. In the simulation, all train schedules were designed to be "conflict-free" (i.e., they would depart from their designated origins and arrive to their assigned destinations without any schedule conflict that could cause a deadlock anywhere throughout the network). Minor conflicts which could cause a delay at sidings/yard tracks or a braking at the 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 at a stop point or yard arrival/departure tracks, the dispatching right was given to the train with higher priority in the following order:
    - HSR (highest priority), commuter, passenger, freight trains (lowest priority)
    - For trains in the same category (e.g., two freight trains), the one which had a higher delay would have higher priority to depart first
4. All trains departed once per day and were designed to arrive at designated destinations regardless of how long it took. In other words, a train may have departed at day one 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 the simulation.
6. No signaling, grade crossing, or train mechanical failures were assumed throughout the network [3].
7. All dispatching rules were governed and maintained in the same for all simulation scenarios of the study. Figure 5 shows the schematic map of the mini-network shown in

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

[3] It is doable 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 in order to evaluate the impact of such incident on the capacity/safety features of other trains along the rest of the network, but such incidents have not been modeled in this study.

Figure 1 and updated with the number of daily trains that were distributed throughout different sections of the network.

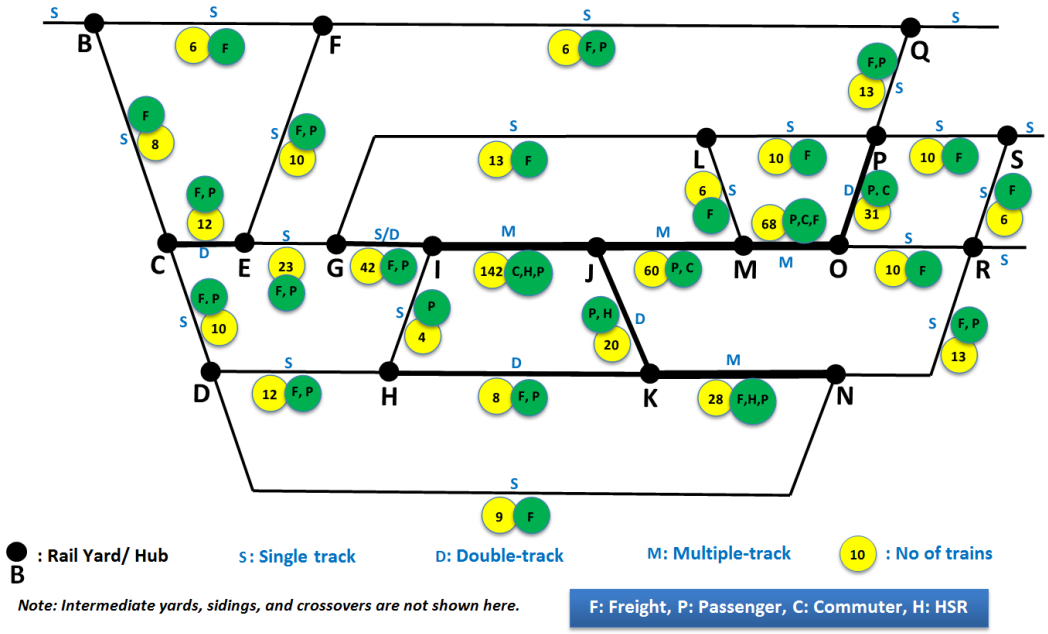


Figure 5. Schematic map of the mini-network showing the number of daily trains planned along each section of the network in addition to the type of traffic and type of corridors

As shown in Figure 5, the central section of the network (I-J-M-O) had more traffic since it was built with at least double-track sections. Section K-N was also developed as a multiple-track corridor, but the estimated capacity of this corridor was lower than the other multiple-track sections because it had mixed traffic of freight, HSR, and passenger trains with a large deviation between their respective operational speeds, particularly between freight and HSR trains. The other parts of the network were developed to have daily traffic of at least six trains a day on the single track sections.

3. Review of Network Simulations Scenarios

The team developed the simulation scenarios of the mini-network study with a focus on the brake characteristics of freight trains to analyze the impact on network capacity and safety features when more advanced braking systems are implemented on freight trains. Researchers developed three simulation scenarios in the study:

- **Scenario 1 -** All freight trains equipped with an advanced braking system (ECP)
- **Scenario 2 -** All freight trains equipped with a conventional braking system
- **Scenario 3 -** Hybrid traffic – a mix of ECP and conventional braking-equipped trains

All simulation scenarios maintained the same network assumptions and inputs, except the braking characteristics of freight trains were different in each scenario to represent the respective characteristics of either conventional or ECP braking systems.

The team extracted the results of each simulation scenario in terms of capacity/safety characteristics for the given scenario. Researchers compared the findings of the respective scenarios in terms of the following parameters and features:

- Overall network velocity and delay measures
- Average velocity and delay measures of each type of train
- Track utilization through selected parts of the network
- Safety measures of operating trains through the network:
    - number of stops at signals
    - number of braking actions
    - number of deadlock conflicts removed from the simulation

A summary of the results for each simulation scenario are discussed in the following sections.

3.1 Scenario 1 Results - Only ECP Equipped Freight Trains

The team used Stringline[4] representation to illustrate the trains' movement in a network. As there are various corridors that can be defined for a given network, eight different Stringlines have been defined in this study to cover all 232 simulated trains throughout the entire network.

Figure 6 shows the Stringline of B-C-E-G-I-J-M-O-P section of the network with a variety of different trains (passenger, HSR, commuter, and freight) operated over the section of network which covers about 886 miles of track.

The single track parts of the corridor are highlighted with one track on the vertical axis of the Stringline diagram (also grayed out throughout the diagram), while the double or multiple-track

[4] A distance-time diagram (also known as train graph) which shows movement and schedule activities of given trains along a given corridor. The horizontal axis of the diagram typically represents the time interval, while the vertical axis shows stop points of trains (sidings and yards) or vice versa. Each Stringline represents one train movement along the corridor in either direction (northbound or southbound).

sections are highlighted with double-track on the vertical axis (also shown in white throughout the chart).

As shown in Figure 6, the time horizon of the train Stringline is extended for almost two days of operations because some of the freight trains that were dispatched on the first day arrived at their designated destination some time on the following days. Also, due to the fact that different sections of the corridor had different traffic congestion levels (similar to that presented in Figure 5) some trains (particularly through I-J-M-O section) may have experienced delays or speed reduction to avoid any deadlock or major schedule conflicts. More details about train delays are discussed in the following parts of this chapter. It should be noted that in all Stringlines of this report, different types of trains are distinguished by different colors as shown below:

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

Figure 7 and Figure 8 present two Stringlines of simulated trains in other corridors of the network with approximate travel distances of 1,656 and 818 miles, respectively. As highlighted in these Stringlines, not every train was planned to operate through the entire corridor because some trains may have had different origins or destinations located in other parts of the network.

As shown in Figure 7, two freight trains were simulated for approximately 1,565 miles of travel between rail hubs 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 are among the heaviest type of freight trains (Type DP-1, as seen in Table 3) weighing over 17,000 tons and measuring over 13,000 feet.

Other trains' Stringlines in this scenario are presented in Appendix A. Certain train performance characteristics of selected trains are also illustrated in Appendix A in terms of speed profile, track speed limits, tractive effort, acceleration, and track gradients along the entire route.

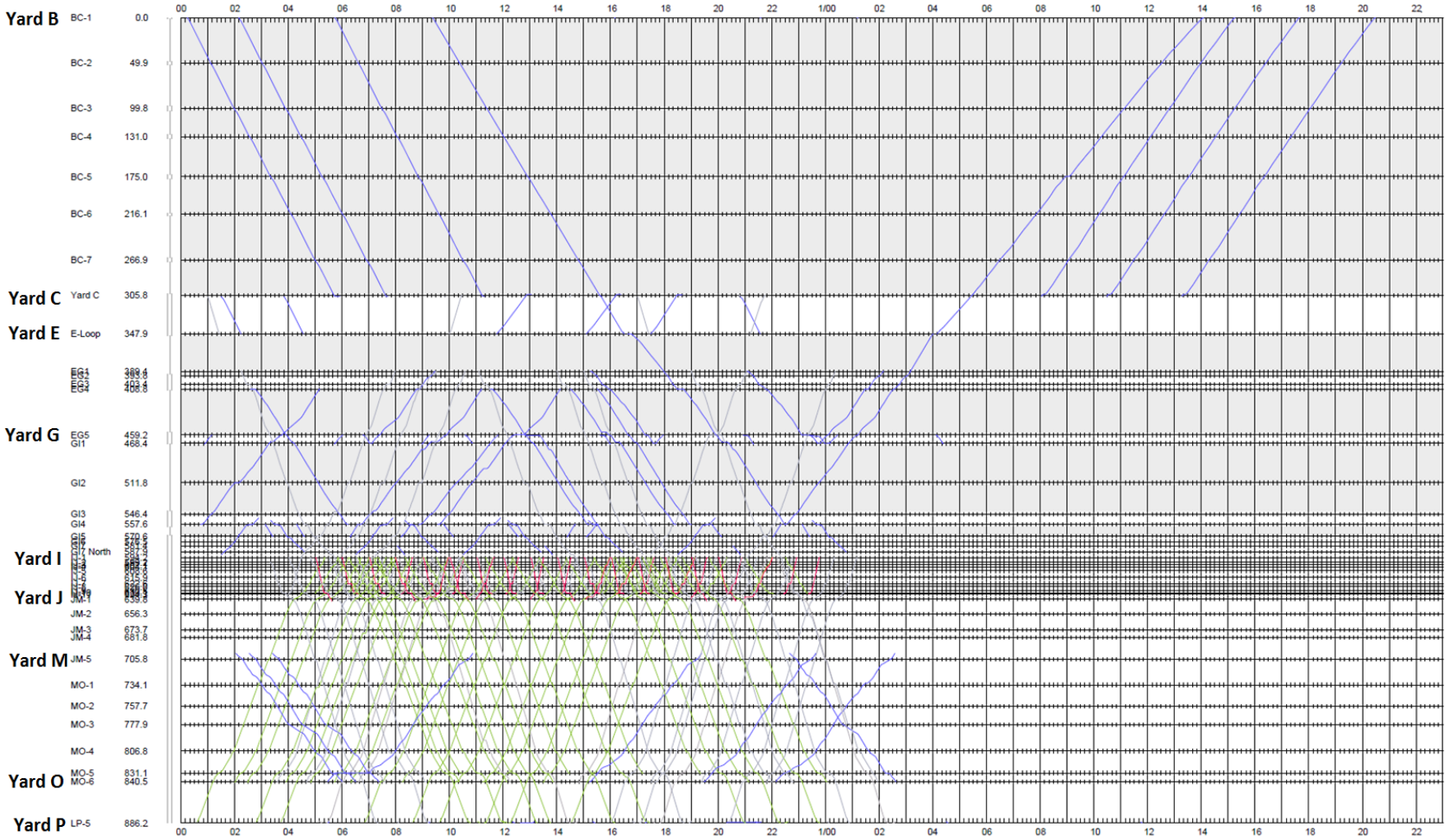


Figure 6. Scenario 1 train Stringlines on B-C-E-G-I-J-M-O-P section of the network, assuming ECP braking system for freight trains

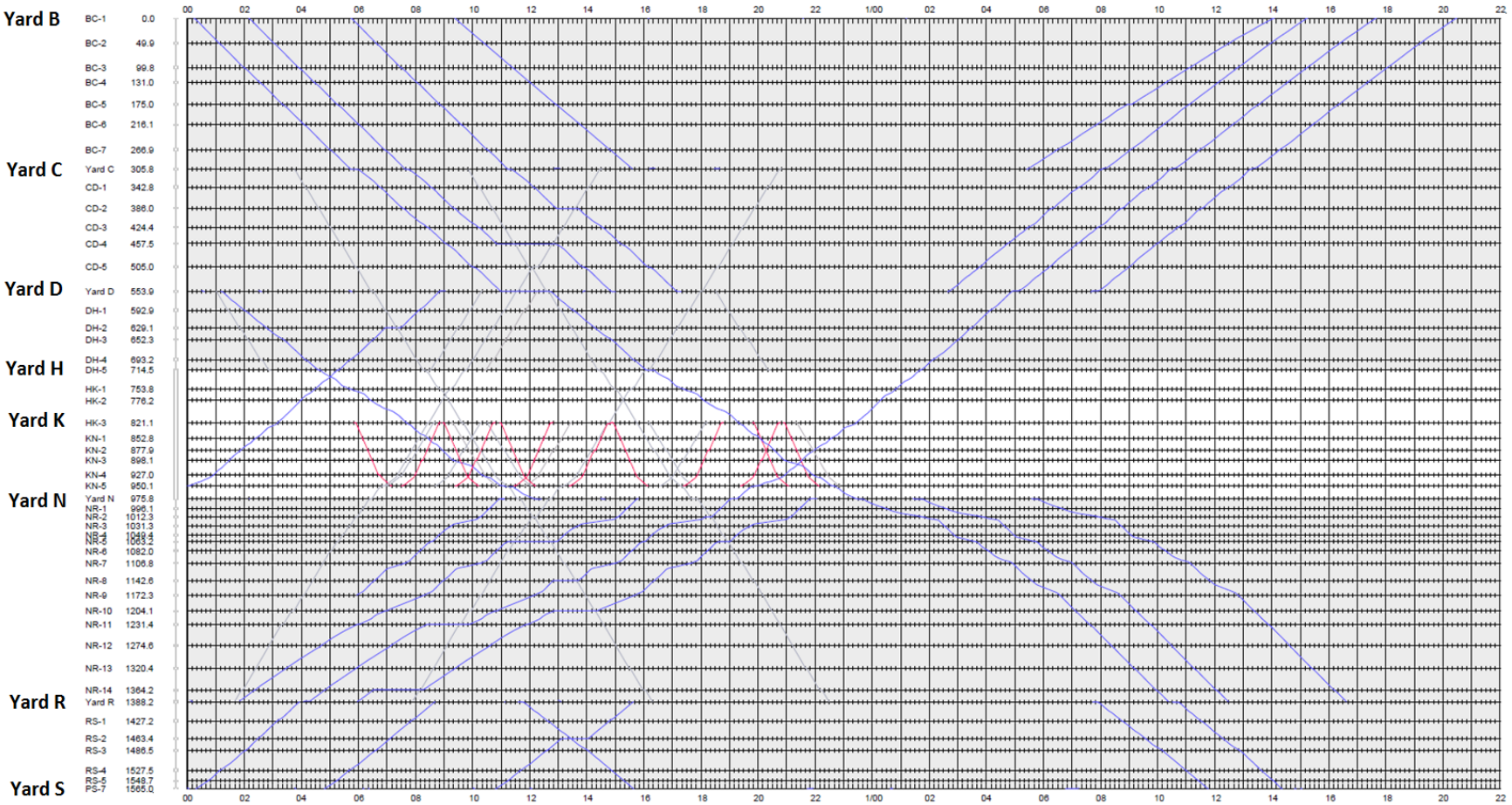


Figure 7. Scenario 1 train Stringlines on B-C-D-H-K-N-R-S section of the network, assuming ECP braking system for freight trains

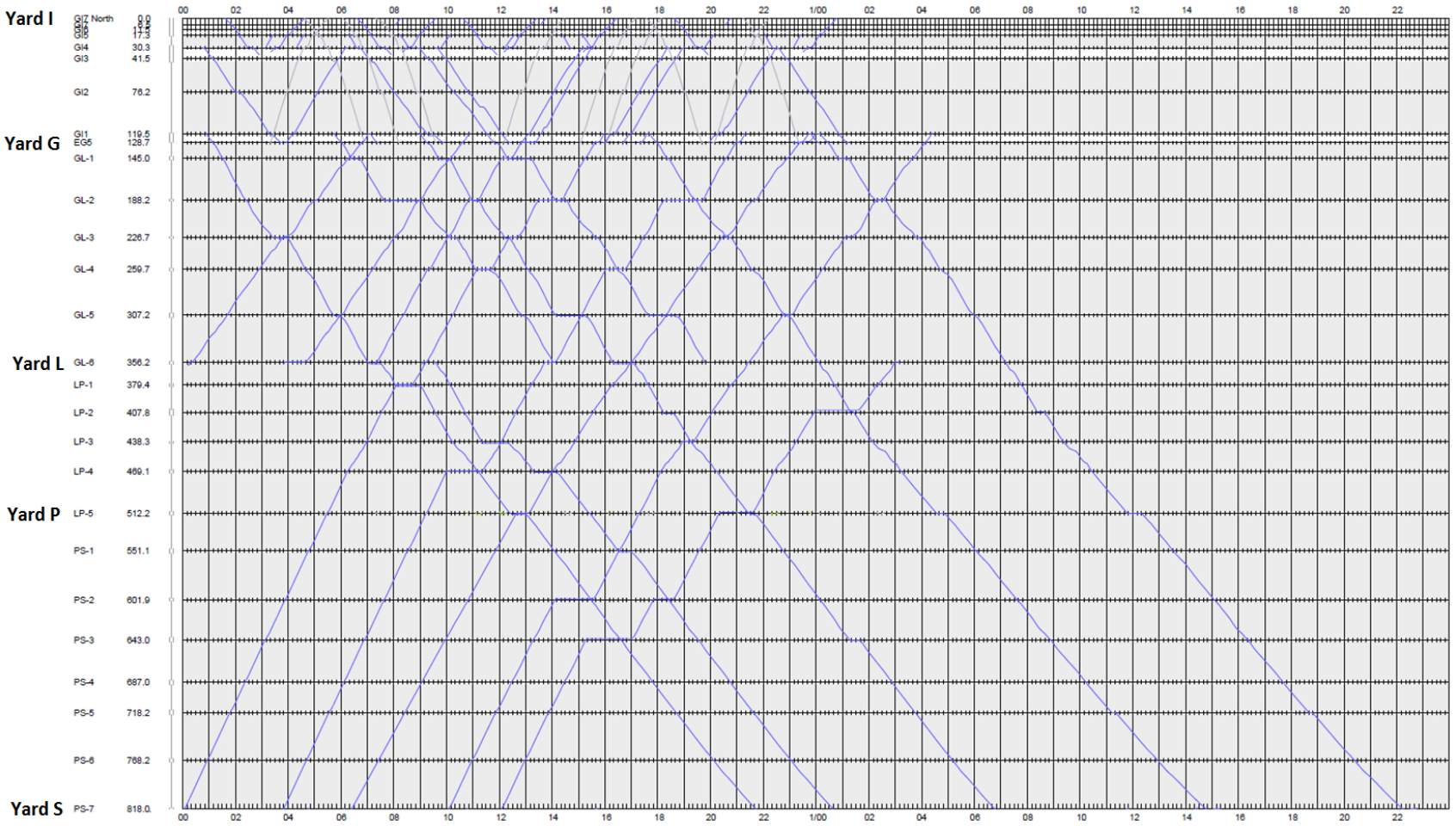


Figure 8. Scenario 1 train Stringlines on I-G-L-P-S section of the network, assuming ECP braking system for freight trains

3.2 Scenario 2 Results - Only Conventional Braking Equipped Freight Trains

The research team conducted the second scenario of this study by simulating the same number of trains through their respective origin-destinations, considering the same model assumptions and parameters of the first scenario, but with adjustments made on the braking characteristics of freight trains to account for the conventional air brake system.

Since the braking systems of the freight trains have been updated in this scenario, it could cause changes in the train handling and speed profile of freight trains and major train conflicts. Deadlock could be expected when simulating this scenario, which was 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 applying the above mentioned techniques did not resolve the deadlock, the team removed one or more train services from the simulation to allow a conflict-free schedule throughout the entire network. Figure 9 presents an example of two deadlock incidents the team observed in I-G-L-M corridor when initiating the simulation for Scenario 2.

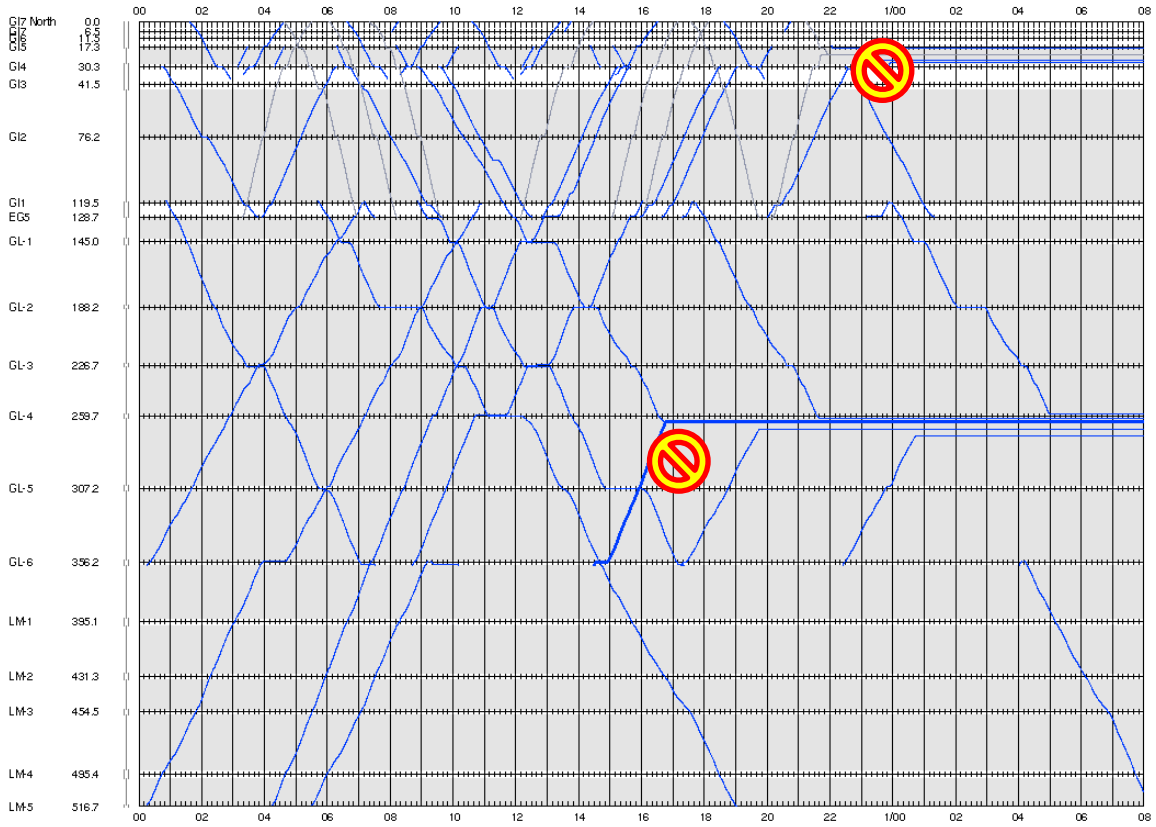


Figure 9. An example of two deadlock incidents observed along I-G-L-M corridor in Scenario 2

As shown in Figure 10, the two major deadlocks were caused by the changes in the braking characteristics of the freight trains (i.e., changing brakes from ECP to conventional). However,

conflicts were resolved after the team applied minor adjustments on the dwell times of the conflicted trains at the stop points prior to the deadlock location.

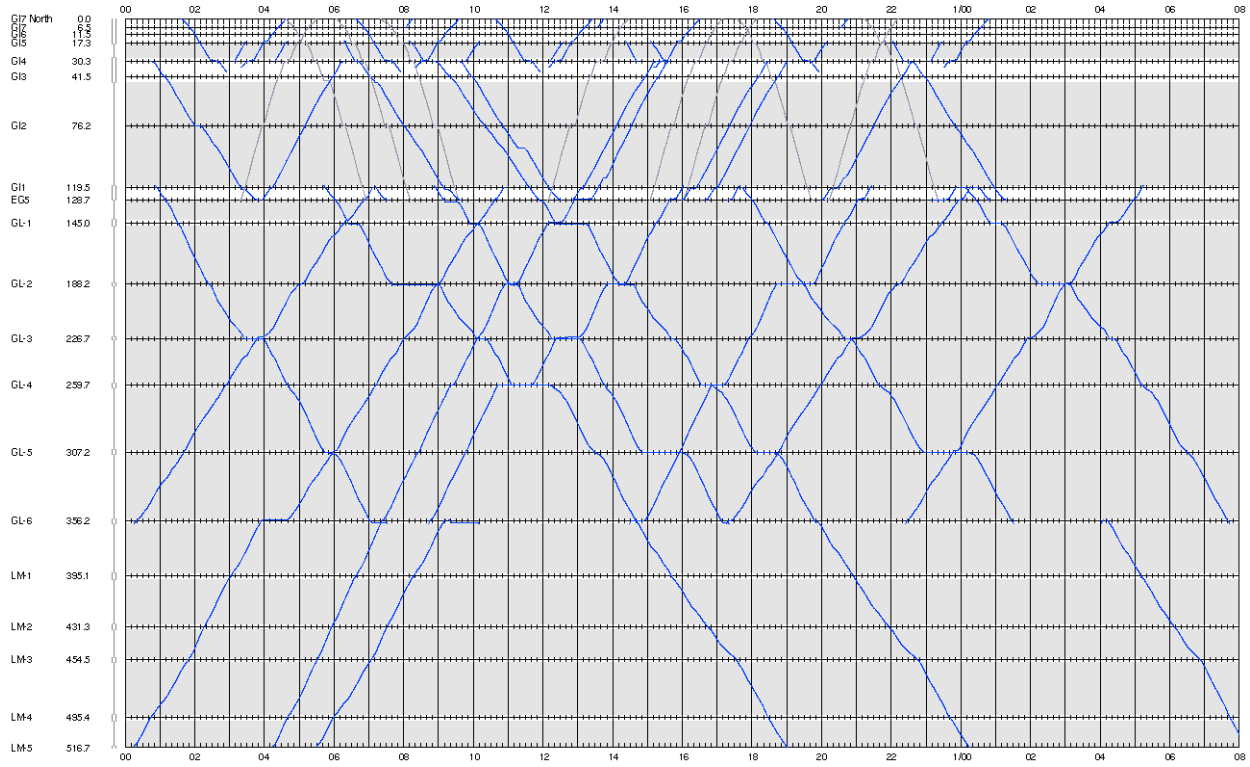


Figure 10. Conflict-free schedule of trains along I-G-L-M corridor after resolving the deadlocks initially observed during Scenario 2

Overall, the research team observed 12 major deadlocks throughout various sections of the network when simulating Scenario 2 and most of them occurred between freight trains. The team cleared all the deadlocks by applying the two resolution techniques, providing a conflict-free schedule for all trains.

Figure 11, Figure 12 and Figure 13 show the Stringlines of the same corridors shown in Scenario 1 (Figure 6 to Figure 8). When compared to the Stringlines from Scenario 1, the new Stringlines appear to be identical to the first simulation run using the ECP braking system on freight trains. However, when the team compared the details of these two runs side by side, certain differences were observed between the outcomes of the simulation runs in terms of network related characteristics. In fact, the second simulation run using conventional air brakes for freight trains caused more delay and slightly different train arrival/departure times in certain sidings/yards. Some of these schedule changes, as compared to the previous run, are highlighted in Figure 11 to Figure 13 with red circles. More details about delay analysis are provided in the following sections. Additional train Stringlines from this scenario and train performance characteristics are presented in Appendix A.

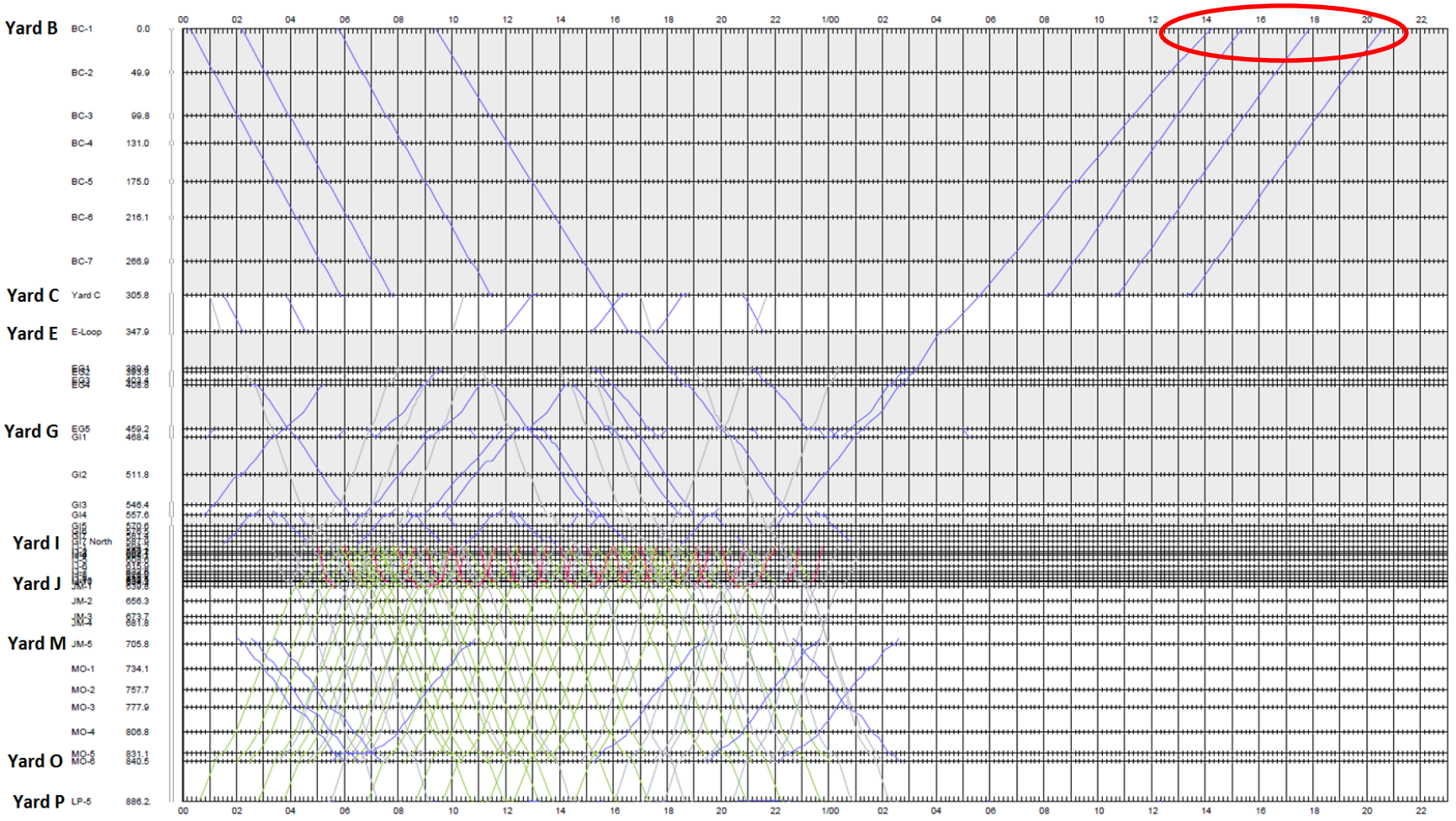


Figure 11. Scenario 2 train Stringlines on B-C-E-G-I-J-M-O-P section, assuming conventional braking system for freight trains

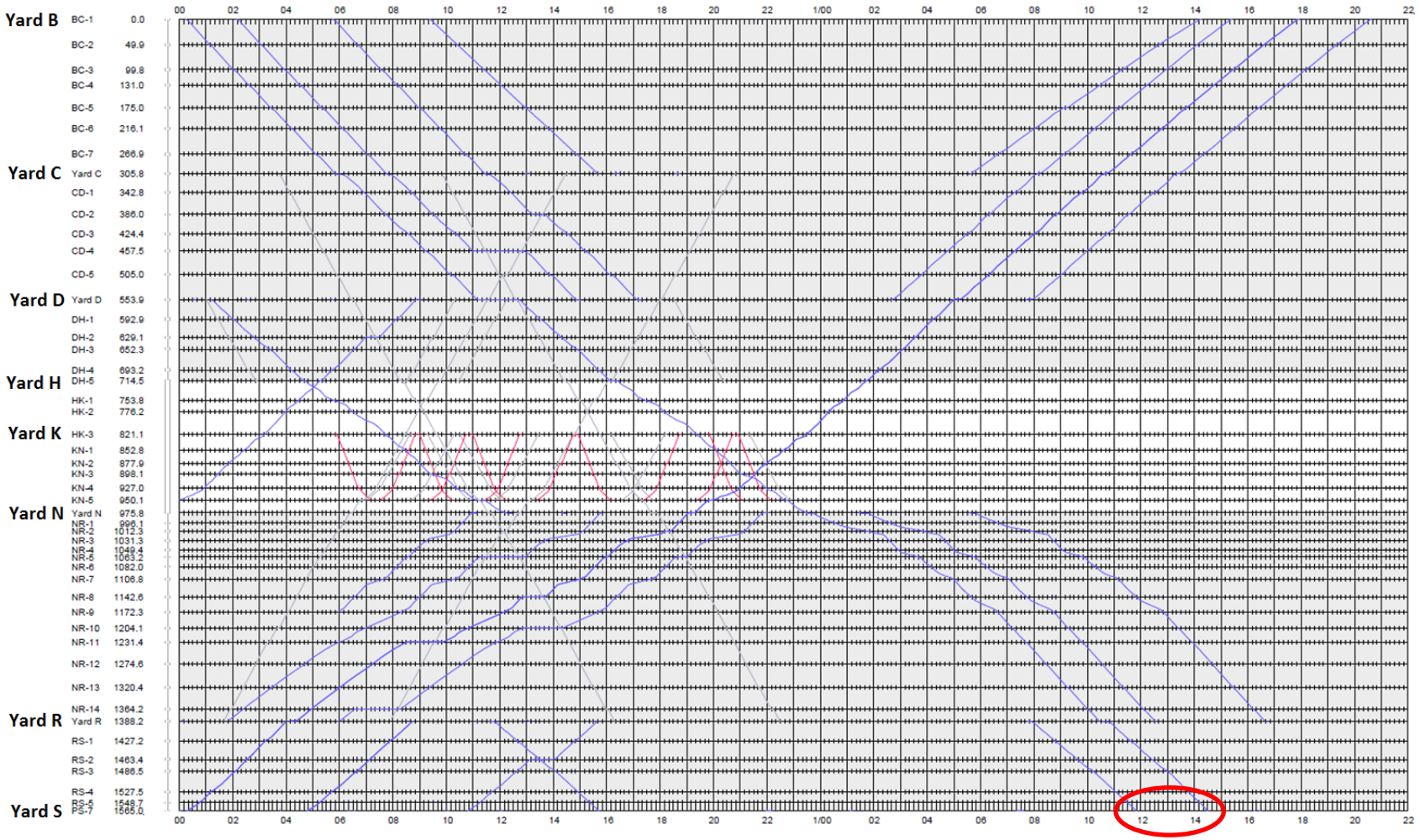


Figure 12. Scenario 2 train Stringlines on B-C-D-H-K-N-R-S section, assuming conventional braking system for freight trains

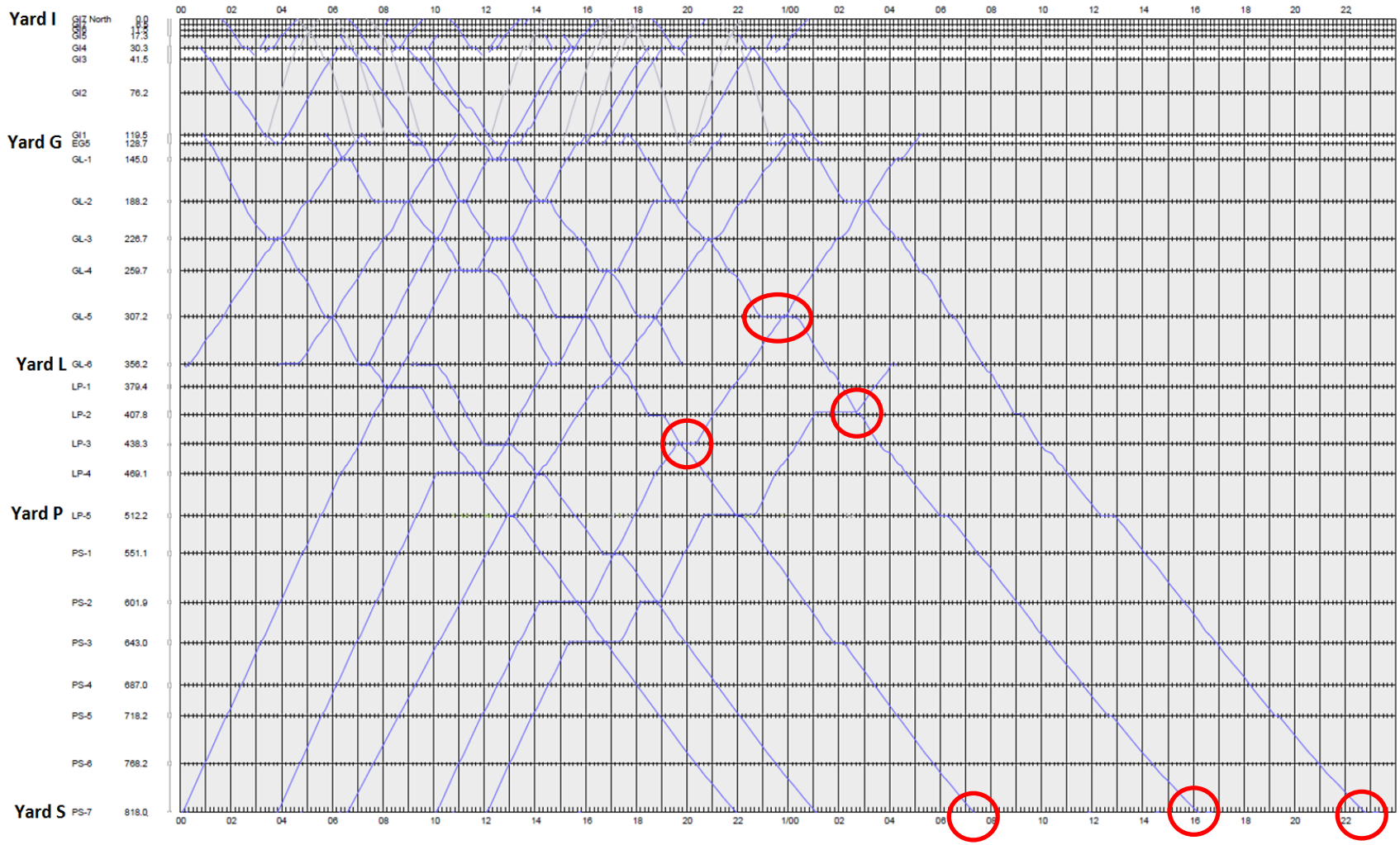


Figure 13. Scenario 2 train Stringlines on I-G-L-P-S section, assuming conventional braking system for freight trains

3.3 Scenario 3 Results - Mixed ECP and Conventional Braking Equipped Freight Trains

Since freight trains with conventional air brake systems cannot be quickly retrofitted with an advanced braking system, this scenario assumes a gradual upgrade over time due to capital cost and operational logistics. In Scenario 3, half of the freight trains in the mini-network were operated under an advanced braking system (Scenario 1) while the other half maintained the conventional braking system (Scenario 2). The team selected freight trains in this scenario to have either conventional or advanced braking systems so that both types of trains were evenly distributed throughout the network.

Overall, the team did not observe any major conflicts (i.e., deadlocks) in Scenario 3, illustrating that a combination of mixed conventional and advanced braking systems could provide a conflict-free schedule for all trains.

Figure 14 shows an example of Stringlines for this scenario throughout B-C-E-G-I-J-M-O-P section of the network assuming mixed conventional and advanced braking systems for freight trains.

When comparing this figure against Figure 6 and Figure 8 (which show the train movements along the same corridor under Scenarios 1 and 2, respectively), the team observed some minor deviations in the train schedules, especially for freight trains. More details about the results of this scenario are provided in the following section.

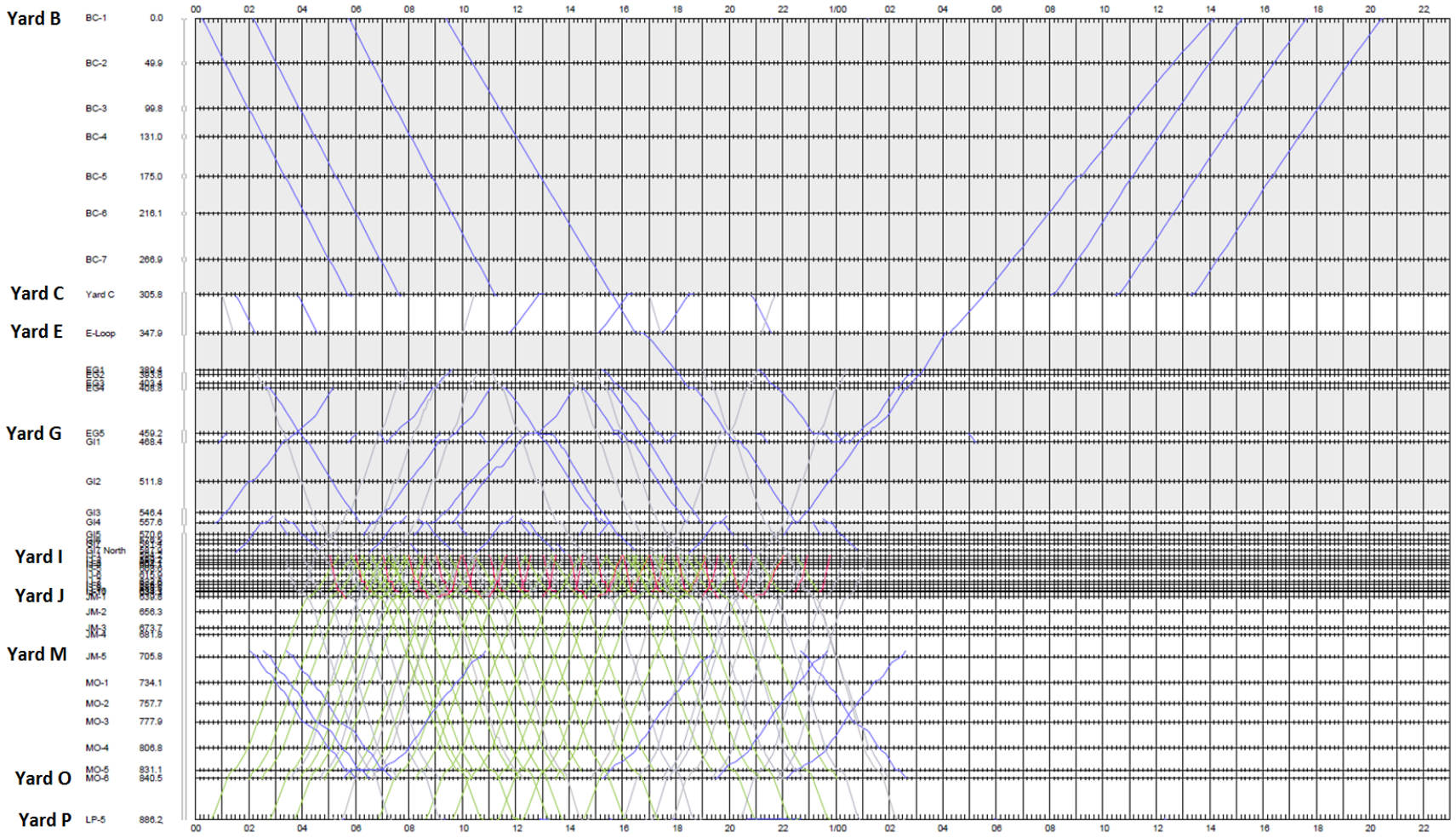


Figure 14. Scenario 3 train Stringlines on B-C-E-G-I-J-M-O-P section of network for mixed conventional and advanced braking systems for freight trains

4. Analysis of Simulation Results

4.1 Scenarios 1 and 2 Comparison

This section compares Scenarios 1 and 2 side by side and highlights the advantages of advanced braking systems on freight trains, if any, considering aspects of network capacity and safety perspectives.

4.1.1 Evaluating Delay, Network Velocity, and Safety Indices

A summary of the results of Scenarios 1 and 2 are shown in Table 4, in terms of average delay and network velocity of different types of trains, as well as train operations safety measures (e.g., average number of station stops, number of en-route braking, and number of stops at signals).

Table 4. Summary of Scenarios 1 and 2 simulation results in terms of network capacity and safety parameters categorized based on each type of train

Train Type	Scenario	No. of Trains	Avg. Distance (miles)	Avg. Delay (sec)	Network Velocity (mph)	Avg. Station Stops	Avg. Route Braking	Avg. Signal Stops
Passenger	**1 (ECP)**	66	301	305	78.6	5.23	6.35	1.02
	2 (Conv.)	66	301	321	78.5	5.20	6.42	1.06
Freight	**1 (ECP)**	78	417	244	38.2	2.72	6.67	0.27
	2 (Conv.)	78	417	**425**	37.8	2.79	**8.23**	0.28
HSR	**1 (ECP)**	32	104	279	89.5	2.75	4.28	0.78
	2 (Conv.)	32	104	279	89.5	2.75	4.28	0.81
Comm.	**1 (ECP)**	56	204	82	63.9	10.14	1.13	0.38
	2 (Conv.)	56	204	77	64.0	10.14	1.13	0.36
Overall	**1 (ECP)**	**232**	**289**	**227**	**57.1**	**5.23**	**4.91**	**0.58**
	2 (Conv.)	**232**	**289**	**291**	**56.9**	**5.25**	**5.46**	**0.59**

Details on the comparison of these two scenarios based on each parameter are explained below.

Average distance

Since all travel parameters (e.g., origin-destination, train routes, and train configuration) were identical in both scenarios, there was no difference between average traveling distances in the two scenarios.

Average delay

Researchers expected that there would be more delays in freight trains equipped with conventional braking systems as the advanced braking system was expected to improve the overall performance. Results showed almost 43 percent more delays in arrival time (425 seconds versus 244 seconds) in freight trains equipped with conventional braking versus advanced braking systems.

The HSR trains had the same number of delays in both scenarios although it was relatively high (279 seconds), most likely because the HSR trains were operated through the most congested parts of the network with a high diversity of train types sharing the same tracks.

The passenger trains had approximately 5 percent fewer delays in Scenario 1 (i.e., ECP equipped freight trains) than in Scenario 2 (i.e., conventional braking equipped freight trains), while the commuter services in Scenario 1 had slightly higher delays (almost 6 percent) compared to Scenario 2. Although their train characteristics were the same, it is possible that the passenger and commuter services had slightly different delays in these two scenarios because resolving major conflicts observed during Scenario 2 (Figure 12 and Figure 13) required some schedule changes for passenger and commuter services.

Overall, and considering all types of trains, the average network delay in Scenario 1 was about 22 percent lower than in Scenario 2.

Network velocity

The network velocity is the average operational speed of all trains of each category weighted based on their respective travel distance. The team found that the network velocities of all types of trains except freight trains was either the same or very similar (less than 0.1 percent difference) in the two scenarios.

The network velocity of freight trains with an advanced braking system (i.e., Scenario 1) was approximately 0.4 mph (slightly over 1 percent) higher than the freight trains in Scenario 2.

Overall, and considering all types of trains, the network velocity of Scenario 1 was approximately 0.4 percent higher than in Scenario 2.

Average number of stops at stations

This parameter can be interpreted differently for freight and passenger trains. Because passenger trains (including commuter and HSR) have predetermined stop locations through their daily schedules, there should be no difference between simulation scenarios in terms of number of stops for these trains. Any higher number of stops at sidings/stations for passenger services can be interpreted as additional meet-pass stops to resolve a potential deadlock, while any lower number of stops can be interpreted as certain trains enforced to miss their scheduled stops to avoid a potential deadlock.

The team determined that the average numbers of stops at sidings in HSR and commuter services were identical in both scenarios, as expected. However, the average number of stops in the passenger train category was slightly lower in Scenario 2, which can be interpreted as missed station stops. For freight trains, the majority of stop points were interpreted as meet-pass stops required to resolve a potential deadlock. Thus, a lower number of stops at sidings for freight services may demonstrate a lower level of idling times spent at sidings.

The team found that the number of observed stop points at sidings for freight trains were slightly higher (approximately 2.5 percent) in Scenario 2 than in Scenario 1. Overall, average stop values at sidings for all trains were almost the same in both scenarios with a slightly higher value (~ 0.3 percent) in Scenario 2.

Average number of route reservation braking

This parameter shows any train braking action recorded by the simulator to reserve the next available block of tracks through the respective route of the train, mostly within the exit/entrance boundaries of stations/yards (i.e., interlocking segments).

It should be noted that a higher value for this parameter can represent a higher risk of schedule conflicts and eventually can demonstrate a higher risk of accidents (i.e., train collisions), especially if it coincides with a human error or a mechanical/signal failure.

The team found that freight trains had almost 19 percent more braking actions in Scenario 2 compared to Scenario 1 due to route reservation conflicts.

Passenger trains in Scenario 2 had a slightly higher value for this safety index due to route reservation issues (almost 1 percent higher). Commuter and HSR services maintained the same respective values for this parameter in both scenarios.

Overall, the average number of braking actions due to route reservation conflicts was approximately 11 percent higher for freight trains in Scenario 2.

Average number of stops at signals

Similar to the previous parameter, the average number of train stops at signals is a safety index that measures how many times on average trains were enforced to stop before or at signal locations because the next block of signals was not available for the respective trains. This parameter can be classified as a subcategory of the braking for route reservation parameter since every train needs to apply brakes to stop at signals.

The team found that freight, passenger, and HSR services had higher train stop values at signals (about 4 percent) in Scenario 2 compared to Scenario 1. However, commuter services in Scenario 2 recorded almost 6 percent fewer stops at signals.

Overall, and considering all types of trains, the value of this parameter in Scenario 2 was slightly higher than in Scenario 1.

4.1.2 Track Utilization Analysis

Track utilization is a capacity metric that shows how a segment of track (e.g., a signaling block, especially through network bottlenecks and sections with high density daily traffic) is occupied/utilized by passing trains during a certain period (e.g., per hour, per day). A higher rate of track utilization can demonstrate a higher railroad asset productivity rate. But for bottlenecks and critical parts of the network, especially within yard boundaries, a very high track utilization rate (usually more than 70 percent [8, 13]) may also increase the risk of train incidents, particularly when positive train control systems are not available to be enforced.

Figure 15 shows the number of daily trains the team operated over 74 selected segments of track throughout different corridors of the network. Researchers selected these segments of track with various lengths from 0.3 miles to ~2 miles mostly located at the critical parts of each corridor (e.g., part of a long signal block, a heavy grade, an entrance, or exist signal block of a busy yard).

As shown in Figure 15 there are various numbers of daily trains, from 6 to 71 trains in a day over the selected tracks. All segments with more than 20 daily trains belong to the corridors with at least 2 main tracks.

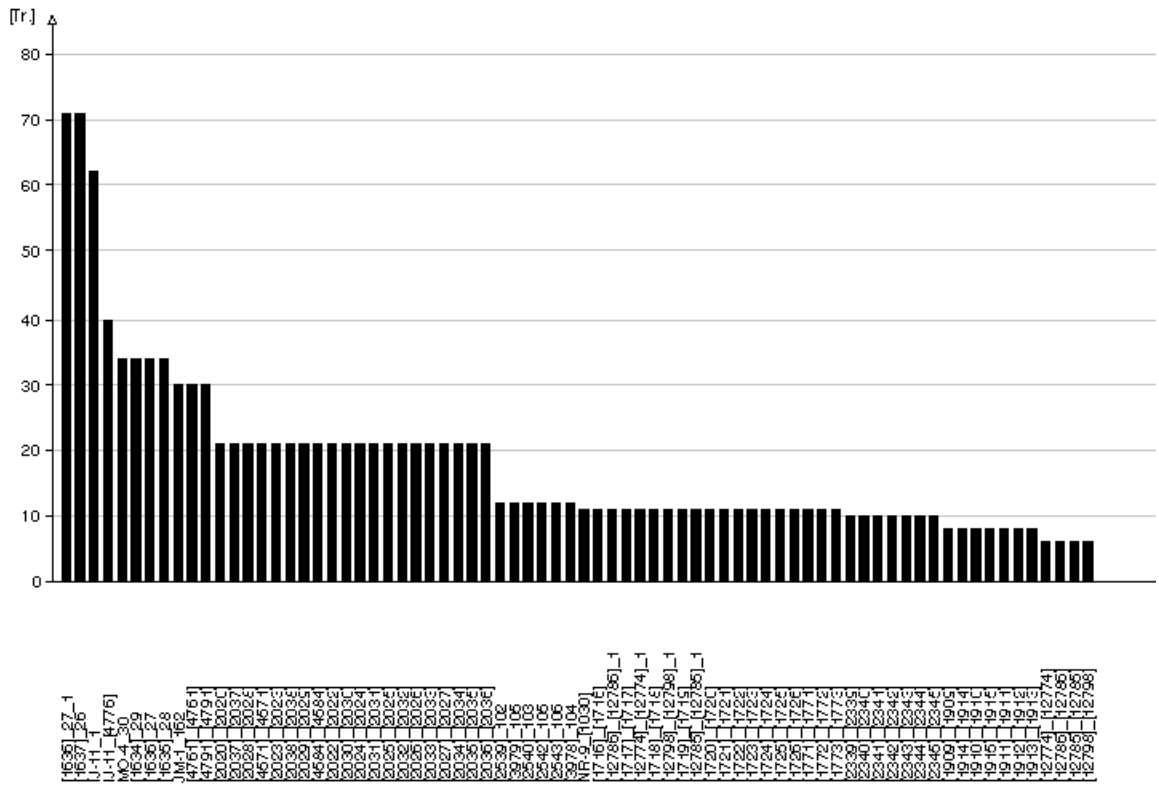


Figure 15. Number of daily trains over selected segments throughout the network

Figure 16 presents the maximum number of trains per hour over the selected segments of track. Different colors on the chart represent different levels of track utilization as highlighted in the figure. Like that for the number of daily trains (Figure 15) there is a significant difference between values of this utilization parameter ranging from one train per hour to nine trains per hour over different segments.

All segments with at least four trains per hour belong to the corridors with at least two main tracks. The team found no difference between simulation scenarios of this study in terms of maximum number of trains per hour over the selected segments.

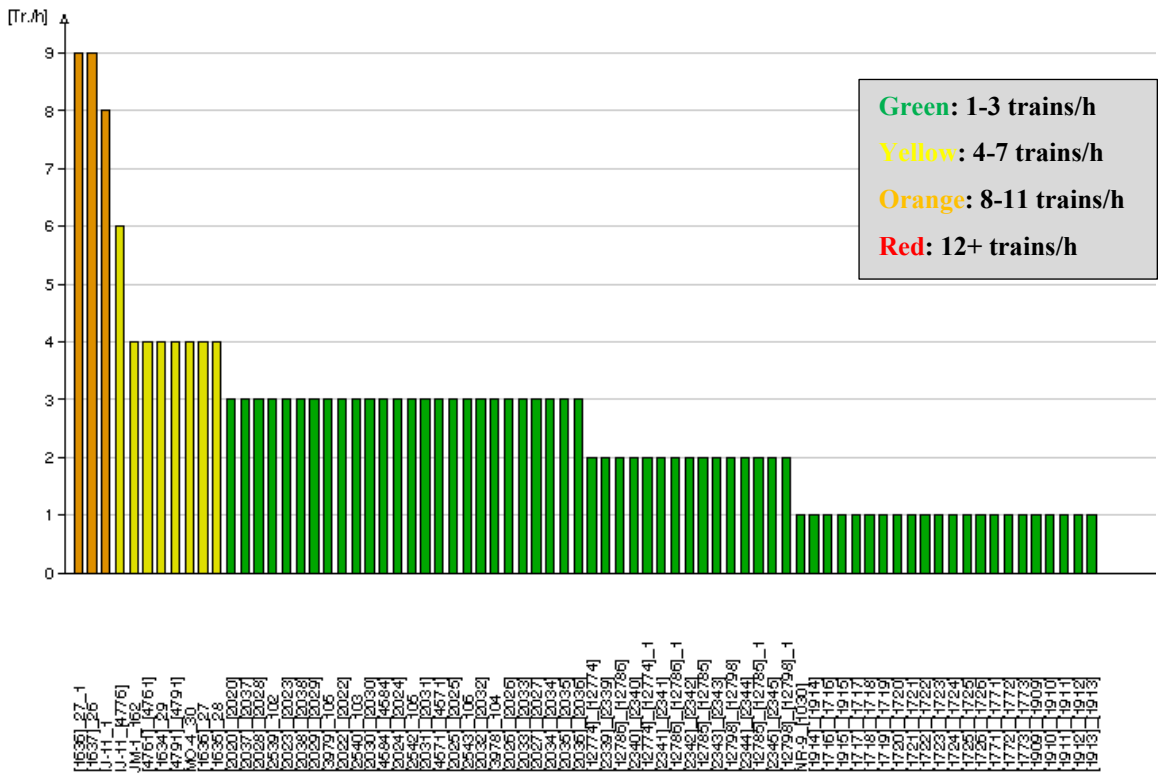


Figure 16. Maximum number of trains per hour over selected segments throughout the network

Figure 17 and Figure 18 show the maximum track utilization rate per hour for different segments of track in Scenario 1 and Scenario 2, respectively. Different colors on the chart bars represent different levels of the utilization rate.

Though Figure 17 and Figure 18 may look identical, there are some minor differences between the results of these two scenarios. In fact, comparing these two figures side by side reveals that 46 of the selected segments have minor differences in their respective track utilization rates between the 2 scenarios, with a range of deviation under 2 percent. As a result, the team concluded that changing the braking characteristics of a freight train may not cause any major impact on the track utilization rate over the track segments.

However, reviewing the track utilization rate can provide a better understanding of how capacity has been consumed and if there is any safety risk associated with the shortage of capacity for a given corridor. As shown in Figure 17 and Figure 18, there are several segments with 100 percent utilization rate per hour, meaning that those segments were completely occupied for at least 1 hour during the day.

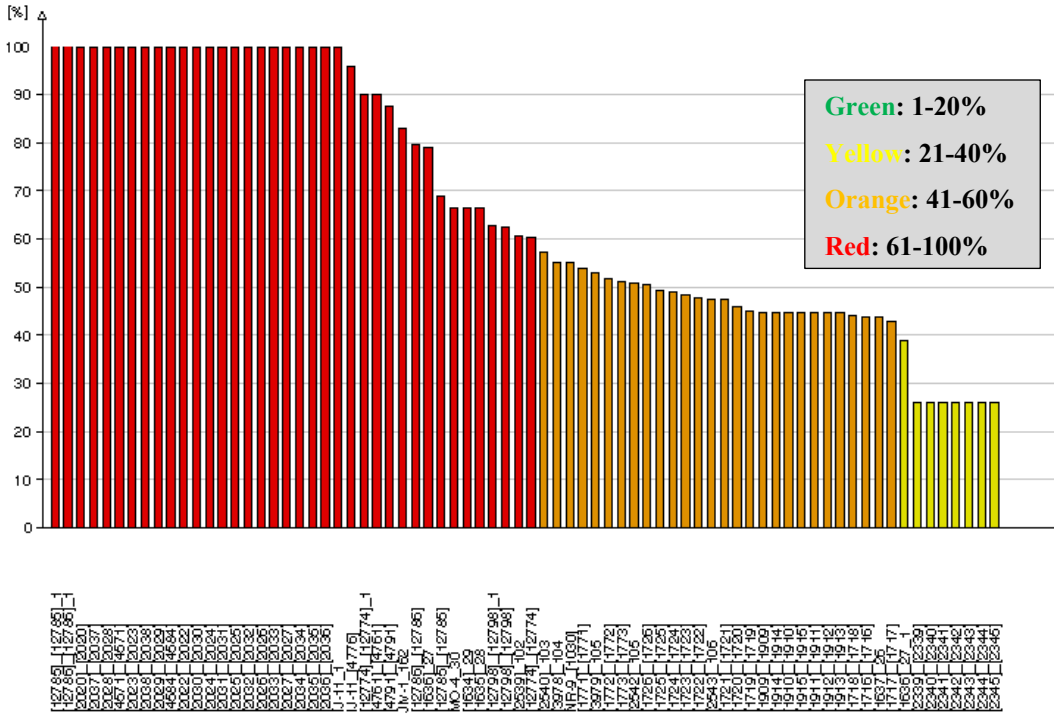


Figure 17. Maximum track utilization rate per hour for selected segments (Scenario 1)

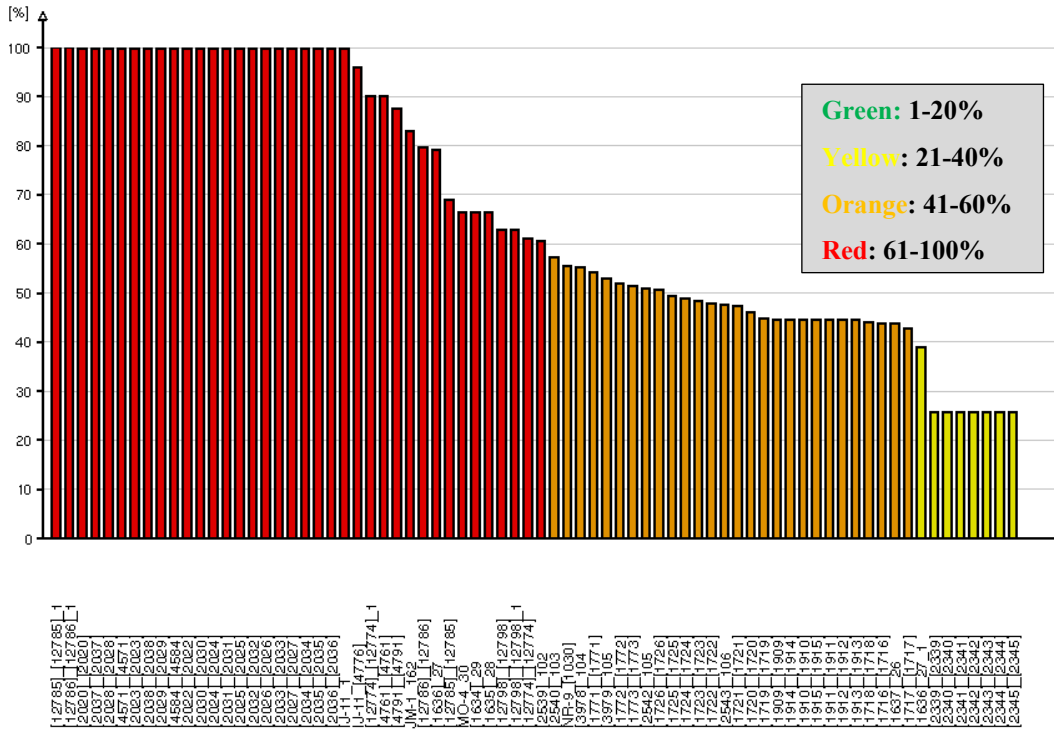


Figure 18. Maximum track utilization rate per hour for selected segments (Scenario 2)

Any track utilization rate over 60-70 percent can raise a red flag regarding capacity consumption and eventually may increase the risk of unsafe operations. However, this could be attributable to several reasons which may not be eventually interpreted as a capacity shortage of the track. For example, a heavy freight train moving slowly along a long signaling block occupies the track as long as the train has not left the signaling block, which will show that segment of track with a high utilization rate.

The team reviewed the selected track segments with 100 percent maximum utilization rates and found:

- Only one of the track segments were among the corridors with a high volume of daily traffic. In fact, the track segments with 71 daily trains (the first two bars presented in Figure 15) had maximum utilization rates of only 26 percent and 43 percent, respectively. These low utilization rates on the segments with such high daily traffic were accomplished by the advanced signaling system (i.e., cab signaling systems and short signal blocks) that was designed throughout the respective corridors of these segments.
- Out of 23 segments with a 100 percent utilization rate per hour, 2 had only 12 trains per day with a maximum of 2 trains an hour. Only one of the remaining segments had a maximum of 3 trains in an hour with only 20 daily trains. Almost all these segments experienced a 100 percent utilization rate because a couple heavy freight trains were moving slowly throughout a long signaling block.
- Only one segment with a 100 percent utilization rate had 62 daily trains (maximum 8 trains per hour) and was identified as one of the track segments in this network with significant capacity shortage and high risk of unsafe operations.

The team found that the other segments with high utilization rates (from 61 to 96 percent) can demonstrate a combination of single track corridors with low daily traffic and multiple-track corridors with high daily traffic. When the team analyzed this parameter with the other track utilization parameters shown in Figure 15 and Figure 16, they concluded that only 8 of the 15 segments had a relative shortage in their capacity limits.

In summary, out of 74 selected track segments, researchers identified a total of 9 segments with capacity shortage that could eventually increase the risk of unsafe operations, especially if occurring with other human errors or mechanical/signal failures.

4.2 Comparing Scenario 3 with Scenarios 1 and 2

This section compares the results of Scenario 3 (i.e., freight trains with mixed ECP and conventional braking systems) with Scenario 1 (i.e., freight trains with an advanced braking system) and Scenario 2 (i.e., freight trains with a conventional braking system). Table 5 summarizes a comparison between these three scenarios in terms of network capacity and safety parameters.

Table 5. Summary of simulation results of all three scenarios in terms of network capacity and safety parameters categorized based on each type of train

Train Type	Scenario	No. of Trains	Avg. Distance (miles)	Avg. Delay (sec)	Network Velocity (mph)	Avg. Station Stops	Avg. Route Braking	Avg. Signal Stops
Passenger	1 (ECP)	66	301	305	78.6	5.23	6.35	1.02
	2 (Conv.)	66	301	321	78.5	5.20	6.42	1.06
	3 (Mixed)	66	301	316	78.6	5.20	6.45	1.05
Freight	1 (ECP)	78	417	244	38.2	2.72	6.67	0.27
	2 (Conv.)	78	417	425	37.8	2.79	8.23	0.28
	3 (Mixed)	78	417	339	37.9	2.79	8.17	0.27
HSR	1 (ECP)	32	104	279	89.5	2.75	4.28	0.78
	2 (Conv.)	32	104	279	89.5	2.75	4.28	0.81
	3 (Mixed)	32	104	279	89.5	2.75	4.28	0.78
Comm.	1 (ECP)	56	204	82	63.9	10.14	1.13	0.38
	2 (Conv.)	56	204	77	64.0	10.14	1.13	0.36
	3 (Mixed)	56	204	77	64.0	10.14	1.13	0.36
Overall	**1 (ECP)**	**232**	**289**	**227**	**57.1**	**5.23**	**4.91**	**0.58**
	2 (Conv.)	**232**	**289**	**291**	**56.9**	**5.25**	**5.46**	**0.59**
	3 (Mixed)	**232**	**289**	**261**	**56.9**	**5.25**	**5.44**	**0.58**

Since Scenario 3 inherited the advanced braking characteristics of half of the freight trains from Scenario 1, the overall results of this scenario are slightly improved over Scenario 2 that used only conventional braking characteristics, but only in terms of average delay and number of stops at signals. More details about each parameter are provided below.

Average delay

The team observed this parameter to fall approximately in the middle for Scenarios 1 and 2. Overall, the average delay in Scenario 3 is improved compared to Scenario 2, but higher than Scenario 1.

Average network velocity

Researchers did not observe any improvement for network velocity of this scenario compared to Scenario 2 (i.e., only conventional braking characteristics).

Average number of stops at stations

The team did not observe any improvement for the number of siding/station stops in Scenario 3 compared to Scenario 2.

Average number of braking for route reservation

The research team did not observe any improvement for this parameter compared to Scenario 2. In fact, Scenario 1 (i.e., only advanced braking characteristics) had much better values compared to Scenario 3, even though half of the freight trains in Scenario 3 inherited the braking characteristics from the Scenario 1.

Average number of stops at signals

This parameter had mixed outcomes in comparison to the other two scenarios. The team reviewed the results of each train category and found this scenario slightly improved the results for number of stops at the signals for freight, HSR, and commuter trains within their respective boundaries, while the results remained higher than expected for passenger trains. Overall, the results of this scenario were almost the same as Scenario 1.

Also, the team compared the track utilization rate of this scenario to the other two scenarios and observed no major changes overall.

In summary, researchers concluded that gradually retrofitting the brake systems on freight trains with ECP can relatively improve the delay status of trains throughout the network and partially reducing the number of unnecessary stops at the signals due to minor conflicts. However, it may not provide any major improvements in terms of other network capacity and safety parameters (e.g., network velocity, number of braking actions at sidings or signals) unless most of the freight fleets are retrofitted with advanced braking systems.

5. Scaling the Mini-Network Results to National Network

5.1 Approach for Scaling-up the Network Parameters

Previous sections discussed the impact of different braking characteristics on freight trains on network capacity and safety features for a mini-network comprised of approximately 5,000 miles of main tracks (over 6,000 miles including multiple-track segments) with 232 daily trains, including 78 freight trains. This section briefly discusses how to extend the results of such a simulation study to the nationwide U.S. rail network based on available information or interpreted data and engineering judgment.

It should be emphasized that multiple parameters and variables can affect the capacity and safety features of a network. However, this study addresses those parameters that have major influences on the network-related components and can also be measured/scaled up considering the metrics investigated in this study.

The parameters the team took into account to extend the model results to the real size of the U.S. rail network are highlighted in Table 6 using the 2018 Railroad Facts published by AAR [14].

Table 6. Summary of parameters used for scaling up the mini-network analysis to the real-sized network

Parameter	Study network	U.S. rail network	Notes
Length of main tracks (miles)	5,000	138,000 *	*Railroad Facts [14]
Annual freight train-miles	12.2 million *	465.3 million **	*Assuming 2 days travel cycle, on average, for freight trains of the study, **Railroad Facts [14]
No. of sidings/yards	150	4,600 *	*Estimated based on 30 miles average distance between sidings/yards throughout the U.S. rail network
% of congested corridors	21% *	21% **	* Estimated based on track utilization rate of study, ** AAR's study on freight network capacity [11]
Age of freight cars	New	~20 years*	*Based on AAR data [15]

Additional details about each parameter and their respective scaling factors are explained below.

Total length of main tracks

The team calculated the total length by comparing the nearly 138,000 miles of main tracks in the U.S. (including class I railroads and all shortline railroads) to the main tracks of the 5,000 miles developed in the mini-network and found the scaling up factor for the network size was ~ 27.6. However, when analyzing network capacity and safety aspects, the impact of the length of the tracks cannot be assumed linear and should be justified with consideration for other parameters of the network as summarized in Table 6. This will be explained in more detail later in this section.

Annual freight train-miles

The total freight train-miles per year shows how extensively the freight trains travel in each network. The value of train-miles for this study (i.e., 12.2 million) was calculated using a 2 day

travel cycle for all 78 freight trains on their respective routes for one year. The 465.3 million train-miles of the U.S. rail network [14] divided by the 12.2 million train-miles in the study returns a value of 38.1 as the scaling-up value for this parameter.

Number of sidings and yards

There is no clear data as to how many rail sidings exist in the U.S. rail network. Assuming an average distance of 30 miles between each 2 adjacent siding/yards through the entire 138,000 miles of the U.S. rail network, the team estimated that nearly 4,600 rail sidings/yards are in operation. The team divided this value by the 150 sidings/yards of the study and found the scaling-up value was 30.7 for this parameter.

Proportion of network with congested traffic

This parameter emphasizes the role of traffic density and network congestion that may aggravate the capacity and safety features of operating trains (at least for a regional territory, if not for the entire network) compared to the same territory with a lower congestion level. Based on the track utilization rate analysis, about 21 percent of the mini-network used in the study has traffic flow near or above the capacity threshold of 70 percent.

However, according to a study about freight network capacity analysis conducted by AAR [11], nearly 13 percent of the U.S. rail network, without considering passenger and commuter services, was at or above the 70 percent capacity limit in the year 2005. The same report predicts 55 percent of the rail network will be above the 70 percent capacity limit in the year 2035. By linear projection, in the year 2020 the rail network experienced roughly 21 percent congestion. Thus, the scale factor for this parameter was estimated to be around 1 for a similar congestion level in the mini-network and the U.S. rail network.

Age of freight fleet

The team modeled all trains in this study to operate without any mechanical or braking problems. However, in real practice the efficiency of braking systems reduces with age, even when equipped with advanced braking components.

According to AAR, the average age of cars in the current U.S. network is 20 years [14]. However, 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 [16, 17], though many braking components (e.g., brake valves and brake shoes) are regularly maintained and refurbished as needed.

According to AAR, in 2017 there were 1,659,965 freight cars available in service logging approximately 34,065 million car-miles [14]. Therefore, the team calculated the average annual mileage of a car to be around 20,522 miles for a given year. This implies that for a each car it may take about 11.6 years to reach the benchmark of 240,000 miles of service.

Based on this data, researchers concluded that most of the U.S. fleet with an average age of 20 years of service maintained 90 percent brake efficiency compared to a brand new car (as assumed in a simulation model). As a result, the scale factor of aged fleet is estimated to be around 1.1 when comparing the age of the U.S. fleet against the simulation model.

Table 7 summarizes the network parameters for scaling up the results of this study into the real size of the U.S. rail network. As explained earlier, the impact of each parameter should be considered through an analytical method that combines all scale factors together for analyzing

each network associated criteria. Additional details for factors such an approach are discussed in the following section.

Table 7. Estimated scale factors of the U.S. rail network against the simulation network

Parameter	Study network	U.S. rail network	Scale Factor
Length of main tracks (miles)	5,000	138,000	27.6
Annual freight train-miles	12.2 million	465.3 million	38.1
No. of sidings/yards	150	4,600	30.7
% of congested corridors	21%	21%	1
Age of freight cars	New	~20 years	1.1

5.2 Impact Factors of Network Parameters

As explained in Section 4, the team used five network-related parameters to assess what improvements can be made when comparing the scenario of freight trains with advanced braking system (Scenario 1) against one with conventional braking characteristics (Scenario 2). Researchers also considered these five parameters when estimating the impact of upgrading the freight braking system throughout the U.S. rail network. The proportional improvements the team estimated for the network in this study are summarized below.

- **Network delay:** 22 percent improvement for Scenario 1
- **Network velocity:** 0.4 percent improvement for Scenario 1
- **Number of stops at stations:** 0.3 percent improvement for Scenario 1
- **Braking actions for route reservations:** 11 percent improvement for Scenario 1
- **Number of stops at signals:** 2 percent improvement for Scenario 1

Researchers used the five scale factors described earlier in this section to evaluate any improvement from upgrading the braking systems on freight trains in the U.S. as estimated in the simulation effort. However, the team had to combine them into an expression or equation to estimate the improvement in each network associated parameter:

$$Y_k = M_k \,.\, Y'_K \qquad \text{(EQ1)}$$

Where:

$\boldsymbol{Y_k}$: Estimated (%) improvement of respective capacity/safety parameter of the U.S. rail network after upgrading freight braking systems (e.g., Y_1 is the % of improvement in network delay)

$\boldsymbol{Y'_K}$: Estimated improvement percentage of respective capacity/safety parameter in the mini-network of the study (e.g., Y'_1 is the % of improvement in mini-network delay; 22%)

$\boldsymbol{M_k}$: Estimated "network impact factor" of respective capacity/safety parameter (K) which should be computed based on different network parameters used to scale up the given mini-network to the national network. In this study, M_k is estimated based on following formula EQ2:

$$M_k = \left(A_{k1}.X_1^{1/3} + A_{k2}.X_2^{1/3} + A_{k3}.X_3^{1/3} + A_{k4}.X_4 + A_{k5}.X_5^{1/2}\right) \qquad \text{(EQ2)}$$

Where:

$\boldsymbol{X_i}$: The scaling factor computed for 5 different network parameters (e.g. $X_1 = 27.6,\ X_2 = 38.1$)

$\boldsymbol{A_{ki}}$: The weighing impact factor for $\boldsymbol{X_i}$; $\sum_i A_{ki} = 1$

The team balanced and justified EQ1 and EQ2 based on the following criteria/constraints:

- If all network characteristics have the same characteristics of the given network of the study, the estimated improvement percentage of the respective network capacity/safety feature must be equal to the initial value. (EQ2=1 or $Y_k = Y_K'$)
- Under no condition, can the value of M_k be more than 3. (e.g., $Y_1 \leq 3Y_1'$)
- Under no condition, can the value of one individual component of equation EQ2 exceed the value of the other components combined.

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

5.3 Estimating Capacity and Safety Improvement over the U.S. Network

Each network capacity/safety parameter (K) can be affected differently when computing the respective network impact factor (M_k), and therefore may have different weighing impact factors when evaluating the improvement percentage of the parameter. For instance, when analyzing the network delay, the impact factor of each network parameter can be weighed uniformly ($A_{1i} = 0.20$), but for evaluating the braking actions for route reservation, the impact factor of network congestion level may have higher weight compared to the total length of the tracks over the network ($e.g.\ A_{41} = 0.15\ ;\ A_{44} = 0.30$).

Table 8 presents the estimated impact factors of each network expansion parameter customized for each network capacity/safety features using EQ1 constraints and assumptions.

Table 8. Estimated impact factors of each network expansion parameter, customized for each network capacity/safety feature

Network Capacity and Safety Features (k)	Impact Factors of Network Expansion Parameters (i)					
	Length of tracks (i=1)	Train-miles (i=2)	No. 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
No. of Station Stops (k=3)	0.1	0.1	0.1	0.4	0.3	1
Braking for Route Reservation (k=4)	0.15	0.2	0.2	0.3	0.15	1
No. of Stops at Signals (k=5)	0.15	0.2	0.2	0.3	0.15	1

As shown in Table 8, the congestion level impact factors have higher weights in almost all network related features because a congested network can rapidly degrade operations safety and capacity. However, the length of tracks has the lowest impact factor weight compared to the other parameters.

The team used the impact factors presented in Table 8 in EQ2 and eventually in EQ1 to assess the improvement of the network criteria that can be expected from upgrading the freight train braking systems to ECP over the U.S. rail network (Table 9).

Table 9. Estimated improvement over the U.S. rail network against the simulated network, as a result of deploying advanced braking systems for freight trains

Network Capacity and Safety Features	Improvement over the Simulated Network (Y_k)	M_k	Estimated Improvement over the National Network (Y_K')
Network Delay	22%	1.87	41.1%
Network Velocity	0.4%	1.99	0.8%
No. of Station Stops	0.3%	1.67	0.5%
Braking for Route Reservation	11%	2.21	24.3%
No. of Stops at Signals	2%	2.21	4.4%

As expected, the highest degree of improvement over the U.S. rail network when upgrading the braking systems on freight trains can be seen in reducing the amount of network delay by 41.1 percent followed by the number of braking actions for route reservation at the signals (24.3 percent reduction) and the number of unnecessary stops at signals (4.4 percent reduction). The other two parameters (i.e., increasing network velocity and number of station stops) showed minor estimated improvements (0.8 and 0.5 percent, respectively) though the operational and financial impacts of these enhancements are not negligible.

While any improvement in network delay, network velocity, and number of stops at stations can be categorized as operational or capacity-oriented improvements, the other two parameters (i.e., braking actions for route reservation and number of stops at signals) can be identified as safety-oriented improvements. Thus, any enhancements of these two parameters due to improving the freight train braking system (in this case, 24.3 percent and 4.4 percent) can help railroads and other respective authorities to improve the safety aspects of daily operations across the U.S. rail network.

6. Summary and Conclusions

Over the last two decades there have been major technology initiatives in the railroad industry to improve the safety level of freight train operations as well as performance of freight rail equipment. One of the technologies in public discussion is the Electronically Controlled Pneumatic (ECP) brake system that not only can improve operations safety but may also enhance the operational aspects of freight trains along their respective corridors.

In this study, researchers evaluated the impact of an advanced braking system (e.g., ECP) on freight trains on the safety and capacity aspects of the U.S. rail network using a benchmark mini-network simulation approach. The research team selected OpenTrack, a widely used network simulation software, to conduct the study. The team developed a hypothetical mini-network comprised of various traffic mixes on corridors like the North American rail network operations.

Overall, researchers modeled about 5,000 miles of main tracks in the simulator. However, considering parts of the network with double and multiple-track segments as well as additional tracks lengths along 150 yards/sidings of the network, approximately 6,200 miles of tracks were built for the simulation.

Researchers scheduled 232 daily trains (a mix of intercity passenger, commuter, HSR, and freight services) in the simulation model including 78 daily freight trains in 17 different configurations.

The team developed three simulation scenarios to analyze the impact of deploying advanced braking systems for freight trains on network capacity and safety features.

- **Scenario 1 –** All freight trains with an advanced braking system (ECP)
- **Scenario 2 –** All freight trains with a conventional braking system (Conventional)
- **Scenario 3 –** Hybrid (Mixed ECP and Conventional freight trains)

The researchers simulated all three scenarios using the same assumptions and network model characteristics except that braking characteristics for freight trains were different for the same train in different scenarios. Also, all trains schedules, as a result of simulation runs, were "conflict-free," meaning that they departed from their designated origins and arrived to their assigned destinations without any schedule conflict that could cause a deadlock anywhere throughout the network.

The team analyzed several network capacity and safety related parameters, including network delay, network velocity, track utilization level, number of meet-pass and stops at stations, number of braking for route reservations, and number of stops at signals for the selected simulation scenarios.

The research team concluded freight trains with an ECP braking system (Scenario 1) provided improved results in terms of network delay and number of braking actions for route reservations with approximately 22 percent and 11 percent improvement, respectively, over Scenario 2. Also, several unnecessary signal stops were eliminated in Scenario 1 (about 2 percent) but the team observed the improvement in network velocity and number of stops at stations to be less than 1 percent.

The team compared Scenario 3 (i.e., mixed conventional and ECP equipped freight trains) to the other two scenarios and concluded that gradually retrofitting the brake systems of freight trains can relatively improve the delay status of trains throughout the network and partially reduce the number of unnecessary stops at signals due to minor conflicts. However, it may not provide any major improvements in terms of other network capacity and safety features (e.g., network velocity, number of braking actions at sidings or signals) unless the entire freight fleet (or at least a major portion of it) is retrofitted with advanced braking systems. The team observed no difference in terms of track utilization rates between the scenarios in this study.

Researchers then extended the results of the simulation scenarios to the real size of the U.S. rail network, assuming certain parameters and assumptions that have more weight on network-related performance components and can also be scaled up considering the metrics investigated through this study. The team used five different expansion parameters to expand the network characteristics of the study to the real size of the national rail network:

1. Total length of tracks
2. Freight train-miles
3. Number of sidings/yards
4. Congestion level of the network
5. Age of fleet

To estimate the overall improvement of deploying advanced braking systems for freight trains over the U.S. network, the team employed an analytical approach using these parameters and assuming respective impact factors for each expansion parameter. The results of using this approach over the U.S. rail network showed certain degrees of improvement in all respective network capacity and safety features.

Researchers found the highest degree of improvement in reducing the amount of network delays by 41.1 percent, followed by a reduction in the number of braking actions for route reservation at the signals of 24.3 percent and the number of unnecessary stops at signals reduced by 4.4 percent. The other two parameters (i.e., increasing network velocity and number of station stops) showed minor improvements, 0.8 and 0.5 percent, respectively) though the operational and financial impacts of these enhancements are not negligible.

The team showed that the impact of braking system technologies can be investigated using a smaller network (e.g., the mini-network simulation used in this study). This allows a strategy to apply the results to the national network either by creating a larger network or developing the scaling approach proposed in this work.

The team found certain topics and research ideas which can be further investigated using the current study.

- Researchers can conduct more in-depth investigation on the network capacity and safety parameters, as the current model presented in this study has not been thoroughly validated and may need to be calibrated or adjusted based on more simulation runs and a larger network size.

- Researchers can conduct sensitivity analysis on the network simulation results as the expansion model assumes certain coefficients and impact factors that may provide different results depending on network characteristics and how the model is calibrated.
- Researchers can evaluate the phasing strategy detailed in this study with more intermediate stages of retrofitting or replacing the freight trains with more advanced braking systems.

Appendix A.

Simulation Characteristics and Validation Comparison

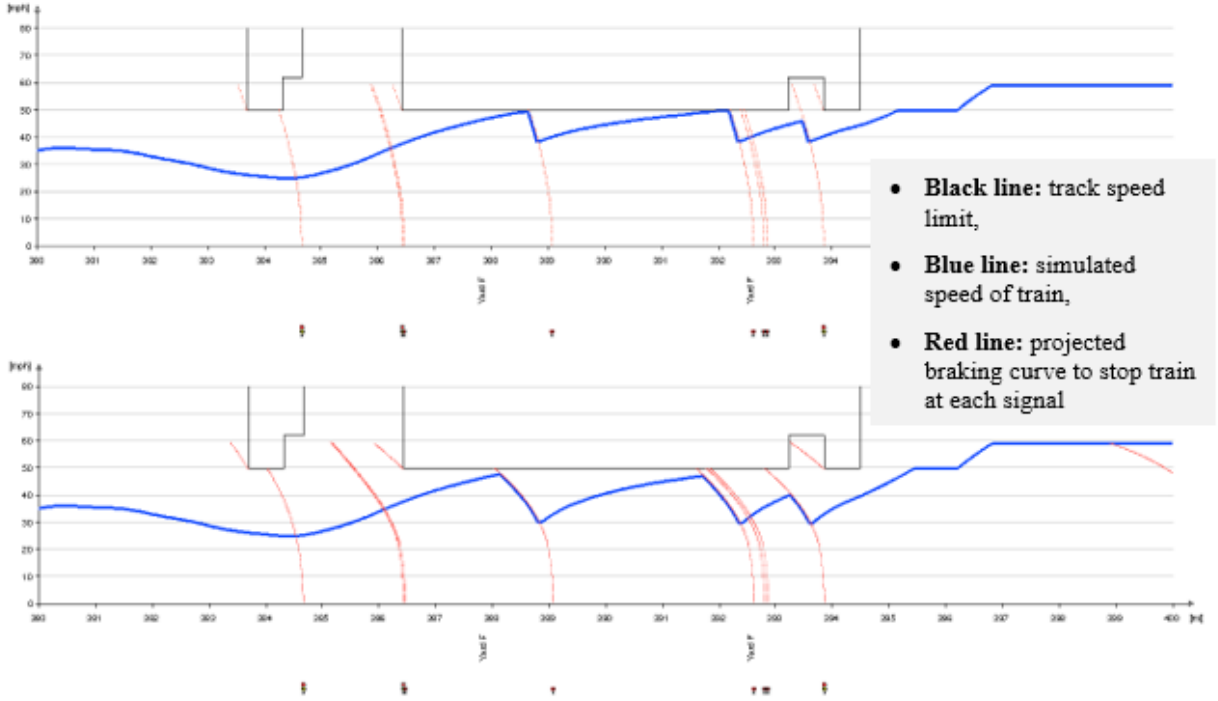


Figure 19. Speed profile of a sample freight train with ECP braking characteristics (top figure) against its simulated operations under conventional braking characteristics (bottom figure)

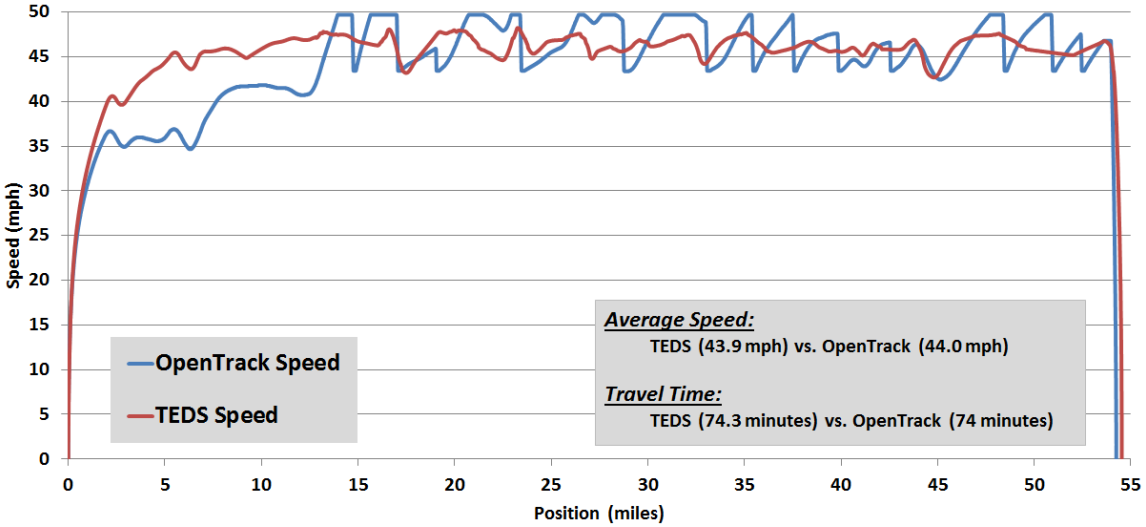


Figure 20. Comparison between speed profiles of a train simulated in OpenTrack (blue) and speed profile of the same train simulated in TEDS (red)

Additional Time-Distance Diagrams of Scenario 1

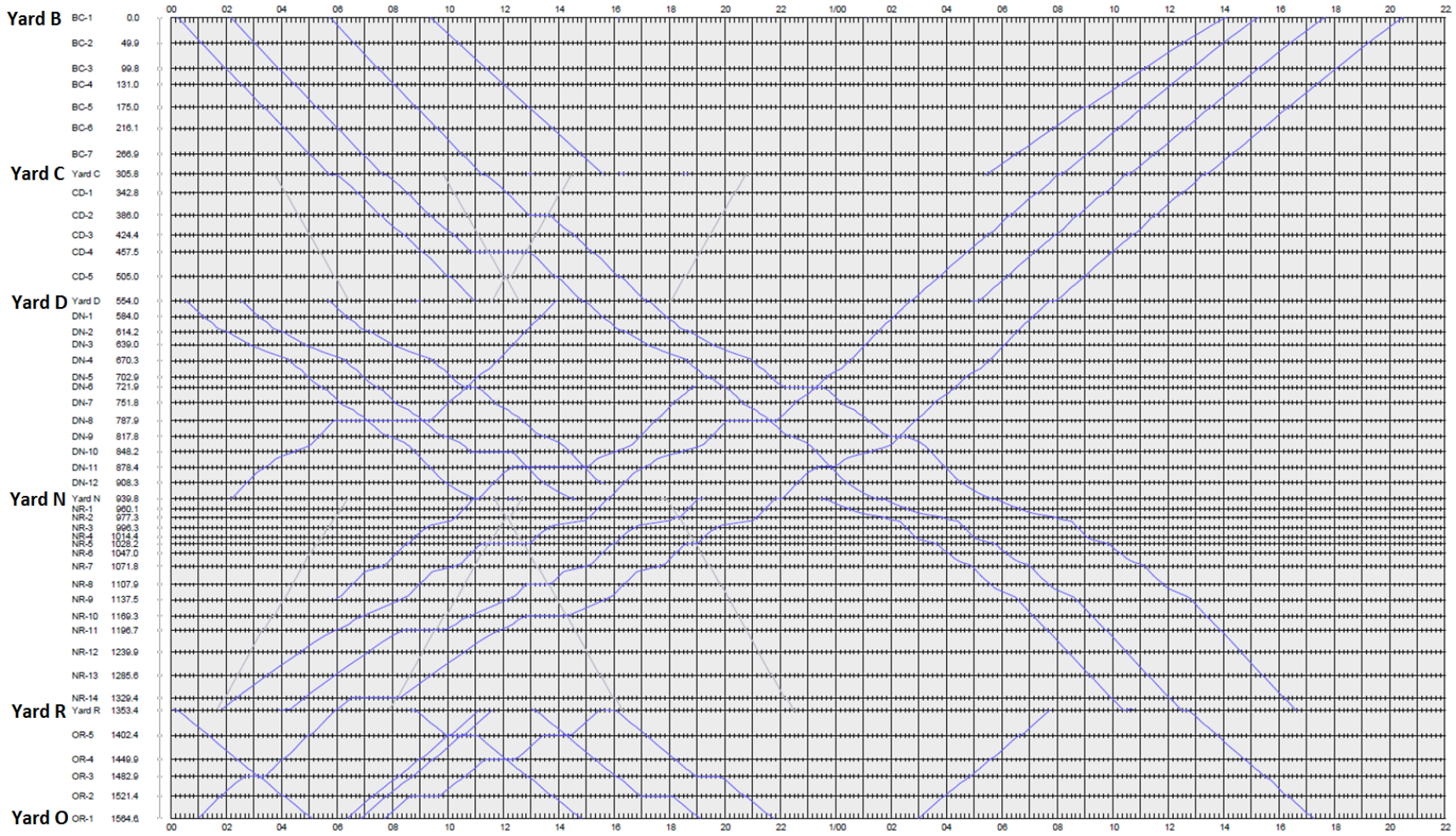


Figure 21. Stringlines for the given trains simulated on B-C-D-N-R-O section of network assuming ECP braking system for freight trains

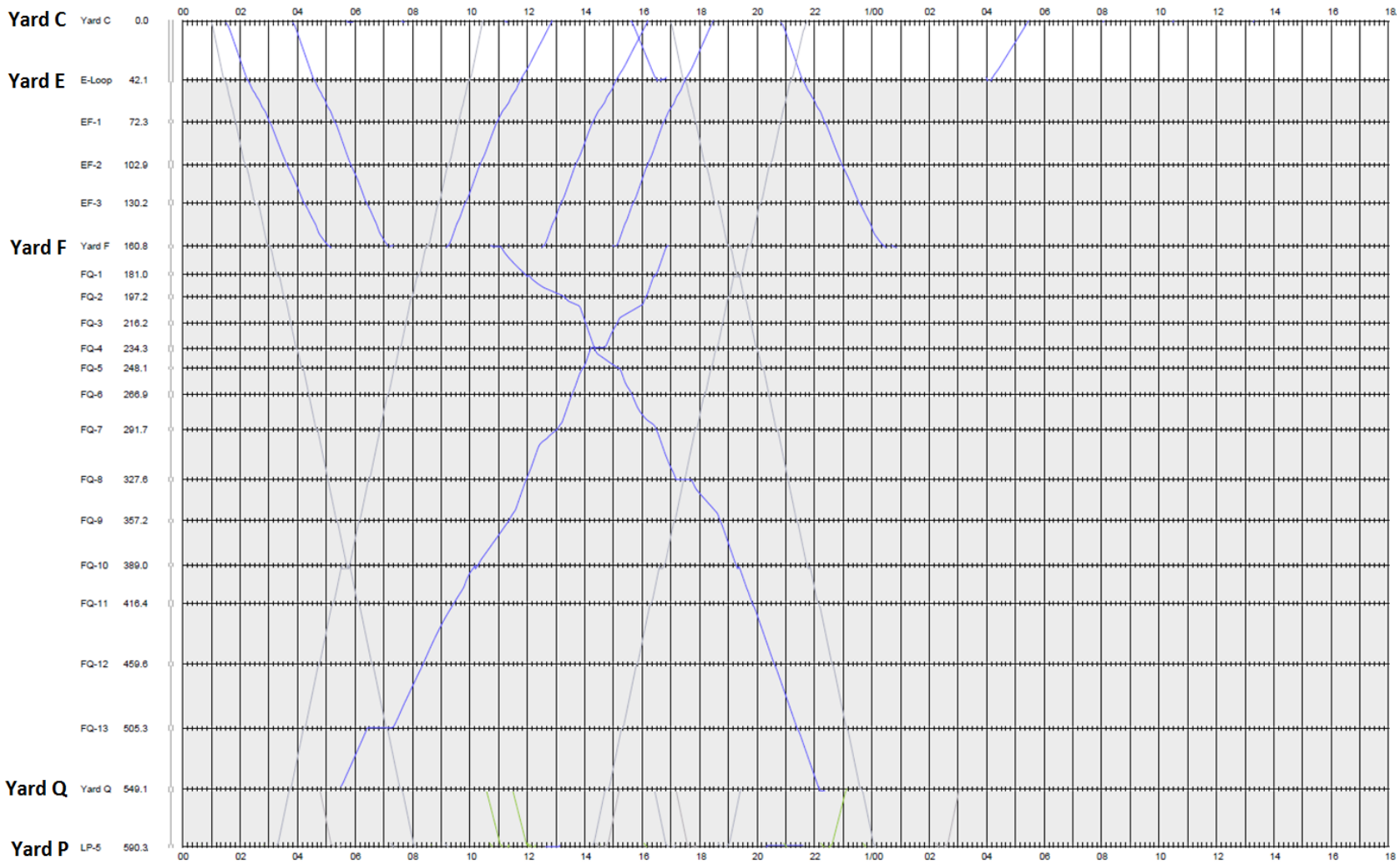


Figure 22. Stringlines for the given trains simulated on C-E-F-Q-P section of network assuming ECP braking system for freight trains

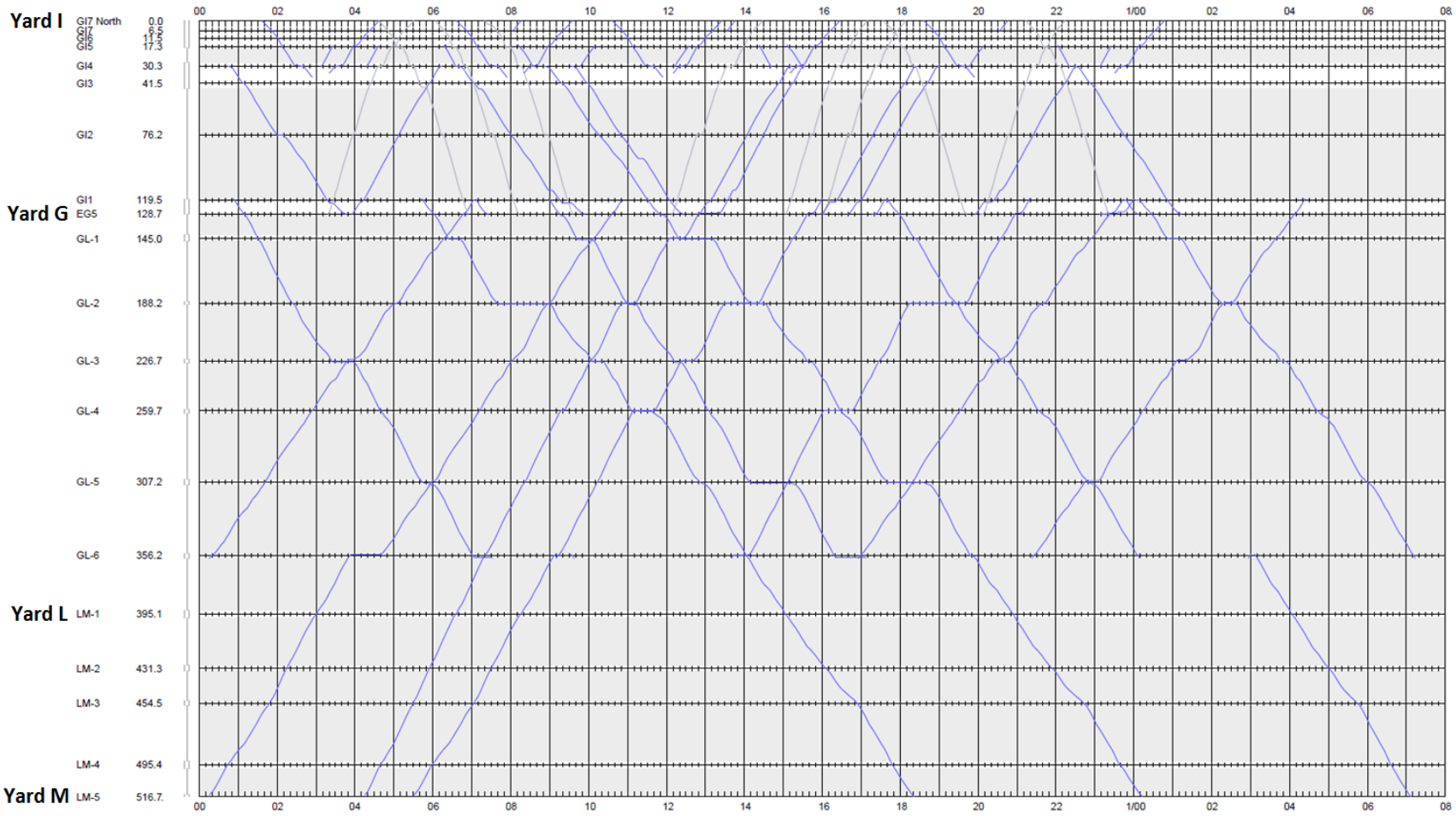


Figure 23. Stringlines for the given trains simulated on I-G-L-M section of network assuming ECP braking system for freight trains

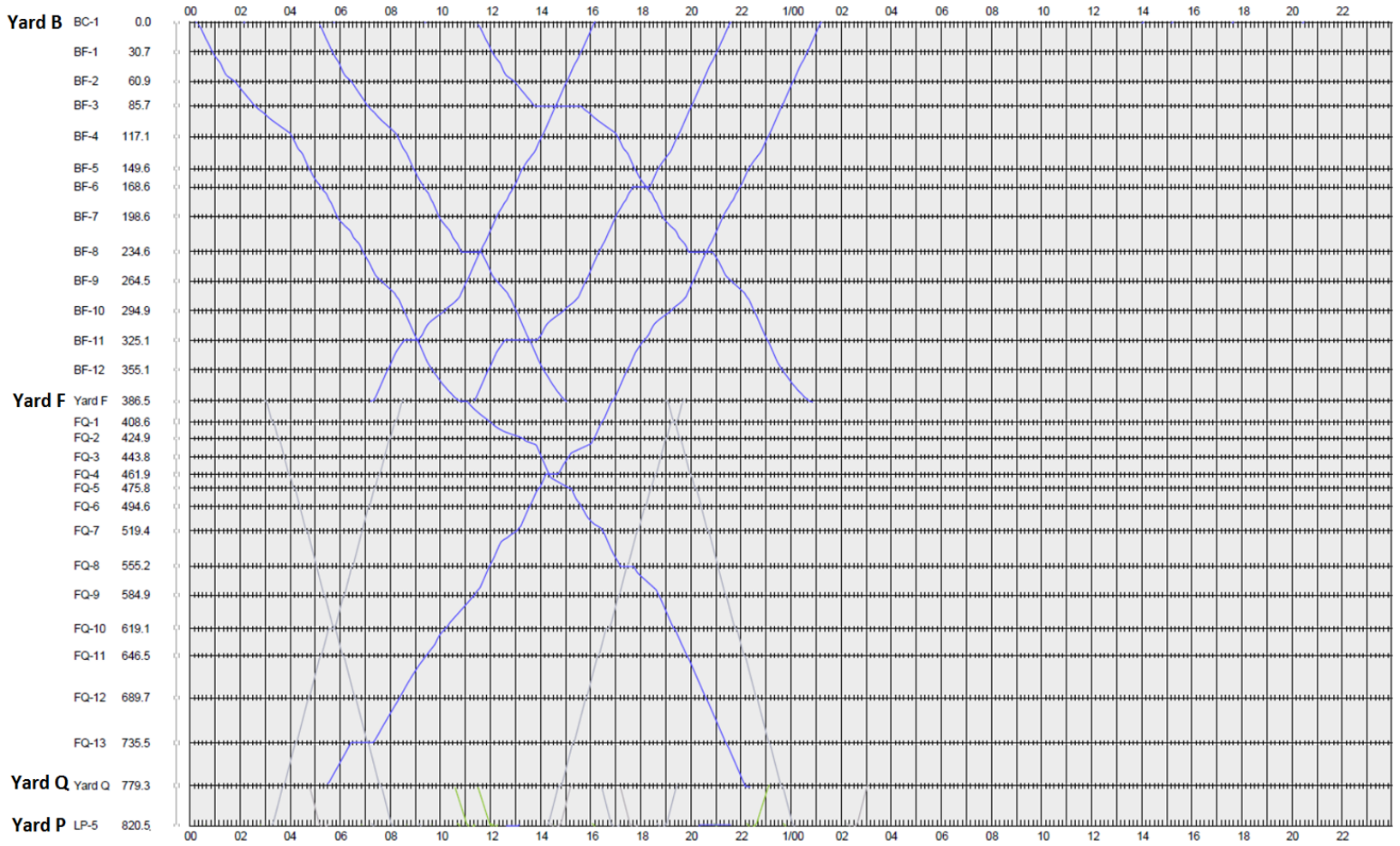


Figure 24. Stringlines of the given trains simulated on B-F-Q-P section of network assuming ECP braking system for freight trains

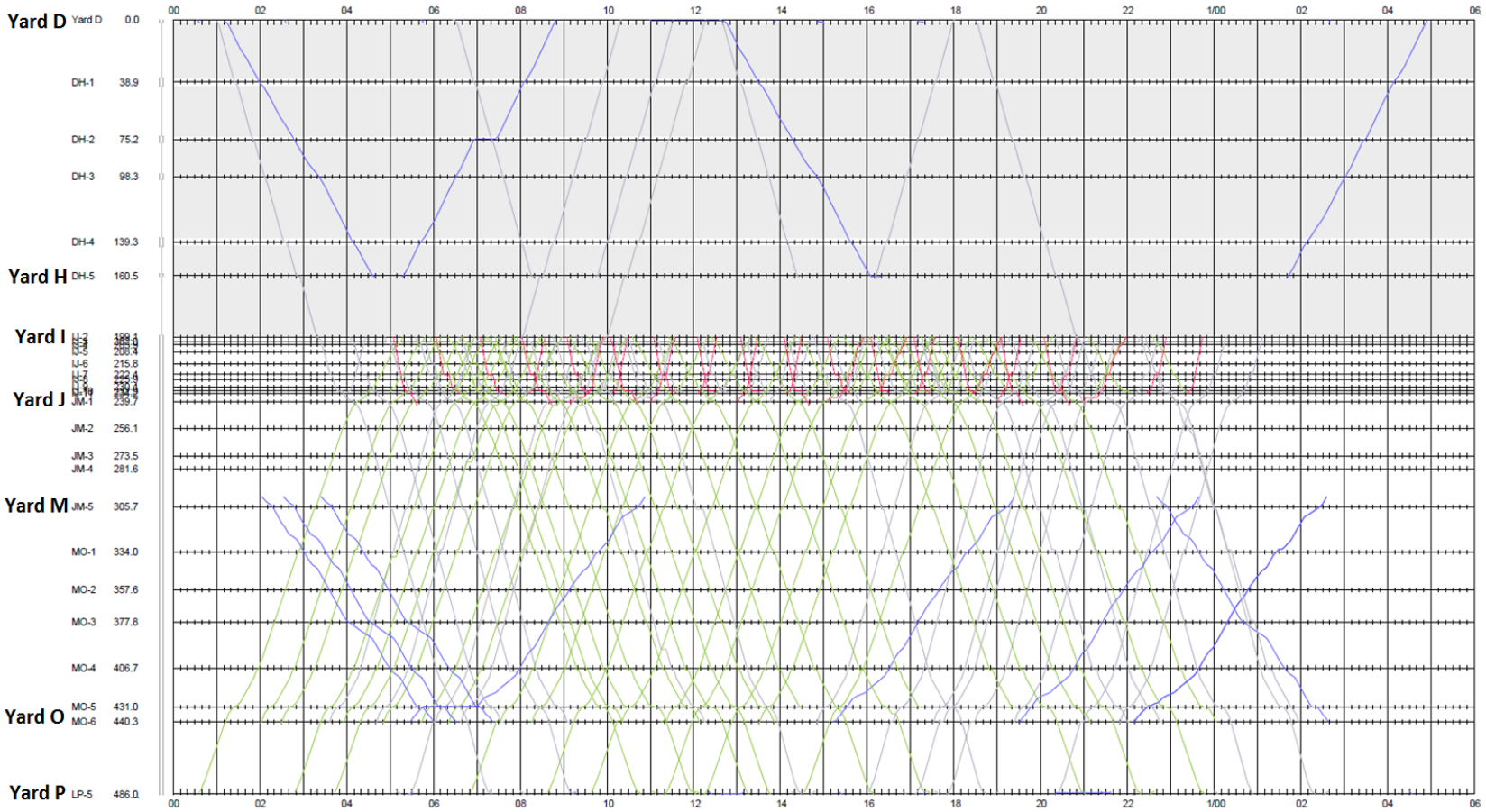


Figure 25. Stringlines for the given trains simulated on D-H-I-J-M-O-P section of network assuming ECP braking system for freight trains

Additional Time-Distance Diagrams of Scenario 2

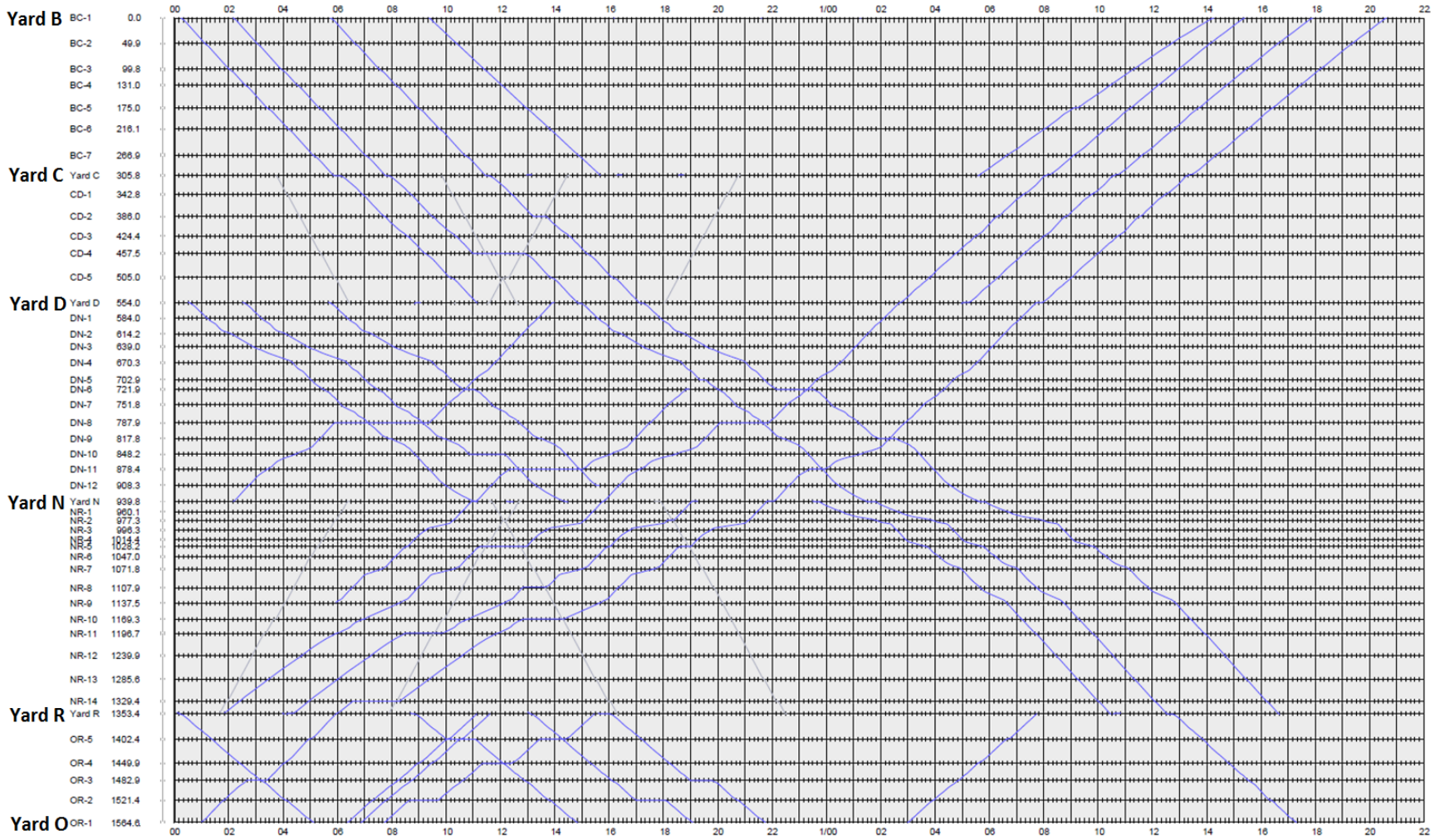


Figure 26. Stringlines for the given trains simulated on B-C-D-N-R-O section of network assuming conventional braking system for freight trains

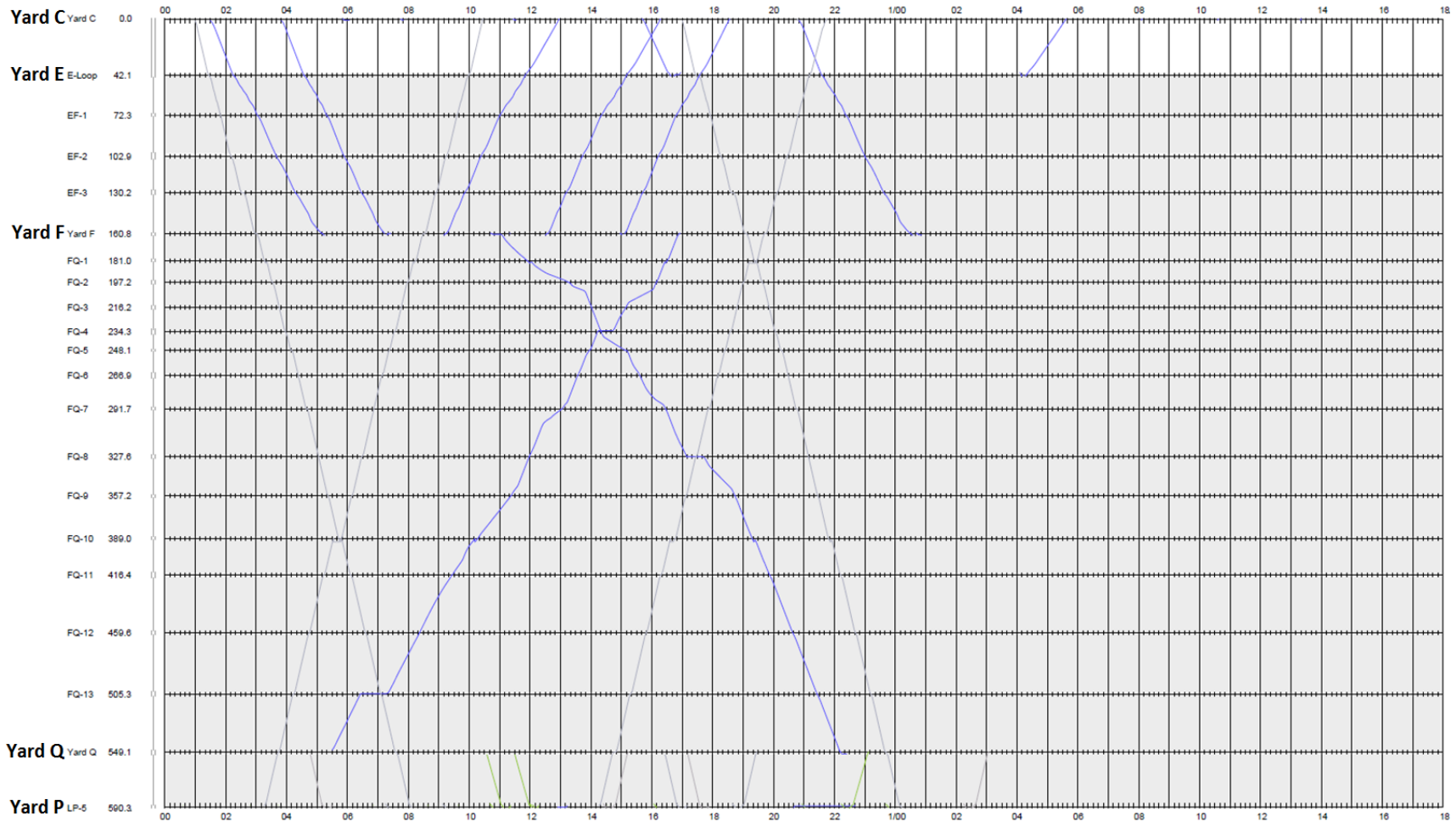


Figure 27. Stringlines for the given trains simulated on C-E-F-Q-P section of network assuming conventional braking system for freight trains

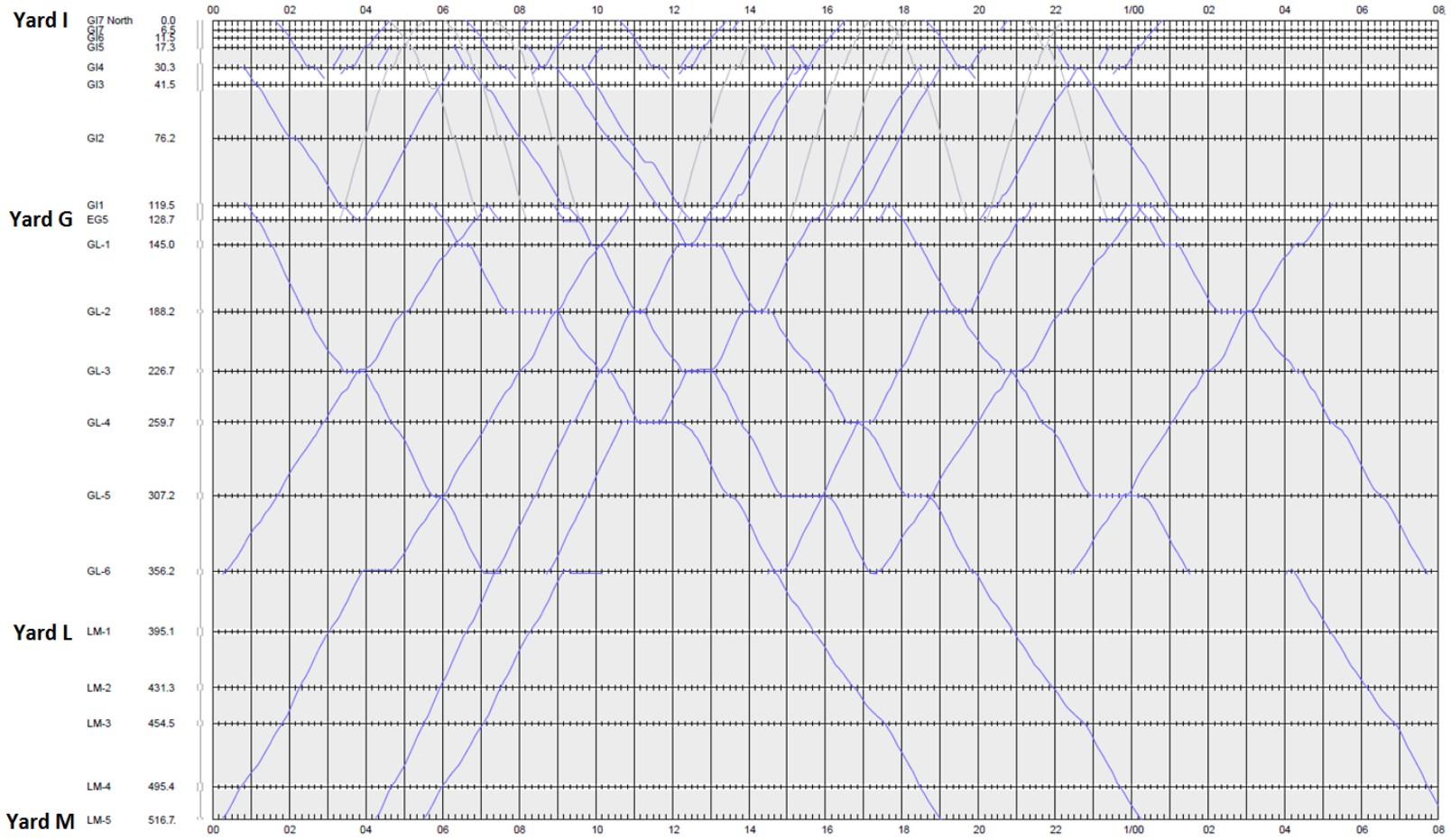


Figure 28. Stringlines for the given trains simulated on I-G-L-M section of network assuming conventional braking system for freight trains

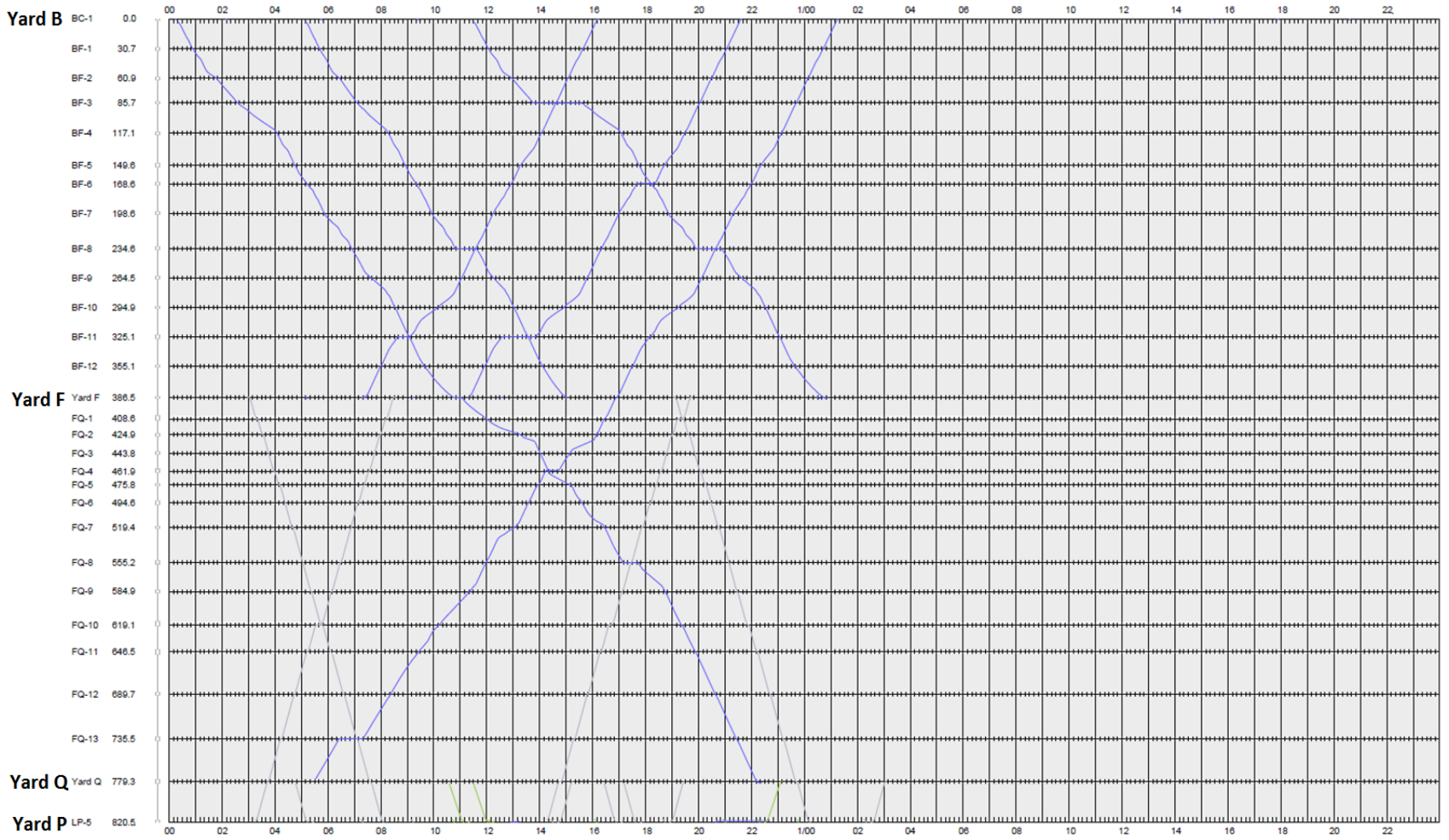


Figure 29. Stringlines for the given trains simulated on B-F-Q-P section of network assuming conventional braking system for freight trains

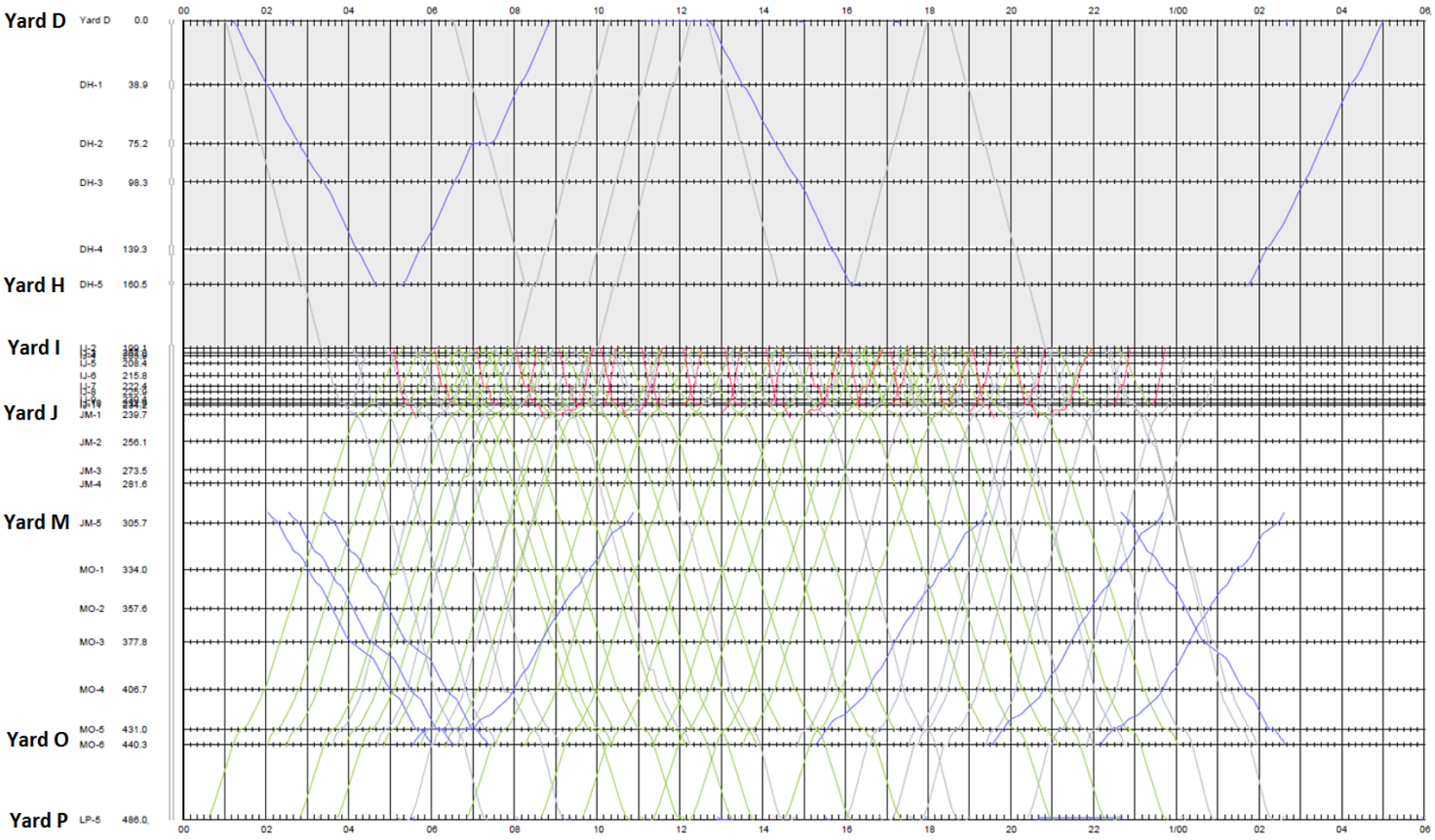


Figure 30. Stringlines for the given trains simulated on D-H-I-J-M-O-P section of network assuming conventional braking system for freight trains

Performance Plots of Selected Trains

A Freight Train with an Advanced Braking System

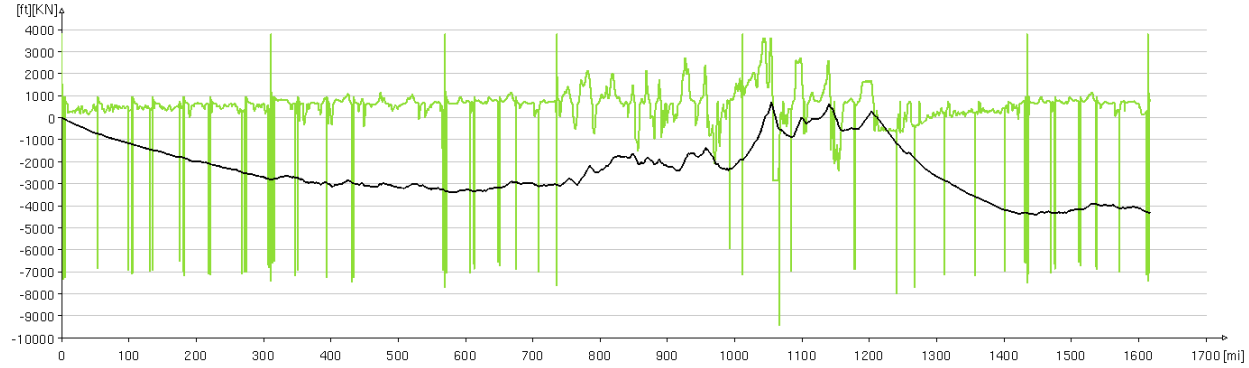


Figure 31. Track elevation (black line) and tractive effort (green line) of simulated freight train "UnitDP1-020-1" with advanced braking system

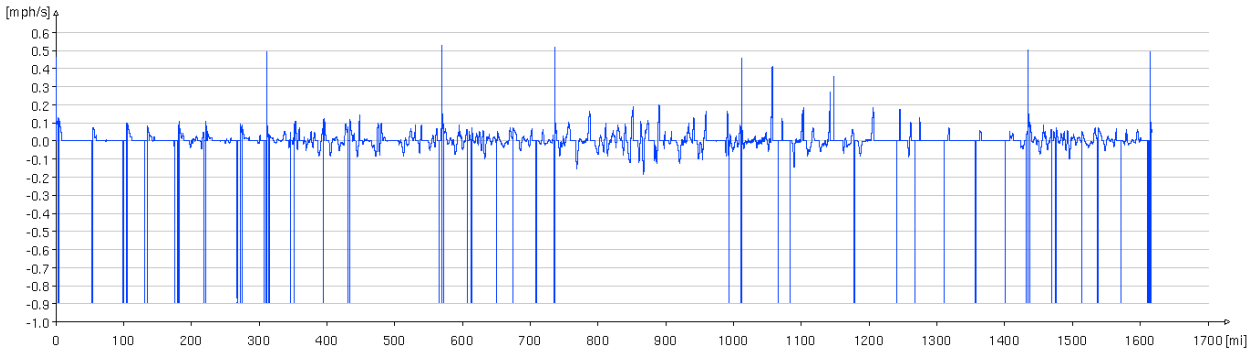


Figure 32. Acceleration profile of simulated freight train "UnitDP1-020-1" with advanced braking system

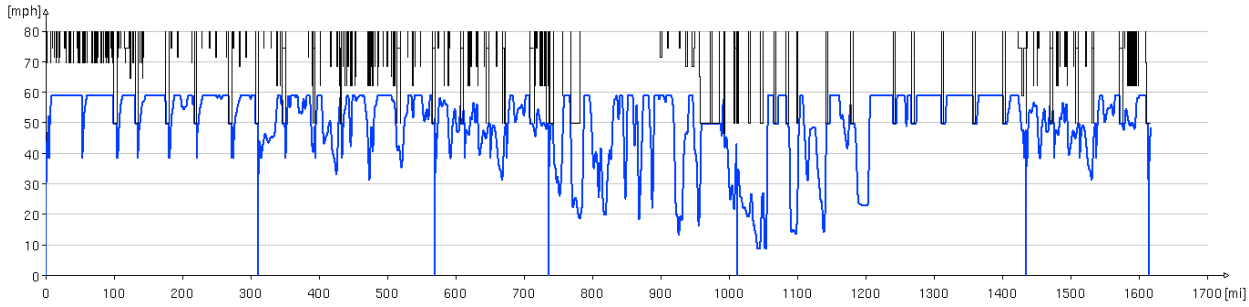


Figure 33. Speed profile (blue line) and track speed limit (black line) of simulated freight train "UnitDP1-020-1" with advanced braking system

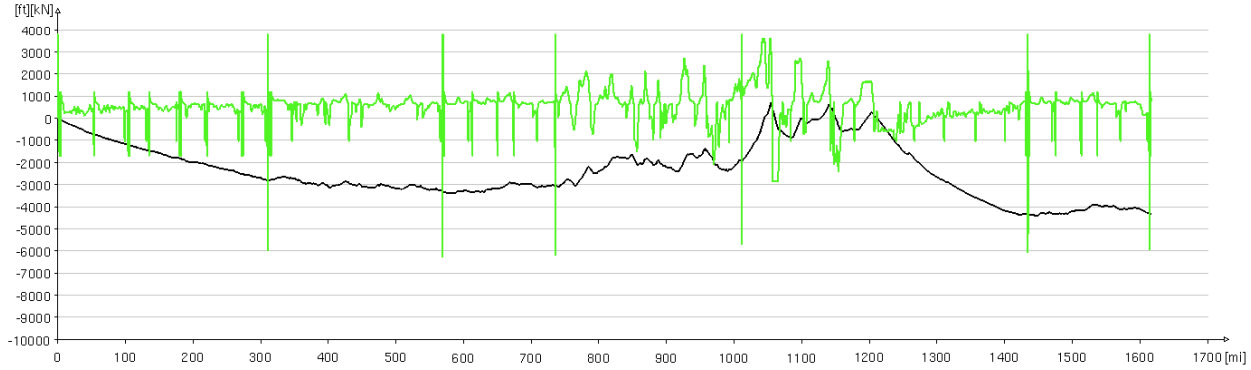


Figure 34. Track elevation (black line) and tractive effort (green line) of simulated freight train "UnitDP1-020-1" with conventional braking system

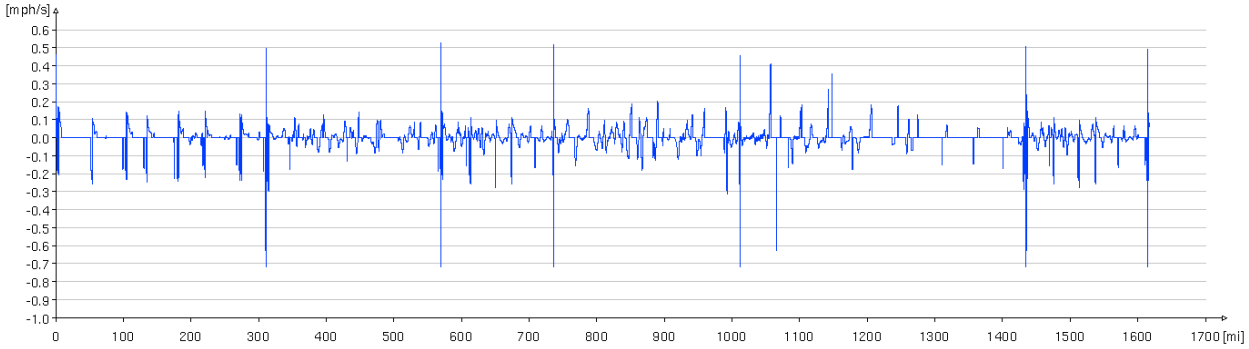


Figure 35. Acceleration profile of simulated freight train "UnitDP1-020-1" with conventional braking system

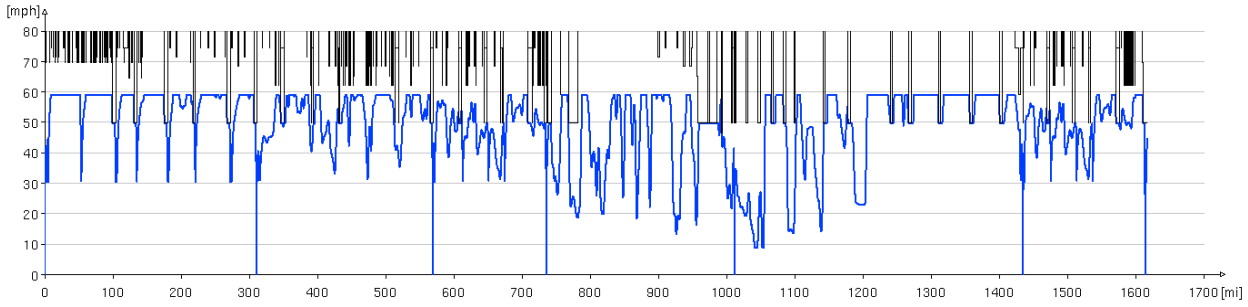


Figure 36. Speed profile (blue line) and track speed limit (black line) of simulated freight train "UnitDP1-020-1" with conventional braking system

A Passenger Train

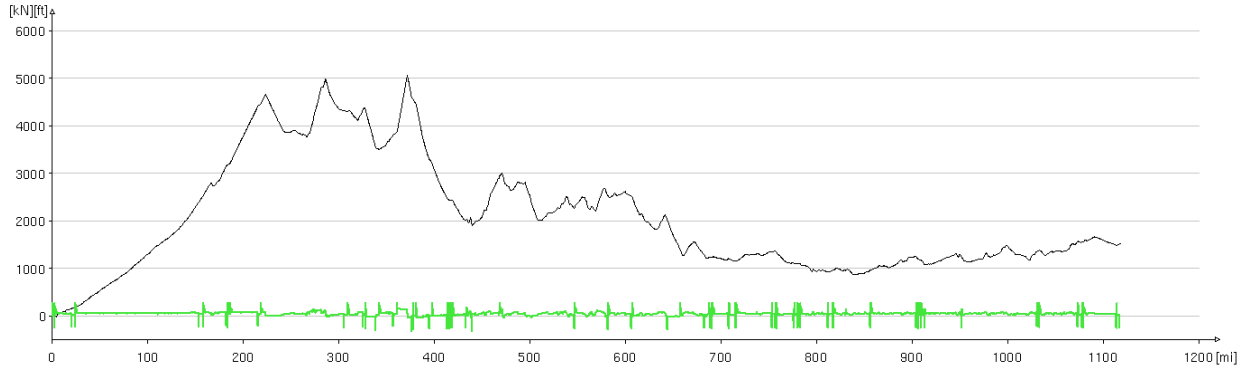


Figure 37. Track elevation (black line) and tractive effort (green line) of simulated passenger train "P0181-CDNR"

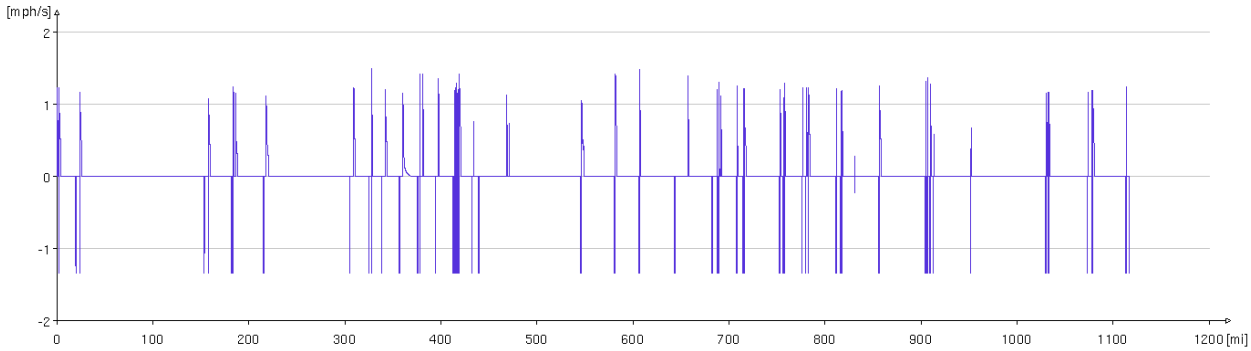


Figure 38. Acceleration profile of simulated passenger train "P0181-CDNR"

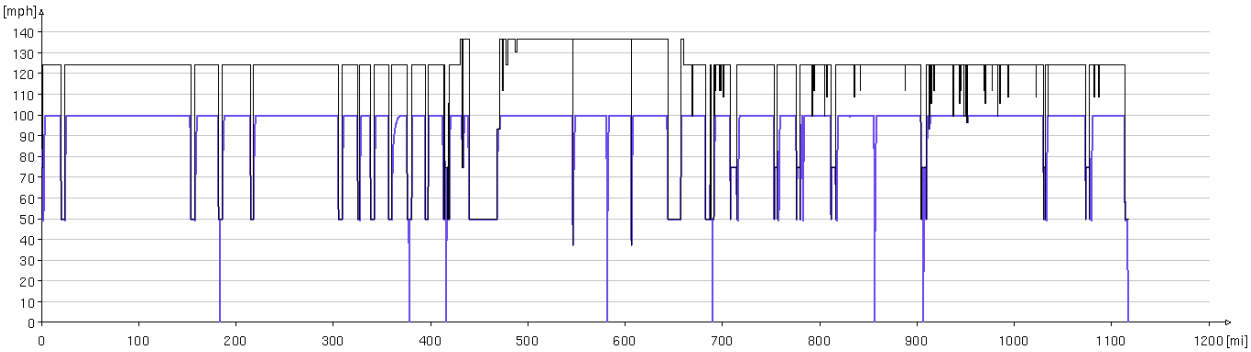


Figure 39. Speed profile (blue line) and track speed limit (black line) of simulated passenger train "P0181-CDNR"

A Commuter Train

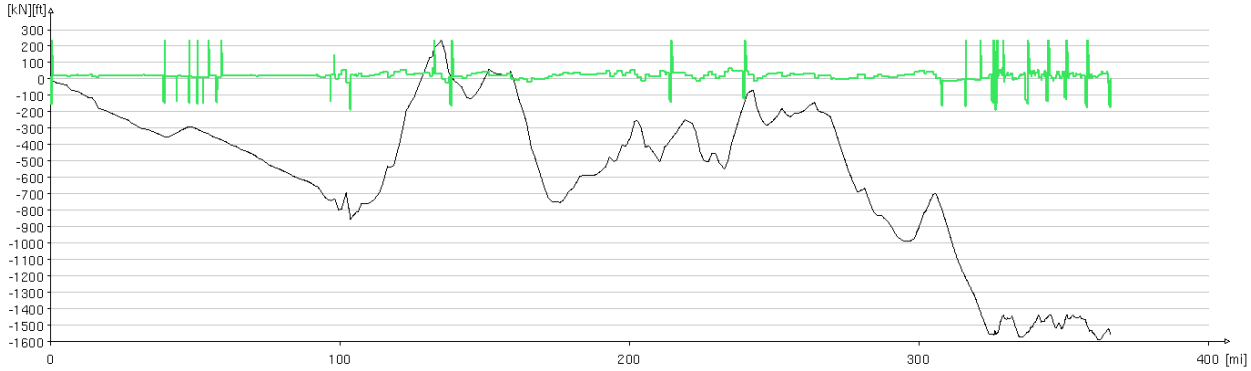


Figure 40. Track elevation (black line) and tractive effort (green line) of simulated commuter train "Comm_641_JQ"

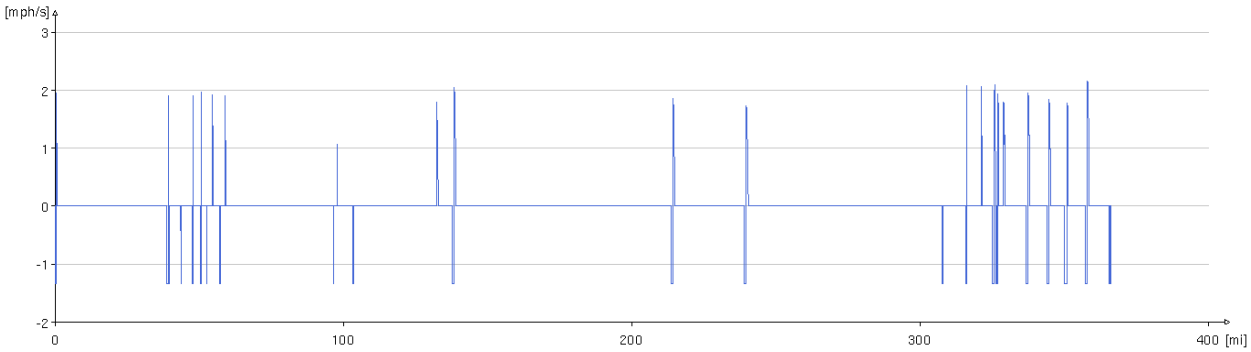


Figure 41. Acceleration profile of simulated commuter train "Comm_641_JQ"

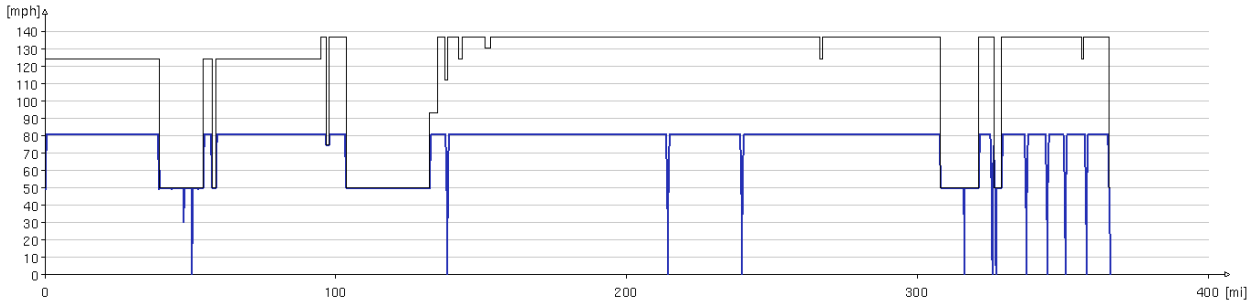


Figure 42. Speed profile (blue line) and track speed limit (black line) of simulated commuter train "Comm_641_JQ"

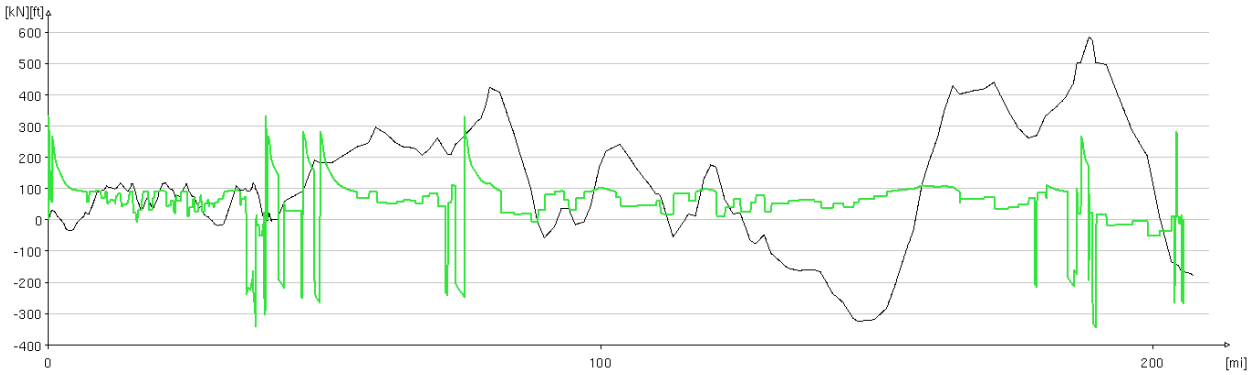


Figure 43. Track elevation (black line) and tractive effort (green line) of simulated HSR train "HSR2126_KN"

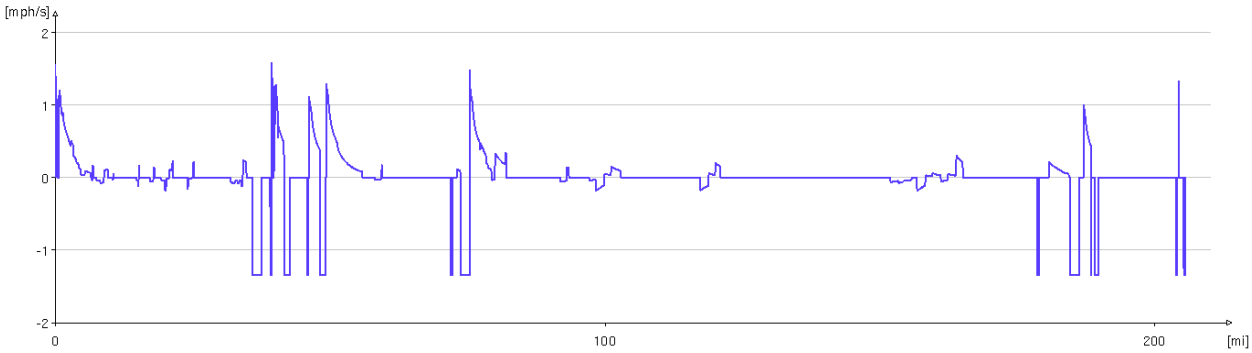


Figure 44. Acceleration profile of simulated HSR train "HSR2126_KN"

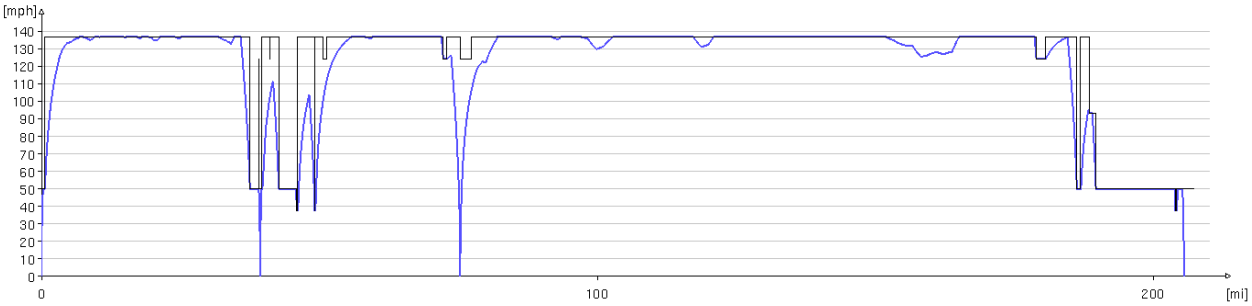


Figure 45. Speed profile (blue line) and track speed limit (black line) of simulated HSR train "HSR2126_KN"

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Abbreviations and Acronyms

ACRONYM	DEFINITION
CCD	Car Control Device
ECP	Electronically Controlled Pneumatic
FRA	Federal Railroad Administration
HSR	High-Speed Rail
PTC	Positive Train Control
RPD	FRA's Railroad Policy and Development Program