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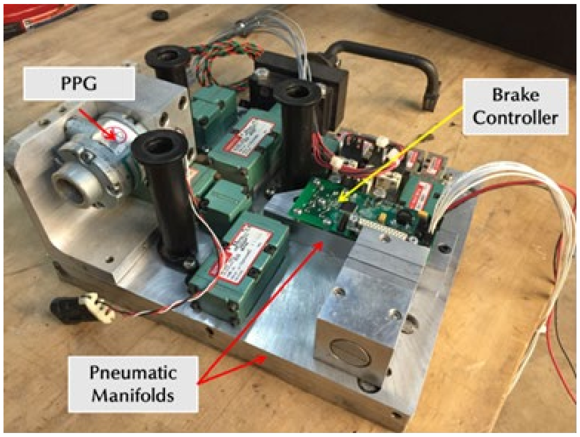
**Office of Research,
Development and Technology
Washington, DC 20590**

Electronically Controlled Pneumatic Brake Device with Pneumatic Brake Emulation – Field Demonstration



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14. ABSTRACT
Electronically Controlled Pneumatic (ECP) brake technology can improve both safety and braking performance of trains. One of the technical barriers is the interchange requirement of a freight car. This barrier can be addressed either by an overlay ECP or an ECP emulator. Under a previous effort, Sharma & Associates (SA) procured three sets of emulator car brake equipment from Zeftron. Hardware and software modifications were identified and implemented to the system to comply with S-4200, including limited fault testing using laboratory setting. This effort reports the interoperability compliance testing of the emulator under field conditions with other ECP industry vendor's locomotive and freight car equipment. Initialization procedures, including car sequencing and train building, were completed under the ECP mode. Graduated application and release tests were performed in RUN and SWITCH and CUTOUT modes. Subsequently, fault tests were conducted as prescribed in S-4200. Pneumatic tests were carried out under emulation mode. The testing revealed minor issues relative to dynamic addressing, sequencing, and low battery detection. Appropriate software modifications were made and tested in the laboratory confirming that the emulator Car Control Device (CCD) passed all required tests. Researchers recommend that the emulator system be evaluated for environmental compliance.

15. SUBJECT TERMS
Air brake, brake controller, Car Control Device, CCD, Car ID module, Electronically Controlled Pneumatic, ECP, brakes, emergency application, end-of-train, EOT, full service application, graduated application, minimum service, graduated release, S-4200

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METRIC/ENGLISH CONVERSION FACTORS

ENGLISH TO METRIC

LENGTH (APPROXIMATE)

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

AREA (APPROXIMATE)

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

MASS - WEIGHT (APPROXIMATE)

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

VOLUME (APPROXIMATE)

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

TEMPERATURE (EXACT)

[(x-32)(5/9)] °F = y °C

METRIC TO ENGLISH

LENGTH (APPROXIMATE)

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

AREA (APPROXIMATE)

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

MASS - WEIGHT (APPROXIMATE)

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

VOLUME (APPROXIMATE)

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

TEMPERATURE (EXACT)

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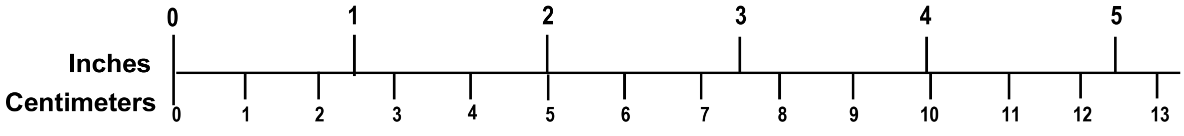
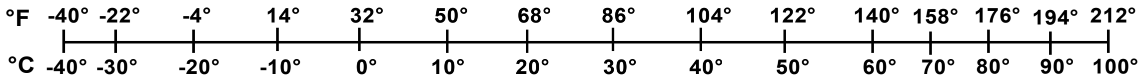
QUICK INCH - CENTIMETER LENGTH CONVERSION



QUICK FAHRENHEIT - CELSIUS TEMPERATURE CONVERSIO



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

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Executive Summary

Electronically Controlled Pneumatic (ECP) brake technology has been shown to improve both safety and braking performance of trains. However, implementation has slowed due to a variety of factors, only some of which are technical. Other impediments are associated with the capital investment required and the unequal allocation of both costs and benefits from implementation among the stakeholders, i.e., the car owners, railroads, and shippers. The primary technical challenge is the incompatibility of ECP and pneumatically controlled pneumatic (PCP) conventional brake systems to operate together in a train; any particular train must operate in one mode or the other, and all cars in that train (with effective brakes) must operate in that mode, i.e., either conventional pneumatic or ECP.

Previously, the Federal Railroad Administration (FRA) funded Sharma & Associates (SA) to investigate technical and economic barriers to ECP implementation [2]. This research identified an incompatibility between ECP and conventional brake systems as a key technical impediment to ECP implementation. This work resulted in the rediscovery of a product that currently exists and was in a reasonably advanced state of development. This product was developed by a company named Zeftron and was prototyped and successfully field tested, albeit in limited settings, prior to the industry standard, S-4200, being finalized and approved by the Association of American Railroads (AAR). From March 13, 2017, and March 12, 2019, FRA funded additional research to investigate the Zeftron emulator technology for its ability to accelerate implementation of ECP brakes through further development of the product and field testing. Researchers conducted the research at SA facilities in Countryside, IL.

The Zeftron emulator is essentially an ECP system with a local, on-board power supply and software capable of emulating the behavior of a conventional pneumatic control valve. As with an overlay ECP configuration, the emulator automatically operates in the ECP mode when it detects voltage on the ECP electric trainline. When ECP mode has ended, it emulates a pneumatic control valve by interpreting, as command signals, changes in brake pipe pressure (BPP) and controlling brake cylinder pressure (BCP) accordingly. The emulator has an integrated air turbine/generator device, called pneumatic power generator (PPG) that develops three-phase alternating current power, rectified to charge up the battery, using air exhausted from the brake cylinder during a brake release. This feature is used when ECP trainline power is not available, such as when the emulator-equipped car is operating in a train equipped with conventional, pneumatically controlled brakes.

In this effort, an ECP emulator system, developed by Zeftron, was upgraded to be hardware and software compatible with industry standard S-4200. Under the reported effort, field testing was successfully completed to demonstrate the functionality of the emulator for both the ECP and pneumatic emulation modes.

Interoperability testing was carried out using an ECP-equipped locomotive, freight car and end-of-train (EOT) device from an established industry vendor of ECP brake equipment, in conjunction with two cars equipped with the ECP emulator.

Tests of ECP initialization procedures, including car sequencing and train building, were completed to verify compliance with S-4200 requirements. Graduated application and release tests were performed in RUN and SWITCH modes, followed by CUTOUT mode tests.

Subsequently, fault tests were conducted to verify compliance with S-4200 requirements.

ECP MODE

INITIALIZATION

- Train build
- Car sequencing

RUN

- Graduated application to full service
- Graduated release
- Emergency application and release/recovery
- Response to head-end unit (HEU) requests for information

SWITCH

- Operate without trainline power
- Graduated application and release
- Electronic emergency

CUTOUT

- Ending ECP mode operation

ECP FAULTS

CAR-LEVEL FAULTS

- Low BCP
- Stuck brake
- Low battery
- Low reservoir pressure

TRAIN-LEVEL FAULTS

- Response to loss of BPP
- Response to loss of HEU beacon

EMULATION MODE

- Minimum application
- Partial application
- Full service application
- Graduated application to full service and release
- Emergency application
- Pneumatic backup

Pneumatic tests were successfully carried out, under emulation mode, to demonstrate that the emulator would be fully compatible in trains with conventional, pneumatically braked cars.

PPG performance data was collected during releases from applications to verify its characteristics. These efforts were completed to demonstrate the emulator's performance and compliance to AAR standards in a field environment. The emulator operated essentially the same as a regular service portion valve in a conventionally-braked train, and it operated successfully as an ECP-compliant Car Control Device (CCD) in an ECP-braked train. More significantly, the emulator operated successfully with other ECP equipment, demonstrating its interoperability. The effort reported here successfully demonstrated the functionality, interoperability and fault testing of the emulator. It is recommended that the emulator system be evaluated for environmental, i.e., vibration, shock and temperature, requirements.

1. Introduction

Electronically Controlled Pneumatic (ECP) brake technology has improved both safety and performance of trains. Various North American railroads have pilot tested ECP trains and expressed the benefits that are readily recognized.

This report discusses research conducted by Sharma & Associates (SA) regarding the demonstration of an ECP emulator to address interoperability requirements of the Association of American Railroads' Standard (AAR) S-4200. Under funding by the Federal Railroad Administration (FRA), this report documents the demonstration tests and the results collected to ensure that ECP braking technology meets AAR's specifications for future use.

1.1 Background

FRA has sought to identify and evaluate viable concepts for accelerating the implementation of ECP brakes throughout the industry, and funded an effort to further the development of such technologies. One such technology, Zeftron Chameleon was tested in revenue service trials in 1999–2000, before the Association of American Railroads' (AAR) current industry accepted standards S-4200 [1].

The Zeftron emulator configuration is essentially an ECP system with a local, on-board power supply and some additional software capable of emulating the behavior of a conventional pneumatic control valve. As with the overlay ECP configuration, the emulator automatically operates in the ECP mode when it detects voltage on the ECP electric trainline. Once ECP mode has ended, it emulates a pneumatic control valve by interpreting changes in brake pipe pressure (BPP), as command signals, and controlling brake cylinder pressure (BCP) accordingly. It has an integrated air turbine device that develops power to charge up the battery during brake release cycles, for use when the ECP trainline is not available, such as when the emulator-equipped car is operating in a conventionally-braked train.

SA investigated and tested the emulator by upgrading specific hardware elements to satisfy both emulation and ECP requirements. In addition, software updates were also necessary for the emulators to fully comply with the AAR S-4200 and S-4230 standards. Figure 1 shows a system diagram of a generic ECP.

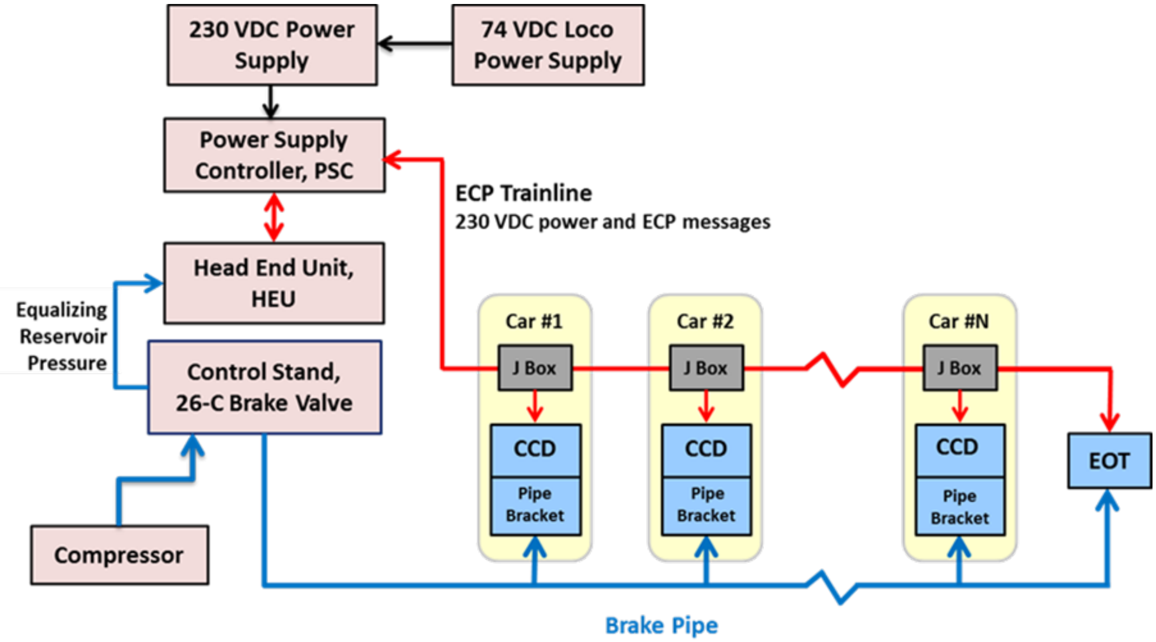

Figure 1 – Generic ECP Train System Layout

After initial functional testing, examining details of the hardware configurations, investigating changes in the S-4200 standard since 2000, and optimizing of the prototype hardware configuration, SA upgraded the Car Control Device (CCD), brake controller and Car ID hardware, and then developed software for the new CCD, brake controller and Car ID modules. These modules were tested for electrical connectivity and inter-module communication. Further, these new hardware modules have been installed in a laboratory test bed consisting of the brake control equipment representing a three-car train. Figure 2 shows the test setup used for the laboratory testing of the emulator system.

Figure 2 – Emulator Equipment Layout in SA Lab

With the car-level hardware and software upgrades, and an S-4200 compliant head-end unit (HEU) simulator, functional testing of the new emulators was executed. These tests were performed and evaluated using the latest S-4200 requirements as acceptance criteria. These tests included verification of correct operation in the various ECP modes (e.g., initialization, run, switch, cutout, and pneumatic backup) as well as the pneumatically controlled emulation mode. Normal brake application and release scenarios, including emergency, as well as limited fault conditions were tested [2].

The pneumatic power generator (PPG), designed to provide power (i.e., when brakes are released) to the brake controller and recharge the battery in emulation mode, has been characterized with respect to its energy output as a function of initial BCP during a release event.

With the lab test-bed scenarios completed, the ECP emulator were tested for interoperability and further fault testing under realistic train environment conditions.

1.2 Objectives

The major objective of this effort was to demonstrate the ECP emulator technology under field conditions to establish and verify that the Zeftron Chameleon ECP emulator was upgraded and developed to meet the AAR's S-4200 requirements, which includes interoperability with any other vendors' ECP technology products.

1.3 Overall Approach

A short test train, led by a locomotive equipped with S-4200 compliant ECP brake equipment, was used for this field demonstration (Figure 3). Two cars with the ECP emulator equipment and one car with an AAR-approved CCD (from third party brake supplier) were present in the train. An end-of-train (EOT) device that meets the S-4200 requirements was also a part of the test train configuration.

1.4 Scope

The scope for the demonstration tests included a representative train with an emulator and other vendors' equipment to address interoperability requirements of the S-4200. The train required an ECP equipped locomotive and ECP an EOT device which meets the S-4200 requirements.

The testing included brake operation functionality in the various ECP operating modes, including features such as application, release and fault conditions as defined in S-4200.

After completing the ECP mode testing, emulation mode tests were to be conducted for pneumatic brake operation. This series of tests were to include brake functionality, such as applications and releases, consistent with the AAR Standard S-467, Control Valve, Freight Brake – Environmental Tests.

Figure 3 – Test Train Consist

This ECP-configured train was tested for brake operation functionality in the various ECP operating modes, including features such as application, release, and fault conditions as defined in S-4200.

Interoperability with other supplier's HEU, CCD, and EOT was also tested in this ECP train configuration. ECP testing of individual cars equipped with the emulator technology was consistent with the requirements of AAR S-4200.

After the ECP mode testing, emulation mode tests were performed with a train configured for pneumatic brake operation. This train included the locomotive operating in pneumatic brake mode, two emulator-equipped cars (i.e., operating in conventional mode), and a car with conventional pneumatic brake equipment.

The emulation series of tests included brake functionality, such as applications and releases, in accordance with the AAR Standard, Single-Capacity Freight Brakes – Performance Specification S-461, to the extent such performance is applicable to a short train of just three cars.

Further, in the emulation mode test series, a sufficient number of tests were planned and conducted to demonstrate the PPG capability to generate sufficient energy during normal train operation to maintain the battery at a voltage level required for successful operation of the brake.

1.5 Organization of the Report

This report is separated in five sections to address the tasks and how SA executed each task.

Section 2 describes the ECP equipment and the data acquisition system used for testing. Section 3 outlines how SA planned to review the test results and evaluate whether the emulators complied with AAR requirements, particularly interoperability with respect to S-4200 and operation in a pneumatic train. Section 4 reviews the test procedures developed from the field demonstration test plan.

Section 5 summarizes the results and evaluates the success for each test performed. Some functional failures occurred during testing, which were identified and resolved during testing or during analysis. Section 5 also describes the performance issues resolved during testing; while Section 6 describes performance issues that were resolved after testing. CCD fault detection and response tests were incorporated into the test plan accordingly. Section 6 describes post-test software modifications and updated performance verification.

Section 7 includes the overall summary and conclusions of the demonstration testing, along with recommendations for future work.

2. Demonstration Location and Equipment

This section describes the ECP brake emulator technology and the data acquisition system used for testing.

2.1 CCD Hardware Description

The emulator CCD has three distinct electronic components: the Communication Module (Comm Module), the Brake Controller, and the Car ID Module. Figure 4 shows how these devices connect to each other. In addition, the CCD has a pneumatic portion which houses all the pneumatic relays and solenoids used to regulate BCP and reservoir pressure. The PPG is the device which charges the batteries during operation.

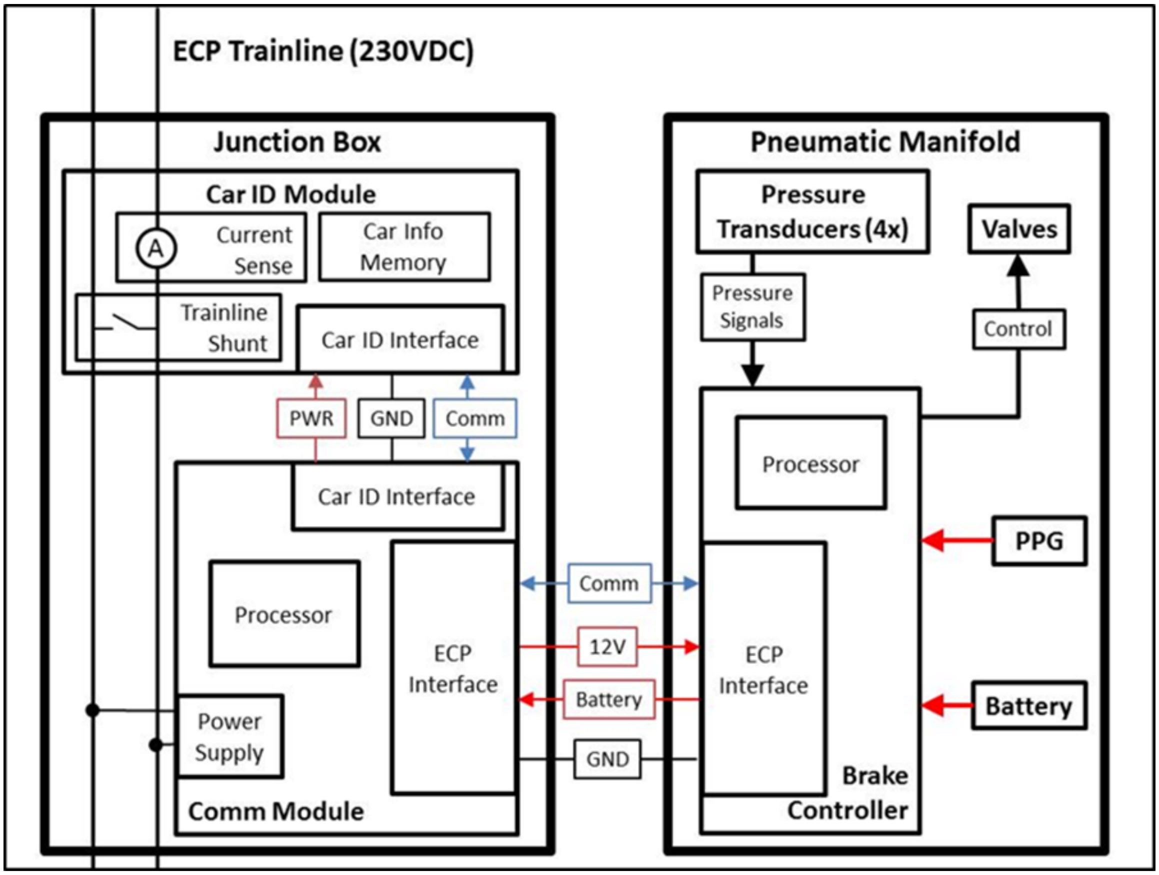

Figure 4 – CCD Block Diagram

The Brake Controller is the device which monitors the brake system pressures and controls the pressure in the brake cylinder. Its core circuitry is based around Texas Instruments' (TI) low-power microcontroller in the TI MSP430 family. The Brake Controller is the only electronic device which operates in emulation mode. In emulation mode, the Brake Controller controls the BCP in response to changes in the BPP by commanding solenoid valves and using feedback from the BCP. In ECP mode, it receives instructions from the Comm Module for applying pressure to the brake cylinder. The Brake Controller is mounted to the CCD pneumatic portion through a pneumatic manifold. Figure 5 shows the CCD pneumatic portion with the Brake Controller circuit board.

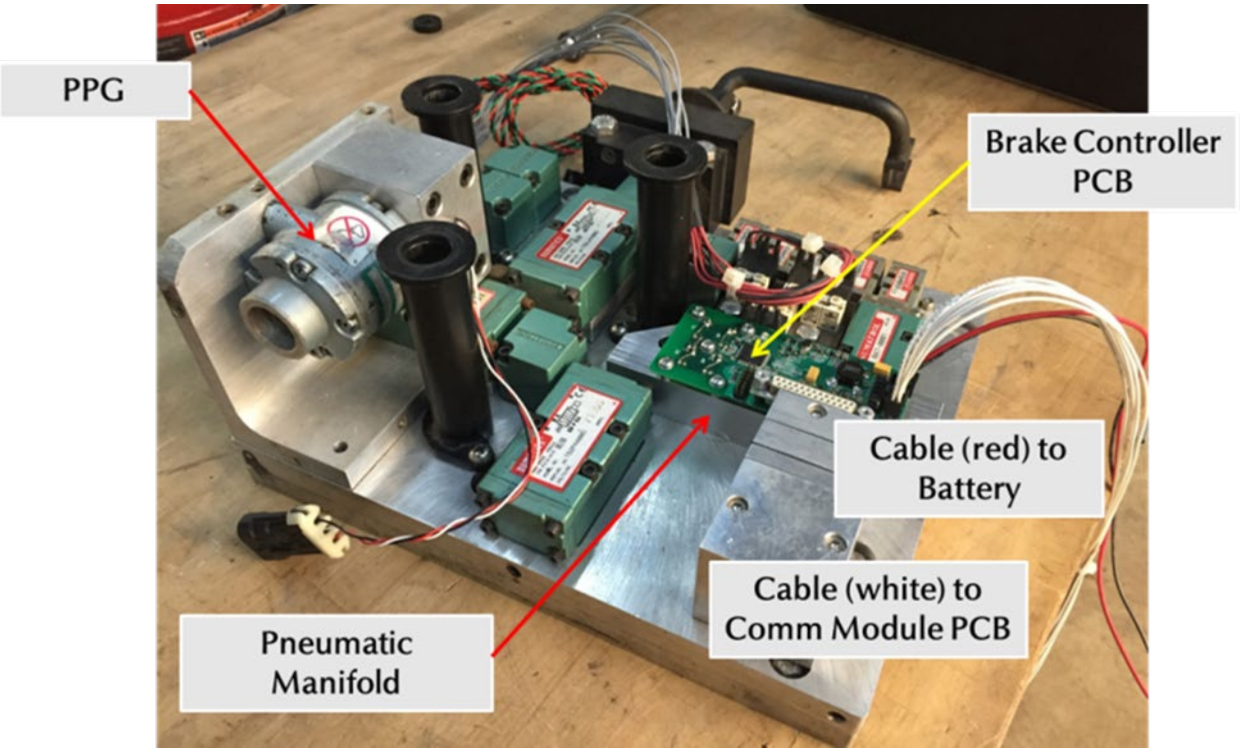

Figure 5 – CCD with Brake Controller and PPG Mounted

The Comm Module is the main CCD processor and ECP node, as described in Section 3.1 of S-4200. The Comm Module's primary functions are to communicate with other ECP devices on the ECP network and instruct the Brake Controller how to apply and release brakes, based on HEU commands. Its core circuitry is based around Echelon's PL3150 Smart Transceiver and configured to operate on a LonWorks network, such as ECP. It is configured only to transmit on ECP as defined in Section 4.0 of S-4230 [3]. In addition, it communicates with the Car ID Module for executing initialization tasks, like reading Car ID information and operating the sequencing hardware. The Comm Module does not operate in emulation mode. The Comm Module is located in the Junction Box with the Car ID Module.

The Car ID Module is the device that stores the car information, as described in Section 3.9 of S-4200. It contains the passive Electronically Erasable Programmable Read Only Memory (EEPROM) device for storing car information, and also houses the electronics used for car sequencing. The Car ID Module is located in the Junction Box with the Comm Module.

The PPG is the on-board external power generator to charge the CCD battery. In a conventional brake system, when releasing the brakes, BCP is vented to atmosphere. However, the pneumatic logic in the CCD manifold is designed to reroute the released air pressure to the PPG's pneumatic turbine. The turbine rotor has a permanent magnet attached, which is contained within the stator housing. When the turbine spins from input air pressure, the magnet on the rotor creates a varying magnetic field inducing voltages on the stator windings. The stator windings are configured to produce a floating three-phase AC signal in a delta configuration. The output electrical energy is then used to charge the battery.

Figure 6 shows a picture of an uncovered assembled emulator CCD without PPG, and an uncovered Junction Box. The emulator CCDs were fully assembled and covered for testing, as shown in Figure 15 and Figure 17.

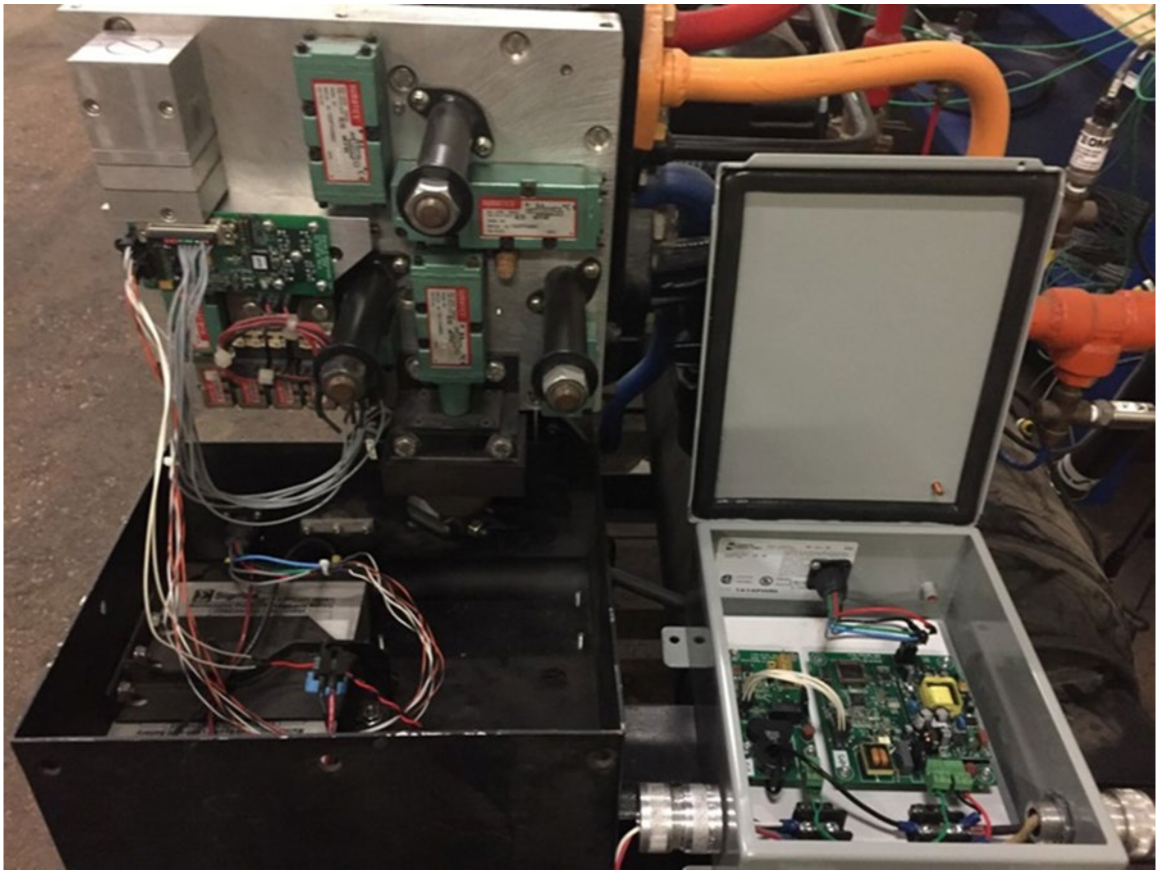

Figure 6 – CCD Manifold (left) and Junction Box (right) – No PPG

2.2 Location and Interoperability Equipment

The field demonstration for validating the emulator occurred at the Indiana Northeastern Railroad (INRR) maintenance shop in Hudson, IN. SA worked with INRR on various past instrumentation and field testing projects. The GP-40 owned by FRA (DOTX-2000) has ECP brake equipment, supplied by an established industry vendor of brake equipment and referred to hereafter as “vendor,”[1] integrated in its electronic brake control system. Figure 7 shows the GP-40 locomotive and Figure 8 shows the ECP brake with integrated HEU.

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[1] New York Air Brake

Figure 7 – FRA DOTX-2000 GP-40 Locomotive

Figure 8 – Vendor's ECP Brake with Integrated HEU in DOTX-2000

This was a stationary test. Locomotive and car handbrakes were applied throughout the entire test. At the facility, there are three gravel cars which SA previously used for field tests. These cars have quick-disconnect ports in their brake system for installing pressure transducers.

SA also installed an ECP EOT (i.e., from the vendor), as shown in Figure 9, at the last car.

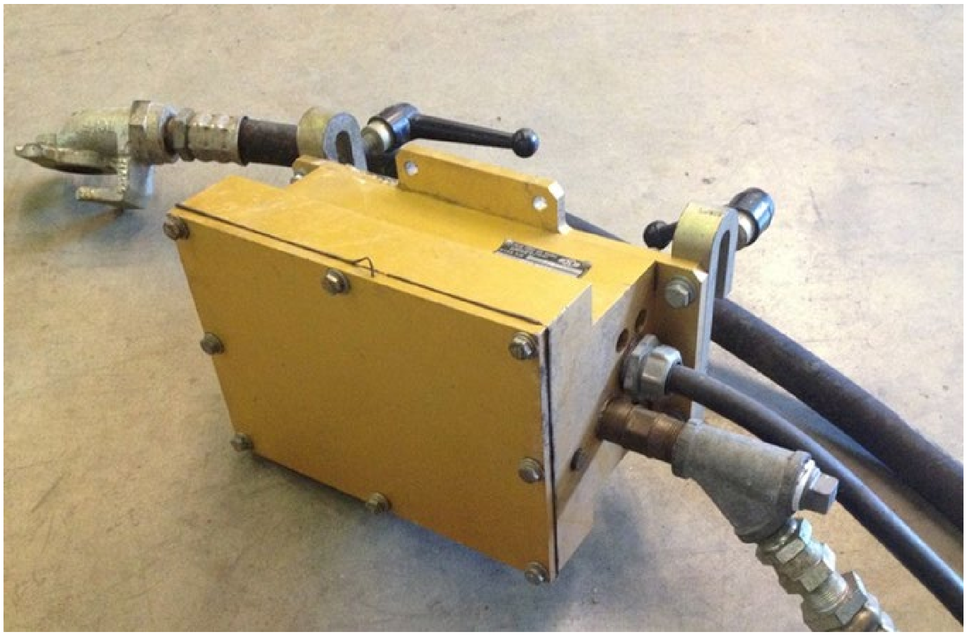


Figure 9 – Vendor's ECP EOT

SA installed emulator CCDs on two of the INRR gravel cars. The third INRR gravel car was used for both the ECP and emulation mode testing. A CCD (i.e., from the vendor) was mounted on the car's control valve for the ECP testing. For emulation mode testing, the vendor CCD was replaced with the pneumatic control valve portion initially equipped on the gravel car. The PPG was installed in the emulator CCD on test car #1.

In addition, digital cameras and small video recorder devices were used to record video of the brake shoes on a wheel and the HEU display.

2.3 Instrumentation

Data was collected using a 32-channel SoMat eDAQlite rugged data acquisition system. In addition to the data acquisition unit, SA used the following sensors to collect various measurements:

- 11X Pressure Transducers:
    - Equalizing reservoir pressure at locomotive
    - BPP at each vehicle (e.g., locomotive and cars)
    - BCP at each car
    - Supply reservoir pressure at each car
- Voltage and current sensors for measuring the PPG output
- LonWorks Network Analyzer on field laptop (i.e., for the ECP test only)

Figure 10 shows the emulator battery current, in emulation mode, for a single brake application with the PPG installed. The current in this plot is the net current of the rectified PPG output and the charging circuit regulation on the Brake Controller to the battery. Battery voltage will also be recorded; however, battery current is a better indicator for PPG effectiveness as it includes the entire charging system.

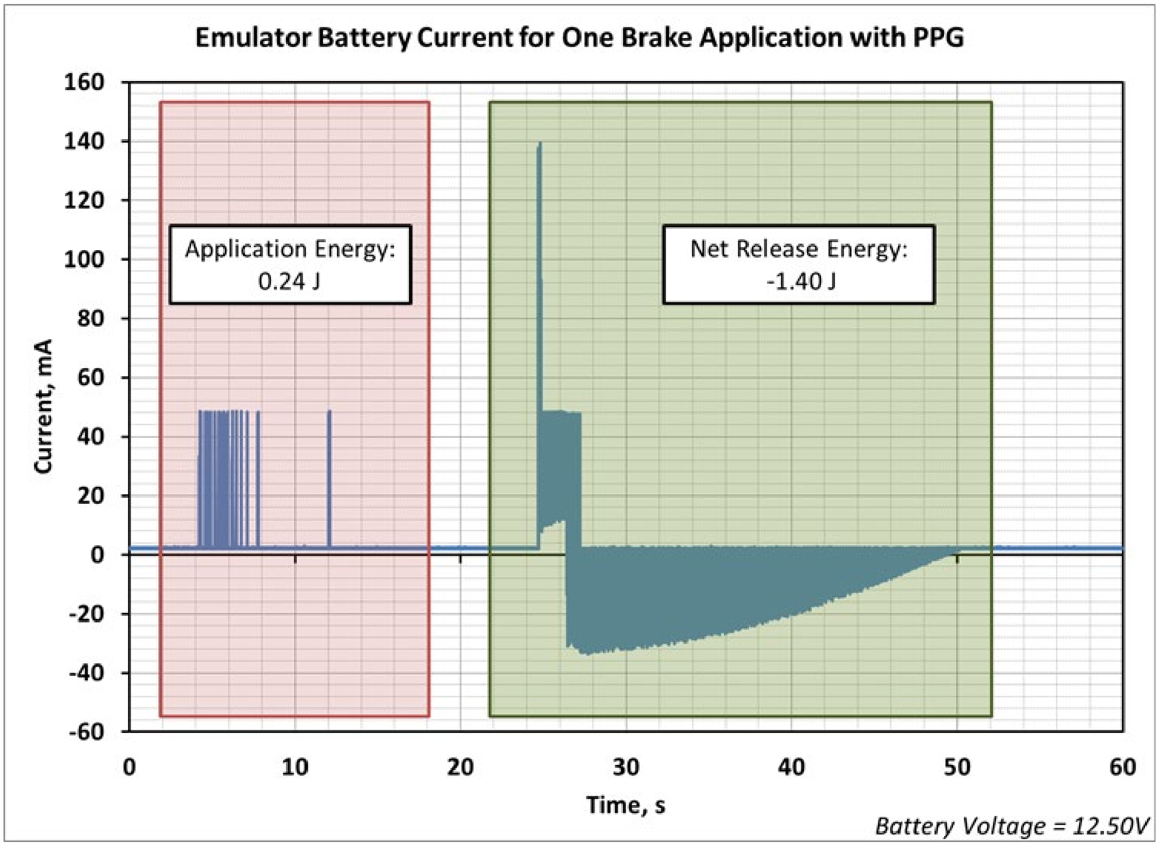


Figure 10 – Representative Plot of PPG Output Current for a Brake Application

Figure 11 illustrates the proposed test consist and instrumentation diagram for the ECP mode testing. As aforementioned and shown in Figure 11, two cars were equipped with the emulator CCD and one car was equipped with the vendor CCD. The diagram also lists the measurements collected at each vehicle. The vendor ECP EOT was installed on the last car in the train.

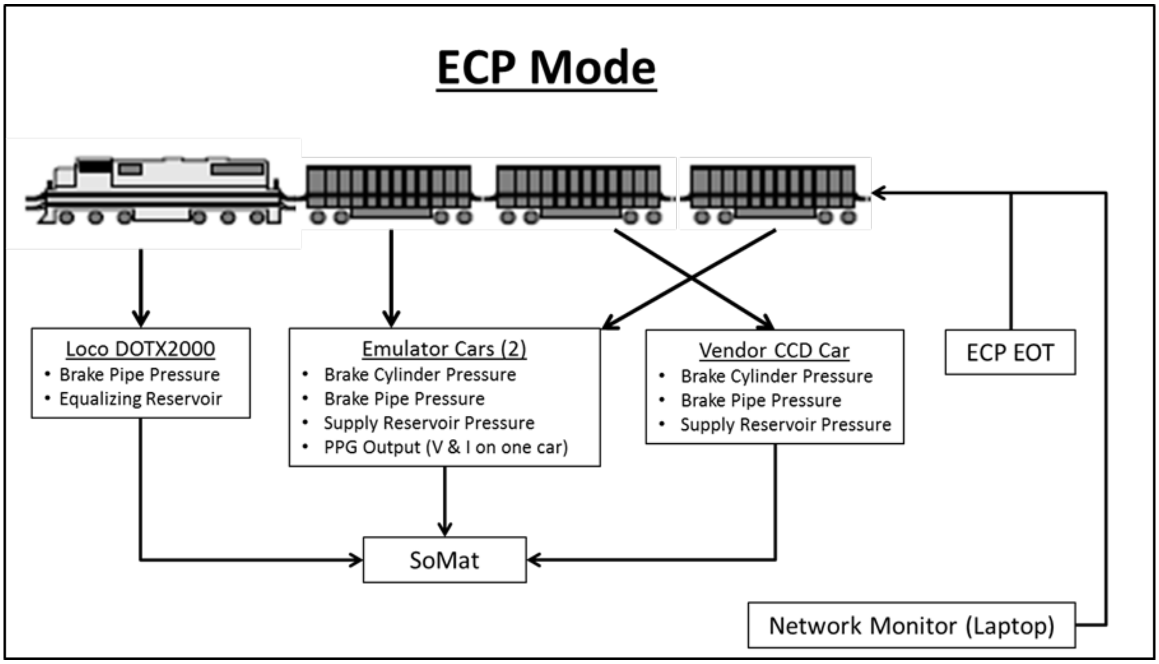
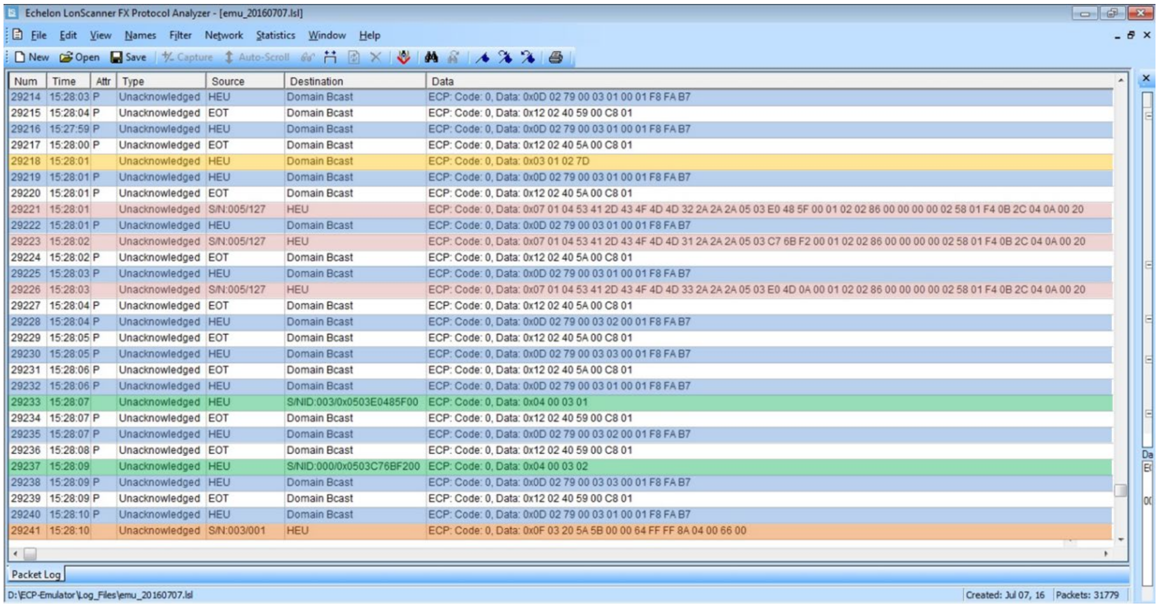


Figure 11 – Test Consist and Instrumentation for ECP Mode Field Demonstration

The network analyzer is an application on the laptop that monitors LonWorks (i.e., ECP) communication on a network through a Powerline to Universal Serial Bus (USB) interface. A screenshot of the network analyzer program during a train-build process is shown in Figure 12.



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29224	15:28:02	P	Unacknowledged	EOT	Domain Bcast	ECP: Code: 0, Data: 0x12 02 40 5A 00 C8 01
29225	15:28:03	P	Unacknowledged	HEU	Domain Bcast	ECP: Code: 0, Data: 0x0D 02 79 00 03 01 00 01 F8 FA B7
29226	15:28:03		Unacknowledged	S/N:005/127	HEU	ECP: Code: 0, Data: 0x07 01 04 53 41 2D 43 4F 4D 4D 33 2A 2A 2A 05 03 E0 4D 0A 00 01 02 02 86 00 00 00 00 02 58 01 F4 0B 2C 04 0A 00 20
29227	15:28:04	P	Unacknowledged	EOT	Domain Bcast	ECP: Code: 0, Data: 0x12 02 40 5A 00 C8 01
29228	15:28:04	P	Unacknowledged	HEU	Domain Bcast	ECP: Code: 0, Data: 0x0D 02 79 00 03 02 00 01 F8 FA B7
29229	15:28:05	P	Unacknowledged	EOT	Domain Bcast	ECP: Code: 0, Data: 0x12 02 40 5A 00 C8 01
29230	15:28:05	P	Unacknowledged	HEU	Domain Bcast	ECP: Code: 0, Data: 0x0D 02 79 00 03 03 00 01 F8 FA B7
29231	15:28:06	P	Unacknowledged	EOT	Domain Bcast	ECP: Code: 0, Data: 0x12 02 40 5A 00 C8 01
29232	15:28:06	P	Unacknowledged	HEU	Domain Bcast	ECP: Code: 0, Data: 0x0D 02 79 00 03 01 00 01 F8 FA B7
29233	15:28:07		Unacknowledged	HEU	S/NID:003/0x0503E0485F00	ECP: Code: 0, Data: 0x04 00 03 01
29234	15:28:07	P	Unacknowledged	EOT	Domain Bcast	ECP: Code: 0, Data: 0x12 02 40 59 00 C8 01
29235	15:28:07	P	Unacknowledged	HEU	Domain Bcast	ECP: Code: 0, Data: 0x0D 02 79 00 03 02 00 01 F8 FA B7
29236	15:28:08	P	Unacknowledged	EOT	Domain Bcast	ECP: Code: 0, Data: 0x12 02 40 59 00 C8 01
29237	15:28:09		Unacknowledged	HEU	S/NID:000/0x0503C76BF200	ECP: Code: 0, Data: 0x04 00 03 02
29238	15:28:09	P	Unacknowledged	HEU	Domain Bcast	ECP: Code: 0, Data: 0x0D 02 79 00 03 03 00 01 F8 FA B7
29239	15:28:09	P	Unacknowledged	EOT	Domain Bcast	ECP: Code: 0, Data: 0x12 02 40 59 00 C8 01
29240	15:28:10	P	Unacknowledged	HEU	Domain Bcast	ECP: Code: 0, Data: 0x0D 02 79 00 03 01 00 01 F8 FA B7
29241	15:28:10		Unacknowledged	S/N:003/001	HEU	ECP: Code: 0, Data: 0x0F 03 20 5A 5B 00 00 64 FF FF 8A 04 00 66 00

Figure 12 – Network Monitor Log of Train-building Process

Figure 13 illustrates the proposed test consist and instrumentation diagram for the emulation mode testing. Like the ECP mode testing, the two cars equipped with the emulator CCD will remain equipped with the emulators. The car that was equipped with the vendor CCD in the ECP mode test was used for the conventionally braked car. The vendor CCD was replaced with the pneumatic service portion initially installed on the car. The network monitor was not utilized, since an ECP network does not exist in a conventional pneumatically braked train.

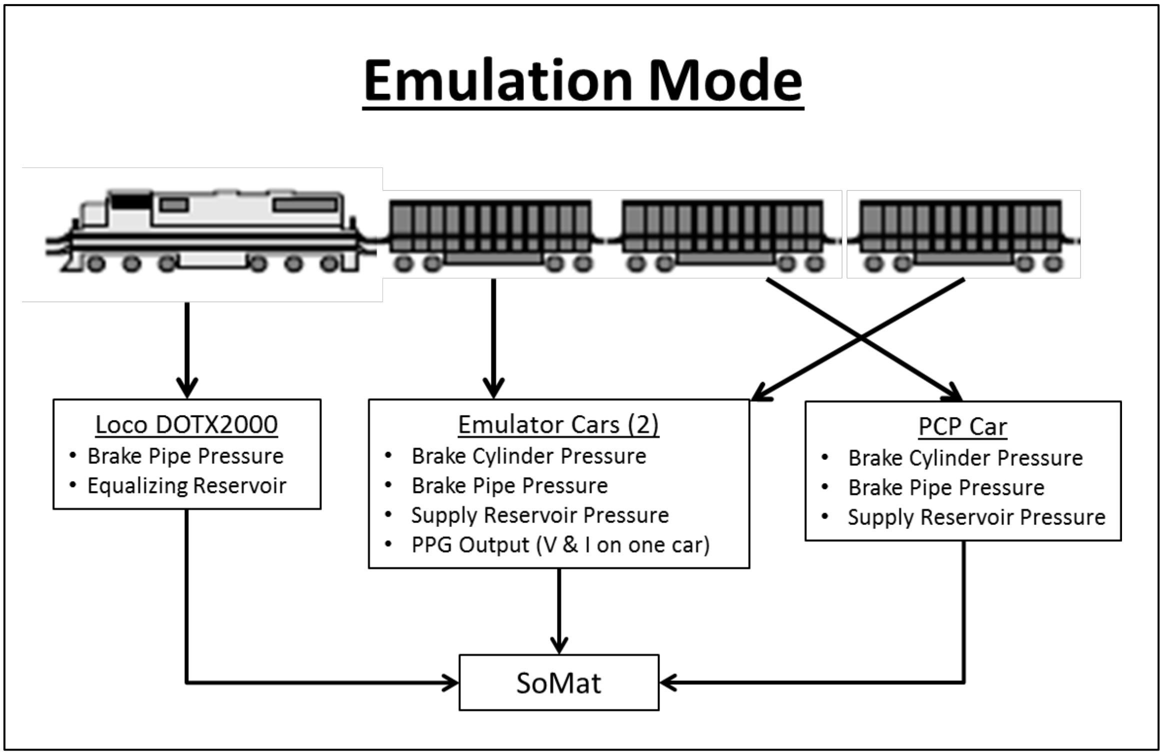

Figure 13 – Field Demonstration Emulation Mode Test Consist and Instrumentation

Figure 14 through Figure 17 shows the instrumented locomotive and test cars. The test cars are shown with the ECP CCDs installed on the appropriate gravel cars, per Figure 11 test consist diagram.

Figure 14 – Locomotive DOTX-2000 Instrumentation

Figure 15 – Emulator #1 Installed on Test Car #1 (IN 913)

Figure 16 – Vendor CCD Installed on Test Car #2 (IN 941)

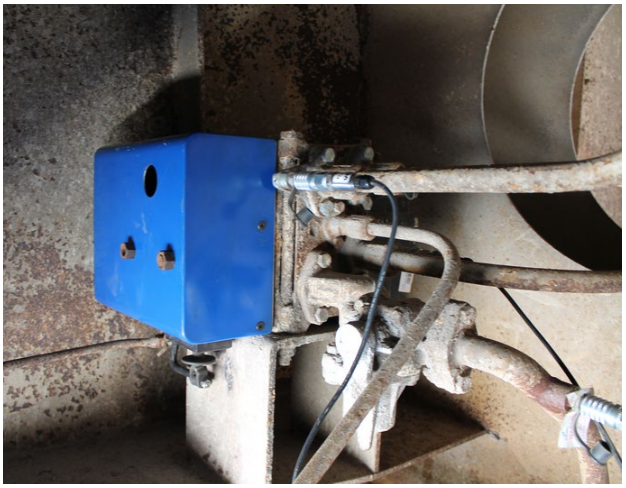

Figure 17 – Emulator #2 Installed on Test Car #3 (IN 909)

Figure 18 shows the vendor ECP EOT mounted on the last test car's B-end knuckle. The EOT is resting on an angled T-bracket that SA fabricated. The angled T-bracket has a cylindrical rod that fits in the knuckle hole, and a welded angle bracket that rests on the top of the knuckle. The EOT has J-shaped hooks that mount to the angle bracket. This is not an AAR approved method for mounting an ECP EOT; this method was just convenient for the field demonstration.

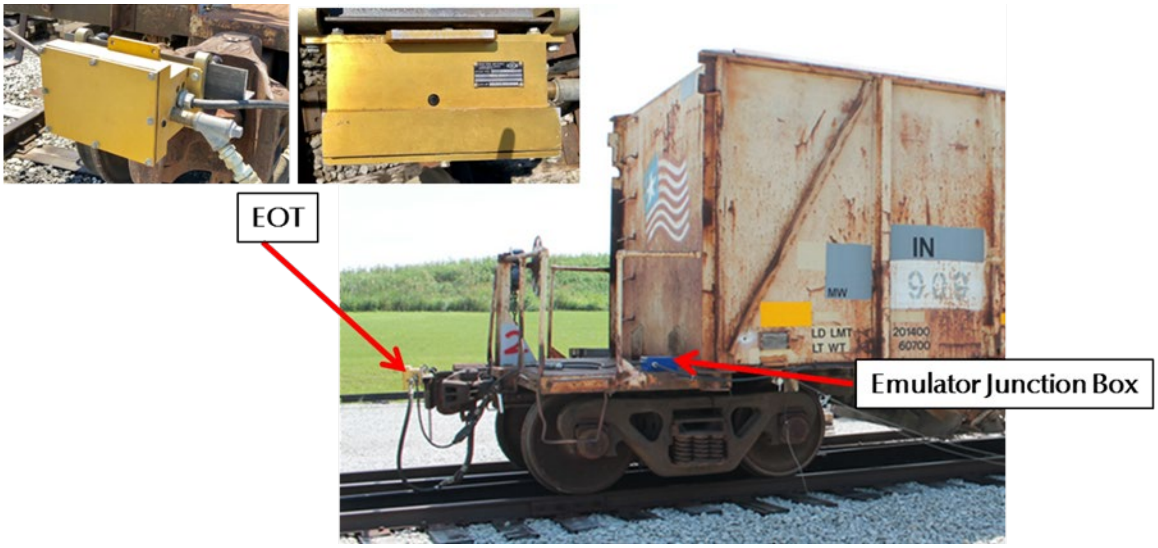

Figure 18 – Vendor ECP EOT and Emulator Junction Box on Test Car #3 (IN 909)

3. Performance Evaluation

The emulator CCDs were evaluated based on the S-4200 standard. In the previous phase, the emulator CCDs were tested for compliance with many functional S-4200 and S-4230 requirements [2]. This project reevaluated many of those requirements with an emphasis on interoperability and brake response times. Each test was conducted to effectively validate emulator compliance with specific S-4200 requirements. Monitoring the vendor CCD in ECP mode testing and a PCP car in emulation mode testing provided an effective means to compare the emulator with approved AAR brake equipment.

Testing was mostly conducted in the order outlined in the test procedure below, with some exceptions explained later. Certain tests were repeated to establish confidence in system reliability.

3.1 Acceptance Criteria

All tests have test-specific acceptance criteria indicated in the respective test procedures. These criteria are based on the requirements outlined in S-4200. Brake test results were evaluated based on the brake control parameters outlined in S-4200, primarily from Sections 4.3.10 and 4.3.11. For general brake control compliance, BCP was evaluated as follows:

- BCP must be calculated from Train Brake Command (TBC) using the formulas given in Section 4.3.10 of S-4200.
- Steady state BCP must be regulated within a ±3 psi tolerance from the target BCP, as outlined in Section 4.3.11 of S-4200.
- Minimum service application must reach the desired steady state minimum service pressure (MSP), calculated as described in Section 4.3.5 of S-4200, from full release within 2.0 seconds.
- Full service application must reach the desired steady state of full service pressure (FSP), calculated as described in Section 4.3.7 of S-4200, from full release between 6.0 and 10.0 seconds.
- Electronic emergency applications must reach the desired steady state pressure (i.e., calculated as described in Section 4.3.8 of S-4200) from a full release between 7.0 and 12.0 seconds.
- Brake release from a full-service application must reach a BCP of 5 psi or less within 6.0 and 15.0 seconds.

4. Test Procedure

FRA approved the test procedure used to test the Zeftron Chameleon technology. This section outlines the testing conducted . The emulator CCD performance was evaluated with respect to S-4200 requirements relevant to CCDs. Testing was conducted by two main test engineers: the operating test engineer and the wayside test engineer. The operating test engineer was responsible for operating the HEU and other locomotive controls from inside the cab. The wayside test engineer was responsible for monitoring data acquisition and inducing certain ECP faults from the wayside.

4.1 ECP Test

A SoMat eDAQlite will be used for data acquisition. All transducers will be connected to the SoMat. All pressure channels will be sampled at 100 samples/second. Electrical measurements for the PPG will be sampled at 2,000 samples/second. The LonWorks Network Analyzer will capture ECP message transactions as they are received by the network monitor. These tests will be executed in a manner which facilitates identifying events during post-processing. The test effort will be documented through notes, pictures and video.

The ECP test consist is subjected to specific tests with respect to each ECP operating mode as described in the following sub-sections.

4.1.1 INITIALIZATION Mode Operation

Testing will commence with demonstrating the functions of train INITIALIZATION mode, as outlined in Section 4.2.3 of S-4200. This includes train building and car sequencing. Train building is the process of querying all vehicles in the consist and populating the HEU's database with each car's information, as described in Section 3.9 of S-4200. For example, car information includes Report Mark, loaded and empty car weight, and braking and reservoir constants. Car Sequencing is the process which determines relative positions of CCDs in the consist and orientation relative to the lead locomotive. The full procedure of car sequencing is outlined in Section 4.2.3.1 of S-4200. Both train building and car sequencing are nearly automated by the ECP network with minimal engineer interaction limited to mostly acknowledgements.

4.1.1.1 Train Building Test

The operating test engineer will initiate the train building process through the HEU interface. Through the network, the wayside test engineer will continually monitor the ECP communication. The HEU will display to the operating test engineer whether train building is successful or not. For train building to be successful, each CCD must be accurately represented in the HEU database with the correct Car ID information.

4.1.1.2 Car Sequencing Test

Car sequencing will be initiated following the train build, by acknowledgment of the operating test engineer. Like train building, car sequencing executes without user interaction, except when faults occur. SA's entire test team will compare the car ordering results with the actual position of the ECP equipment relative to the lead locomotive. For sequencing to be successful, the car ordering results must be an exact match with a ± 0 position tolerance. SA will document additional feedback from the HEU. In the case of sequencing failures, SA will review the network log and record all relevant information from the HEU regarding the sequencing process. Unsuccessful sequencing will not be a reason to abort field demonstration.

The operating test engineer will acknowledge any HEU feedback before proceeding.

4.1.2 RUN Mode Operation

After the train initialization process is complete, the operating test engineer will switch operating modes to RUN mode through the HEU interface—typically RUN mode is automatically selected after train building. RUN mode is described in Section 4.2.5 of S-4200. This mode is the main operational mode for ECP, and is selected when the train is fully configured and ready for normal road operations. Once all reservoirs are fully charged, the operating test engineer will begin executing ECP brake applications.

4.1.2.1 Graduated Application Test

First, the operating test engineer will perform a graduated application to full service. The operating test engineer will change the TBC to 10 percent (i.e., minimum service pressure) and wait for all brakes to correctly apply. This will be confirmed on the wayside, by the wayside test engineer monitoring the brakes and network log. After all cars apply their brakes to 10 percent, the operating test engineer will increment the TBC by 10 percent, step by step, until the TBC reaches 100 percent (i.e., full-service application).

4.1.2.2 Graduated Release Test

Next, the operating test engineer will perform a graduated release to full release. TBC will be decreased in 10 percent decrements until all the brakes are fully released.

4.1.2.3 Electronic Emergency Test

An electronic emergency application will then be performed. The operating test engineer will change the TBC from 0 to 120 percent in one step. Once all CCDs initiate the electronic emergency application, an electronic emergency interlock will be set for at least 120 seconds, as described in Section 4.4.16 of S-4230. After the emergency interlock time concludes, the operating test engineer will release the interlock, causing the HEU to change the TBC to 100 percent. Then the operating test engineer will manually release the brakes from 100 to 0 percent.

4.1.2.4 Auxiliary Functions Tests

The operating test engineer accessed the auxiliary menus in the HEU to query specific CCDs. The operating test engineer queried each CCD for all available Car Static Information. Each CCD is supposed to respond with a Car Static Info message according to Section 5.1.1 of S-4230. Next the operating test engineer queried CCD Specific Information from each CCD. Each CCD is supposed to respond with a Device Info (e.g., CCD) message according to Section 5.2.5 of S-4230. Then, the operating test engineer queried each CCD’s diagnostics. Each CCD is supposed to respond with the Diagnostic Response message described in Section 5.8.4 of S-4230.

The operating test engineer will then cut out one CCD and change the TBC to 50 percent. The cut-out CCD should not apply its brakes and the cut-in CCDs should apply approximately 32 psi (i.e., within the steady-state pressure tolerance) to their BCPs. The operating test engineer will then cut in the CCD that was previously cut out. The newly cut-in CCD should regain control of its brakes and apply 32 psi to its BCP. Next, the operating test engineer will change the TBC to 0 percent. All CCDs should respond by releasing their brakes. This test is to be repeated for each CCD.

4.1.3 SWITCH Mode Operation

SWITCH mode operation will be tested as outlined in Section 4.2.6 in S-4200. The purpose of SWITCH mode is to allow ECP operation without an EOT, as during switching operations. Any fault conditions and exceptions will be remedied prior to starting SWITCH mode testing. The operating test engineer will reset all exceptions, release all brakes, and wait for all the reservoirs to fully charge.

4.1.3.1 Trainline Power

The operating test engineer will change the operating mode to SWITCH mode and turn off trainline power through the HEU interface. Trainline power should remain off for the entirety of the SWITCH mode testing. Successful operation of the subsequent tests without trainline power will confirm that SWITCH mode does not need trainline power.

4.1.3.2 Graduated Application and Release Test

The operating test engineer will execute a graduated application to full service and a graduated release to full release. The same procedure from the RUN mode graduated application test will be performed; i.e., increase the TBC in the HEU beacon to 100 percent in increments of 10 percent, then decrease the TBC to 0 percent in decrements of 10 percent. Brakes must adhere to the brake response times outlined in the acceptance criteria.

4.1.3.3 Electronic Emergency Test

The operating test engineer will perform a one-step electronic emergency brake application as described for the RUN mode test. Expected results are also the same as in the RUN mode test.

4.1.4 CUTOUT Mode Operation

CUTOUT mode operation is outlined in Section 4.2.7 of S-4200. The primary purpose of CUTOUT mode is to shut down ECP when trainline power is off, or to quickly cut out all cars and release brakes before switching operations. Any fault conditions and exceptions will be remedied prior to starting CUTOUT mode testing. The operating test engineer will reset all exceptions, ensure that all CCDs are cut in, release all brakes, and wait for all of the reservoirs to fully charge.

4.1.4.1 Brake Release Test

Before changing operating mode to CUTOUT mode, the operating test engineer executed a service application between 10 and 100 percent. All cars should apply the brakes accordingly. Once all CCDs report stable BCP values, the operating test engineer switched the operating mode to CUTOUT mode. All the CCDs should fully release their brake applications and all BCPs should return to 0 psi.

4.1.4.2 No Response Test

The operating test engineer will change the TBC to 0 percent. No changes in the CCDs should occur. Then, the operating test engineer will change the TBC to between 10 and 100 percent. All cars must maintain a full release.

4.1.5 Fault Testing

Fault testing will be performed in either SWITCH mode or RUN mode. Fault testing encompasses testing ECP normal and critical exceptions outlined in Section 4.4 of S-4200. Car-level fault testing, as described by ECP normal exceptions in S-4200, includes Low Brake Cylinder Pressure and Stuck Brake (i.e., under the parent term Incorrect BC Pressure), Low Reservoir Pressure, and Low Battery Charge.

SA developed a device to induce “Incorrect Brake Cylinder” faults in the emulator CCDs. Called the BCP Fault Switchbox, this device is installed in one of the CCDs at a time. In the emulator’s pneumatic portion, there is a solenoid valve for applying BCP and another solenoid valve for releasing BCP. The brake controller controls these solenoids directly. The BCP Fault Switchbox interfaces between the brake controller and the solenoid valves, interrupting the energizing circuits, and thus affects whether the brake controller can actuate these two solenoids. If the circuit to the brake application solenoid is open, then the brakes cannot be applied. Similarly, if the circuit to the brake release solenoid is open, then the brakes cannot be released. Other CCD operations are not affected. This switchbox device will be installed in the emulator CCD on Test Car #1 prior to testing, shown in Figure 19.

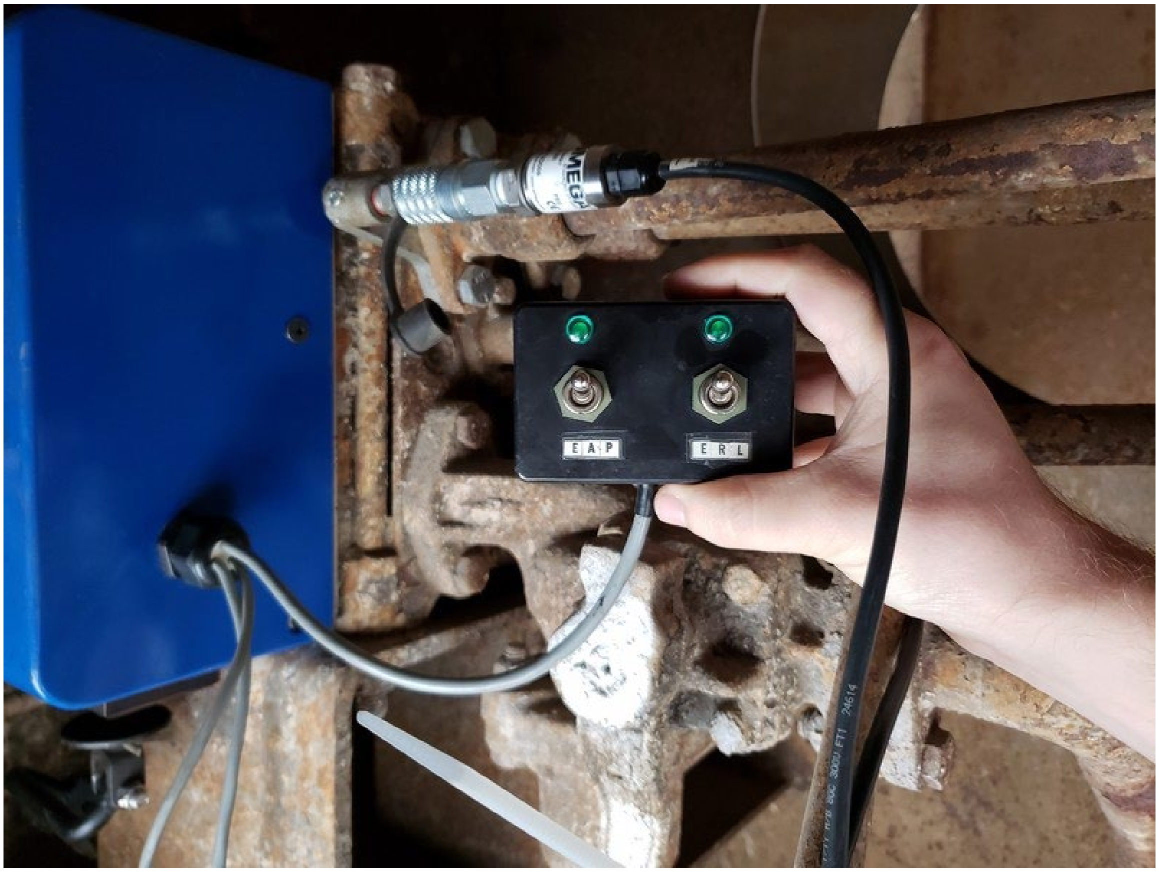

Figure 19 – BCP Fault Switchbox Connected to Emulator on Test Car #1

Train-level fault testing, as described by ECP critical system exceptions in S-4200, includes Loss of BPP and Loss of HEU beacon.

4.1.5.1 Low BCP Test

Low BCP will be tested to validate the requirements outlined in Section 4.4.12 of S-4200. The brakes will be initially completely released. The wayside test engineer will then switch off the brake application circuit via the BCP Fault Switchbox. The operating test engineer will then execute a service application. All CCDs, except for the emulator under test, should apply their brakes accordingly without inducing an exception. The CCD with the switchbox should not apply its brakes and it should report a low BCP. The HEU should warn the operating test engineer of this condition, but not automatically cut-out the CCD. The wayside test engineer will then switch on the brake application circuit via the switchbox. The CCD under test should then appropriately resume normal operation by reporting an Incorrect BCP Exception Cleared message, and it should start applying the brakes normally. The operating test engineer will maintain the brake application for the next test.

4.1.5.2 Stuck Brake Test

Stuck brake will be tested to validate the requirements outlined in Section 4.4.12 of S-4200. Ensure that the brake application from the previous test is still applied; if the brakes are not applied, the operating test engineer must perform a service application. The wayside test engineer will then switch the brake release circuit off by opening the circuit via the Brake Cylinder Fault Switchbox. The operating test engineer will then execute a full release. All CCDs, except for emulator under test, should release their brakes accordingly without inducing an exception. The emulator under test should not fully release its brakes and should report a stuck brake condition. When the HEU receives this fault message, it should command the CCD to cut-out. The wayside test engineer will toggle the brake release circuit switch to the closed position. The CCD under test should then resume normal operation by reporting an Incorrect BCP Exception Cleared message and releasing the brakes normally. The operating test engineer will then cut-in the subject CCD.

4.1.5.3 Low Battery Test

Low battery charge will be tested to validate the requirements in Section 4.4.10 of S-4200. The operating test engineer will ensure the trainline is powering all the CCDs and that normal power mode is on for all CCDs. If low power mode is on, the operating test engineer will change the dynamic configuration such that normal power mode is turned on. In one CCD, the wayside test engineer will disconnect the battery cable to the Brake Controller board without affecting any other connections. The CCD under test should report a low battery exception, but continue to operate normally. When the HEU receives the message, it should log that CCD as inoperative. The wayside test engineer will then reconnect the original battery. The CCD under test should then report a Low Battery Exception Cleared message to the HEU. When the HEU receives the cleared message, it should log the CCD as operative again.

4.1.5.4 Low Reservoir Pressure Test

Low reservoir pressure will be tested to validate the requirements in Section 4.4.6 of S-4200. The brakes must be fully released, such that TBC is 0 percent. The wayside test engineer will pull the manual release rod on one of the emulator CCDs to vent the supply reservoir pressure to 50 psi. When the emulator under test reads a pressure of about 56 psi in the reservoir, it should transmit a low reservoir exception message. When the HEU receives the message, it should log that CCD as inoperative. The wayside test engineer will then release the manual release rod to allow the supply reservoir to charge back up. When the CCD reads a pressure above 67 psi in the reservoir, it should clear the fault condition and transmit a Low Reservoir Exception Cleared message to the HEU. When the HEU receives the cleared message, it should log the CCD as operative again.

4.1.5.5 Response to Loss of BPP

Loss of BP pressure will be tested to validate the requirements in Section 4.4.3.3 of S-4200. Without disconnecting the brake pipe or the ECP trainline, the wayside test engineer will close one of the angle cocks between the second and third cars. Next, the operating test engineer will cut out the brake pipe at the locomotive brake valve, thus allowing the BPP to reduce due to system leakage. Confirm that the front section of pipe is reducing faster than the rear section, by comparing BPP reported at the second and third cars. The leakage rates should be adjusted if necessary, to obtain this condition (i.e., reduce leakage in rear section or increase leakage in front section). When the pressure in the front section of pipe falls below 50 psi, the first two cars should transmit critical loss of BPP messages. All CCDs should then initiate an electronic emergency brake application (i.e., the brake pipe is not vented), on account of having received loss of BPP messages from two separate devices, as described in Section 4.4.4 of S-4200. At the same time, the HEU should have also received the loss of BPP messages and will command the TBC to 120 percent. The wayside test engineer will slowly reopen the closed angle cock, taking care not to generate a pneumatic emergency that would dump the BPP. The operating test engineer will cut in the locomotive brake valve to charge the pipe. Once the pipe reaches above 61 psi, the fault should be recovered and the HEU should command the system to reset fault logic, as described in Section 4.4.4.6 of S-4200, allowing control of the brake system to be restored and the train brake cylinders to be released.

4.1.5.6 Response to Loss of HEU Beacon

Loss of HEU beacon will be tested to validate the requirements in Section 4.2.2.2 of S-4200. The wayside test engineer will disconnect the trainline between the first car and the second car. After about 6 seconds (i.e., six missed HEU beacons), the second and third CCDs should transmit messages indicating loss of HEU beacon faults. Immediately after the two CCDs report the exception, they should initiate an electronic emergency, as they enter the multiple CCDs critical loss state, outlined in Section 4.4.4 of S-4200. The first CCD should not receive it as the communication link is disconnected, so it should not apply an emergency. The HEU should also not receive it, but should act accordingly to Section 4.4.2.3, “HEU does not receive CCD’s Response to Status Query” and Section 4.4.5, “Reduced Percentage of Operative Brakes” of the S-4200. Since the HEU cannot receive status messages from the second and third CCDs, it should mark them as inoperative. If the fault is being induced in RUN mode, and since the percent of operative brakes would then drop below 85 percent (i.e., operative brakes would be 33 percent of three cars), the HEU should command a penalty full-service application. Five seconds after the two CCDs apply emergency brakes, they should transmit critical loss relay messages instructing all CCDs to enter a critical loss state and initiate an electronic emergency too. The wayside test engineer will reconnect the trainline. Soon after, the first CCD and HEU should receive the critical loss messages and act as follows. The first CCD should self-initiate an emergency and the HEU should automatically command a TBC of 120 percent. Once this is accomplished, the critical relay messages should cease, but the CCDs should maintain their electronic emergency cylinder pressure associated with the TBC of 120 percent. After the ECP emergency interlock is over (i.e., approximately 2 minutes), the operating test engineer will release the brakes as described in earlier electronic emergency testing (i.e., in RUN mode), which should cause the CCDs to recover their fault logic and release their cylinder pressure.

SA will briefly review the data collected before proceeding to emulation testing.

4.2 Emulation/Pneumatic Test

The section describes the planned procedures for the emulation pneumatic testing.

4.2.1 Setup

The operating test engineer will exit ECP mode through the HEU interface, according to the procedures in Sections 4.2.7 and 4.3.17 of S-4200. SA and INRR will replace the vendor CCD with the original ABDX valve on the second instrumented car, per the diagram in Figure 13. All necessary tests will be performed as required for setting up a pneumatic train. SA will inspect all instruments and sensors for working condition. SA will resolve any malfunctioning instrumentation. Once SA determines all instruments are in working condition, SA will restart a new data recording session. As a reminder, the network monitor will not record anything in emulation mode.

4.2.2 Minimum Application

The operating test engineer will initiate a minimum application: move the brake valve handle to the minimum service position, at 7 psi reduction. After confirming the BCPs have stabilized at around 10 psi, the operating test engineer will release the brakes and allow the system to charge the reservoirs.

4.2.3 Partial Application

The operating test engineer will initiate a partial application by reducing the BPP by 15 psi. After confirming the brakes have stabilized, at around 33 psi, the operating test engineer will release the brakes and allow the system to charge the reservoirs.

4.2.4 Full Service Application

The operating test engineer will initiate a full-service application by moving the brake valve handle to the full-service position, reducing the BPP by about 26 psi. After confirming the BCPs have stabilized at equalization pressure, about 64 psi, the operating test engineer will release the brakes and allow the system to charge the reservoirs.

4.2.5 Graduated Full Service Application and Release

The operating test engineer will initiate a graduated full-service application by first reducing BPP at the brake valve to the minimum service position, a 7-psi reduction. Then, gradually reduce the BPP, in 5–10 psi increments, until a full-service application is achieved. After confirming the brakes have stabilized at equalization pressure, 64 psi, the operating test engineer will release the brakes and allow the system to charge the reservoirs.

4.2.6 Pneumatic Emergency

The operating test engineer will initiate a pneumatic emergency application by rapidly exhausting the brake pipe. After confirming the brakes have stabilized at around 78 psi, the operating test engineer will release the brakes and allow the system to charge the reservoirs.

4.2.7 Pneumatic Backup

The pneumatic backup is a means for applying a pneumatic emergency application without electrical power. In most cases, ECP operation will take precedence over pneumatic backup, as prescribed in Section 4.3.19 of S-4200. Therefore, to independently test the pneumatic backup, trainline power must be off and battery power must be off.

The wayside test engineer will disconnect the battery from a single emulator. Then, the operating test engineer will initiate a minimum service application by reducing the BPP by 7 psi. As shown from previous service application testing, the powered emulator and the ABDX valve service portion should apply 10 psi to their brake cylinders. The unpowered emulator CCD should not supply any pressure to its brake cylinder. Then, the operating test engineer will charge the brake pipe, releasing the BCP from the powered CCDs. Next, the operating test engineer will fully vent the brake pipe at a service rate. As the BPP reduces, the powered CCD and ABDX valve should apply to full service cylinder pressure. When the brake pipe falls below about 20 psi, both CCDs should quickly apply to emergency cylinder pressure.

5. Test Results and Analysis

This section describes the field testing activities and associated observations. Some of the activities performed diverge somewhat from the test procedure described in the previous section. This was necessary to account for exigencies encountered with the equipment in the field. These procedural modifications notwithstanding, the activities executed in the field effectively tested the same functions and capabilities of the emulator CCD as the planned procedure was designed to test.

The following sub-sections analyze the success of each test, by comparing the observed results to the acceptance criteria.

During testing, unanticipated errors with the emulator CCDs prevented executing certain tests and demonstrating certain features. SA identified many of these issues, and remedy them by updating the CCD software in the field. Additional tests were then performed to demonstrate compliance. Other issues were unresolvable in the field or were later identified during analysis. These issues were resolved and tested in SA's lab.

5.1 Data Processing

All data acquisition files were converted to human readable text files, e.g., comma separated or tab delimited format. All channels were filtered. The network logs were also converted to a human readable text format. Important events in the data acquisition were synchronized with the respective network monitor logs to further identify brake response times and other software and hardware latency. SA plotted various comparative time histories for brake responses (i.e., BCP from the data acquisition) and identified on the plots when the brake application started, from the network log. The following results and analysis assess whether the CCDs successfully performed each brake application per the S-4200 response times. Test-specific plots are also presented.

5.2 ECP Test Results

This section describes the results from testing the device in ECP mode.

5.2.1 INITIALIZATION Mode Operation

This section describes the results from testing the device in ECP INITIALIZATION mode test.

5.2.1.1 Train Building Test

Several tests of train building were performed and all were successful. The HEU found all three CCD devices in the train and correctly recorded their information, as shown in Table 1.

Table 1 shows device information of the CCDs from a typical train build process; this information was the same for all train builds. The information shown was either read from the Car ID Module (e.g., Report Mark) or results from the initializing ECP mode (e.g., ECP Address).

Table 1 – Device Information Queried During Train Building Procedure

Abbreviated CCD Name	EMU1	EMU2	Vendor CCD
ECP Address (Subnet/Node)	3/1	3/2	3/3
Message Version	1	1	0
Manufacturer ID	Zeftron	Zeftron	Vendor
Report Mark	IN 913	IN 909	NS196849
Unique ID (Neuron ID)	05010B36EC00	05010B36E200	001250463100
Manufacturer Revision Level	1	1	0
S-4200 Compatibility Version	2	2	2
S-4230 Compatibility Version	2	2	2
Device Characteristics	86	86	0D
Vehicle Type	****	****	GOND
Vehicle Length (ft)	53.1	53.1	68.0
Empty Weight (lbs)	50,000	50,000	89,100
Loaded Weight (lbs)	263,000	263,000	263,000
Number of Axles	4	4	4
Operable Brakes	1	1	1
Empty/Load Device	0	0	0
Status Info	20	20	0

SA programmed the static car information for the emulators into their Car ID modules prior to the field demonstration. The report marks for both emulators correctly correspond to the gravel cars on which they were installed. The vendor CCD car information was originally programmed by the vendor for installation on a gondola car; and, therefore, does not accurately represent the information for the gravel car on which it was installed during this test. Certain parameters that did not affect performance were programmed to the default values listed in the S-4200 (e.g., vehicle types for both emulator test cars were programmed to "****").

The minimum service BCP (i.e., MSP) for both the emulator CCDs and the vendor CCD was 7 psi. This value was programmed into the emulator Car ID, and confirmed by test results.

BCP levels attained in ECP mode are controlled by each CCD according to its FSP, a parameter calculated by the CCD based on several inputs. These inputs include the car's weight, the CCD's local brake constant and reservoir constant, and the train Net Braking Ratio (NBR) and BPP setpoint transmitted from the HEU.

From the network log, it was observed that the train NBR was set to 12.0 and the BPP setpoint was set to 91 by the HEU in the lead locomotive. Table 1 shows the loaded weight of all gravel cars set at 263 kips. The brake constant and reservoir constant for the emulator cars were assigned the default values, 572 and 0.711 respectively, in their Car ID modules. This resulted in a FSP at a fully loaded weight of 54 psi for the emulator cars. Although the brake constant for the vendor CCD car cannot be read directly, its FSP at fully loaded weight is about 64 psi, based on observations of its cylinder pressure with 100 percent TBC. Therefore, the BCPs measured for the emulator cars were scaled by the ratio of FSPs (i.e., 64/54) so that the cylinder pressure levels for any given brake command could be directly compared between emulators and vendor CCD.

5.2.1.2 Car Sequencing Test

Throughout field demonstration testing, all sequencing results were displayed as "Sequencing – Partial" on the HEU display. After analyzing the network logs, it was determined that none of the sequencing procedures were successful.

Sequencing failed during the field demonstration for a few reasons. The main reasons were as follows:

- Location of power supply controller (PSC) relative to lead HEU was never determined
- Car orientation was never determined

These issues were identified only after analyzing the network logs. SA corrected the emulator software accordingly and demonstrated the fix and S-4200 compliance in the lab. The post-test efforts for rectifying these issues are outlined in Section 6.

Car sequencing tests were unsuccessful in the field, but subsequently fixed and successfully demonstrated in the lab.

5.2.2 RUN Mode Operation

This section describes the results from testing the device in ECP RUN mode.

5.2.2.1 Graduated Application Test

Figure 20 shows the brake responses for a graduated service application and graduated release in ECP RUN mode. The TBC was incremented gradually from 0 to 100 percent, as described in the test plan.

As shown in Figure 20, each CCD's brake response follows the TBC trend. The timing between vendor CCD and the emulators is very close. As described earlier, the BCPs measured for the emulators were scaled by the FSP ratio (i.e., 64/54) to highlight the correspondence with vendor CCD cylinder pressure. All CCDs correctly applied FSP and intermediate service pressures, based on the linear conversion in S-4200.

The emulators performed successfully for the graduated application tests in RUN mode.

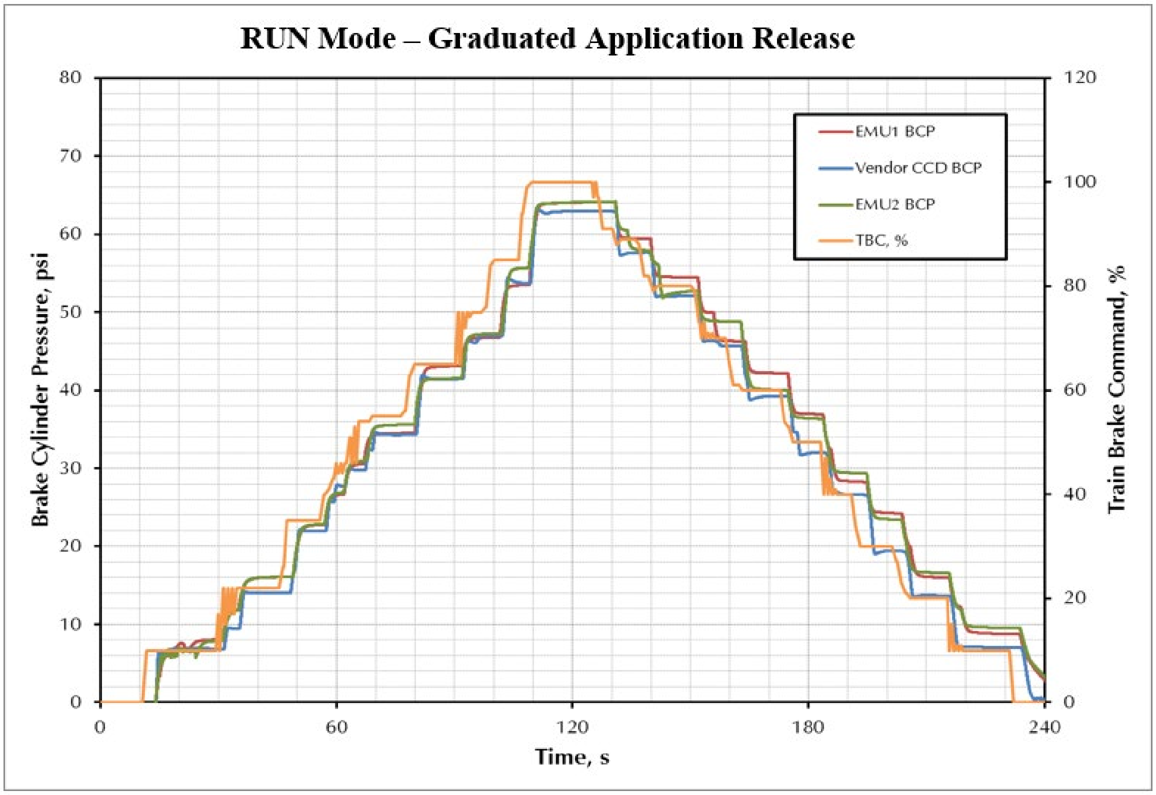

Figure 20 – Graduated Application and Graduated Release Brake Response, in RUN Mode

5.2.2.2 Graduated Release Test

Figure 20 also shows the graduated release test, performed after the graduated application. The brake responses for the emulators, EMU1 and EMU2 follow the TBC trend and vendor CCD trends. The measured service pressures match their respective calculated targets to within established tolerances.

The emulators performed successfully for the graduated release tests in RUN mode.

5.2.2.3 Electronic Emergency Test

Figure 21 shows the CCDs brake response to an electronic emergency. The BCPs for the emulators follow the TBC command and the vendor CCD pressure trend. When the emergency was released, after the 2-minute interlock period had expired, the CCDs responded with a full-service application. After that, a full release was manually commanded and the CCDs brake cylinders exhausted appropriately.

The emulators performed successfully for the electronic emergency tests in RUN mode.

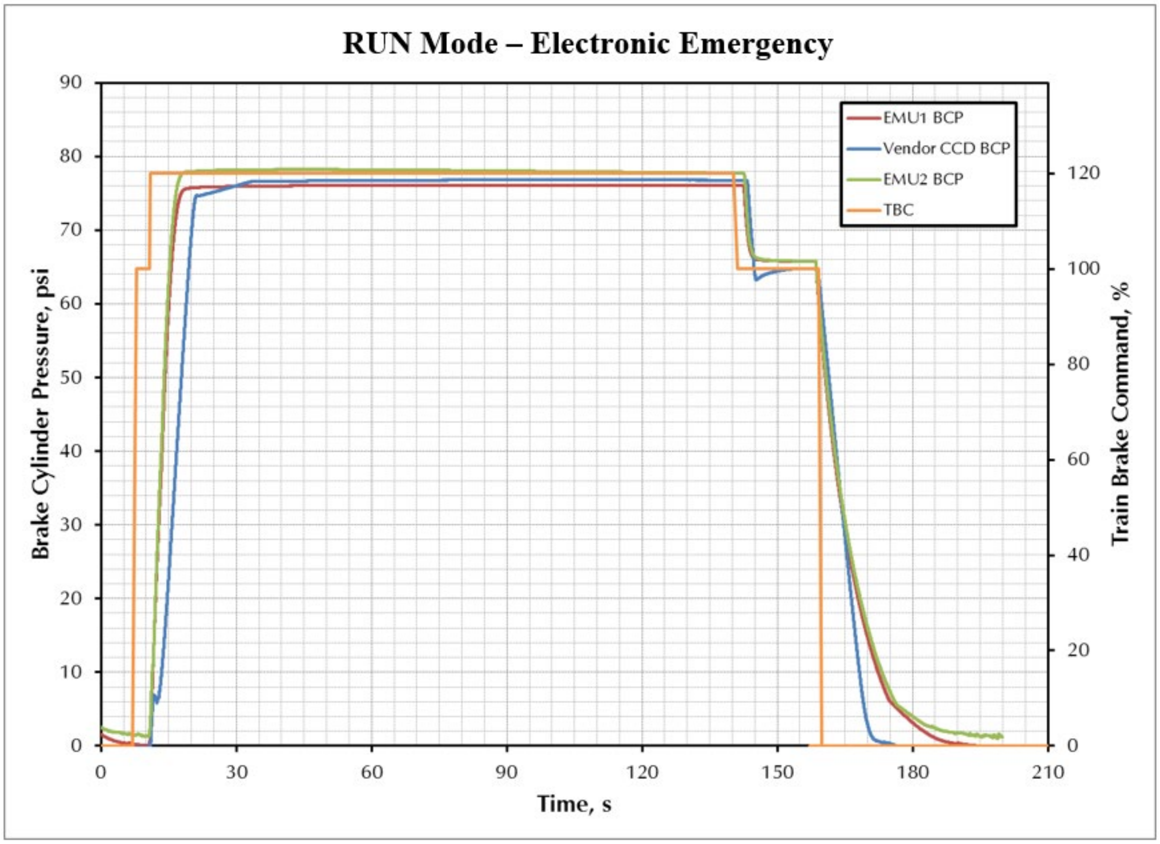

Figure 21 – Electronic Emergency Application and Release, in RUN Mode

5.2.2.4 Auxiliary Functions Tests

After train building, information from connected CCDs was readily accessible and displayed through the HEU screen, including certain static car parameters and local pressures. However, other variables were not accessible, as originally expected. For example, battery percent charge was available from CCD status responses, but the HEU reported battery voltage. The battery voltage is typically queried from a diagnostic power test. When this power test was performed, the HEU queried the CCDs for battery voltage information. It was confirmed through the network log that the power test was performed using mostly manufacturer-specific transmissions. The vendor CCD successfully responded with its battery voltage, which was then displayed on the HEU screen. However, since these messages were not standard, queries to the emulator CCDs were not successful and, consequently, battery voltages for the emulator CCDs were not accurately displayed.

The individual cut-out brake tests were not performed as planned because there were not enough CCDs in the test consist. With only three cars in the train, cutting out an individual CCD (i.e., through the HEU) caused the percent operative brakes to drop to 67 percent. Consequently, the HEU commanded a fault-initiated full-service application since the percent operative brakes was below the 85 percent threshold. This penalty prohibits any further manual intervention until the percent operative brakes rises above 85 percent. Although the test was not conducted according to the original plan, all three CCDs responded as expected: the two CCDs that remained cut-in performed the penalty brake application, while the cut-out CCD did not respond.

5.2.3 SWITCH Mode Operation

This section describes the results from testing the device in ECP SWITCH mode.

5.2.3.1 Trainline Power

The main purpose of the trainline power test is to verify that, when operating in SWITCH mode, ECP devices can operate without trainline power (i.e., assuming sufficiently charged batteries). This test was successfully demonstrated by transitioning the train to SWITCH mode, instructing the PSC to turn off trainline power, and then performing the same brake application and release tests as executed during RUN mode testing.

The emulator CCDs functioned normally in SWITCH mode, without trainline power; so, the emulators passed the trainline power test.

5.2.3.2 Graduated Application and Release Test

Figure 22 shows a graduated application to full service and then an ECP/electronic emergency brake application. The TBC was gradually increased, in increments of approximately 10 percent, until a full-service application at 100 percent was reached. Once the brakes stabilized, the brake handle was moved to the emergency position, to command a 120 percent brake application. After the emergency interlock was released, the TBC was changed to 100 percent, and then a full release was performed.

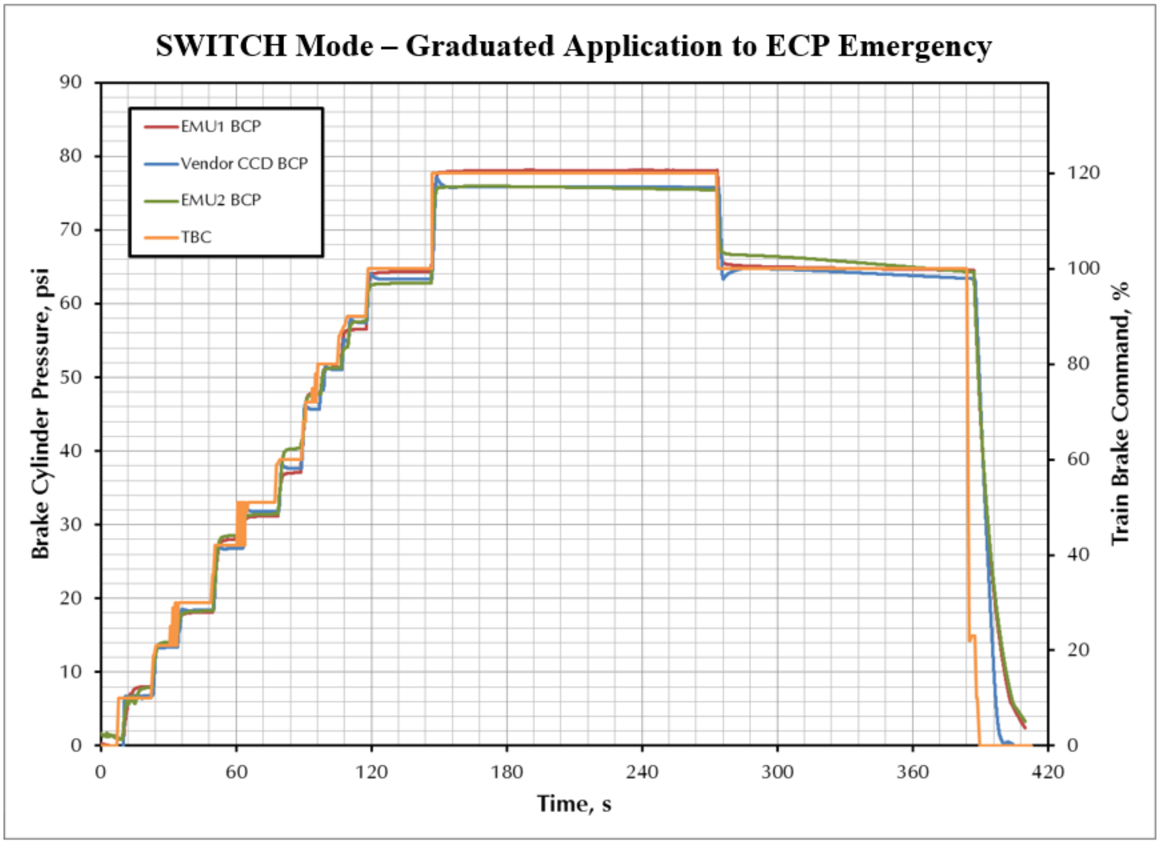

Figure 22 – Graduated Application to ECP Emergency, in SWITCH Mode

A graduated release from full service is shown in Figure 23. The response times and cylinder pressures of the emulators are comparable to those of the vendor CCD, and are within the specified tolerances of values calculated in accordance with S-4200.

Based on the emulators’ performance, as shown in Figure 22 and Figure 23, the emulators pass the graduated application and release tests in SWITCH mode.

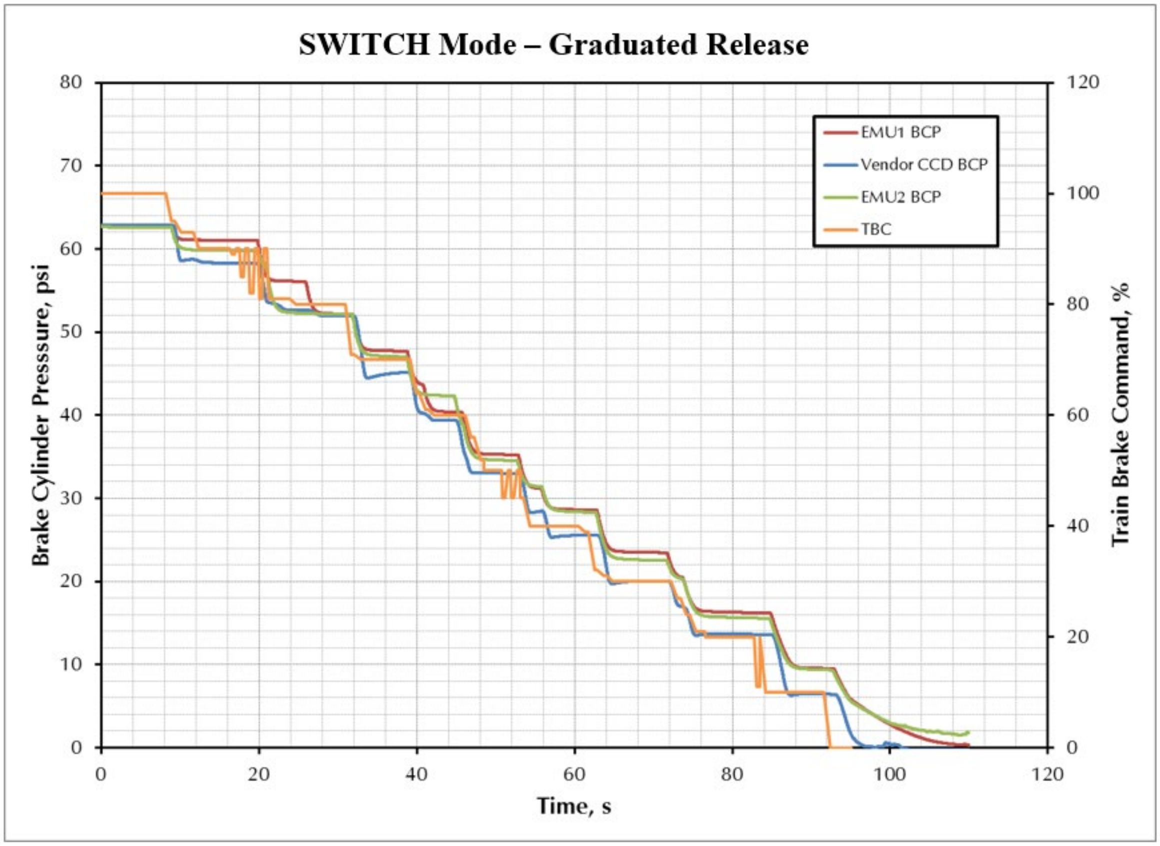

Figure 23 – Graduated Release from Full Service, in SWITCH Mode

5.2.3.3 Electronic Emergency Test

Multiple electronic emergencies were performed in SWITCH mode. One example is shown in Figure 22, after the graduated application. Once the brakes stabilized at full service, the brake handle was moved to the emergency position, to command a 120 percent brake application. After the emergency interlock was released, the TBC was changed to 100 percent, and then a full release was performed.

The emulators applied the correct cylinder pressure for the commanded ECP emergency application and release, as well as matching the vendor CCD response; and performed successfully for the electronic emergency test in SWITCH mode.

5.2.4 CUTOUT Mode Operation

Prior to field testing, it was unknown how the HEU would perform in ECP CUTOUT mode. Though S-4200 dictates how ECP equipment must perform to ensure compatibility, the methods and details of individual component operation are typically left to the manufacturer’s discretion. Through field testing with the vendor HEU, it was observed that after entering CUTOUT mode, ECP mode is effectively halted. The HEU, for a few seconds, instructs all ECP devices to enter ECP CUTOUT mode; and then it stops all transmissions. In compliance with S-4200 Section 4.2.7.2, this effectively ends ECP operation.

When ECP mode ends in an ECP train, the brake control reverts to pneumatic braking. Regular ECP CCDs release their brakes. The emulator CCDs go into emulation mode when this occurs. Any subsequent brake application will drop the BPP since the brake handle controls both conventional braking and ECP braking. So, when the brake handle moves to a service position, regardless of whether the train is in ECP or conventional mode, the operational emulators will respond with a brake application.

This behavior prohibits testing a "No Response" condition for emulator devices. Additionally, if the brake handle remains at a service position when ending ECP mode, the emulator devices will perform the equivalent conventional brake application. Therefore, the proposed tests were not able to be performed as written.

An example of this behavior is shown in Figure 24.

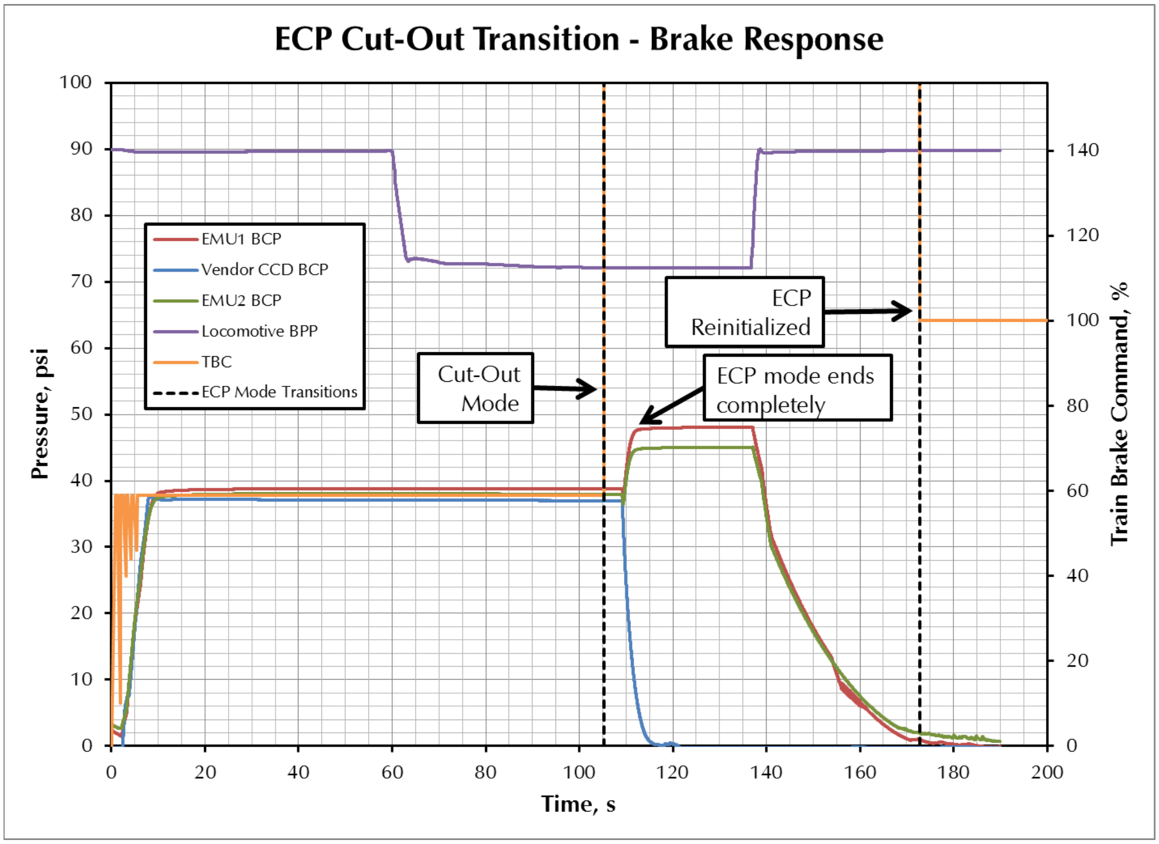

Figure 24 – Brake Response to Ending ECP Mode

Figure 24 shows the brake response of the CCD valves during a mode transition with an active brake application in effect. Initially, the test consist was in ECP SWITCH mode with a 59 percent partial service application. About a minute after the application started, the brake pipe was reduced by about 18 psi. As expected, this BPP reduction did not affect the CCD valves brake response. At about 105 seconds, the ECP mode was changed to CUTOUT mode, as indicated by the first vertical dashed line.

About 5 seconds later, and without any manipulation, the HEU stopped transmitting beacons and ECP mode ended, as shown at 110 seconds. When ECP mode ended, the vendor CCD, which is not an emulation device, released its brakes. In contrast, the emulators respond to the steady-state brake pipe reduction and increase their BCP accordingly. At around 137 seconds the brake handle was moved to full release. BPP increased and the emulators released their BCP. The emulators' brake responses between 110 seconds and 180 seconds demonstrate pneumatic brake emulation behavior, which will be further demonstrated in the results from emulation/pneumatic testing in Section 5.3.

5.2.5 Fault Testing

In addition to brake control and normal ECP functionality, standard ECP faults were tested. Each fault was induced independently as outlined in the test plan. The fault detection and recovery processes were captured via the recorded data and the network message log; and they were also observed at the HEU display. During the field test, both emulator CCDs successfully performed fault detection and recovery for all fault conditions except for the low battery fault. After the field demonstration, SA identified and resolved the issues with the battery fault logic in the emulator CCDs. The low battery fault test was then performed in SA's lab and the emulator CCDs demonstrated full compliance.

To analyze fault testing results, SA synchronized the network log with the collected data files. By synchronizing the log with the recorded brake system pressure time histories, SA could correlate the times that fault messages were transmitted and when the faults occurred, or were recovered, with the corresponding system pressures. All pressure data shown in the plots below were extracted from the data acquisition system (i.e., SoMat). All TBCs and message indications were extracted from the network log. Emulator #1, at Test Car #1, was the device under test for all fault testing, unless otherwise indicated.

5.2.5.1 Low BCP Test

Incorrect brake cylinder faults are split between two distinct faults: low brake cylinder and high brake cylinder. The high cylinder pressure fault can be further broken down into high BCP and stuck brake, depending on the desired target cylinder pressure—calculated from the TBC.

Figure 25 shows the BCP time histories of the CCD for low brake cylinder fault. Superimposed on the plot are the TBC and the moment when the low cylinder fault was transmitted, both taken from the network log. The starting time, 0 seconds, was arbitrarily chosen to adequately show the TBC transition from 0 to 44 percent. This same starting time was also used for the other Incorrect BCP fault and recovery response plots.

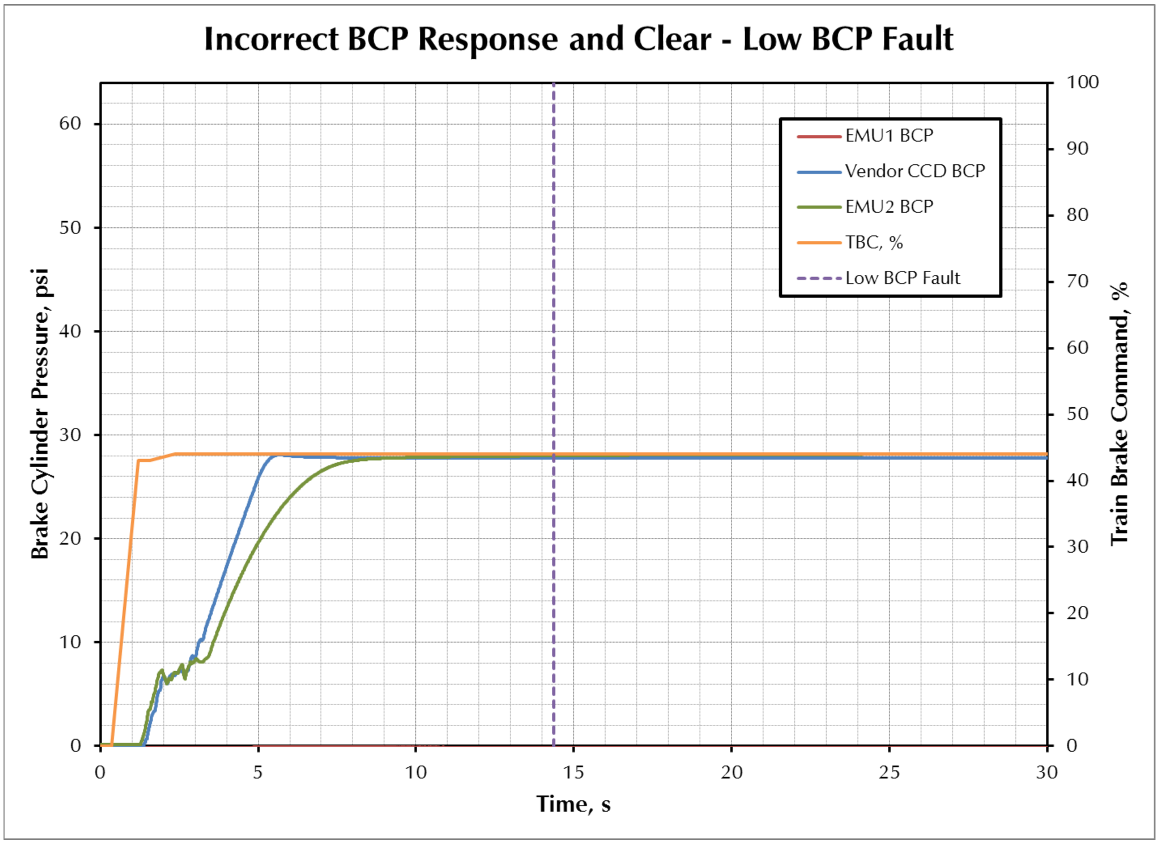

Figure 25 – Low Brake Cylinder Fault on Emulator #1

For this test, SA turned off the application switch to Emulator #1 using the BCP Fault Switchbox. The TBC was set to 44 percent at time = 1 second in Figure 25. The vendor CCD and Emulator #2 correctly applied their brakes, but the cylinder of Emulator #1 remains at zero pressure (i.e., red trace hidden behind the horizontal axis). As shown by the dotted line in the plot, the low brake cylinder fault message was transmitted from Emulator #1 roughly 13 seconds after the TBC stabilized. This is roughly 5 seconds after both the vendor CCD and Emulator #2 CCD brakes were fully applied, indicating that Emulator #1 correctly detected and reported a low cylinder fault condition.

Figure 26 shows the time history for recovering the low cylinder fault. The application switch on Emulator #1 was closed at around 239 seconds. After the switch was fully closed, Emulator #1 started to apply its brakes to the appropriate cylinder pressure. Emulator #1 transmitted a recovery message at around 244 seconds, immediately after the cylinder pressure reached within the +/- 3 psi tolerance of the steady-state pressure.

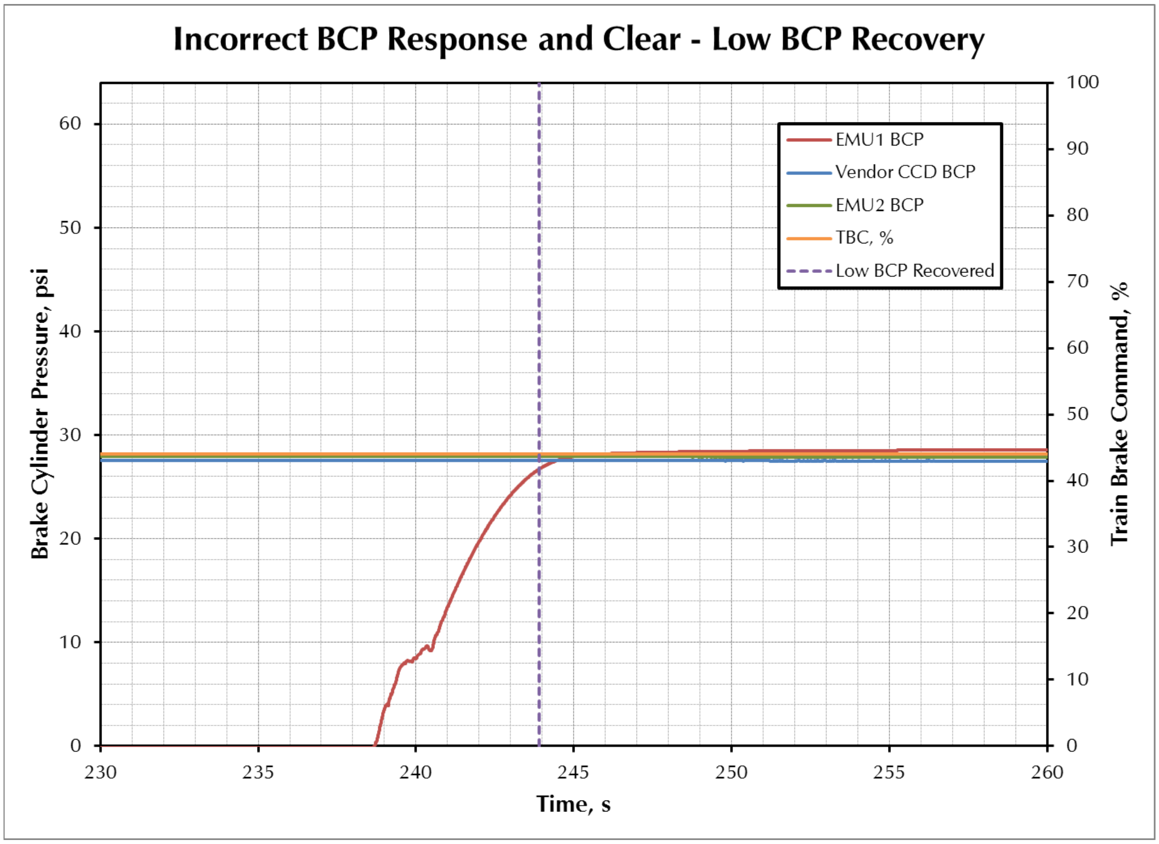

Figure 26 – Low Brake Cylinder Fault Recovered on Emulator #1

The response times shown in Figure 25 and Figure 26 and the network log information indicate that the emulator successfully executed the low BCP test.

5.2.5.2 Stuck Brake Test

With the brakes still applied from the previous test, the high BCP fault logic was tested on Emulator #1. The release switch on Emulator #1 was turned off, and all brakes were commanded to release via the HEU. Figure 27 shows the response of the CCD to this fault condition.

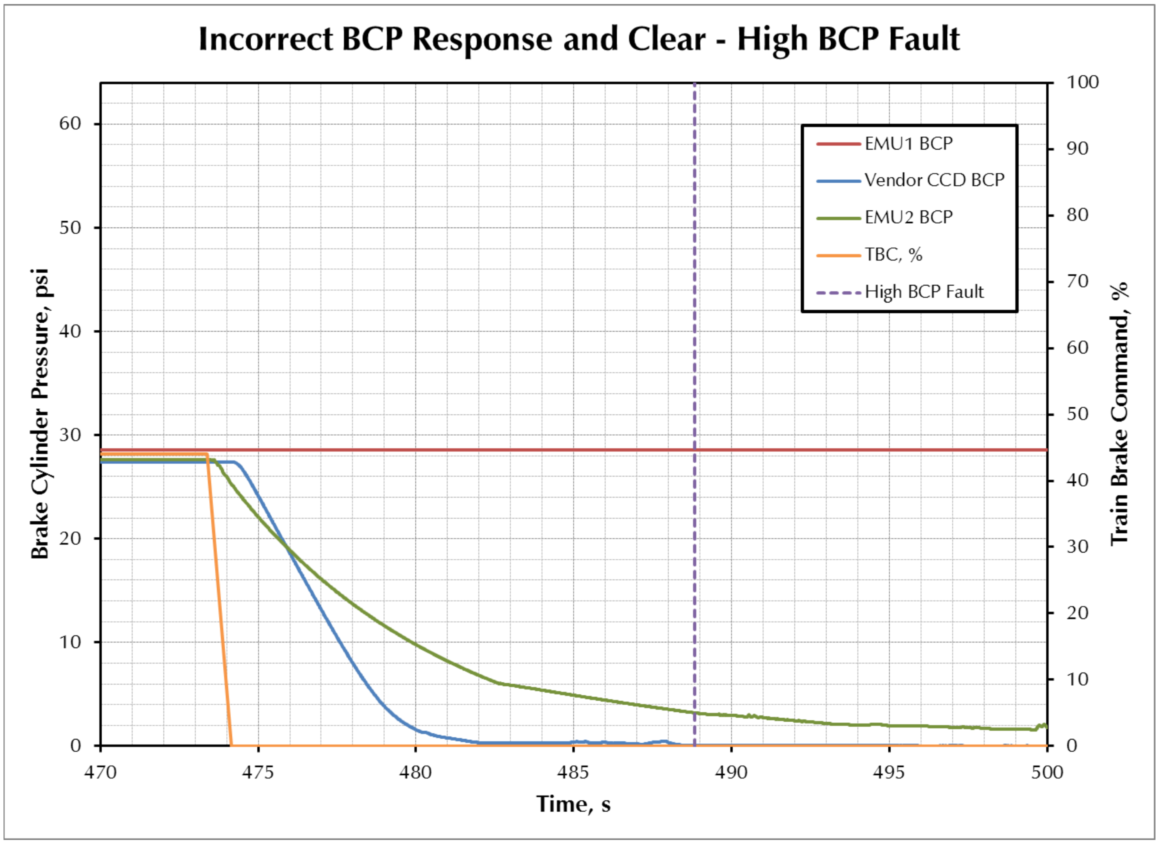

Figure 27 – High Brake Cylinder Fault Generated on Emulator #1

As shown in Figure 27, the command to release the brakes was sent at around 474 seconds. Both the vendor CCD and Emulator #2 released their brakes successfully. Emulator #2's release rate is slightly slower than that of the vendor CCD, but within S-4200 tolerances. After around 15 seconds from when the release was commanded, Emulator #1 transmitted a high brake cylinder fault message.

Figure 28 shows Emulator #1 cylinder pressure as it recovers from its high cylinder pressure fault. The TBC remains at 0 percent from the previous test. Both the vendor CCD and Emulator #2 brakes also remain fully released throughout this test. At approximately 678.5 seconds, the release switch at Emulator #1 was turned on. Then, Emulator #1 immediately started to release its BCP. After approximately 8 seconds, Emulator #1's cylinder pressure reached 5 psi, at which point the fault recovery message was sent. This is in accordance with the S-4200 recovery procedure.

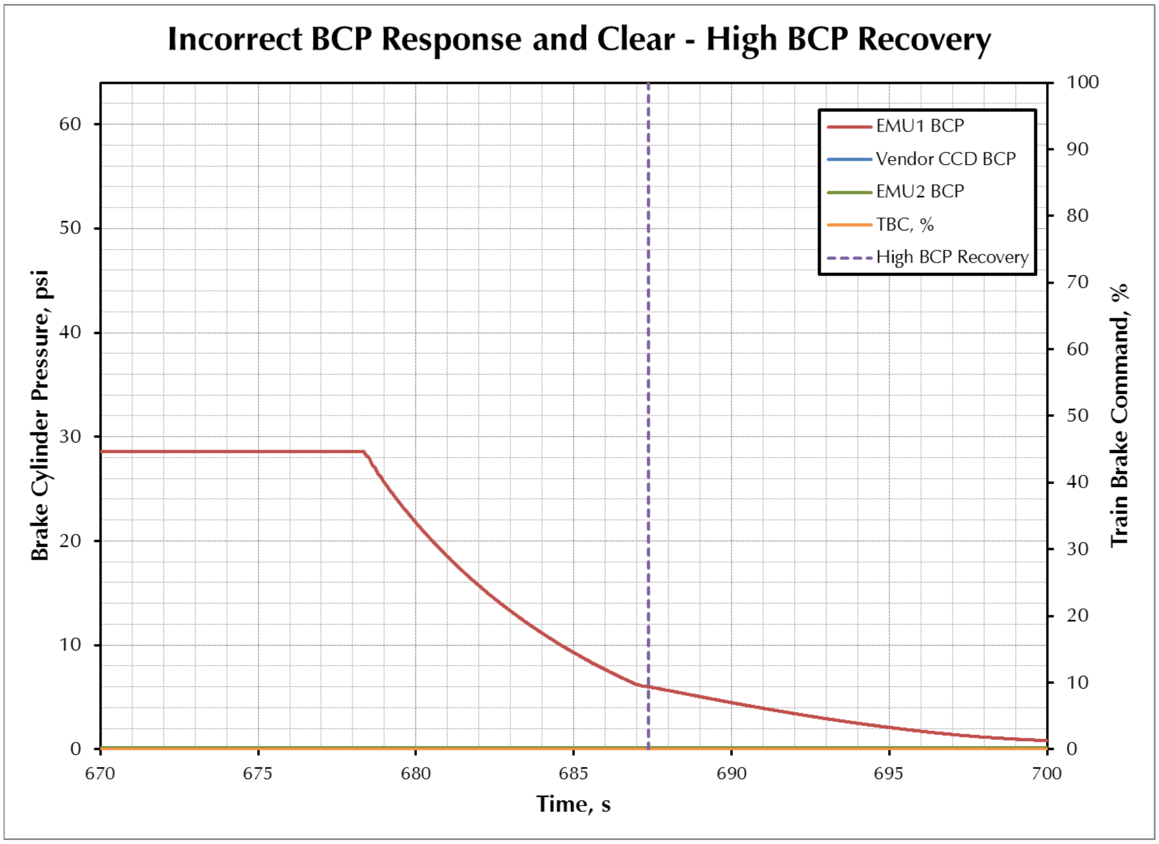

Figure 28 – High Brake Cylinder Fault Recovered on Emulator #1

The response times shown in Figure 27 and Figure 28 indicate that the emulator successfully executed the high BCP test.

5.2.5.3 Low Battery Test

The low battery fault test was conducted on both the emulator CCDs during the field demo. For each emulator, the CCD front cover on the pneumatic portion was opened, and the battery was completely disconnected from the emulator. After monitoring the HEU display and network log, it was apparent that the emulators were not performing battery voltage measurements appropriately. With the trainline on and the batteries disconnected (i.e., essentially removed from the system), the emulators reported that their battery voltage was still nominal when it should have been zero.

To charge the emulator's battery and power the emulator circuits effectively, the ECP trainline voltage is stepped down from 230 VDC to 12 VDC using an onboard power supply. This 12 VDC source is electrically parallel to the points at which the battery measurement is taken. Since the battery itself was disconnected, it was suspected that the emulators were reading this 12 VDC power source rather than the actual battery voltage.

Since this problem was not correctable in the field, this test was deemed unsuccessful. The problem was later resolved and successfully tested in the lab to demonstrate compliance.

5.2.5.4 Low Reservoir Pressure Test

The low reservoir pressure fault test was conducted with nominal initial conditions. As mentioned, Emulator #1 was the test car for inducing the low reservoir pressure fault. The manual release rod on test car #1 was actuated to reduce the supply reservoir pressure until the fault was reported to the HEU. The rod was then released to allow the reservoir to charge up again.

Figure 29 shows the time histories of all the CCD reservoir pressures, with annotations indicating when Emulator #1 transmitted low reservoir fault and recovery messages.

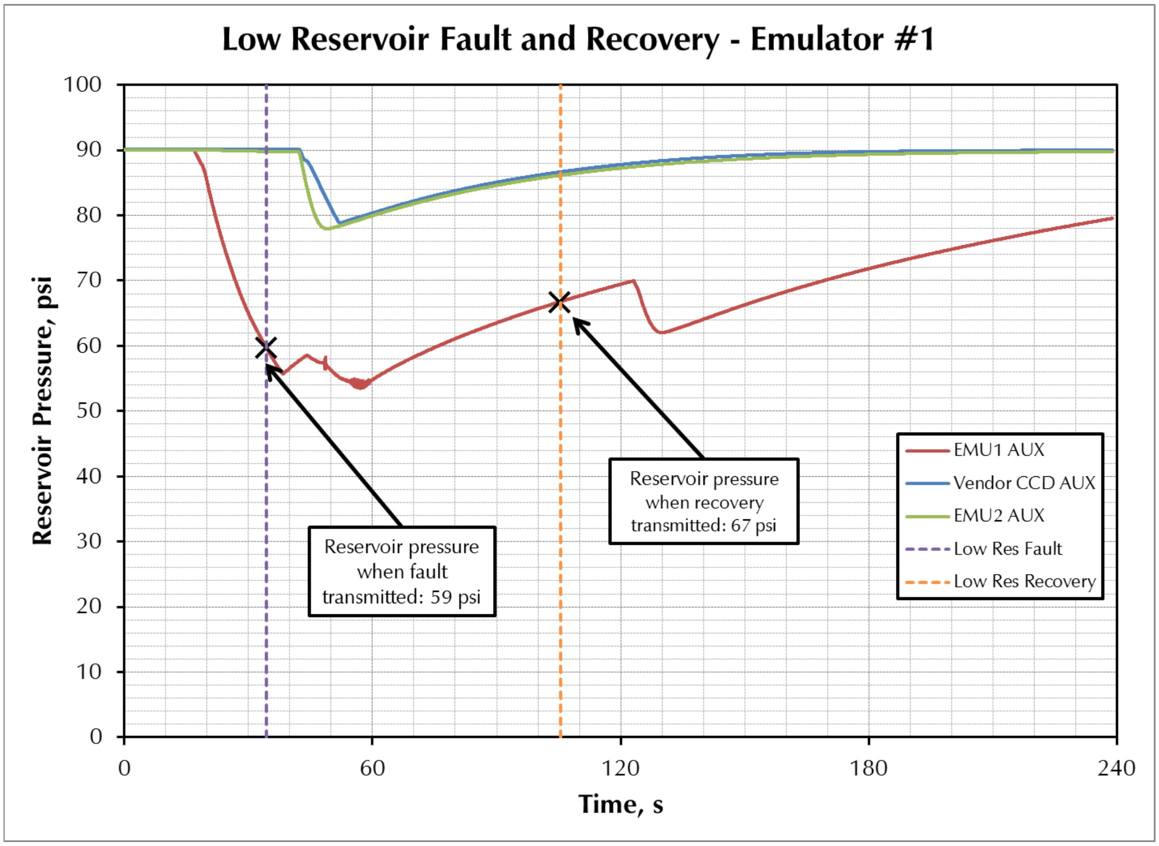

Figure 29 – Low Reservoir Fault and Recovery on Emulator #1

As shown in Figure 29, the fault message was transmitted when the Emulator #1's reservoir pressure dropped below 59 psi. This is in accordance with the pressure indicated in S-4200. The supply reservoir pressure was allowed to continue dropping to about 54 psi before letting the reservoir charge back up. About a minute later, when the reservoir pressure reached approximately 67 psi, the Emulator #1 transmitted a low reservoir recovery message, indicating the fault no longer exists. This trigger pressure is also in accordance with the recovery pressure outlined in S-4200.

These results indicate that the emulator passed the low reservoir fault test.

5.2.5.5 Response to Loss of BPP

The loss of BPP fault was performed by pneumatically isolating the train (i.e., closed angle cock) between test cars #2 and #3, halting brake pipe charging at the locomotive, and slightly opening the brake pipe angle cock at the front of the locomotive, thus allowing the BPP to drop rather rapidly on all vehicles except car #3. This test was performed multiple times to ensure that the rate of BPP reduction did not induce a pneumatic backup emergency application. Figure 30 shows the BPP for each car during this loss of BPP test. Note that the BPP at test car #1 (e.g., EMU1) is identical to that of test car #2 (i.e., vendor CCD), and their curves lay on top of one another in the plot.

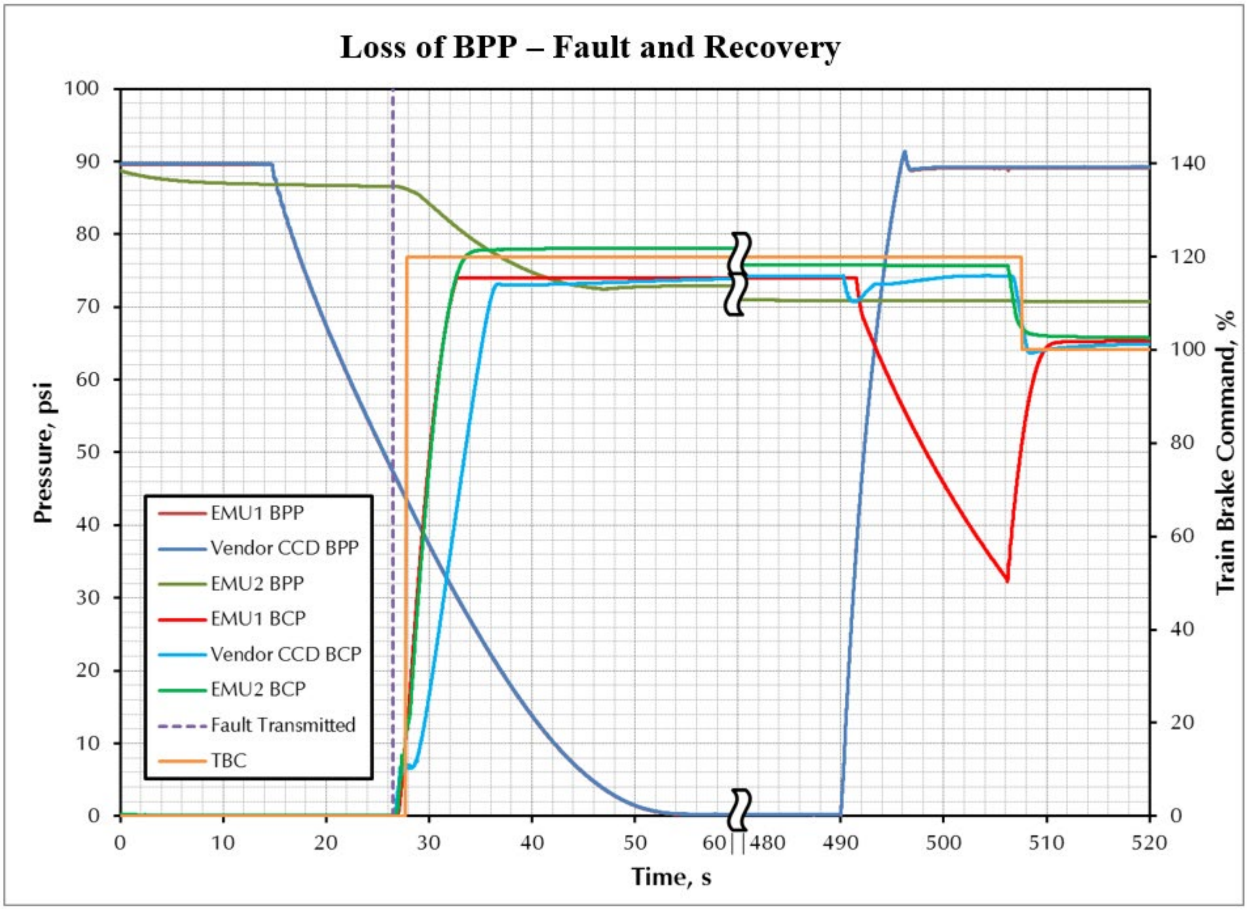

Figure 30 – Loss of BPP Fault and Recovery on Test Cars #1 and #2

Initially, BPP at test car #3 (EMU2) dropped slowly due to leakage at that car. After cracking open the angle cock at front of locomotive, the BPP at test cars #1 and #2 dropped rapidly with identical trends. At around 26 seconds, the BPP in both test cars #1 and #2 drops below 50 psi and their CCDs both transmit the loss of BPP fault message. Test car #3 BPP remains above the fault threshold, so it did not transmit a fault message. Because both test cars #1 and #2 experienced the fault within 5 seconds of each other, a critical relay loss occurred and both cars performed a self-induced electronic emergency application. As soon as test car #3 received both these messages, it also performed a self-induced emergency application. Both conditions leading to a self-induced emergency application comply with Section 4.4.4.1 of S-4200. The HEU receives these fault messages and broadcasts a train-wide emergency application (i.e., TBC = 120%). This BPP fault logic also complies with S-4200.

The brake pipe at the front of the train (i.e., up to the closed angle cock between car #2 and car #3) was completely vented for approximately 3 minutes. Then, after recovering the brake pipe charging, the angle cock at the front of the locomotive was closed allowing the brake pipe to charge back up. When the BPP rises above about 60 psi, the fault is recovered internally in test cars #1 and #2. After the BPP was restored to 90 psi and the emergency was released at the HEU, the CCDs were commanded to full service (i.e., TBC = 100%) and the cylinders responded accordingly.

This fault detection and recovery behavior is compliant with S-4200. Therefore, the loss of BPP fault and recovery test was successful.

5.2.5.6 Response to Loss of HEU beacon

The loss of HEU beacon fault was tested by manually disconnecting the ECP trainline between test cars #1 and #2, and allowing cars #2 and #3 to miss six HEU beacons. In 2014 and more current versions of S-4200, the loss of the EOT beacon and loss of HEU beacon threshold is 6 seconds. The recovery process was to reconnect the trainline soon after seeing the fault appear on the network monitor. This test was performed twice: one time in RUN mode and one time in SWITCH mode.

When this test was performed in RUN mode, a loss of EOT beacon occurred, and was reported to the HEU, before a loss of HEU beacon could occur in the CCDs. The HEU is compliant to an S-4200 version before 2014, so when the HEU missed the EOT beacon for 3 seconds, a Missed EOT Beacon Fault occurred in the HEU before a loss of HEU beacon fault could occur in the CCDs. Therefore, the test was repeated in SWITCH mode as described below.

The fault test performed in SWITCH mode showed the appropriate behavior for a loss of the HEU beacon. Since the EOT is not needed in SWITCH mode, the loss of the HEU beacon could be tested in isolation. When the wayside test engineers disconnected the ECP trainline, and waited 6 seconds, the CCD at both car #2 and car #3 registered a loss of the HEU beacon. Immediately after each CCD transmitted a fault message, both CCDs went into critical relay logic. Per critical relay logic, the CCDs applied electronic emergency brake applications. Around this same time, since the HEU was not receiving status responses from these CCDs, the percent operative brakes reduced below the critical threshold of 85 percent. Then, the HEU commanded the CCD at car #1, which was still electrically connected and responding to the HEU, to apply a fault induced full-service brake application. Once all CCDs applied their brakes, the test engineer proceeded to recover the fault by having the wayside test engineer reconnect the ECP trainline, and the operating test engineer acknowledge the fault and recovery on the HEU screen.

This fault detection and recovery behavior is compliant with S-4200. Therefore, the loss of HEU Beacon fault and recovery test was successful.

5.3 Emulation/Pneumatic Test

This section describes the results from testing the device in pneumatic emulation mode.

5.3.1 Minimum Application

Figure 31 shows the brake responses for both emulators and the ABDX valve for an approximate 7 psi brake pipe reduction, i.e., a minimum service application.

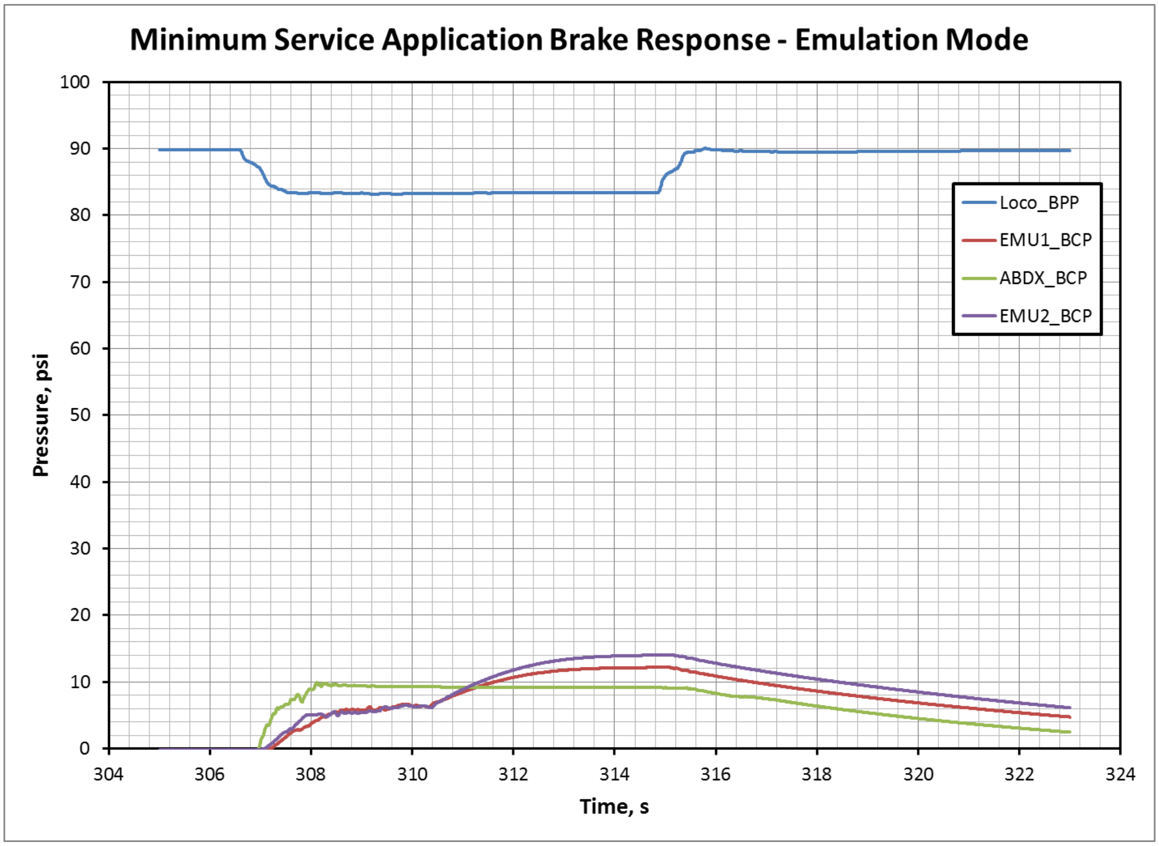

Figure 31 – Minimum Service Application Brake Response in Emulation Mode

While the cylinder pressure build-up response is slightly different between the ABDX valve and the emulators, their behavior is substantially similar. The steady-state cylinder pressures are clustered between 10 and 14 psi, which is consistent with AAR standards for freight brake performance. Thus, the minimum service application test was successful.

5.3.2 Partial Application

Several partial brake applications were performed in pneumatic mode. Figure 32 shows an exemplar time history plot of the BCP responses to a partial application.

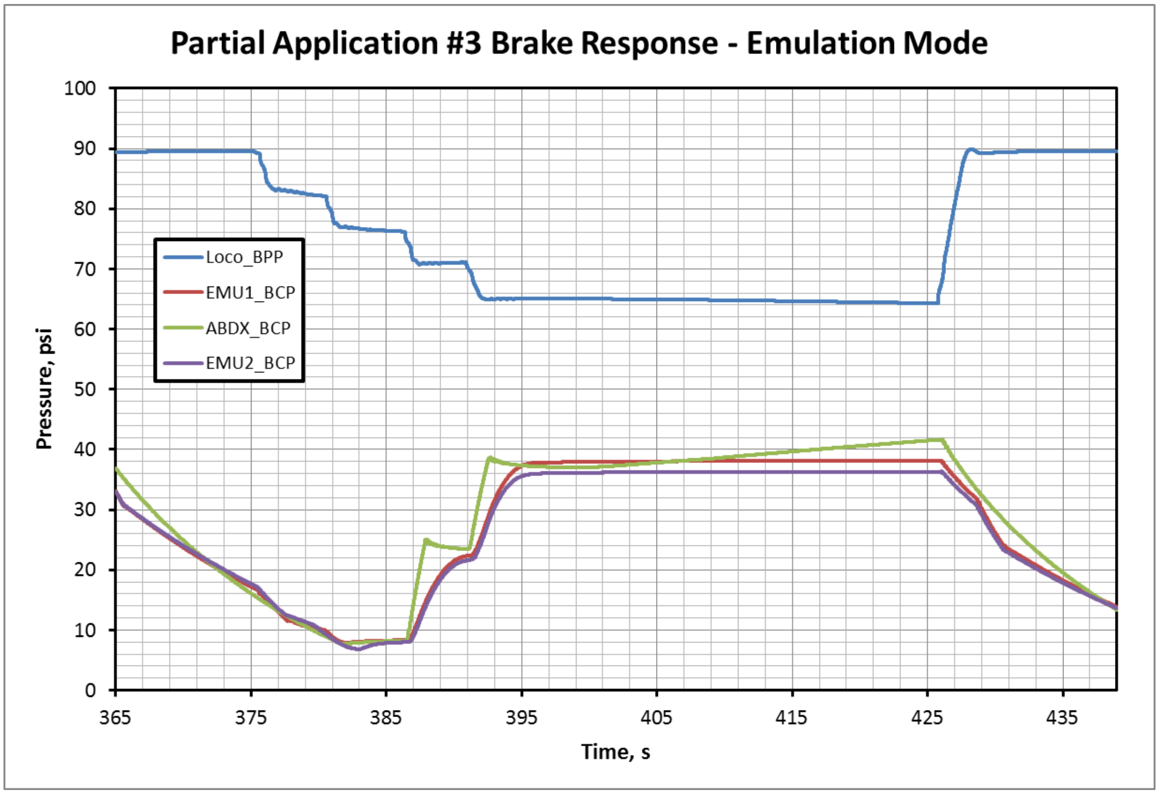

Figure 32 – Partial Application Brake Response in Emulation Mode

As shown in Figure 32, this partial application began soon after the release from a previous brake application. The start of the application occurred while the reservoirs were still charging and the brake cylinders were still venting. When there was sufficient pressure in the reservoirs (i.e., greater than the BPP), the valves ceased venting and held at about 8 psi. Upon the next brake pipe reduction, the valves begin to route pressure to the brake cylinders. The emulators behaved similarly to the ABDX valve during this brake application. All brake cylinder responses are within acceptable tolerances. Thus, the partial brake application test was successful.

5.3.3 Full Service Application

A full-service brake application is shown in Figure 33. The BCP response of the emulators lags behind the ABDX valve at the beginning of the build-up. However, their slightly greater build up rate allows the emulators to reach full service cylinder pressure level at the same time as the ABDX valve. The cylinder values at full service, about 60 psi, are lower than nominal FSP (i.e., about 65 psi) because the reservoirs were not fully charged when the brake pipe reduction was made. As shown in Figure 33, the reservoirs were at about 83 psi when the reduction was initiated, at time = 736 seconds. Nevertheless, the steady state value of the emulators' cylinder pressure matches that of the ABDX valve within the accepted tolerance. Thus, the performance of the emulators functionally matches the ABDX valve; and therefore, the full-service application test was successful.

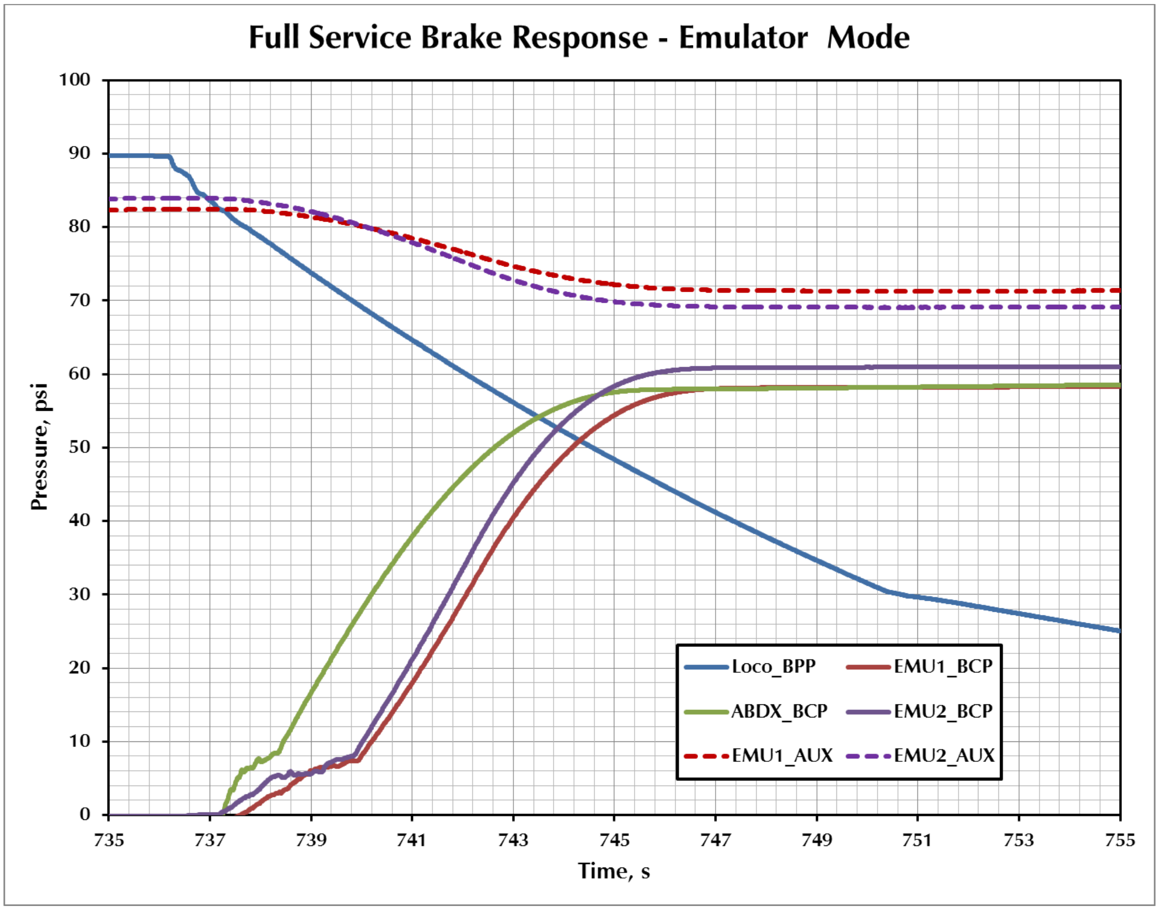

Figure 33 - Full Service Brake Response in Emulation Mode

5.3.4 Graduated Full Service Application and Release

The graduated full-service application and release test was performed by gradually moving the brake handle to the handle-off position. The BCP responses for this test are shown in Figure 34.

The BCP build-up trends for the emulators closely match that of the ABDX valve up to FSP. The cylinder values at full service, about 52 psi, are lower than nominal full-service pressure (i.e., about 65 psi) because the reservoirs were not fully charged when the brake pipe reduction was made; in fact, the cylinders were still releasing when the reduction was initiated, at time = 537 seconds.

At time = 566 seconds, the brake pipe was sufficiently low that the pneumatic backup feature of the emulators activated, raising their cylinder pressures by about 15 percent, in accordance with emergency cylinder pressure level requirements.

The cylinder pressure trends during release are also closely matched. Thus, the graduated service application and release test was successful.

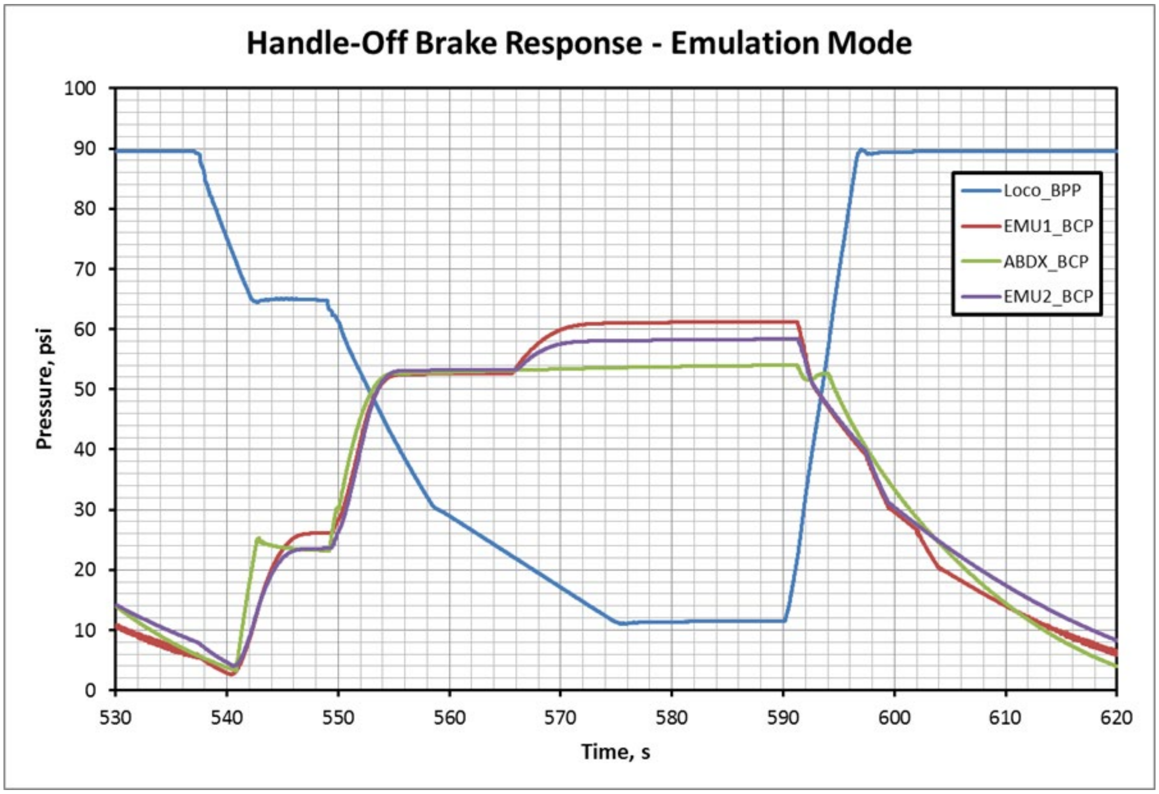

Figure 34 – Graduated Brake Application to Handle-off, then Release, in Emulation Mode

5.3.5 Pneumatic Emergency

A full pneumatic emergency was performed by moving the brake handle to the emergency position, rapidly dumping the BPP. The brake cylinder responses for this test are shown in Figure 35.

As shown in Figure 35, all valves apply pressure to their respective brake cylinders appropriately for a pneumatic emergency application. The trends are all very similar, and all valves attained the same steady-state emergency cylinder pressure within the accepted tolerance. The values of the steady-state cylinder pressures attained in this test are slightly less than the nominal emergency cylinder pressure because the reservoir pressures were not fully charged at the time of emergency brake initiation. Thus, the pneumatic emergency test was successful.

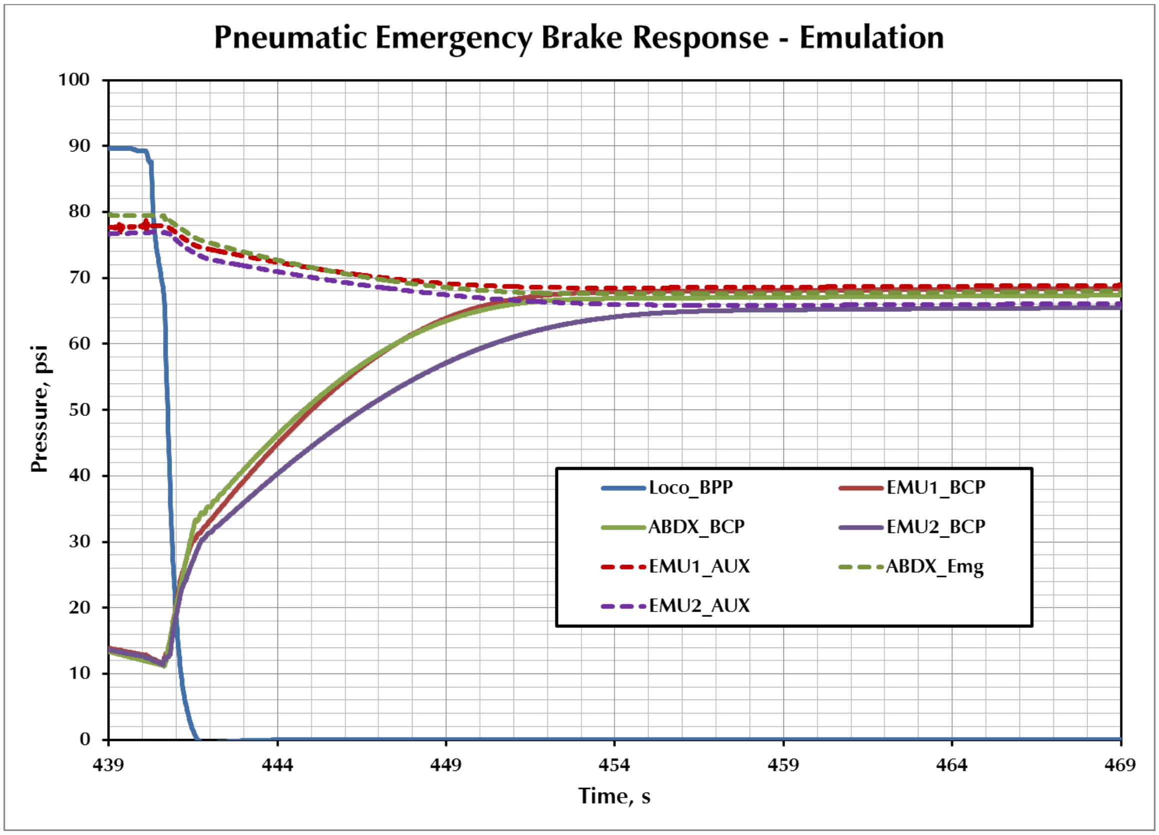

Figure 35 – Pneumatic Emergency Brake Response in Emulation Mode

5.3.6 Pneumatic Backup

The last test conducted in emulation mode was to demonstrate the pneumatic backup feature in an emulator. This is a necessary safety function for every CCD device, including standalone and overlay type ECP devices. When the BPP is low (i.e., less than about 20 psi), the pneumatic backup feature applies an emergency brake application. This is a purely pneumatic/mechanical response, built into the pneumatic portion, and must operate even when there is no electrical power available to the ECP device.

For this test, the power to the emulator on Test Car #1 was removed: ECP trainline power was off and the battery on Test Car #1 was disconnected. The BPP was then reduced at a service rate using the over-reduction and handle-off positions of the engineer's brake valve.

The brake responses for all three valves during this test are shown in Figure 36. At first (i.e., up to about 2,655 seconds) the ABDX valve and emulator on Test Car #3 (EMU2) respond with a full-service brake application. EMU1, on Test Car #1, did not respond because it had been deactivated by loss of power. Hence, its BCP remained at zero. As the BPP continued to decrease into the over-reduction zone, the cylinder pressures of the operating valves did not increase because they were already at equalization pressure.

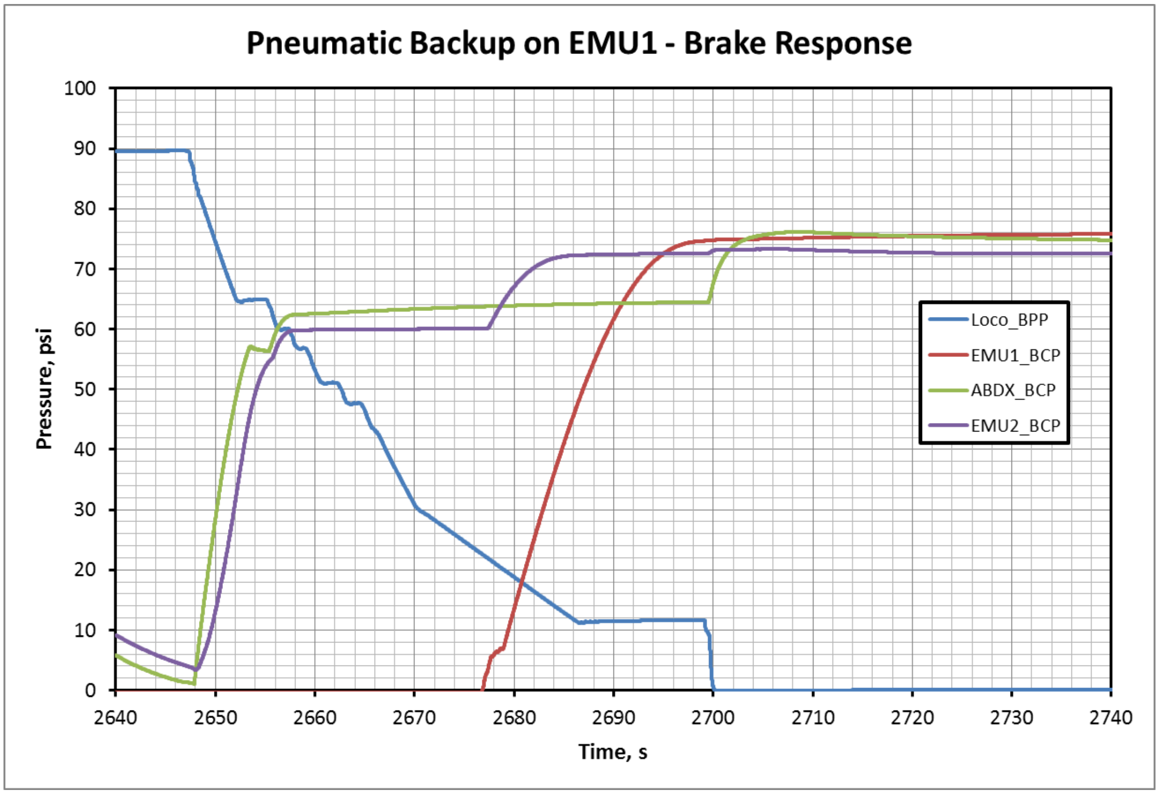

Figure 36 – Pneumatic Backup Brake Response for Emulator on Test Car #1

At each emulator, the pneumatic backup feature took control of the BCP when the BPP dropped below 22 psi. The supply reservoir and brake cylinder equalized, creating an emergency brake application 20 percent higher than full service. This occurred at both emulators, one with electrical power and the other without.

In contrast, the ABDX valve was not affected when the BPP dropped below 20 psi and settled at 10 psi as a result of the handle-off position of the brake valve, because conventional pneumatic control valves do not have the pneumatic backup feature. However, when the brake valve was moved to the emergency position at time = 2,700 seconds, rapidly dropping the BPP, the ABDX valve did respond with an emergency application.

The final emergency BCP values resulting from pneumatic backup in the emulators match the ABDX valve emergency cylinder pressure within the accepted tolerance.

The emulator successfully demonstrated the pneumatic backup feature, therefore, the pneumatic backup test was successful.

6. Post Test Modifications and Testing

As mentioned earlier, certain emulator CCD performance failures arose during testing. Many of these issues were readily identified and resolved by SA in the field. Further testing was then performed to verify the issues were resolved, and demonstrate ECP compliance. Other issues were identified during testing, but their causes were unknown; and there were other issues that were later identified during analysis.

Based on the test results and acceptance analysis, certain software modifications were necessary to ensure complete S-4200 compliance and interoperability. These software modifications were verified only in the lab. The issues that were observed during field testing and subsequently resolved in the SA lab are listed in Table 2.

Table 2 – CCD Performance Failures and Correction Methods

Error Description	Origin	Cause	Solution
CCDs would not respond to device queries	During testing	CCDs (Comm Module) expected only current HEU Beacons, based on message length and contents. **(Backwards compatibility issue)**	Software modification in the field—additional conditions allowed for parsing older messages.
HEU was unable to readdress conflicting CCDs	During testing	Unknown **(Dynamic addressing issue)**	Software modification in the field—implemented static addressing.
Sequencing failed	During testing	CCD (Comm Module) routine to set PSC location occurred during HOLD phase, which never occurred in field demo. CCD state machine expected LEAD SENSE phase, whereas S-4200 allows skipping this when the PSC is on the same locomotive as the HEU.	Software modification in the lab—restructured PSC location sensing subroutine; changed sequencing state machine to allow going from PREPARE phase to either LEAD SENSE or RESET COUNT phase.
Low battery fault not detectable	During testing	CCD (Brake Controller) did not isolate trainline voltage from battery voltage during battery voltage readings.	Modification in the lab—the charger circuit IC has an “enable” pin that isolates the battery voltage from the charging input voltage.

All issues discovered during this project, either during testing or during analysis, were identified and resolved, except dynamic addressing.

6.1 Backwards Compatibility

The backwards compatibility issue occurred early in testing. During normal operation the HEU polls each CCD for its information, one at a time, in a round-robin method. There are data fields in the HEU beacon that specify which CCD is supposed to reply. During the train build process, the CCDs were successfully queried and the HEU's database was successfully populated. However, the emulator CCDs would not respond to HEU beacon queries.

The problem was promptly identified as a backwards compatibility issue. The emulator CCDs were expecting only HEU beacons with message structures complying with the most recent version of the S-4200 standard. Essentially, the emulators would ignore older style HEU beacons. The emulator software was modified to continue testing. Extra conditional statements were introduced in the software to determine how to parse incoming HEU beacons, depending on its message length and version number.

After uploading the new software to the emulators, the CCDs responded appropriately to the HEU beacons and field testing continued.

6.2 Dynamic Addressing

All emulator CCDs are programmed with the same application software, so they all start with a standard ECP-CCD address that is not unique. This improves the emulator's versatility in the field, cuts down on programming time, and is a good general practice when the control network uses dynamic addressing, as is the case in ECP. Initially, CCDs were mounted with unique addresses, previously assigned during lab testing. After resolving the backwards compatibility issue and uploading the new software to the emulators, these address assignments were erased and the emulators were given the standard address. This required the HEU to reassign each CCD with a unique address during train building.

Typically, if all CCDs have unique addresses, it is unnecessary for the HEU to assign new ones. If there is more than one CCD with the same address, this causes communication issues on the ECP network, and can manifest itself in operational issues, as seen during testing.

When rebuilding the train, the HEU did not resolve the conflict when presented with two CCDs with the same address. Both CCDs would respond to the same address when polled, thus the HEU display was unable to parse the data appropriately. SA introduced a temporary fix in the software to statically assign unique addresses to these emulators, to be implemented only for the field demonstration. This allowed SA to continue testing. Train building proceeded successfully, and there were no longer any communication conflicts.

It is still unknown why the vendor HEU was unable to assign new addresses to the CCDs. However, the CCD's response to dynamic addressing was successfully demonstrated in the lab with the HEU simulator running software compliant with the train building process specified in S-4200.

6.3 Sequencing

Throughout field demonstration testing, all sequencing results were displayed as "Partial" on the HEU display. After analyzing the network logs, it was determined that none of the sequencing procedures were successful. The reason that sequencing failed during the field demonstration was also determined. The main cause of sequencing failure involved the sequence state machine in the emulator software; specifically, its inability to recognize when the lead locomotive sense phase was being skipped by the HEU.

For CCDs to determine their position in the train, they must know the location of the PSC relative to the lead HEU. The location of the PSC affects how many current pulses each CCD will count during the Pulse Count phase. The PSC's relative location is found during the Lead Sense phase. If it is known that the PSC is on the same locomotive as the lead HEU, then, according to S-4200, the Lead Sense phase can be skipped during sequencing. If the Lead Sense phase is skipped, then ECP devices should recognize that the lead HEU and PSC are at the same end of the ECP train. This distinction is important: whether the PSC is on the same locomotive as the lead HEU does not affect CCD, it is important whether the PSC is at the same end of the train as the lead HEU. The emulator software did not adequately realize this logic, and thus the emulators never successfully performed sequencing. SA updated the emulator sequencing state machine software to resolve this issue.

S-4200 does not explicitly specify when a CCD is supposed to determine relative orientation, so the emulator's were programmed to determine it during the sequence phase called Hold Count phase. During testing, the HEU never entered the sequencing Hold Count phase, thus the emulators never determined their orientations or positions. After software restructuring, orientation was determined once all information outlined in item 6 of Section 4.2.3.1.5 in S-4200 was known.

After software modifications, sequencing tests in the lab were conducted for various scenarios, including a mockup of the field demonstration case. In lab testing, an additional regulated DC power supply was attached to the last CCD's junction box rack to mimic a PSC at the end of the train. Only one power supply at a time was active: supplying the 24 VDC low-voltage sequencing power to the ECP trainline test rack. Typical electrical isolation precautions were taken to ensure safe operation. The HEU simulator shunted the ECP trainline in compliance with the sequencing switchable load requirements. The tested scenarios included:

- No Lead-Sense phase (like the field demo case—CCDs lead-sense flag is initialized to false and remains false)
- Lead-Sense phase with lab power supply (e.g., PSC) and HEU simulator at same end (i.e., CCDs see no pulse and lead-sense flag is set to false)
- Lead Sense phase with lab power supply (e.g., PSC) and HEU simulator at different ends (i.e., CCDs see a pulse and lead-sense flag is set to true)

Each scenario was tested multiple times. For each scenario, the emulator CCDs were able to successfully determine lead sense status and calculate orientation and position. Thus, the emulators successfully performed sequencing for all scenarios.

6.4 Low Battery Fault-Detection

The inability to detect a low battery in the emulator originated in the battery charging circuit. The battery is charged through the trainline and PPG output. The battery voltage measurement is electrically parallel to the charging circuit's input power. When measuring the battery voltage, it is essential to isolate the battery from input power. There is a dedicated integrated circuit chip on the Brake Controller responsible for regulating input charge to the battery. SA updated the software to momentarily turn off the charging circuit, effectively isolating the battery, when measuring the battery voltage. This software fix was tested and successfully demonstrated in the lab.

7. Conclusion and Recommendations

SA tested the upgraded Zeftron emulators in a field service environment, using AAR compliant ECP equipment and AAR compliant pneumatic equipment. Since emulators were designed to operate in both an ECP train and conventionally braked train, testing was divided into two distinct test modes: ECP mode and pneumatic mode. A test plan was developed to effectively validate the emulators for S-4200 compliance, and compliance to the standards for conventionally braked equipment.

The field demonstration was performed at INRR using a single locomotive, with an integrated ECP HEU and approved ECP functionality, and three gravel cars. Two cars were equipped with the emulator CCDs in place of the service portions on the control valves. The other gravel car was equipped with either the vendor CCD or an ABDX valve, for the ECP and emulation tests respectively. An ECP EOT was mounted on the last car.

The locomotive and gravel cars were instrumented to record various pressures, including: BPPs at all vehicles, BCPs and reservoir pressures on the gravel cars, and equalizing reservoir pressure on the locomotive. In addition, voltage and current on the emulator's battery were recorded to indirectly measure the onboard PPG's performance. Since ECP devices communicate on a control network, SA also monitored and captured the network traffic to further verify S-4200 compliance.

The field demonstration was executed according to the developed test plan outlined in Section 4. Several brake application and releases, at various target pressures, were performed in ECP mode. Also, several ECP-specific functions, like train-building and device information querying, were performed. Results from these tests were reported in Section 5.

SA processed some of the data through filters to reduce noise and synchronized the data with the network logs. By synchronizing the data, SA was able to evaluate the emulator's performance with respect to brake response times and its response to specific faults. SA determined that the brake response times (i.e., the time from receiving a brake command to the time that target cylinder pressure is attained) were within the ECP standard tolerances. Thus, normal applications and releases were deemed successful.

In addition to brake control and normal ECP functionality, standard ECP faults were tested. Each fault was induced independently as outlined in the test plan. The fault detection and recovery processes were captured via the recorded data and the network message log; and they were also observed at the HEU display. During the field test, the emulator CCDs successfully performed fault detection and recovery for all fault conditions except for the low battery fault. After the field demonstration, SA identified and resolved the issues with the battery fault logic in the emulator CCDs.

All brake applications and many of the auxiliary function tests were performed successfully during testing. However, there were some tests that required modifying the emulator software to continue testing: notably, a backwards compatibility issue, for which software was updated in the field and testing, continued. Even after updating the software, some tests failed during the field demonstration. After completing the field demonstration, SA analyzed the recorded data and network logs to identify the causes of these failures. Analysis of the network logs also provided further validation of the successful tests.

The failures experienced during field testing were scrutinized to identify the causes and develop solutions. The emulator operations that failed during testing were:

- Responding to HEU beacons appropriately
- Accurately determining car position during sequencing
- Detecting a low battery

The failure to respond to HEU beacons was remedied during testing, by updating the software's backwards compatibility.

Sequencing failed during field testing because the subroutines for determining the location of the train's power supply controller relative to the lead HEU were incorrectly implemented. This issue was not identified in the previous phase because the testing for sequencing, although S-4200 compliant, was not exhaustive. After rearranging conditions in the sequencing state machine (i.e., in the emulator software), successful sequencing was exhaustively demonstrated in the lab.

Lastly, the inability to detect a low battery in the emulator originated in the battery charging circuit. The battery is charged through the trainline and PPG output. The battery voltage measurement is electrically parallel to the charging circuit's input power. So, when measuring the battery voltage, it is essential to isolate the battery from input power. There is a dedicated integrated chip on the Brake Controller responsible for regulating input charge to the battery. SA updated the software to momentarily turn off the charging circuit when measuring the battery voltage, effectively isolating the battery for voltage measurement. This software fix was fully tested and compliance was demonstrated in the lab.

Another issue presented itself during testing, for which a solution cannot be identified. Throughout testing, the HEU was unable to assign new ECP addresses during train building. If all CCDs in an ECP train have unique ECP addresses, then this process is skipped. However, if two or more CCDs have the same address, this can cause issues. Dynamic addressing by the HEU is an essential ECP function during train building to prevent operational issues. As a direct result of an addressing conflict, as seen during testing, CCDs with the same ECP address will respond to the same HEU beacon when polled. This compromises the integrity of the ECP train database in the HEU and prevents any single-car monitoring, configuration, or operation.

SA manually assigned unique addresses to the CCDs to appropriately conduct the field demonstration. This fix was only developed for the field demonstration. The cause for this failure is still unknown, and therefore a solution cannot be presented. However, this does not impede the performance of the emulators, since address reassignment according to the standard was successfully demonstrated numerous times in SA's lab using the HEU simulator.

Through testing and after modifying the emulator software accordingly, SA demonstrated the emulator's performance and compliance to the AAR standards in a field environment. The emulator operated essentially the same as a regular service portion valve in a conventionally braked train, and it operated successfully as an ECP compliant CCD in an ECP braked train. More significantly, the emulator operated successfully with other ECP equipment, demonstrating its interoperability.

The effort reported here successfully demonstrated the functionality, interoperability and fault testing of the emulator.

It is recommended that evaluation of the emulator for environmental compliance be conducted for vibration, shock and temperature condition requirements. Such an evaluation will result in the ECP emulator technology which meets all performance requirements.

8. References

1. Electronically Controlled Pneumatic (ECP) Cable-Based Brake System – Performance Requirements, AAR MSRP S-4200, 2014.
2. Sharma & Associates, Accelerating Implementation of ECP Brake Emulator Technology, Technical Report No. DOT/FRA/ORD-19/26, Washington, DC: U.S. Department of Transportation, Federal Railroad Administration, August 2019.
3. Intratrain Communication Specification for Cable-Based Freight Train Control Systems, AAR MSRP S-4230, 2014.

Abbreviations and Acronyms

ACRONYMS	EXPLANATION
AAR	Association of American Railroads
BCP	Brake Cylinder Pressure
BPP	Brake Pipe Pressure
CCD	Car Control Device
Comm Module	Communication Module
ECP	Electronically Controlled Pneumatic
EEPROM	Electronically Erasable Programmable Read Only Memory
EOT	End-of-Train
FRA	Federal Railroad Administration
FSP	Full Service Pressure
HEU	Head-End-Unit
INRR	Indiana Northeastern Railroad
MSP	Minimum Service Pressure
NBR	Net Braking Ratio
PCP	Pneumatically Controlled Pneumatic
PPG	Pneumatic Power Generator
PCS	Power Supply Controller
SA	Sharma & Associates
TI	Texas Instruments
TBC	Train Brake Command
USB	Universal Serial Bus