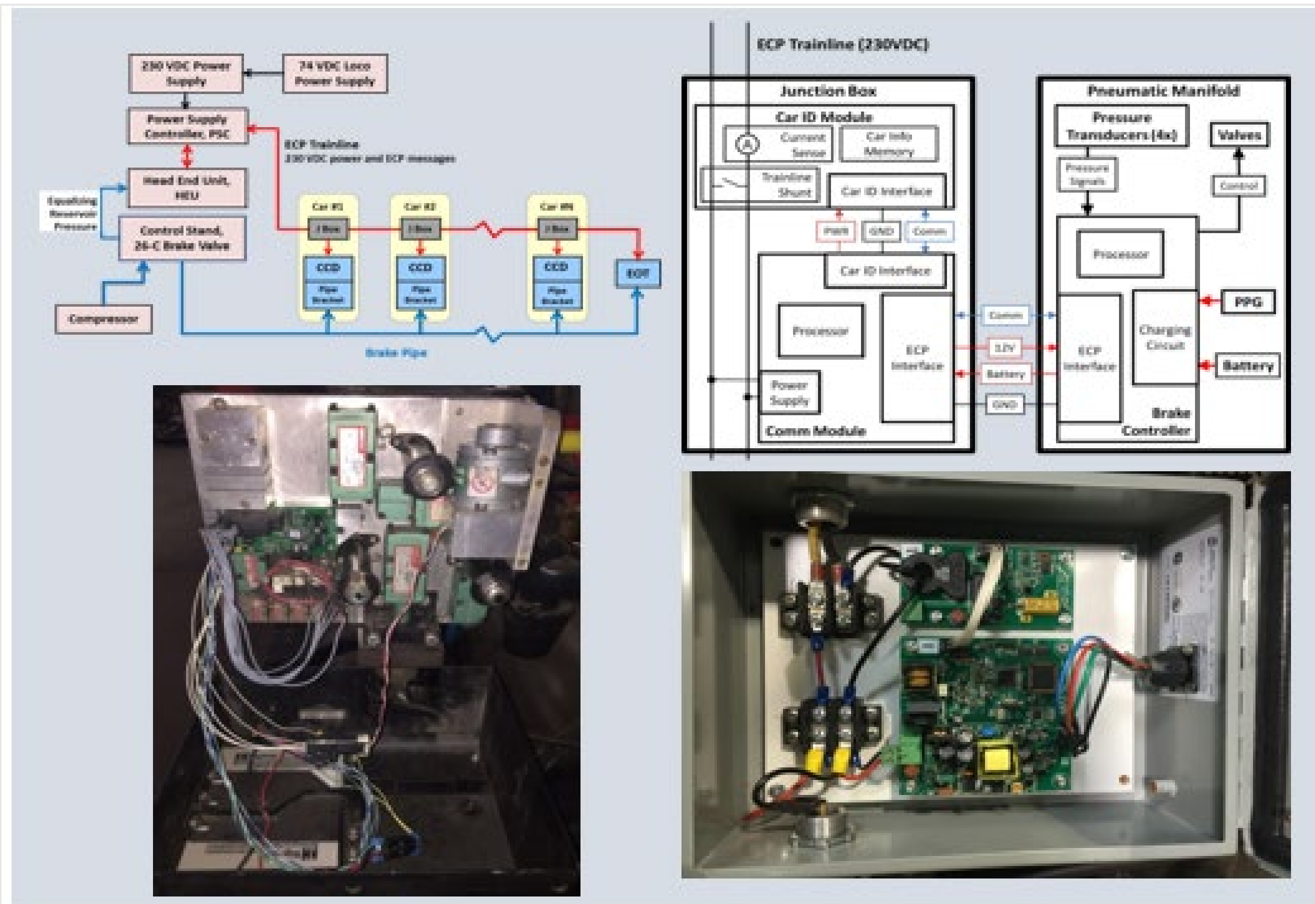
U.S. Department of Transportation

Federal Railroad Administration

Accelerating Implementation of ECP Brake Emulator Technology

Office of Research, Development and Technology
Washington, DC 20590



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13. ABSTRACT (Maximum 200 words)

One of the major barriers to implementation of Electronically Controlled Pneumatic (ECP) brake technology is a freight car's interchange requirement, i.e., it should run in trains made of interchange qualified car. An overlay ECP or an ECP emulator can address this barrier.
This project advanced an ECP emulator developed during the early development phase of ECP technology. The efforts included procuring a representative set of the emulator equipment, identifying and developing necessary upgrades, and conducting testing laboratory testing for compliance with the Association of American Railroads' (AAR) industry standard S-4200.
Sharma & Associates, Inc. (SA) procured three sets of ECP car brake equipment and a locomotive control stand with head-end unit. After initial functional testing, a required hardware and software upgrade for S-4200 compliance were identified, and three modules were developed for communication, brake control, and car sequencing and identification functions. The existing software was split to align with the three module's functions and developed further to meet S-4200 standards. Evaluation of the upgraded emulator in the laboratory was completed, including limited fault testing. Interoperability compliance tests, including a field demonstration with other ECP industry vendor's equipment, are recommended to establish the emulator as S-4200 compliant.

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Air brake, brake controller, car control device, Car ID Module, electronically controlled pneumatic brakes, ECP, End of Train, EOT, device, 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)

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[(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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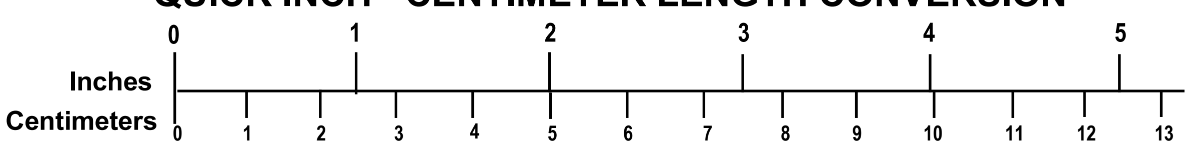

QUICK FAHRENHEIT - CELSIUS TEMPERATURE CONVERSIO

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

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

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Executive Summary

The Federal Railroad Administration (FRA) funded research that investigated emulator technology for accelerating the implementation of Electronically Controlled Pneumatic (ECP) brakes.From August 77, 2013 to October 6, 2016, Sharma & Associates, Inc. (SA) performed ongoing research that involved procuring a representative set of the ECP emulator equipment to investigate the existing technical and functional status of the hardware and software. Modifications/upgrades to the emulator design were made so that it would meet required mechanical, electrical and communication specifications and achieve technological compatibility with existing interchange requirements per the applicable Association of American Railroads' (AAR) standard S-4200.

SA developed new hardware modules for the car identification and sequencing, brake control, and trainline communication modules. This development also required significant software development for individual module functionality and S-4200 compliance.

After module-level testing, SA assembled a three-car test bed with an ECP-compatible End of Train (EOT) device. The head end unit (HEU) function was emulated by a laptop, which performed the train build, car sequencing, and brake application and release functions by issuing S-4200 compatible commands and processing communications from the emulators.

Laboratory tests were conducted to verify functionality according to the S-4200 requirements. The laboratory functional testing proved that the modified/upgraded emulator system meets the basic S-4200 requirements and is a potential solution to one of the major barriers to ECP implementation.

To complete the interoperability tests for the emulator, a field demonstration with other vendors' equipment in the "test train" should be conducted. This would require an ECP-equipped locomotive, cars with ECP Car Control Devices (CCD), and an ECP-compatible EOT device.

ECP brake technology has improved the safety and braking performance of trains. However, implementation has slowed due to a variety of technical and non-technical factors. Incompatibility of ECP with pneumatically controlled conventional brake systems is the primary technical challenge. 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., conventional pneumatic or ECP. Emulator technology can accelerate the realization of the safety benefits of ECP brake in a more cost-effective way.

Prior work conducted by SA, for FRA investigated technical and economic barriers to ECP implementation and identified incompatibility between ECP and conventional brake systems as a key impediment to ECP implementation. This work led to the rediscovery of an emulator product that was developed by ZefTron. This emulator technology was in a reasonably advanced state of development, and it was prototyped and successfully field tested, albeit in limited settings, prior to the finalization and approval of the industry standard S-4200 by the AAR.

The emulator consists of 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. If no voltage is present, it emulates a pneumatic control

valve by interpreting changes in brake pipe pressure as command signals and controlling brake cylinder pressure accordingly. The tested emulator has a pneumatic power generator (PPG)—an integrated air turbine/generator device—that uses air exhausted from the brake cylinder during a brake release to develop three-phase alternating current power. This power is rectified and used to charge up the battery. This feature is used when ECP trainline power is not available, such as when the emulator-equipped car is in a train with cars equipped with pneumatically controlled brakes and the train is operating in the conventional (pneumatically-controlled) brake mode.

1. Introduction

Since their inception nearly 150 years ago, the conventional pneumatically controlled brakes used on freight trains have continually evolved. In this system, the signals for controlling the brakes on each car are also transmitted through the brake pipe in the form of pressure fluctuations in the pipe. Valves incorporating complex pneumatic logic control the application and release of the brakes at each car by sensing the brake pipe pressure (BPP) signals and directing air to or from the brake actuation cylinder as appropriate.

While the propagation rate of an emergency brake application approaches the speed of sound (theoretical maximum for signal propagation in air), a service application signal is still significantly slower. For a typical modern train, service brake initiation at the rear may be 10–15 seconds later than at the front of the train. This delay can lead to high buff forces as lightly braked cars toward the rear run in to more heavily braked cars in front.

Electronically Controlled Pneumatic (ECP) brakes also use compressed air, delivered via the brake pipe and stored locally, to provide the brake actuation force. The essential difference, however, is that electronic, rather than pneumatic, logic is used to control ECP brakes. The signal propagation with ECP brakes is essentially instantaneous; a braking command issued from the lead locomotive is received at each vehicle in the train simultaneously (within a few tenths of a second). In addition, since the Car Control Devices (CCD) at each car used closed-loop feedback to control its brake cylinder pressure (BCP), the braking force build-up at each car is quite uniform, thereby minimizing inter-car coupler forces due to disparate braking rates between cars.

1.1 Background

ECP brake technology can improve the safety and performance of trains. However, implementation has been slowed by 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. The primary technical challenge is the inability of ECP and conventional brake systems to operate together on 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. Thus, the entire train must be equipped with ECP brakes to accrue the benefits of implementation. The Federal Railroad Administration (FRA) seeks to identify and evaluate viable approaches that accelerate the industry's implementation of ECP brakes.

Prior work conducted by Sharma & Associates, Inc. (SA), which occurred under an FRA-funded effort investigating technical and economic barriers to ECP implementation, identified incompatibility between ECP and conventional brake systems as a key impediment to ECP implementation. FRA recognizes this and supported efforts to identify the functional and hardware requirements for an "ECP Emulator" that would address this issue.

The previous work resulted in the rediscovery of a product that currently exists and was in a reasonably advanced state of development. Since the product, protected by US patents, is in this advanced state of development, a "from scratch" development of an emulator system is unnecessary. Herein, this product is referred to as the ECP Emulator, and was developed by ZefTron, Inc. It was previously prototyped and successfully field tested, albeit in limited settings. Further, development was shelved and abandoned before the approval of the

Association of American Railroads' (AAR) industry standard S-4200. Therefore, the product could provide basic ECP functionality but was not in compliance with the S-4200 requirements.

The ECP Emulator is essentially an ECP system with a local on-board power supply and it includes software capable of emulating the behavior of a conventional pneumatic control valve. The emulator automatically operates in the ECP mode when it detects voltage on the ECP electric trainline. If no voltage is present, it emulates a pneumatic control valve by interpreting changes in the BPP as command signals, and controlling BCP accordingly. The emulator has a pneumatic power generator (PPG), an integrated air turbine/generator device that uses air exhausted from the brake cylinder during a brake release to develop three-phase alternating current (AC) power, which is rectified to charge up the battery. This feature is used when ECP trainline power is not available, such as when the emulator-equipped car is operating in a conventional train.

For this effort, SA teamed with ZefTron to obtain abandoned emulator equipment from their warehouse and advance the concept/prototype emulator design to meet current industry standards for interoperability. Further testing and development would make the product available to apply for AAR approval and certification. Such a device would significantly enhance the speed of ECP brake system adoption because it would be an alternative to overlay ECP systems.

To successfully complete the project's objectives, SA identified the major activities that defined the overall work scope covered here. The following are the activities and their results described in detail in this report:

- To conduct an ECP Emulator technology review.
- To conduct a cost-benefit analysis of current emulator technology.
- To investigate the emulator's compatibility with existing equipment, the technical requirements, and the AAR Section E-II standards and specifications regarding the proposed emulator.
- To make needed design changes to the emulator to meet required mechanical, electrical and communication specifications for technology compatibility with existing interchange requirements.
- To conduct functional and fault testing under laboratory conditions to confirm as much S-4200 compliance as possible.

1.2 Objectives

The objective of this project was to investigate, evaluate, and develop a technology to help overcome the biggest barrier—interchange requirements for compatibility with the conventional air brake equipped car fleet—to ECP implementation.

1.3 Overall Approach

The overall approach used in this effort was to conduct a technology review, cost-benefit analysis, implementation of industry design and compliance requirements, emulator technology improvements, and prototyping procurement and pilot testing to demonstrate the functionality of the selected emulator for the advancement of ECP implementation.

1.4 Scope

The work scope included an assessment of the candidate emulator from the view of functionality and AAR S-4200 compliance. Further, any hardware and software development were to be thoroughly tested under a laboratory environment to evaluate if the updated configuration met the functional and compatibility requirements.

1.5 Organization of the Report

This work was conducted as follows:

Section 2 provides a review of the ECP emulation technologies including the motivation and development efforts.

Section 3 comprises the description of a cost-benefit model for the emulator technology including the assumption and discussion of analysis.

Section 4 reports on the ZefTron's ECP Emulator, the procured equipment from the, initial testing of the system and identification of components availability for further development.

Section 5 describes the requirements of an emulator function, compliance with industry standards such as interoperability and source of power for emulation mode application.

Section 6 covers preliminary testing to determine if the obsolete hardware chip replacement is appropriate to be compatible with software.

Section 7 describes the approach to re-design of the CCD board in view of lower power consumption goals.

Section 8 is mainly concerned with the re-architecting of the communication and brake control software and compatibility with the message structure in S-4200.

Section 9 covers testing of the re-designed system including the hardware, software and fault conditions.

Sections 10 and 11 concludes the future work scope and the recommendations.

2. ECP Emulator Technology Review

As the ECP technology evolved, there has been need to address the path to implementation impeded by the AAR interchange rules. The ECP as designed required an ECP equipped car to run only in an ECP train reducing the unfettered usage of the car. Although the over lay ECP has been available, it requires the car to be equipped with two systems; the ECP and the conventional pneumatic brakes, further adding to the cost of car. This issue has led to exploring the ECP emulation, i.e., an ECP technology which could default to the conventional pneumatic brake functionality under non-ECP mode.

2.1 Description of Technology

Freight car braking systems store compressed air in a local reservoir on each car and use it to provide the necessary application force between the brake shoe and wheel that slows a train. The compressed air is generated by a locomotive compressor then conveyed to each car's reservoir via the brake pipe, which is a continuous conduit running the length of the train. Conventional pneumatic brake systems transmit the signals for controlling the brakes on each car through the brake pipe in the form of pressure fluctuations inside the pipe.

Since pneumatic freight brakes were invented nearly 150 years ago, they have evolved, and there have been incremental improvements to increase the speed of the brake signals' propagation. Features such as accelerated service release (introduced in the ABD valve) and accelerated application (ABDW valve) have provided steady improvements in the response of the air brake system. While the propagation rate of an emergency brake application currently approaches the speed of sound (which is the theoretical maximum for signal propagation in air), a service application signal is still significantly slower. For a typical modern train, service brake initiation at the rear may occur over 10 seconds later than at the front of the train. This delay can lead to high buff forces as lightly braked cars toward the rear run into more heavily braked cars in front.

ECP brakes, which are relatively new, also use compressed air delivered via the brake pipe and stored locally, to provide the brake actuation force. However, ECP breaks are controlled by electronic, rather than pneumatic, logic. In place of the pneumatic control valve, the CCD, which is an electronic processor that responds to digital commands, directly controls the BPC at each car. Digital brake command signals originate at the head end unit (HEU) on the lead locomotive and are conveyed to each car via an electric cable running the length of the train (ECP trainline). Locomotive-mounted power supply equipment provides the power, which is transmitted via the ECP trainline, to charge the CCD batteries. Figure 2-1 shows a system diagram of an N-car ECP train.

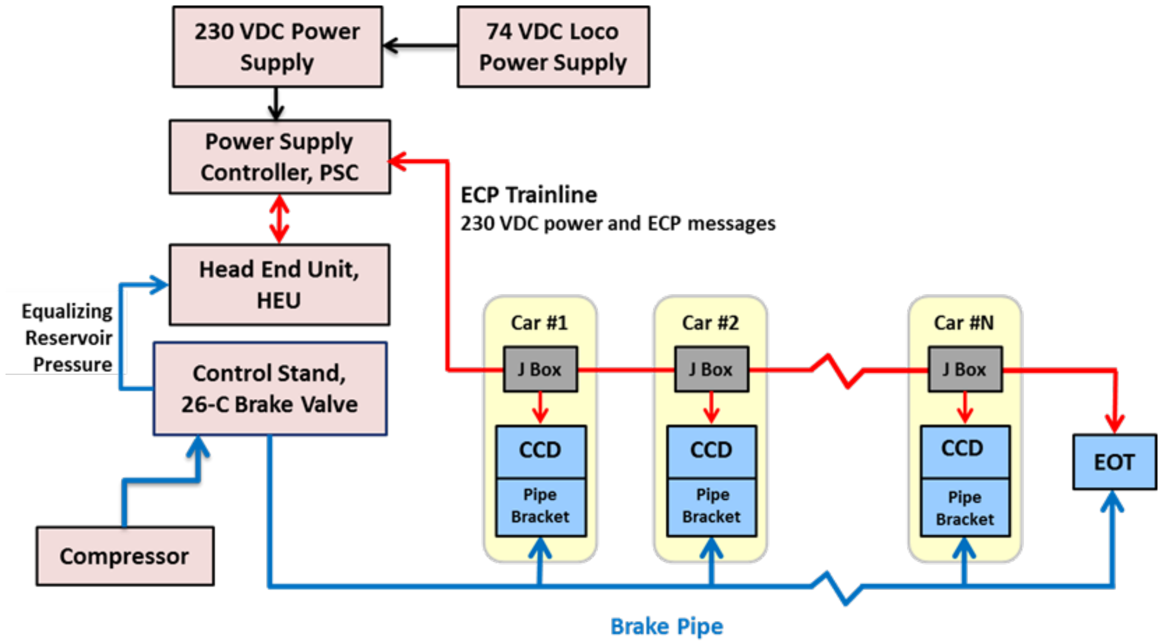


Figure 2-1 – Generic ECP Train System Layout

Signal propagation with ECP brakes is essentially instantaneous; a braking command issued from the lead locomotive is received at each vehicle in the train simultaneously (within a few tenths of a second). Since the CCD at each car uses closed-loop feedback to control its BCP, the braking force build-up at each car is quite uniform, which minimizes inter-car coupler forces due to disparate braking rates between cars. Unlike conventional pneumatic brakes, ECP brakes can be released in gradual steps. Since the brake pipe is not used to convey braking signals, the supply reservoirs on each car are continuously charged (whether the brakes are applied or not). These characteristics make the ECP brake system much more controllable than the conventional pneumatic system and it also yields the following benefits:

- Permits shorter stops and quicker returns to operating speed after stopping for meeting a lower speed limit.
- Reduces or eliminates the need for cycle braking and power braking practices, which increases fuel efficiency.
- Reduces wheel and brake shoe wear, and provides fatigue life extension of structural components.
- Enhances safety against derailments due to lower intercar forces during braking and reduced pile-up damage resulting from derailment with train separation caused emergency application.
- Provides a more intuitive approach to operation, which reduces training requirements for new engineers.
- Enhances the application of automated brake operation by allowing tighter feedback control loops.

2.2 Incompatibility of ECP with Existing Pneumatic Brake System

One reason why ECP brakes have not been widely adopted is that they are incompatible with conventional pneumatically controlled pneumatic (PCP) brakes. Since ECP brakes rely on electronic control signals, they cannot be controlled by BPP like PCP brakes. A car with standalone ECP brakes cannot be used with PCP equipped cars. Cars equipped with ECP brakes can only be used in ECP-braked trains with ECP-equipped locomotives, which would require a bimodal set of railroad operations during the fleet conversion period. Such trains would be operationally inefficient and costly for the railroads.

One of the simplest solutions for preventing incompatibility is to install both ECP and conventional pneumatic brake systems on a car. When the proper voltage is detected on the electric trainline, the ECP system is active and the pneumatic system is isolated. Conversely, when the voltage is not present, the conventional pneumatic system is operative and the ECP system is in sleep mode. The switch from one mode to the other occurs automatically, without any manual action required at the car. This configuration, normally referred to as an "overlay," can be applied to new cars or retrofitted to existing cars. Unfortunately, the additional costs of purchasing and maintaining a redundant braking system on an ECP equipped car that may see very little service during the life of the car.

Another way to integrate ECP and PCP cars is with an "emulator" device. This configuration is essentially an ECP system with a local, on-board power supply and some additional software that emulates the behavior of a conventional pneumatic control valve. As with the overlay configuration, the emulator will automatically operate in the ECP mode when it detects voltage on the ECP trainline. If no voltage is present, it will emulate a pneumatic control valve by interpreting the BPP fluctuations as command signals and control BCP accordingly.

2.3 History of Development

Recognizing the value of operating trains that are composed of cars with different brake systems was a critical factor that led to the widespread integration of ECP braking into the general interchange fleet. Several ECP brake system configurations, which offer compatibility with conventional brakes, have been proposed, developed, and deployed to various degrees. The two major brake manufacturers in the U.S. market offer both standalone and overlay ECP systems.

An overlay ECP system (the OzECP brake) was a retrofit application designed for the Australian market [5]. In the U.S., manufacturers GE Transportation Systems (GETS) and ZefTron pursued emulator ECP development.

After various trials with different embodiments, the basic ECP ideas were finalized during the 1990's, and by the year 2000 the AAR developed the Manual of Standards and Recommended Practices (MSRP)-E-II (including performance requirements, S-4200), a set of industry standards for electronically controlled brake systems. This standard was meant to assure the industry that ECP equipment from different manufacturers would operate together satisfactorily in the same train. Although the AAR initially supported development of both wireless and wired ECP systems, the 42xx family of standards (MSRP, E-II) addresses only cable-based ECP technology.

2.3.1 GE Transportation Systems Emulator ECP

GE Harris Railway Electronics, a subsidiary of GETS, developed a radio-based emulator ECP system, designated EPX®. The individual components, HEU and CCDs, establish a wireless communication network to transmit braking signals through the train. The system can operate in either ECP mode (CCDs respond to ECP commands from the HEU) or in the pneumatic emulation mode, in which the CCDs emulate a conventional control valve and respond to BPP reduction signals. The EPX emulator system was installed on the BHP Iron Ore trains in Australia and it operated effectively for several years. In this deployment, the on-board power system (combination of axle generator and battery) proved inadequate, so alternate power sources were investigated. As a result, a pneumatically-powered generator arrangement, in which electrical energy was stored in a bank of ultra-capacitors instead of a battery, was pursued. This unit was designed to draw air from the auxiliary reservoir in relatively short, controlled bursts to ensure that the pneumatic brake system performance was not diminished [4]. After these activities, GE Harris has apparently ceased development of this system.

2.3.2 ZefTron

ZefTron, an entity created by the railcar equipment supplier ZefTek, developed and marketed their Chameleon™ ECP brake system, featuring a pneumatic brake emulator, from the mid-1990's to the early 2000's. While ZefTek is now owned by Wabtec, the ZefTron Chameleon™ technology and patents were retained by the original owner.

The Chameleon™ ECP system was tested from 1999 to 2001 on a Western Fuels Association (WFA) 55-car unit coal train running on a private line in New Mexico [7]. The system was operated in both the ECP and emulation modes (separate runs). Maintenance issues were considered to be minor, although flat spots occasionally developed on wheels during these trials. It was suspected that a stuck brake condition was occurring when a CCD would temporarily revert to emulation mode while the train was operating in ECP mode. This condition is now recognized and addressed by the current AAR standard (i.e., S-4200) for ECP interoperability.

ZefTron also developed and patented an integrated air turbine/generator device, called a PPG, which uses air exhausted from the brake cylinder during a brake release to develop three-phase AC (which is rectified to direct current [DC]). This feature is used to supplement battery charging when ECP trainline power is not available, for example, when the emulator-equipped car is operating in a conventional PCP train. The PPG system was field-tested (in about year 2001) on the Duluth, Missabe and Iron Range Railway, where the ZefTron CCD with PPG was installed on two cars and run in emulation mode.

Although full AAR approval (including a full 150-car test rack complement of CCDs) was not sought, some testing of the Chameleon™ system was performed on Transportation Technology Center, Inc.'s (TTCI) test rack. The testing demonstrated that the emulator system was compatible with conventional pneumatic equipment, and some interoperability with ECP equipment from other manufacturers (New York Air Brake [NYAB] and Wabtec) was also demonstrated.

ZefTron stopped their service trials and discontinued the development of Chameleon™ ECP by 2004. At that time, work was progressing on the train sequencing feature and a prototype version of the electronics that used much less power was being developed. Also at this time, the AAR standard for ECP braking (i.e., S-4200) was in the early stages of being adopted and revised by the industry. So, the ZefTron system, while it provided basic ECP functionality, was not in substantial compliance with the S-4200 requirements.

3. Cost-Benefit Analysis of ECP Emulator Technology

The economic viability of emulator ECP technology was evaluated by conducting a cost-benefit analysis. This analysis compared emulator ECP to the existing ECP technologies: overlay and standalone. As expected, the results of such an analysis are sensitive to the costs of the various types of ECP equipment. To explore this sensitivity, the economic analysis model was used to investigate how the costs of various ECP options affect the strategy of accelerated ECP implementation.

3.1 Description of Economic Model

A detailed cost-benefit analysis model, developed by SA for FRA, was used to evaluate the economics of converting the United States railcar fleet to ECP braking technology [8]. This model was based on previous cost-benefit analyses, including the 2006 FRA report by BAH and the 2007 FRA Notice of Proposed Rulemaking – Regulatory Analysis [1] [3]. Consideration of emerging and established ECP technologies, reports of ECP users' experience around the globe, and analytical simulations also contributed to development of the model. In addition to considering all the cost and benefit elements included in the previous analyses, the SA approach also included elements that were discussed, but not quantified, in the previous studies. Specifically, these were the elements accounted for: benefits due to increased network capacity and the costs attributable to the time that rail cars sit idle.

Cost categories include railcar and locomotive ECP equipment and maintenance, as well as initial and annual training. Benefits are derived from reduced accidents and environmental remediation cost, fuel savings, injury and fatality reduction, decreased in-service failure delay, regulatory relief, terminal dwell time reduction, decreased train delay, and reduced wheelset replacement and brake shoe consumption.

To address a transition to ECP for the entire U.S. fleet, the cost-benefit analysis model was developed to handle the differing economics of applying ECP brakes to railcars intended for unit trains as opposed to applying them to railcars intended for general mixed merchandise trains. Thus, the unit train portion of the fleet was analyzed separately from the general interchange portion of the fleet. This was done to account for the difference in the way the railcars are used in trains from a brake system compatibility perspective. A primary characteristic of unit train operations—trains generally remain intact, using a fleet of identical type cars, without interchanging equipment with the general fleet—enables the use of standalone ECP brakes for cars in this service. In contrast, mixed train operations must accommodate the building of trains with general interchange cars which, during the conversion period, may have either ECP or conventional brakes. The two separate analyses account for this difference by applying standalone ECP brakes to the unit train fleet conversion and emulator (or overlay) ECP brakes to the mixed train fleet conversion. Since these two analyses are independent, their results are valid whether their respective fleet portions are converted simultaneously, sequentially, or with any amount of temporal overlap. This assumption of independence is accurate to the extent that cars and locomotives assigned to each fleet portion are not interchanged with the other fleet portion. This is a reasonable assumption since, once the ECP conversion process begins, there would be an increasing incentive to keep these portions of the fleet segregated.

Many previous analyses have concluded that conversion (especially for new cars, but also for retrofits) should proceed directly to standalone ECP rather than to overlay or emulator ECP. The lower capital cost of standalone ECP brake equipment, combined with the eventual goal of having all cars converted to ECP and hence no further need to maintain the conventional brake equipment, are typical arguments offered for this position. While these arguments are valid, they ignore the lost opportunity costs incurred when a car sits idle. The so-called “idle car cost” represents the lost revenue accrued to the railcar equipped with standalone ECP for the portion of time it sits idle, due to its lack of compatibility with conventionally braked cars, while a car with a compatible brake set is used. In contrast, a railcar with emulator or overlay ECP does not suffer this idle car cost. To assess the impact of the idle car cost, the mixed train fleet conversion was analyzed in two different ways: first with overlay ECP and then with standalone ECP brakes. The disadvantage of applying standalone ECP to the mixed train conversion is accounted for by adding the idle car cost to the cost-benefit model. The idle car cost calculation is based on the annual net revenue associated with an average car and an assumed utilization rate that is dependent on the percentage of the fleet that is equipped with ECP brakes. This utilization rate represents the portion of time that an average car operates in ECP mode. The results of this comparative assessment show that overlay or emulator ECP is preferred to standalone ECP if a railroad chooses to convert the mixed train portion of the fleet.

3.2 Assumptions and Input Data

The conversion of the U.S. railcar fleet to ECP brakes was analyzed independently on two separate portions of the fleet: 1) cars used in unit and unit-like trains (e.g., intermodal), which are assumed to convert to standalone type ECP; and 2) cars used in general interchange service, which are assumed to convert to emulator type ECP brakes. The results of these two analyses were combined to obtain the net present value (NPV) of converting the entire U.S. fleet to ECP brakes.

As in the 2007 FRA Regulatory Analysis, a 10-year conversion period is assumed for migrating the U.S. railcar fleet to ECP, at a constant linear rate of 10 percent per year [3]. The overall size and composition (dedicated unit train vs. general interchange type car) of the total fleet is assumed to remain constant, at 2010 values. Similarly, the rates of new car production and rebuilding of existing cars are also assumed to remain constant, at levels equal to their respective average rates over the past 10 years. The analyses were carried out over a 20-year evaluation period using a discount rate of 7 percent. The NPV criterion was used to evaluate the value of the cash flow stream associated with the conversion to ECP.

The estimated costs to install various types of brake systems on a new car are shown in Table 3-1. These costs, except for the emulator, are based on information from the 2014 FRA report [4]. The cost of installing emulator ECP brakes on a new car is estimated to be less than that of overlay ECP, and will probably be more than that of standalone ECP.

Table 3-1 – Cost to Install Brake System on New Rail Car

Type of Brake System	Cost
Conventional Pneumatic Brake	$4,000
Standalone ECP Brake	$6,000
Emulator ECP Brake	$7,000
Overlay ECP Brake	$8,500

3.3 Discussion of Results

Results of the economic analysis are presented in Figure 3-1. In this figure, the value of converting to emulator ECP brakes is shown for a range of emulator equipment costs, and is compared to a conversion to overlay ECP.

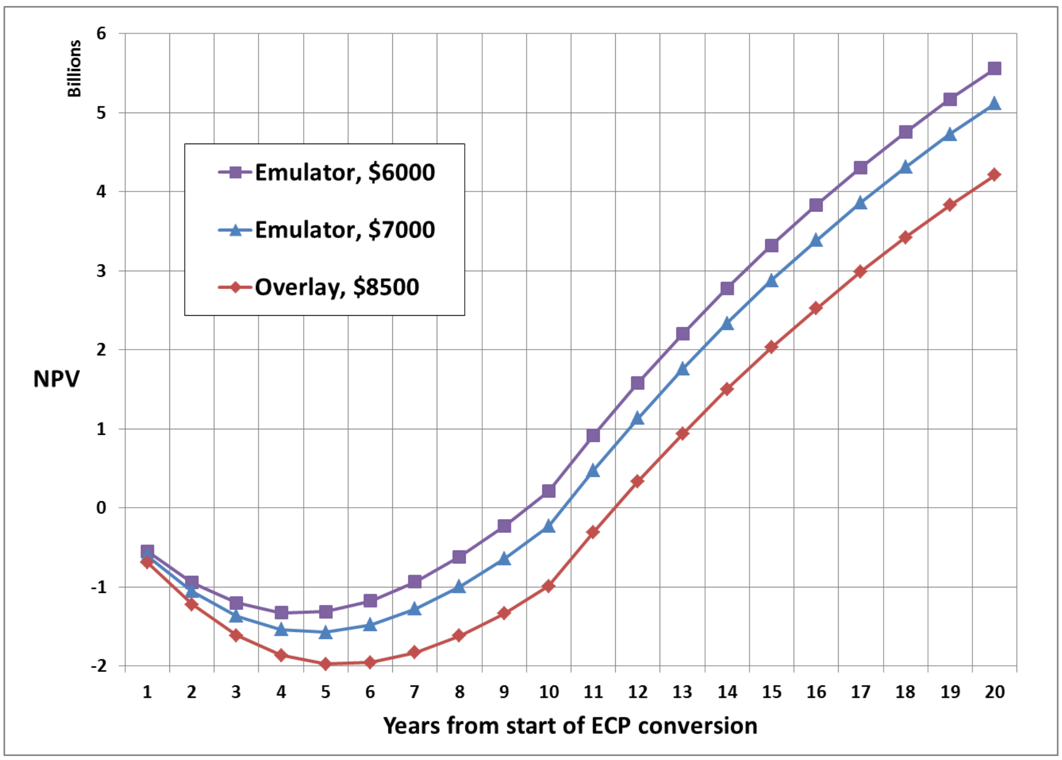


Figure 3-1 – Net Present Value of Converting U.S. Railcar Fleet to ECP

The overall net benefit of converting the U.S. fleet to ECP, using emulator technology for interchange cars, is on the order of $5 billion after 20 years, with a payback period of about 10 years. The ECP Emulator shows a clear advantage when compared to overlay ECP. For mid-range cost assumptions, the emulator has a 20 percent higher NPV after 20 years and a

10 percent quicker payback period. If the cost of emulator ECP approaches that of standalone ECP, then the payback time, compared to overlay ECP, can be reduced by as much as 2 years.

4. Evaluation of the Status of Emulator Technology

To evaluate the emulator, SA approached ZefTron Inc. to determine the status of the equipment salvaged from their prototype set tested on trains in the year 2000. It was agreed that SA should visit their warehouse to discuss the project needs and identify what equipment was essential to pursue the project.

4.1 Procurement and Inventory of Emulator Equipment

In the fall of 2013, several meetings were held with former ZefTron employees to discuss resuming development of the emulator system and bringing the CCD component into compliance with the current AAR standards for ECP performance and interoperability. SA visited their facility to inspect the emulator ECP valves and other components from the earlier trials as well as associated equipment for testing and development of the system, and assessed the extent of the inventory available.

A test bed for evaluating the performance of the emulator CCD was shipped to the SA lab. This test bed included:

1. Three car-sets of air brake equipment, which were mounted on portable racks with emulator and ECP portions in a single housing. The brakes were part of the set that had been tested on the WFA coal train.
2. Three emergency portions
3. One AAR-style locomotive control stand
4. Additional components required for a complete ECP system were also obtained: the HEU control device, a power supply and its controller, trainline cable, junction boxes, and an End of Train (EOT) device.

The completed test facility is shown assembled in the SA lab in Figure 4-1. A representative system diagram for a generic ECP train is shown in Figure 2-1, while the test bed follows this layout for three cars.

Figure 4-1 – Test Bed for Emulator ECP Assembled in the SA Lab

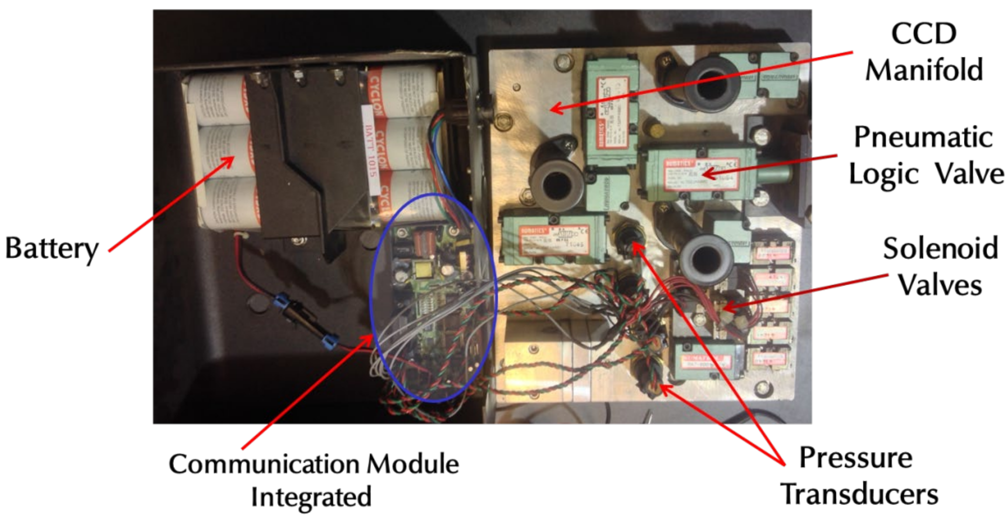


Figure 4-2 – Emulator CCD, as Received

Figure 4-2 shows the interior of a CCD from ZefTron. The black housing (on the left side of the image) has been removed and is sitting next to the pneumatic manifold portion (on the right). The battery and electronics (communication, emulation software and pneumatic control) are mounted in the housing/cover, while the pneumatic valves and pressure transduces are mounted on the manifold. The three black rings on the manifold are mounting posts: stand-off tubes through which bolts are inserted to hold the housing in place and provide securement of the entire CCD assembly to the car's pipe bracket (shown more clearly in Figure 4-3).

In the spring of 2014, ZefTron sold the warehouse property and was no longer able to store the development equipment. SA obtained several additional CCD valves, dozens of ECP trainline cables and connectors, some prototype electronic boards and PPG parts, testing fixtures, pneumatic control valve portions, and numerous spare parts.

Two initiatives that ZefTron was pursuing when the project was suspended were the PPG and a revised arrangement of the electronics that separated ECP communications from the pneumatic brake control functions. This two-printed circuit board (PCB) arrangement included a brake controller board with integrated pressure transducers that draw very low power. The ECP communication functions remained on the board mounted in the housing/cover. Figure 4-3 shows the CCD manifold with the prototype PPG and low power brake controller board in place. Pressure transducers (not visible in Figure 4-3) are mounted on the underside of the brake controller PCB and connect to the CCD manifold through passageways in a smaller, intermediate manifold.

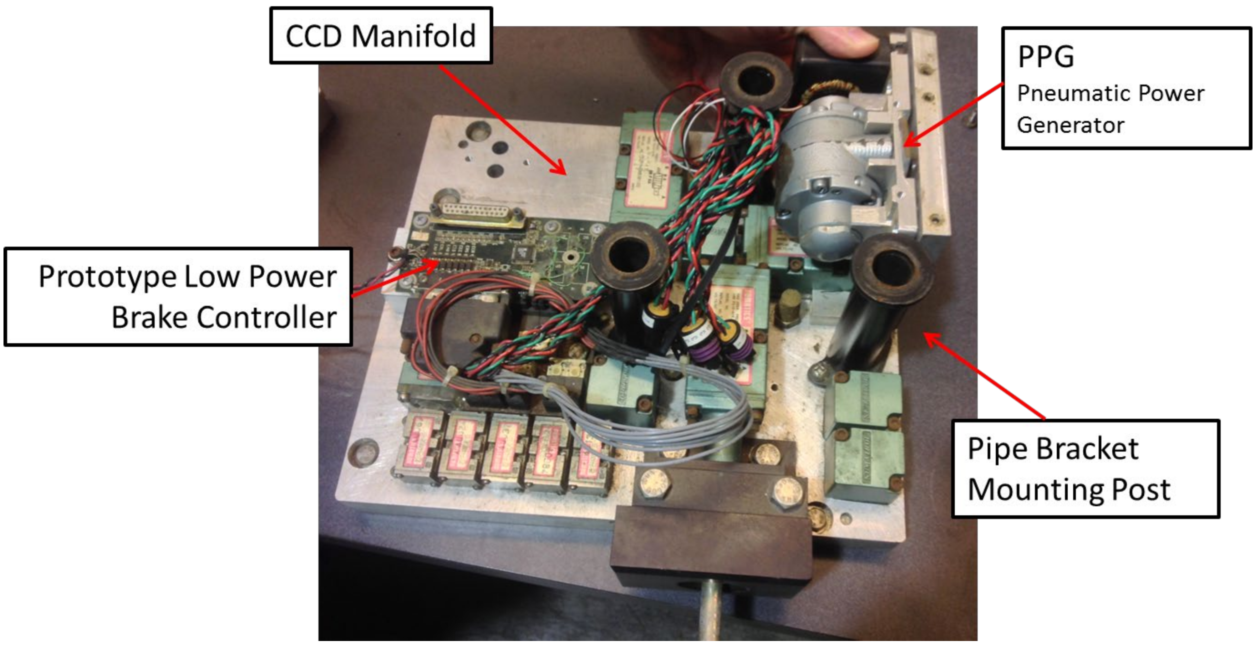


Figure 4-3 – Emulator CCD with Prototype Low Power Board and PPG

4.2 Functional Testing of Emulator Equipment

After more than 10 years of sitting idle, several components in the assembled test bed required maintenance or replacement. The battery packs in the CCDs were replaced. Filters in the pneumatic portion of the CCD, particularly in the supply reservoir charging port, were clogged with a fine dust and needed to be cleaned. The independent brake valve in the control stand was repaired and instrument tubing on the car brake racks was replaced due to excessive leakage. Repairs to the electronics in the HEU were also required.

Once the air brake test bed and ECP control systems were refurbished and restored to working order, the CCDs were tested in both ECP and pneumatic (emulation) modes. The equipment performed as expected in both operational modes.

For the pneumatic tests, the cable from each CCD to trainline junction box was disconnected, thereby isolating the CCD from any external signal or power source. As long as the batteries were sufficiently charged, the CCD responded properly to brake pipe reductions and releases, both service and emergency. The power draw in emulation mode, with the system as received from ZefTron, was not excessive. The CCD still functioned properly after 3 days; by that time, it had fully charged BPP and power on. The system also functioned properly in the ECP mode, including train building, brake application, graduated release, and electronic (no brake pipe reduction) emergency. The ECP-required pneumatic back-up feature, in which emergency BCP develops upon loss of BPP, was also functional.

4.3 Transceiver Obsolescence

ZefTron developed the emulator CCD using Echelon's Power-Line Transceivers (PLT)-10 and the Neuron® 3150 microcontroller (Figure 4-4).

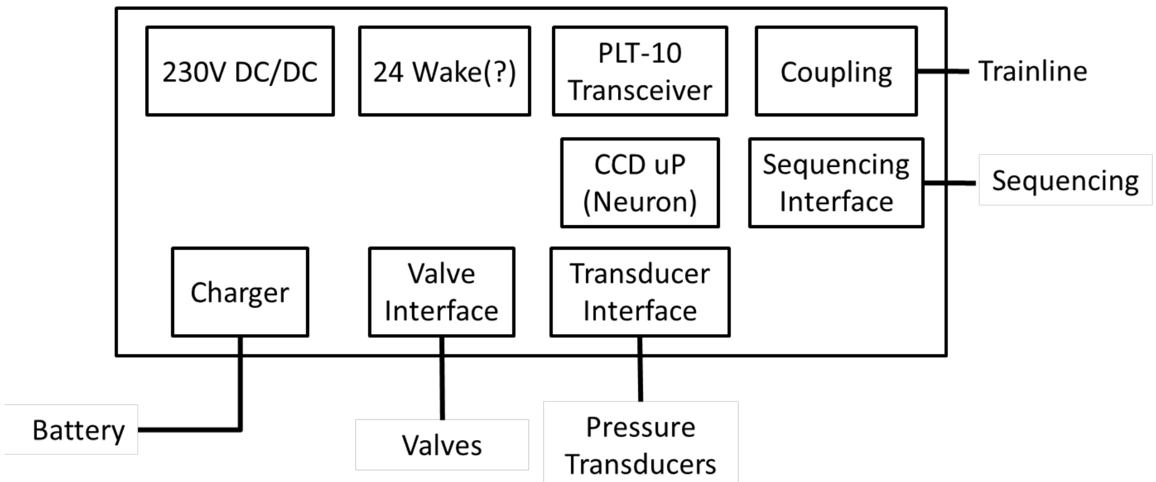


Figure 4-4 – Functional Layout the as Received CCD with PLT-10 Transceiver

When ZefTron was developing their emulator CCD, the industry had settled on the communication technology and protocol used by the Echelon PLT-10, and this protocol was specified in the early AAR standard. However, the PLT-10 chip was discontinued soon thereafter and the recommended replacement was the Echelon PLT-22. In response, the AAR ECP standard changed to accommodate the evolving technology and all ECP manufacturers had to comply with the new transceiver specifications. Though the two technologies rely on the same power-line transmission methods, different bit rates and carrier frequencies make the two transceivers incompatible with one another. The dual-board configuration ZefTron developed incorporated the new PLT-22 transceiver. Figure 4-5 shows a concept of this two-board configuration with the PLT-22 transceiver instead of the PLT-10 transceiver.

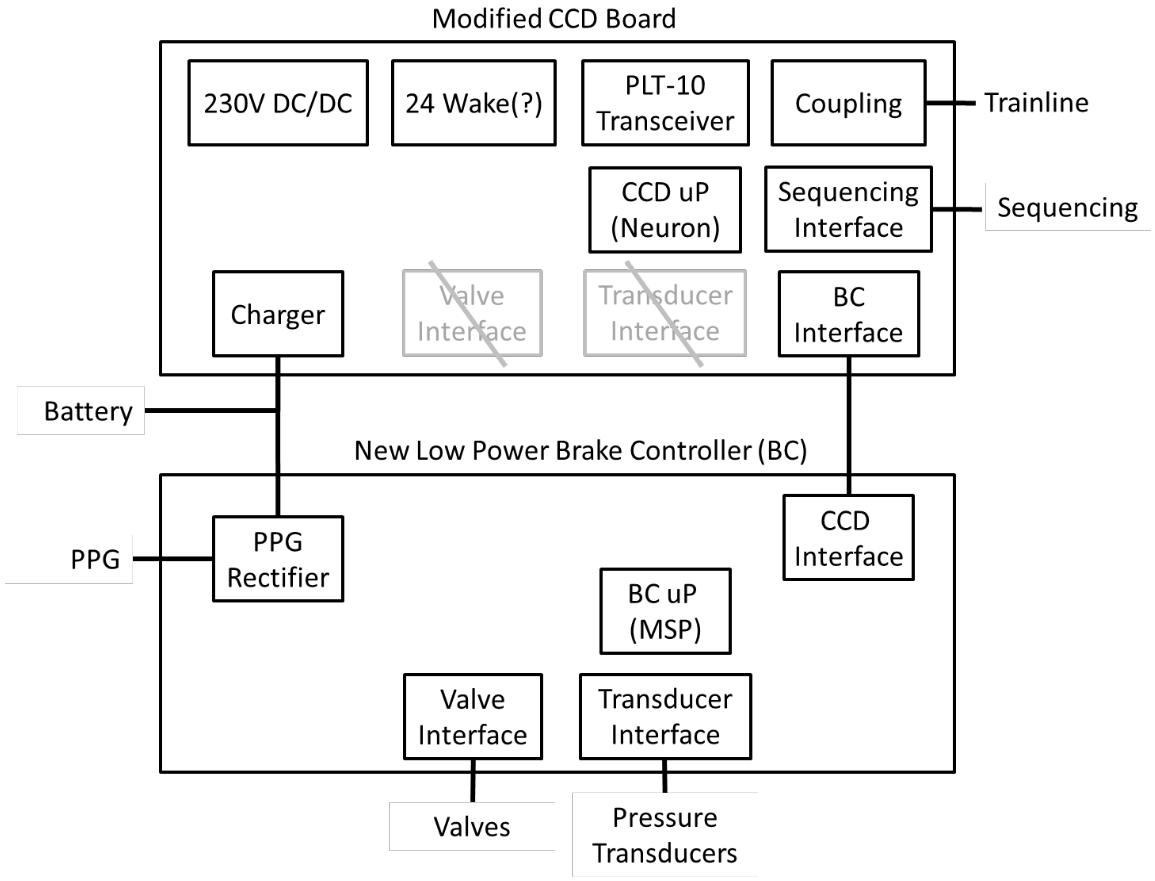


Figure 4-5 – Planned Prototype Dual-Board Configuration with PLT-22 Transceiver

Furthermore, Echelon discontinued the PLT-22 stand-alone transceiver due to technological upgrades. A new device, called a smart transceiver, combined the transceiver (PLT-22) and microcontroller (Neuron® 3150) functionality into one integrated circuit, called the PL3150. Since any further development of the CCD for high volume production would need to use the PL3150, it was decided, for this project, to design new CCD hardware that accommodates the currently available technology (PL3150).

5. CCD Development Plan

The emulator CCD as received had the trainline communication, Car ID and brake controller integrated into one printed circuit board. The S-4200 requires that Car ID hardware and the firmware reside separate from the CCD. Further, emulator software has to function in the absence of ECP train power and thus led to re-evaluation of the hardware and software configurations in the as-received CCD.

5.1 Interoperability with Other ECP Brake Equipment

As part of the AAR MSRP S-4200 standard, any manufacturer's ECP equipment must operate with other ECP manufacturer's equipment on a per vehicle basis. For instance, the Car ID module and CCD on a given car must be from the same ECP manufacturer, but any ECP-equipped freight car must be able to operate with freight cars equipped with any other ECP manufacturer's equipment. The S-4200 and S-4230 were written to ensure interoperability between different manufacturer's ECP equipment.

In this phase, the main objective was to develop an industry compliant CCD with emulator capabilities. By developing the CCD per the S-4200 and S-4230 requirements, the CCD would be interoperable with other manufacturer's ECP equipment.

5.2 Interoperability with Existing (Conventional) Brake Equipment

An emulator CCD must be able to perform in an ECP brake train and in a conventional brake train. In addition to complying with the AAR standards for ECP brakes, an emulator CCD must comply with the AAR standards set out for pneumatic conventional train brake equipment: S-461, S-462, S-464, and S-467 [2]. It is essential to the successful performance of conventional trains that the emulator CCD performs the same as an existing pneumatic service portion.

A majority of the emulation interoperability was tested by ZefTron during the emulator's development. However, this functionality was also retested during this phase to ensure successful operation for the updated emulator.

5.3 Sustainable Manufacturability

Electronic technology advances very quickly compared to train technology. As seen with the obsolete transceiver, advancements in electronics could greatly impact the technology for which they are used. Thus, the design process aims to design the emulator with easily obtainable electronics that should stay relevant in the market for the foreseeable future. There are of course unknowns with certain electronics, however, having a sustainable design was part of the new design criteria.

5.4 Compliance with Industry Standards

ECP equipment in freight trains in North America must comply with the requirements outlined in AAR MSRP Section E-II, "Electronically Controlled Brake Systems." The functional ECP requirements are specified in the S-4200 standard [2]. The communication requirements are specified in the S-4230 standard [6]. As the Section E-II standards were still in development while ZefTron was testing its emulator, the ECP equipment procured from ZefTron was not compliant.

5.4.1 Messaging Updates

The S-4200 standard implicitly uses Echelon's LonWorks® protocol to define the ECP network [2]. There are two distinct methods for communicating between LonWorks® devices, according to message type: network variables and explicit messages. For ECP communication, the message type is explicit messages. Network variables and explicit messages can't transmit information between each other, though any LonWorks® device could use either or both in its application. The ZefTron ECP system almost exclusively used network variables for communication. As part of the overall software development, SA had planned to update the communication software and use explicit type messages only.

5.4.2 Car Sequencing

In the ECP system, a database of the train consist is created in the HEU. The process of creating that database is called "train building." This database allows train personnel to have localized control of any specific vehicle in the consist. For example, car information and ECP operation for any car can be displayed to the engineer on the HEU interface. Also, the database can be used to detect car-specific faults and cut out inoperable cars. ZefTron's CCD was capable of performing train building, but it used a noncompliant method to complete the task. To comply with the train building requirements, the software routines would have to be updated in conjunction with the messages as described above.

While train building can detect the position of each car in a train consist, car sequencing can also achieve this goal. If the location of a faulty car in an ECP train consist is known, that can be a useful tool for resolving any issues. Sequencing was not implemented fully in the ZefTron CCD. Since the S-4200 requires specific hardware and software routines to fully perform sequencing, the team planned to implement sequencing in the CCD and Car ID module then validate its operation.

5.4.3 Car ID Relocation

The Car ID Module is an ECP device that stores information about the freight car in non-volatile memory. The modules are physically tied to the freight car of which it stores information. The S-4200 standard requires that if a CCD needs to be replaced on a car, the Car ID Module remains with its car. The Car ID Module also contains the hardware necessary for sequencing. In ZefTron's design, the car information was statically stored in the CCD. The plan was to develop a new Car ID Module to store the car information; contain the sequencing hardware; and determine a satisfactory location for the mechanical requirements.

5.5 On-Board Power Source

The ECP trainline delivers power to each device and provides the medium for communication. In certain conditions (such as switching), ECP communication must be maintained while the trainline power is low or off. Thus, an on-board power source is required for each CCD. The S-4200 lists the required characteristics for these on-board power sources, or rechargeable batteries. The batteries used in the existing emulator can be seen in Figure 4-2. SA had planned to procure new rechargeable batteries to ensure the on-board power source requirements would be met. The new batteries chosen were sealed-lead acid rechargeable 12 V batteries.

The CCD battery is a ubiquitous requirement for all types of CCDs: standalone, overlay, or emulator. However, since an emulator must operate in both ECP and pneumatic trains, a more robust power supply system is required. When operating in a conventional pneumatic train, an emulator CCD does not have the ECP trainline to supply power to its onboard battery, so it would use more energy from the battery than its standalone counterparts. To help mitigate power consumption, ZefTron developed a generator that produces energy to charge the battery. This device, called a PPG, uses air exhausted from the brake cylinder during brake releases to produce electrical energy. The PPG was only minimally tested and thus not fully integrated into their emulator CCD. SA developed plans to characterize the performance of this device and integrate it into the new emulator CCD.

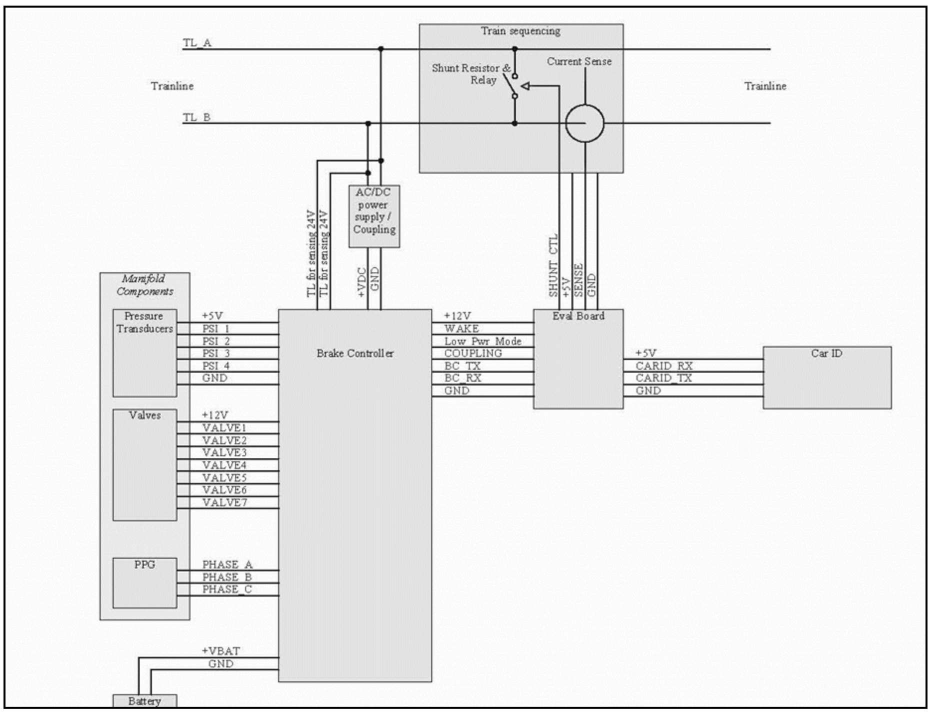


Figure 5-1 – Proposed CCD Architecture

In addition to the PPG, it was decided that designing the new CCD for two physically separate devices would help optimize power consumption and overall system integrity. This dual-board configuration would optimize emulator development by focusing on two modular devices. The eventual system diagram is shown in Figure 7-1, in Section 7 of this report.

The proposed architecture with signal and system integration of the emulator CCD can be seen in Figure 5-1. This diagram shows all of the proposed electrical connections and signals between the two boards, the pneumatics, Car ID module, and the ECP trainline.

6. Preliminary Testing

To evaluate the replacement of PLT-10 with PLT-22 and to assess if it was functionally compatible with the rest of the hardware and amenable to software changes, it was decided that a development environment to test the implementation along with necessary software changes needed.

6.1 Echelon Software Development Tools

SA procured Echelon's Minikit, a set of software development tools for embedded microcontrollers used in power-line communication. Included in the Echelon Minikit package were multiple Power-Line evaluation modules based on its PL3150 processor (PL3150 Evaluation Board), a Universal Serial Bus (USB) interface for programming and network monitoring, and a software package that was the integrated development environment. Echelon had developed a specialized network protocol for use with their technology called LonWorks®. This protocol is the basis for ECP communication. Echelon devices are programmed using a specialized language called Neuron® C, which is based off of ANSI C. The programs included in the suite are as follows: Nodebuilder (main IDE with compiler), Nodeload (programmer), LonScanner® Network Analyzer, and LonMaker (for device configuration on LonWorks®). This report will refer to the LonScanner Network Analyzer as the Network Monitor.

6.2 PLT-10 Replaced with PLT-22

As explained earlier, the original power-line transceiver in the ZefTron CCD, PLT-10, became obsolete and was effectively replaced by the PLT-22 model. Due to electronic upgrades, the standalone PLT-22 technology was embedded in Echelon's newer microcontrollers, called smart transceivers. The PL3150 smart transceiver is effectively the combination of the Neuron® 3150 microcontroller and PLT-22 transceiver. Though other smart transceivers exist with PLT-22 communication, the PL3150 smart transceiver was chosen to be the best option for new CCD development.

SA first decided to replace the PLT-10 with the PLT-22 on the CCDs, with the hopes of easing into the design phase and minimizing the changes necessary for the upgrade. Initially, this was thought to be possible since the PLT-10 and PLT-22 use the same physical package and peripheral interface. However, after testing the CCDs with the PLT-22 replacements, it was found that differences in the transceivers coupling circuits made this effort futile.

7. CCD Hardware Development

The evaluation efforts reported in the previous section led to a decision that for an emulator system that would be functionally meet S-4200 requirements and remain viable in future as the underlying electronic hardware evolves, the CCD would have to be redesigned. This also offered an opportunity to separate the CCD and brake controller functions to meet the low energy profile under the emulation mode.

7.1 Dual-Board Configuration

The CCD was redesigned to accommodate the new power-line technology and meet additional hardware requirements outlined in S-4200. The S-4200 specifies power regulations for all ECP devices, including the power on the ECP trainline and batteries for individual devices. In normal ECP mode, the ECP trainline continuously charges the batteries. If applicable, an emulator device is required to run for a minimum of 48 hours without external power (e.g., ECP trainline).

To ensure compatibility with the CCD power requirements, it was proposed that the CCD functionality be physically separated into two boards. The main CCD processor and ECP communication functionality would be placed on the Communication Module (Comm Module) board, while the brake control for ECP and emulation would exist on the Brake Controller board. The Comm Module was developed around the PL3150 Smart Transceiver from Echelon, and the Brake Controller was developed around a Texas Instruments MSP430 microcontroller.

The Comm Module core circuitry was designed for effective communication over the ECP network and power utilization of the trainline. It contains the coupling for the transceiver to transmit and receive messages, as well as the DC power converter for converting the trainline 230 VDC to 12 VDC for use on the Comm Module. The majority of the remaining hardware was designed to interface with the Brake Controller and interface with the Car ID module.

The Brake Controller core circuity was designed to interface with the CCD manifold solenoids and pneumatic relays. The Brake Controller has an interface to the Comm Module. Additional circuity was developed to charge the battery using power from the trainline. The Brake Controller board's battery would also be charged by a PPG, which was developed by to accommodate the S-4200 battery requirements.

It was determined that the Brake Controller would be mounted inside the CCD Manifold. The Comm Module would be mounted inside the Junction Box. Figure 7-1 shows the block diagram of both components in the dual-board configuration. The block diagram also shows signal connections and the connections to the CCD manifold and ECP trainline.

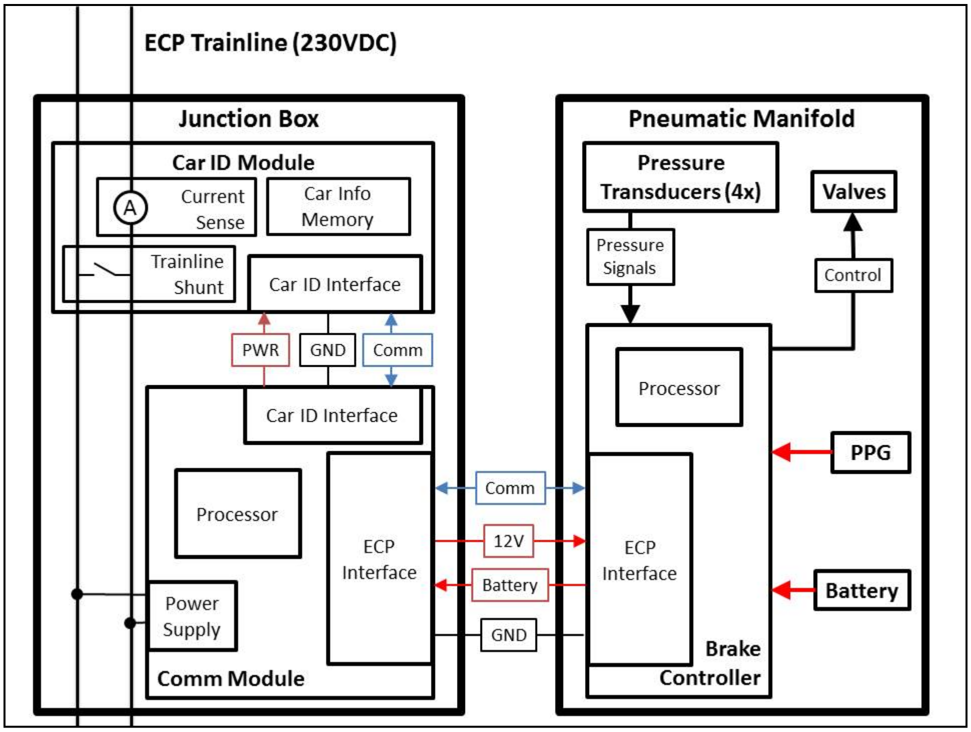


Figure 7-1 – CCD Block Diagram

7.2 PPG Description

The PPG is the on-board external power generator that will charge the CCD battery. The emulation capabilities must function even after a certain amount of downtime, thus ZefTron developed this generator. In a conventional brake system, the BCP is vented to atmosphere when the brakes are released. However, ZefTron designed the pneumatic logic in the CCD manifold to route 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 (Δ) configuration. The output electrical energy is then used to charge the battery.

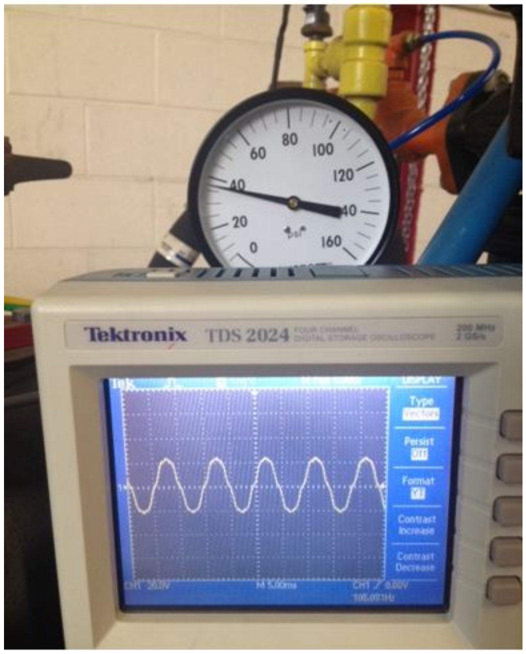


Figure 7-2 – PPG Test with Oscilloscope

To appropriately design the Brake Controller board so the battery can be charged, the PPG needed to be characterized for its power generation capabilities. SA conducted a series of tests of applying pressure through the PPG's turbine and visualizing the phase voltage on an oscilloscope. Figure 7-2 shows the results of releasing an initial BCP of 40 pounds per square inch (psi) and the induced EMF from a single phase of the PPG.

After this basic characterization of the PPG, a three-phase rectification circuit and charging circuit were designed on the Brake Controller so the battery can be properly charged.

7.3 Low Power Pressure Transducers

While redesigning the CCD to fit the two-board scheme, it was necessary to incorporate new pressure transducers. Pressure transducers were selected for their low power consumption so they could contribute to a more efficient Brake Controller. A special manifold was designed to mount the Brake Controller and pressure transducers to the CCD. The left image of Figure 7-3 shows the pneumatic manifold mounted to the CCD manifold, and the right image shows a side view of the Brake Controller with pressure transducers attached.

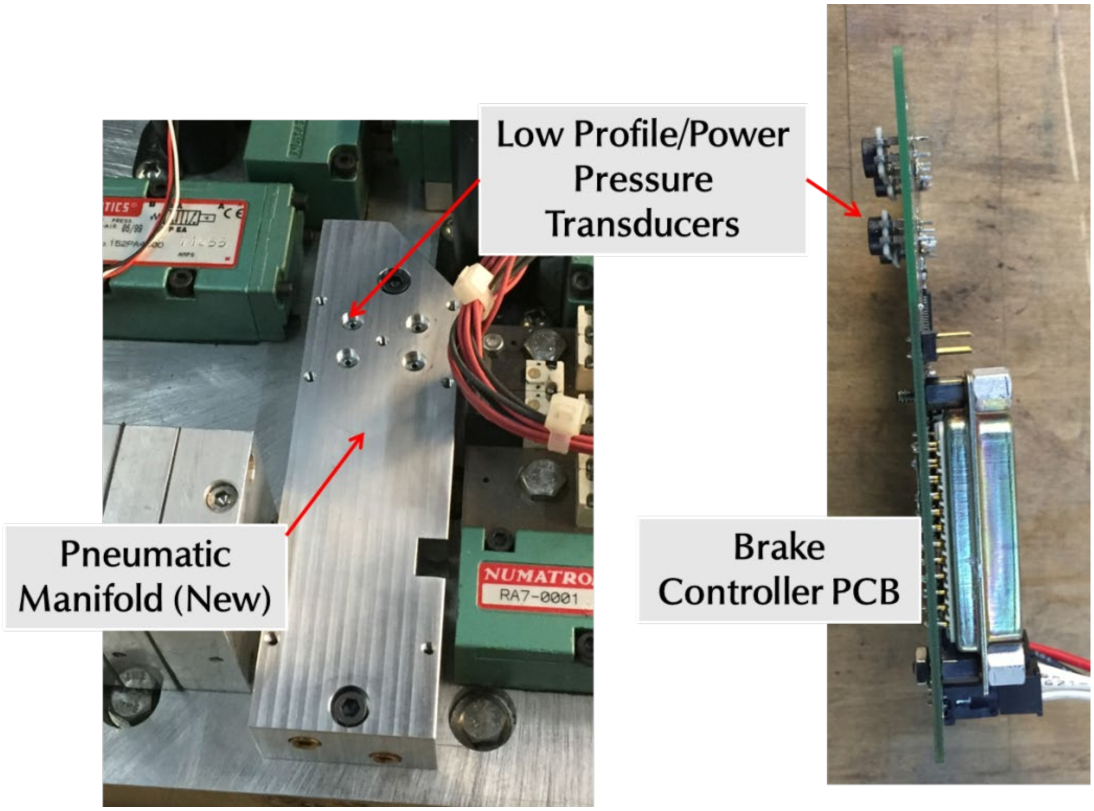


Figure 7-3 – Brake Controller Manifold and Pressure Transducers

7.4 Pneumatic Manifold

Modeled after the mounting device for the ZefTron low-power board prototype, the Pneumatic Manifold connects the Brake Controller PCB directly to the pneumatic plate in the CCD manifold (which is referred to as the CCD Wormplate due to the numerous intricate passageways connecting brake component volumes and pneumatic relays). This manifold is shown in Figure 7-3. Passageways in the Pneumatic Manifold connect the pressure volumes in the CCD Wormplate to the appropriate pressure transducers on the Brake Controller. O-rings and spacers were used to pneumatically seal the Brake Controller pressure transducers to the manifold. Figure 7-4 represents an assembly drawing for installing the Brake Controller to the manifold and attaching it to the CCD Worm Plate.

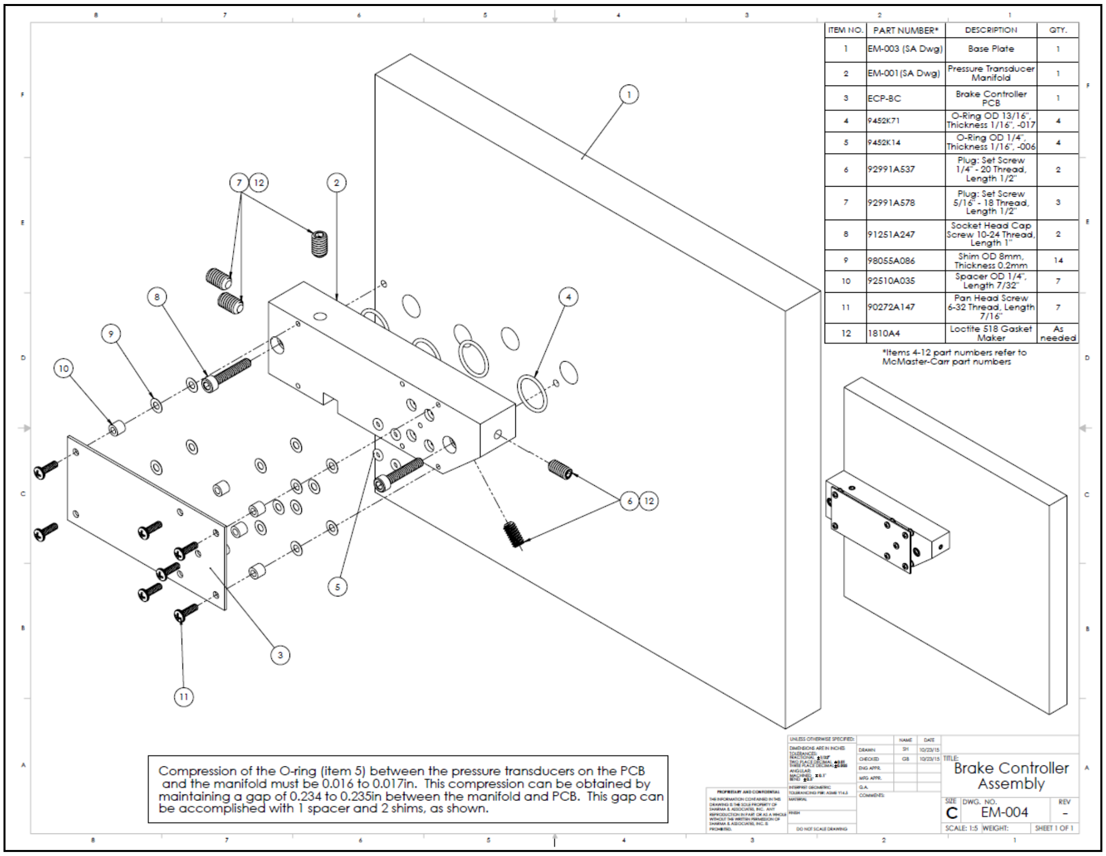


Figure 7-4 – Brake Controller Assembly with Manifold

7.5 Pressure Transducer Calibration Device

The pressure transducers on the Brake Controller need to be calibrated to accurately read the pressure of the volumes to which they are attached. After choosing the final pressure transducers and developing the pneumatic manifold, SA built a device to calibrate the pressure transducers. The calibration device was designed using the same layout from the pneumatic manifold, to ensure a proper connection to the Brake Controller. The ports on the calibration device are all internally connected to a single volume to ensure pressure transducers are calibrated uniformly. Figure 7-5 shows this device and how it connects to the Brake Controller. By relating the pressure gauge readings to the output of the pressure transducer Analog to Digital Converter (ADC) values, the transducers could be appropriately calibrated in the Brake Controller firmware.

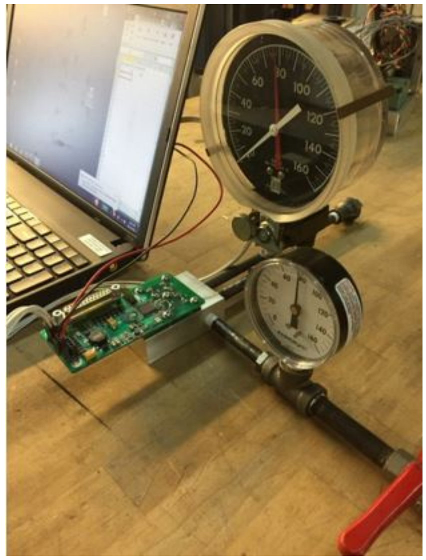


Figure 7-5 – Calibration Device

A representation of an assembled CCD (Manifold Only portion) is shown in Figure 7-6.

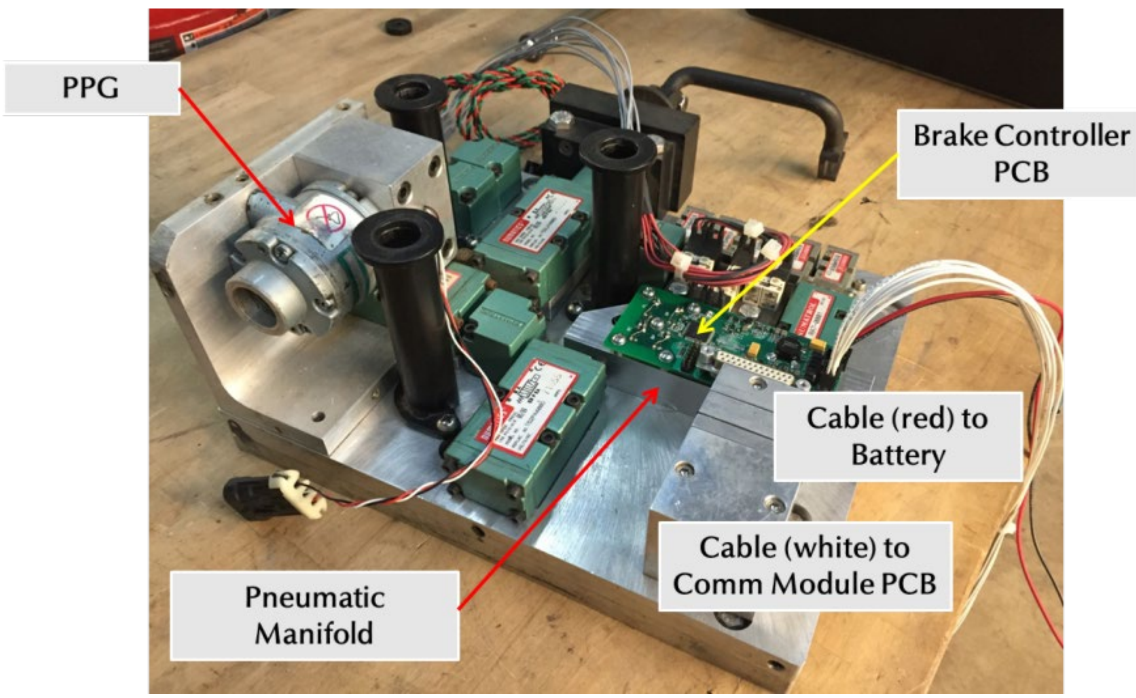


Figure 7-6 – CCD with Brake Controller and PPG Mounted

7.6 Communication and Car ID Modules Development

7.6.1 Separate Boards in Junction Box

When developing the dual-board scheme, it was determined the optimal location for the Comm Module would be the Junction Box. The Car ID Module is required to be physically tied to the

Junction Box as well. However, the S-4200 also requires the Car ID Module be functionally and physically separated from the CCD, so that in case of CCD replacement, the information embedded in the Car ID is not affected.

The Comm Module board was developed around the PL3150 microcontroller. Additional circuitry was developed to interface with peripherals and devices, manage power, and communicate with the Brake Controller, Car ID Module and on the ECP network. The Car ID Module consists of a single electrically erasable programmable read-only memory (EEPROM) chip for containing Car ID information, and the necessary sequencing hardware. The information embedded in the Car ID memory is listed in Car ID Module description in Section 3.9 of S-4200 [2]. This report will typically refer to the Car ID Module's EEPROM chip as the Car ID. Figure 7-7, Figure 7-8, and Figure 7-9 show the PCB layout, CAD model, and physical circuit board of the Comm Module.

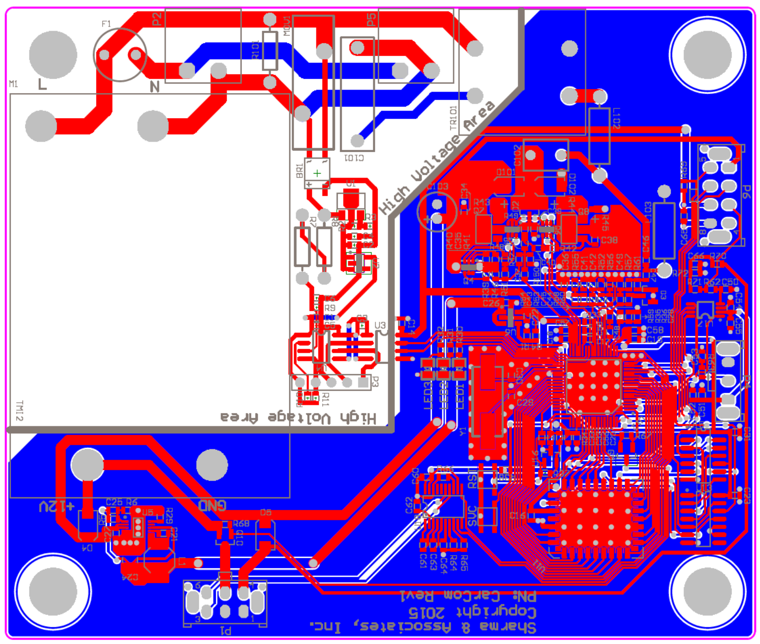


Figure 7-7 – Comm Module PCB Design Layout

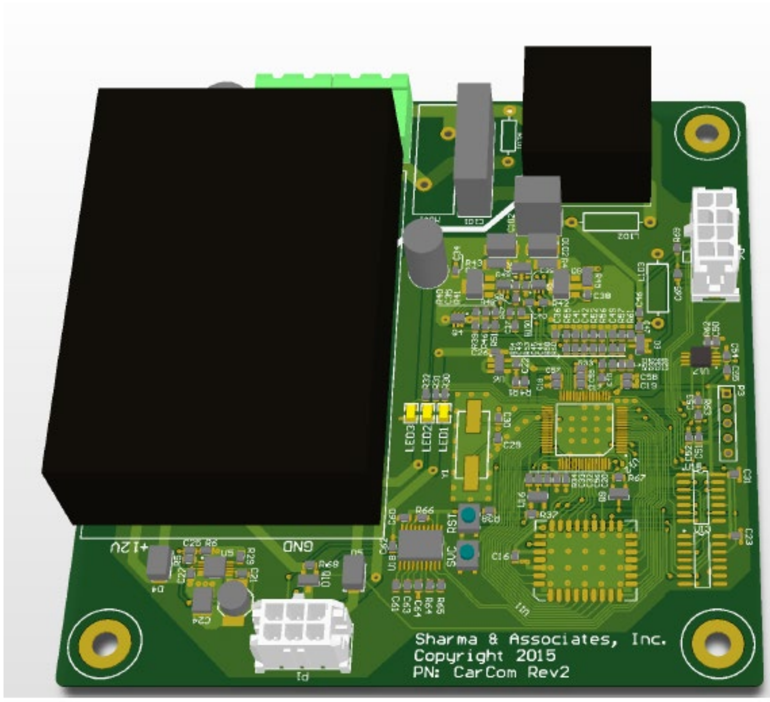


Figure 7-8 – Comm Module CAD Model

Figure 7-9 – Comm Module Board

Figure 7-10, Figure 7-11, and Figure 7-12 show the PCB layout, CAD model, and physical circuit board of the Brake Controller.

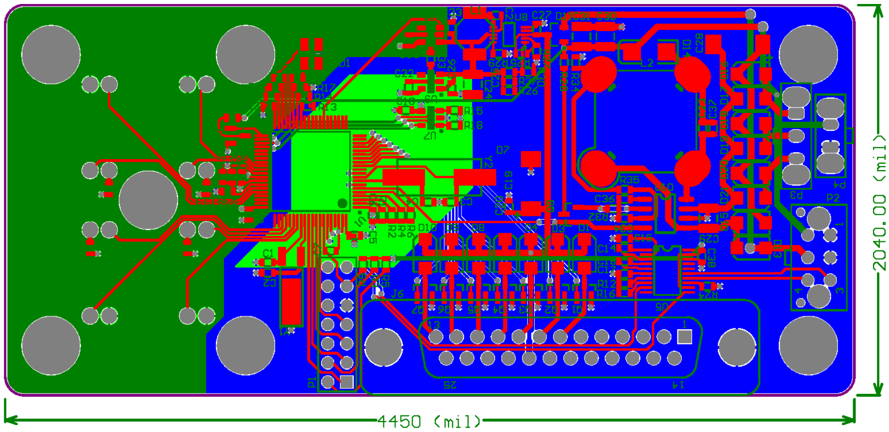


Figure 7-10 –Brake Controller PCB Design Layout

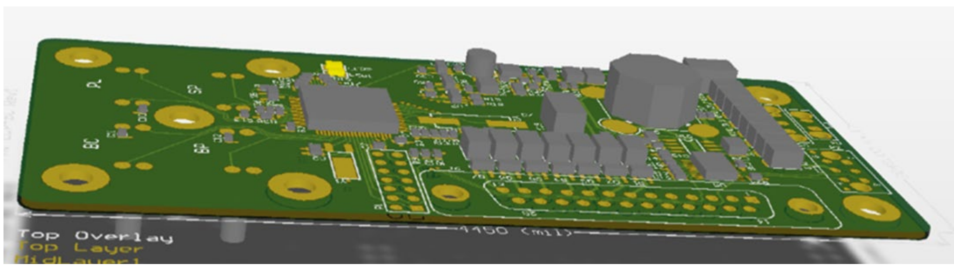


Figure 7-11 – Brake Controller CAD Model

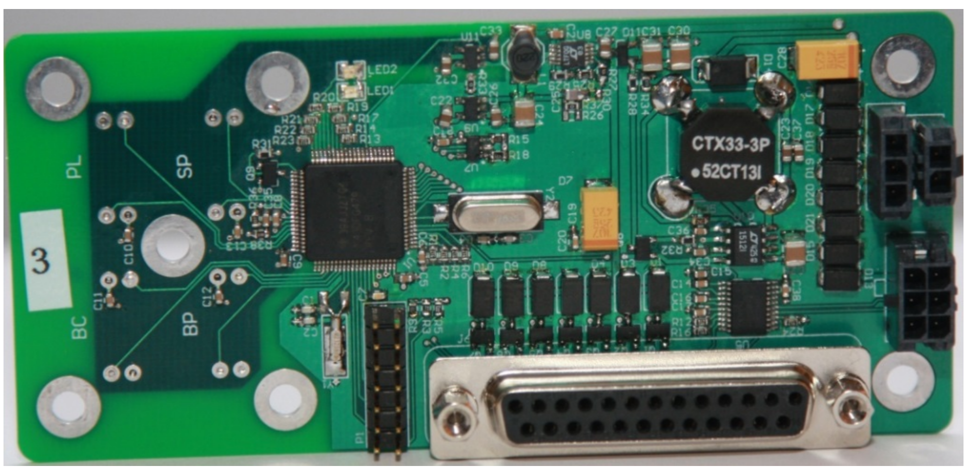


Figure 7-12 – Brake Controller Board

Figure 7-13, Figure 7-13, and Figure 7-15 show the PCB layout, CAD model, and physical circuit board of the Car ID Module.

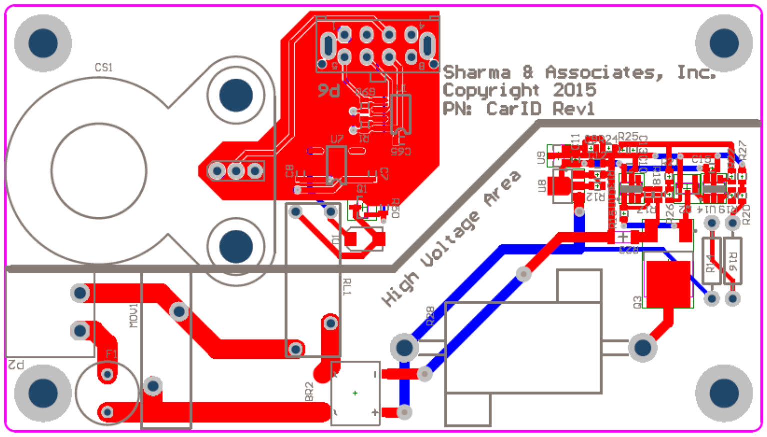


Figure 7-13 – Car ID Module PCB Design Layout

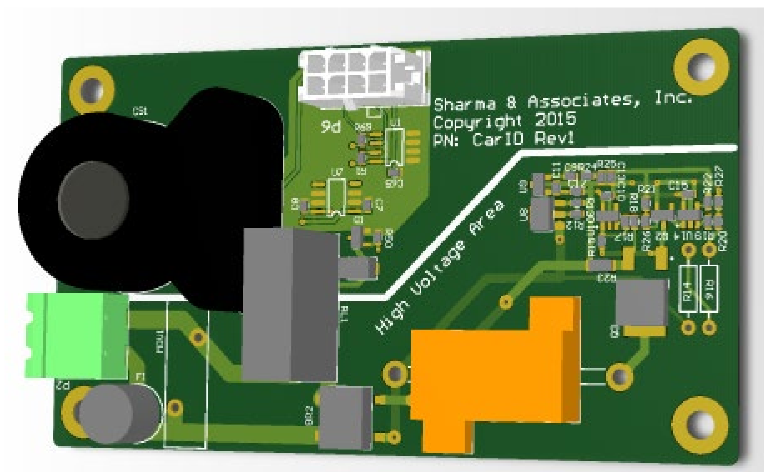


Figure 7-14 – Car ID CAD Model

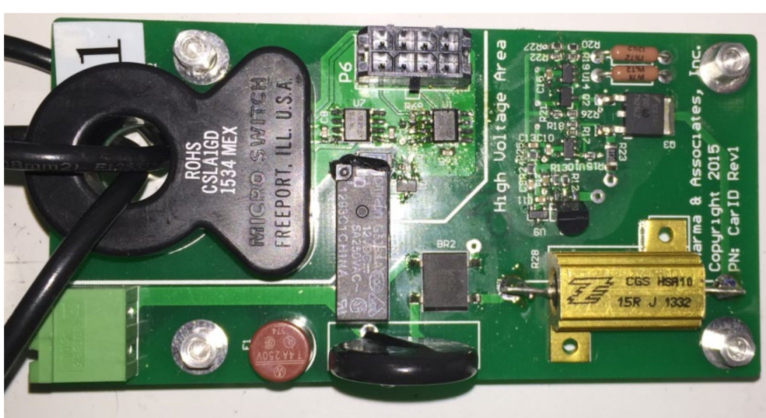


Figure 7-15 – Car ID Module

Figure 7-16 shows an assembled Junction Box with the Comm Module and Car ID Module installed.

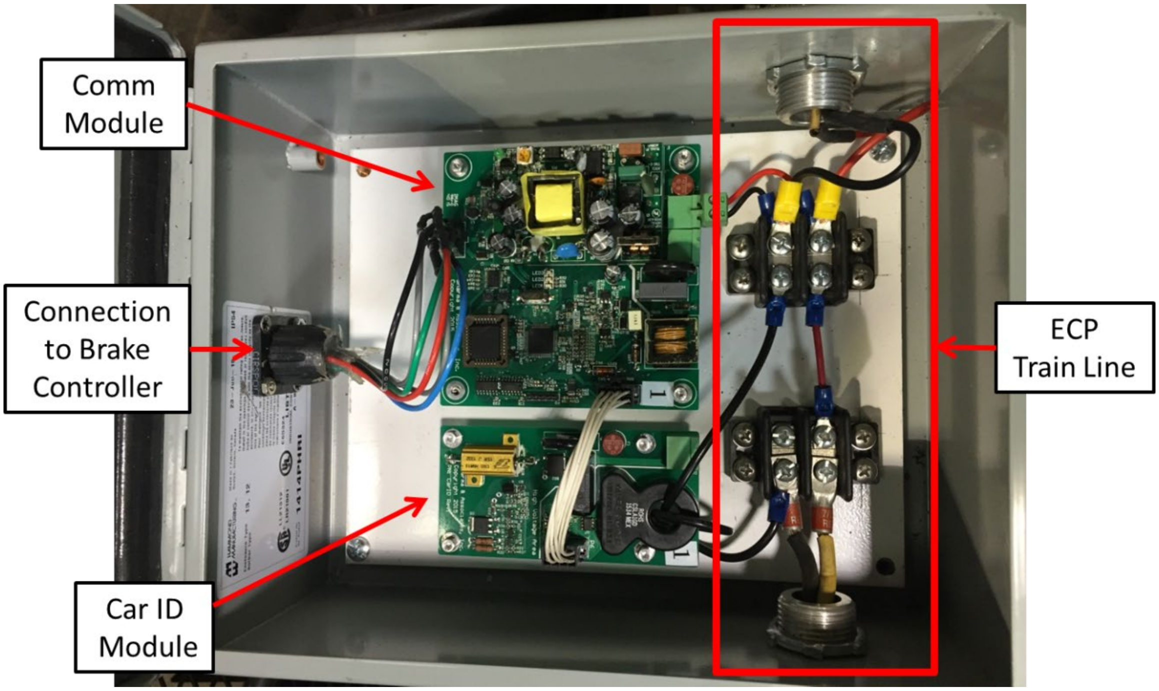


Figure 7-16 – Assembled Junction Box with Comm Module and Car ID Module

7.7 Provision for Local Network of Peripheral Devices

There is a requirement in the S-4200 that the CCD has a hardware provision for hand brake sensor and operation. However, the standard currently does not require an actual implementation of a hand brake sensor or control. Thus, two pins have been allocated on the Comm Module for a peripheral device network for interfacing with hand brake controls.

8. CCD Software Development

Software for the CCD was completely rewritten for the new hardware (with only a few exceptions). Since S-4200 was finalized after ZefTron had abandoned their development, the software received from ZefTron was not compliant with S-4200, primarily with the use of messages and interoperability. Furthermore, the software would need to be written for each board in the dual-board configuration (Brake Controller and Comm Module).

8.1 Communication Module Software

The Comm Module software was written in Neuron® C, a language developed by Echelon for their microcontrollers. Neuron® C is syntactically based on ANSI C and contains many of the C libraries and functions. However, it was specifically designed for Echelon hardware and it uses the LonWorks® protocol.

Since the Modulator uses Echelon's LonWorks® communication protocol, there are two types of messages that can be used to transmit data between LonWorks® devices (e.g., ECP devices). As ZefTron developed its ECP system prior to the functional standardization, ZefTron had written the communication almost exclusively with network variables type messages instead of explicit type messages (which are required by S-4200). This required changes to the way messages were written how data was used to populate the data fields of the messages. Software was also written to accommodate the power management, Car ID data transfer, general fault monitoring, and other S-4200 requirements.

New Comm Module software was compiled using the Nodebuilder IDE and then it was uploaded to the device via the network with the NodeLoad Utility application and a PL-20 USB interface connected to the power-line network. Afterwards, the Comm Module was configured using the LonMaker program.

A terminal emulator, as well as Echelon's development suite, was often used to test functions and internal processes in the Comm Module. A serial communication program was used to test the inter-board communication between the Brake Controller and Comm Module. Figure 8-1 shows a typical benchtop setup for testing the Comm Module software.

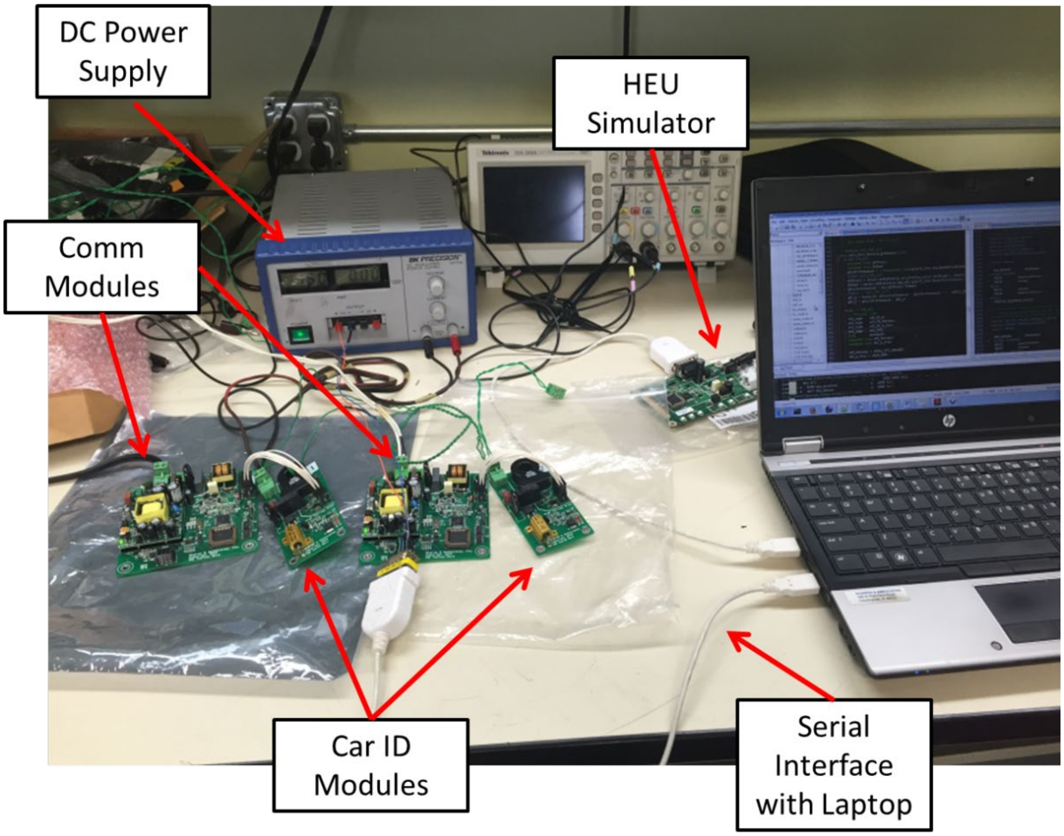


Figure 8-1 – Representation of Software and Hardware Testing

8.2 Brake Controller Software

The Brake Controller software was rewritten for a version of embedded C that was specific to the TI MSP430 platform. The integrated development environment used to compile the software was Code Composer Suite from Texas Instruments. The TI MSP430 Flash JTAG programmer was used to download the application onto the microcontroller, in-circuit. Many of the same algorithms previously used for emulation and brake control from the ZefTron CCD were ported to the new Brake Controller.

8.3 Inter-board Communication

8.3.1 Protocol

A communication protocol was designed to transfer data between the Comm Module and Brake Controller. Each device communicates using a serial UART and uses 5-byte messages to send and receive data. The baud rate is 4,800 bps with 1 start bit and 1 stop bit, as well as 8-bit transmission and no parity bit. In the protocol, the Comm Module starts communication, and the Brake Controller responds and performs any necessary actions. Pressure readings and brake control functions are transferred through this link. During ECP mode, messages are transmitted from the Comm Module to the Brake Controller every 100 ms. The message that instructs the Brake Controller to apply a target BCP is called the “Apply Brake” command.

8.3.2 ECP/Emulation Switching

When powered on, the Brake Controller initially enters emulation mode. In contrast, when powered on the Comm Module enters ECP mode. To enter ECP mode and stay there, the Brake Controller must receive an "Apply Brake" command from the Comm Module every 100 ms. The Comm Module also instructs the Brake Controller to supply battery voltage to the Comm Module as the Controller enters ECP mode.

There are multiple methods for ending ECP operations, but there is only one procedure for entering emulation mode. When ECP mode ends, whether by engineer command or timed shutdown, the Comm Module instructs the Brake Controller to shut off battery power to the Comm Module, and then stops communication. In a normal transition, the trainline will be powered down. So, when the battery is commanded off, the Comm Module will turn itself off. Since the Brake Controller will receive no further "Apply Brake" commands, the Controller will go into emulation mode.

8.3.3 Brake Cylinder Pressure Control

In ECP mode, the brake cylinder target pressure is calculated by the Comm Module and regulated by the Brake Controller. During normal operation, the HEU transmits the train brake command (TBC) as part of the HEU Beacon. The TBC is the engineer commanded amount of pressure to fill the brake cylinder for applying the brakes, expressed in percent of the full-service BCP. When a CCD receives the HEU Beacon, it converts the TBC to the respective target BCP based on the table in Section 4.3.10 of S-4200 [2]. The Comm Module transmits an "Apply Brake" message (sent every 100 ms) to the Brake Controller with the new target pressure. The Brake Controller then opens the pilot valve to allow the appropriate amount of air pressure to flow from the reservoir to the cylinder, using specific pneumatic relay solenoids. The Brake Controller regulates the cylinder pressure within an acceptable margin of ± 3 psi [2]. Subsequent TBCs change the "Apply Brake" message and the BCP accordingly. Additional requirements for regulation are outlined in Section 4.3.11 of S-4200.

When the CCD is cut-out, the target pressure changes to 0 psi, regardless of the percent TBC in the HEU beacon.

During certain fault-conditions, the target pressure changes to 120 percent (ECP emergency), regardless of the percent TBC in the HEU Beacon.

8.4 Message Updates

All the network communications were rewritten to adhere to the communication requirements in S-4200 and S-4230. Originally, network communications were written using network variables, but the S-4230 requires the use of explicit message types. These two distinct methods for transmitting data over a LonWorks® network are incompatible with one another, which required a change in how a message was written, sent, received, and parsed. Also, there were also many new messages that needed to be implemented. The S-4230 defines each message by enumerating every byte in any message, along with source and destination, and other transmission details. In Figure 8-2, the CCD Status Response is an example of how a message is structured. The messages adhere to these data fields and transmission details.

5.4.3 CCD Status Response (0,15)

Source:	CCD	*Message Rate:*	On request (1-Hz effective)
Dest:	HEU Lead/Requesting Node	*Service Type:*	UNACKD
Msg Type:	Explicit	*Addressing:*	UNICAST
Msg Code:	0x00	*Data Size:*	15 bytes
Priority:	No		

Description: This message is sent from a CCD in response to the HEU beacon when its subnet/node address matches. It also is sent in response to a Device Status Query.

Field Name	Size	Value/Range (Resolution)	Default	Notes
MSG ID NUMBER	1	15 Only	15	
MSG VERSION	1	0 to 255	3	
STATUS	1	Bit 0: 0 = CUT-IN 1 = CUTOUT Bit 1: 1 = HEU Cutout commanded Bit 2: 1 = Isolated Critical Loss Bit 3: 1 = CCD Fault Detected Bit 4: 1 = CCD Inoperative Bit 5: 1 = CRC Error Count Threshold Bit 6: 1 = Low Reservoir Bit 7: 1 = Low Battery	0	A A A A B
BRAKE PIPE PRESSURE	1	0 to 250 psi (LSB = 1 psi)		
RESERVOIR PRESSURE	1	0 to 250 psi (LSB = 1 psi)		
BRAKE CYLINDER PRESSURE	1	0 to 250 psi (LSB = 1 psi)		
PERCENT BRAKE APPLIED	1	0 to 250% (LSB = 1%)		
CAR LOAD	1	Bits 0–6: 0 to 100% (LSB = 1%) Bit 7: 0 = HEU E/L command valid 1 = HEU E/L command mismatch		 C
HIGHEST PRIORITY ACTIVE EXCEPTION	2	0 to 65534		D
POWER STATUS	1	Bits 0–3: Battery Charge (LSB = 10%) Bits 4–6: Not Used (set to 0) Bit 7: 1 = Trainline Power Detected		E
AUX STATUS	1	Bits 0–1: 0 = Handbrake Status Unknown 1 = Handbrake Released 2 = Handbrake Applied 3 = Not Used (Invalid) Bit 2: 1 = Crosstalk Detected Bits 3–7: Not Used (Set to 0)		 F
TRAIN ID	3	Per paragraph 4.3.4 of this standard		G

Figure 8-2 – Excerpt from S-4230 Section 5.4.3 Defining the CCD Status Response [6

When the values of a message from a network log are compared to the message's definition in the S-4230, the message's contents can be deciphered. The notes referenced in the "Notes" column in Figure 8-2 can be found in the full definition of the CCD Status Response in S-4230 [6].

For example, Figure 8-3 displays the contents of a CCD Status Response message after it was extracted from a network log (see Figure 9-7 for full message, line 29241). The data is formatted in hexadecimal and starts after the "0x." The respective field names are listed above. The message in Figure 8-3 shows that: it is a CCD Status Response of version 3; the CRC Error Count is over the threshold; BPP = 90 psi; Reservoir = 91 psi; BCP = 0 psi; Percent Applied = 0 percent; Car Loaded 100 percent; there are no exceptions; battery is charged 100 percent and there is trainline power, and a Crosstalk has been detected with a Train ID of 0x006600.

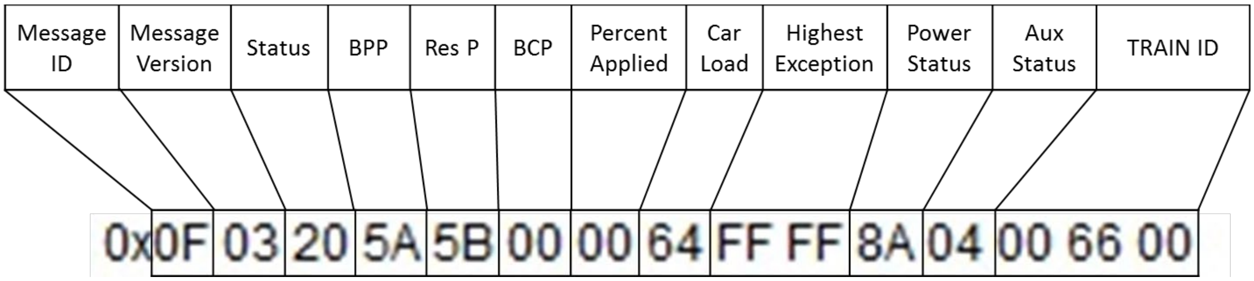


Figure 8-3 – Data Contents of CCD Status Response Message

8.5 Exception and Fault Handling

Minimal exception and fault handling procedures were initially implemented in the ZefTron CCD. However, the exceptions were not compatible with the requirements (similar to the message update issues). The exception and fault handling requirements are laid out in Section 4.4 of S-4200, with message definitions in S-4230. S-4200 also outlines the procedures for clearing exceptions, once the problem has been resolved.

Available exceptions include Low Reservoir Pressure, Low Battery, and Unable to Control Brake Pressure. Once most of these exceptions are found on a particular CCD, the CCD sends a message that indicates the fault. Once the fault is resolved, a message is sent to clear the exception. Exceptions such as Loss of HEU Communication and Loss of Brake Pipe Pressure are defined as critical and have more specific handling requirements. For example, a critical exception has different responses, depending on whether the fault is localized to the device or whether multiple devices experience the same fault. If a fault is train-wide, the CCD forces an electronic emergency application and enters a Critical Loss Relay mode. Then, the CCDs monitors communication for a certain period, and the emergency application is relieved only when certain criteria have been met.

Most faults were tested using a Brake Controller communication utility, which could communicate with the Comm Module instead of the Brake Controller (or vice versa), effectively simulating the other device’s communication. By sending a user-manipulated Brake Controller message using this communication utility, the user can control what pressure values and battery voltages the Comm Module receives. This allowed SA to test normal exceptions, such as by sending a low battery value in a message, without affecting the actual battery charge or Brake Controller code. However, the program does not allow for extensive conditional procedures, which made the software difficult to use when generating faults that induce brake applications, like critical exceptions. For critical exceptions, it was necessary to force the fault in the actual car system. This was done by either stopping HEU beacons (and other HEU communication) or manually releasing the BPP. Additionally, sometimes non-S-4200 messages were created to monitor internal timers and variables to ensure the S-4200 procedures were being met.

Furthermore, faults have to be sent in a determined hierarchy, while only the highest priority message will be sent when multiple exceptions occur.

8.6 Train Building

Train building occurs during ECP initialization. In this process, three main messages, all new in the CCD software, are transmitted. As specified, the HEU broadcasts a request to all trailing devices in the train for device information. In that message, there is a randomizing interval for CCDs to use to calculate when the CCD should reply with its car information. This further mitigates message collisions and ensures an efficient train-build process. Prior to receiving this message, the CCD has already retrieved car information from the Car ID. Each CCD then responds with its Car Information using its Neuron® ID as its address. Next, the HEU is responsible for matching Neuron® IDs with an ECP address (i.e., subnet/node [S/N] address) and responding to each CCD by assigning its ECP address to that device. From then on, the CCD will respond to messages with that S/N address. In future train builds, the CCD will be able to update its S/N address, granted that ECP mode has reset or the HEU has commanded the CCD to unlock its address for changing. Otherwise, the CCD will not change its address.

The train building process was implemented in software. The Car ID data transfer was achieved using Inter-Integrated Circuit (I^2C) communication between the Car ID EEPROM and the PL3150 processor on the Comm Module. Software testing and validation for train-building was performed on a system level.

8.7 Car Sequencing

Car sequencing requires that the software and the hardware are integrated. To perform sequencing, each car (CCD and Car ID) uses a current sensor to measure trainline current and employs a shunt to create a current-pulse on the trainline. In addition, sequencing hardware must regulate the current produced when the trainline is shunted within a certain range. The main procedure for ordering cars during sequencing is:

1. All CCDs are instructed to count trainline current pulses.
2. Each CCD, one at a time, is instructed to apply and release its shunt to create a current-pulse.
3. Once all CCDs have created a pulse, each CCD determines its position based on the number of pulses it counted, orientation of its car relative to the lead locomotive, and how many cars are in the train.

The sequencing hardware is located on the Car ID, though the Comm Module controls the shunt and reads the information from the current sensor. The current sensor is a linear output Hall-Effect ratiometric current transducer. When current passes through the internal magnet, a change in voltage (proportional to the supply voltage) is induced. The output voltage is quantized by an external 12-bit ADC. Through software and proper calibration, the Comm Module reads the ADC value and converts the 12-bit value back to current for proper sequencing. The PL3150 processor communicates with the ADC using the Serial Peripheral Interface (SPI) protocol. The SPI protocol was bit-banged in the Comm Module software. A current pulse is well-defined by the S-4200 by its width and amplitude. Certain software functions were programmed to count only pulses based on the sequencing period and amplitude.

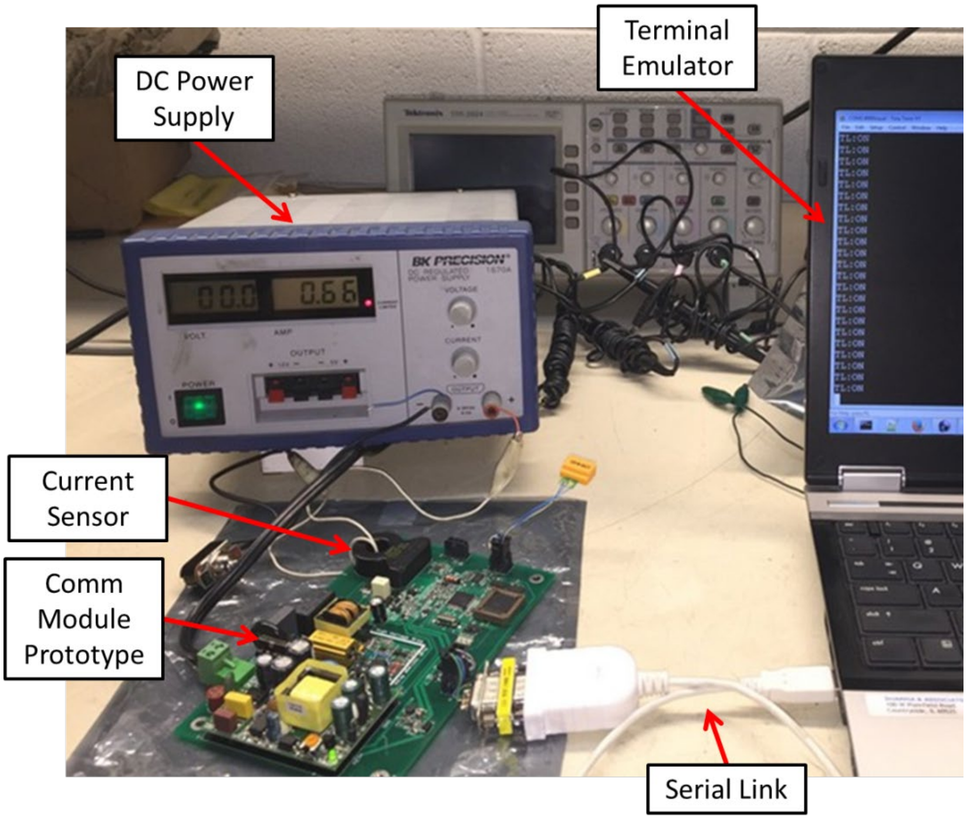


Figure 8-4 – Preliminary Current Sensor Testing for Car Sequencing

Exhaustive testing was performed on the current sensor and ADC to ensure the software accurately converted the 12-bit ADC value to the actual current through the sensor. Figure 8-4 illustrates a preliminary test of the current sensor using a DC power supply as a current source and monitoring the response from the Comm Module's current amplitude detection routine via a terminal emulator. A terminal emulator was extensively used for testing the current sensor and ADC to verify pulse detection met the S-4200 requirements.

The shunt and current regulation circuit were tested to ensure that applying and releasing the shunt would create the appropriate trainline current pulse. A software routine was developed to shunt the trainline for a certain period to produce the appropriate current pulse. This was confirmed by visualizing shunt relay's coil voltage on an oscilloscope and comparing it to the pulse defined in the S-4200.

Sequencing employs a well-defined procedure that has been implemented in the software. The HEU leads the sequencing process by commanding devices when to read the trainline current, when to shunt the trainline, and when to report its sequencing results. Each CCD is responsible for calculating its position in the train based on 1) its pulse count, 2) how many devices are in the train, and 3) the orientation (A-end leading or B-end leading) relative to the lead locomotive.

Once independent sequencing routines were confirmed, further testing was conducted with fully integrated sequencing software. After confirming a single device's operation, multiple devices were connected and tested for car sequencing.

9. System Testing

To demonstrate that the emulator CCD device was compliant with the requirements of the S-4200 and S-4230 standards, it was essential to clearly enumerate each applicable ECP CCD requirement and devise concise methods for its validation. Since the scope of this project was limited to development of the CCD, compliance verification was also limited to this device; i.e., performance of other ECP system components (such as HEU, power supply controller [PSC], and EOT) was not evaluated. Thus, SA created a test matrix, Table 12-1 in Appendix A, that lists applicable ECP CCD requirements from S-4200 with their associated verification test procedures. By successfully executing each task in this table, SA can demonstrate compliance of the emulator CCD, with traceability to each applicable requirement of S-4200.

Figure 9-1 shows the layout of the ECP Emulator test stand at SA's lab. The control stand is at the far left, and to the right of the control stand are three single-car brake test stands.

Figure 9-1 – SA Lab Emulator Equipment Layout

Each single car brake stands had its service portion replaced with the new CCD emulator Manifold. All CCD Manifold covers were removed during testing to monitor the equipment more efficiently. The brake pipe, ECP trainline, and junction boxes are behind the brake test racks. Figure 9-2 shows an open CCD manifold and an open Junction Box to view the entire CCD emulator system, without PPG.

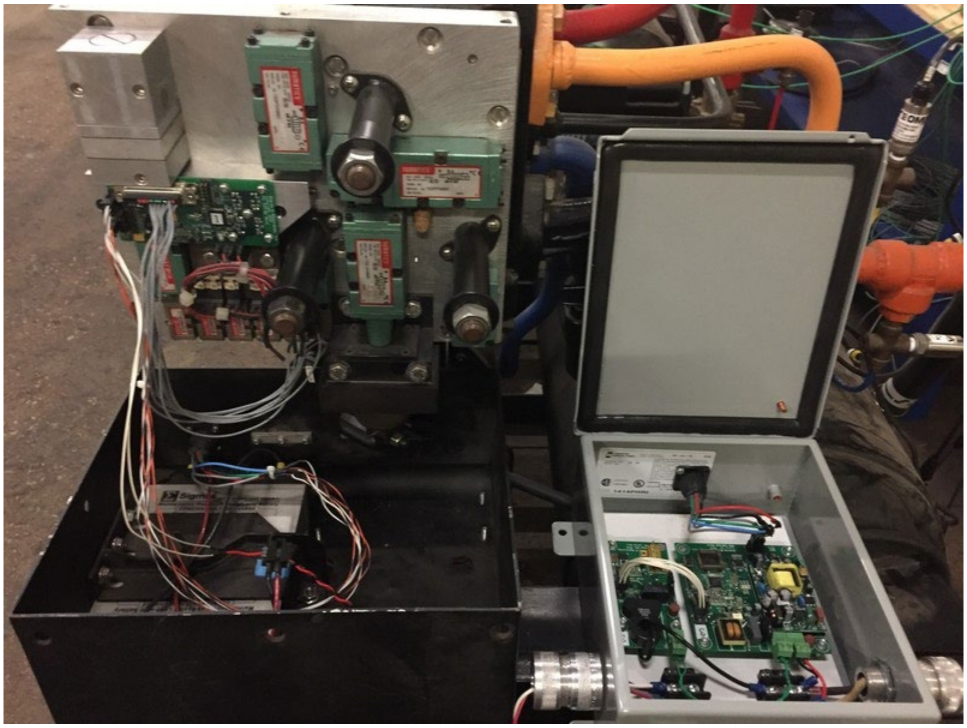


Figure 9-2 – CCD Manifold (left) and Junction Box (right)—No PPG

9.1 Development Environment for Emulator HEU

ZefTron developed its HEU on a PC104 using embedded C++. Additional Echelon modules were integrated into the HEU for communicating with LonWorks®. The HEU was compiled on a Microsoft® Windows 98 computer in the Borland C++ development environment. SA had successfully experimented with updating the ZefTron HEU software and had tested many CCD software upgrades through this method. However, the method was cumbersome and time consuming, so SA determined that a new device for validating the CCD operation could be built with additional capability, which would be more efficient and beneficial.

9.2 Development of Message Testing Devices

To test the CCD's software, SA created software that performed selected HEU functionality with a PL3150 development board. The device, called HEU Simulator, would not be a fully compatible HEU, but it could send any HEU message at will and perform selected HEU operations. The HEU Simulator software provided the user with a wider range of options for manipulating the message data more than the HEU would allow. By creating a flexible testing device, SA was able to expedite CCD testing without creating a fully compliant HEU. The Simulator was used to confirm train building, car sequencing, normal operation, fault conditions, power management, and other operations. It would connect to a terminal emulator, running on a laptop, to display information and allow the user to send and update messages on the network. The typical testing setup of the HEU Simulator is shown in Figure 9-3. Figure 9-4 shows a screenshot of the HEU Simulator Graphical User Interface (GUI) and Network Monitor side-by-side.

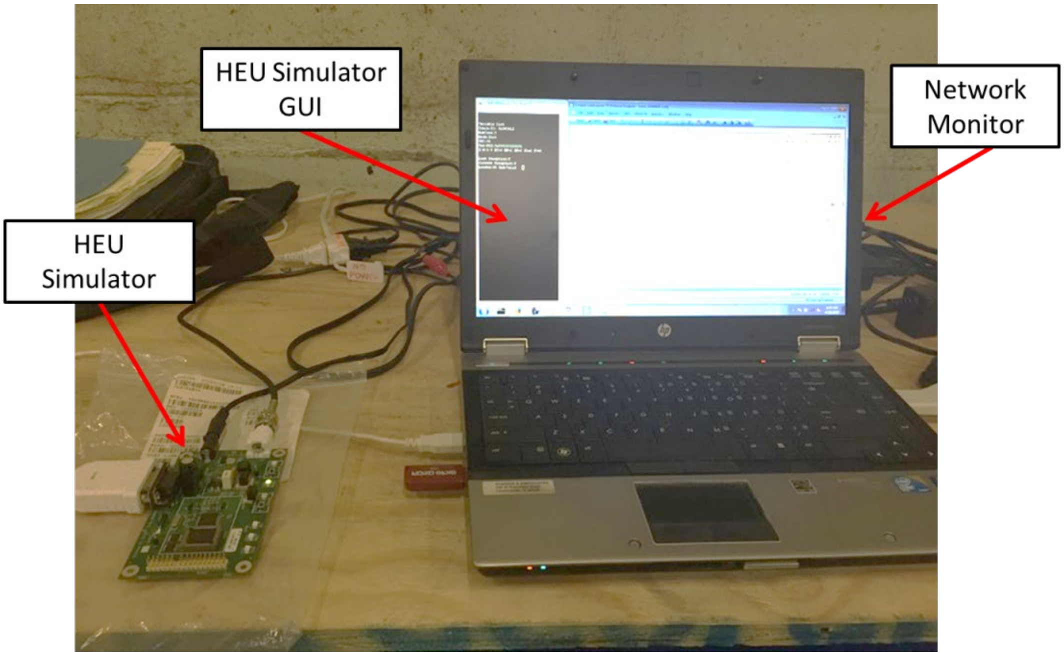


Figure 9-3 – ECP Testing with the HEU Simulator

As mentioned earlier, a Brake Controller communication utility simulated Brake Controller communications to test Comm Module software. Specifically, this utility tested faults by sending manipulated pressure readings and battery voltages to the Comm Module. This communication utility was also used to calibrate the pressure transducers for the Brake Controller.

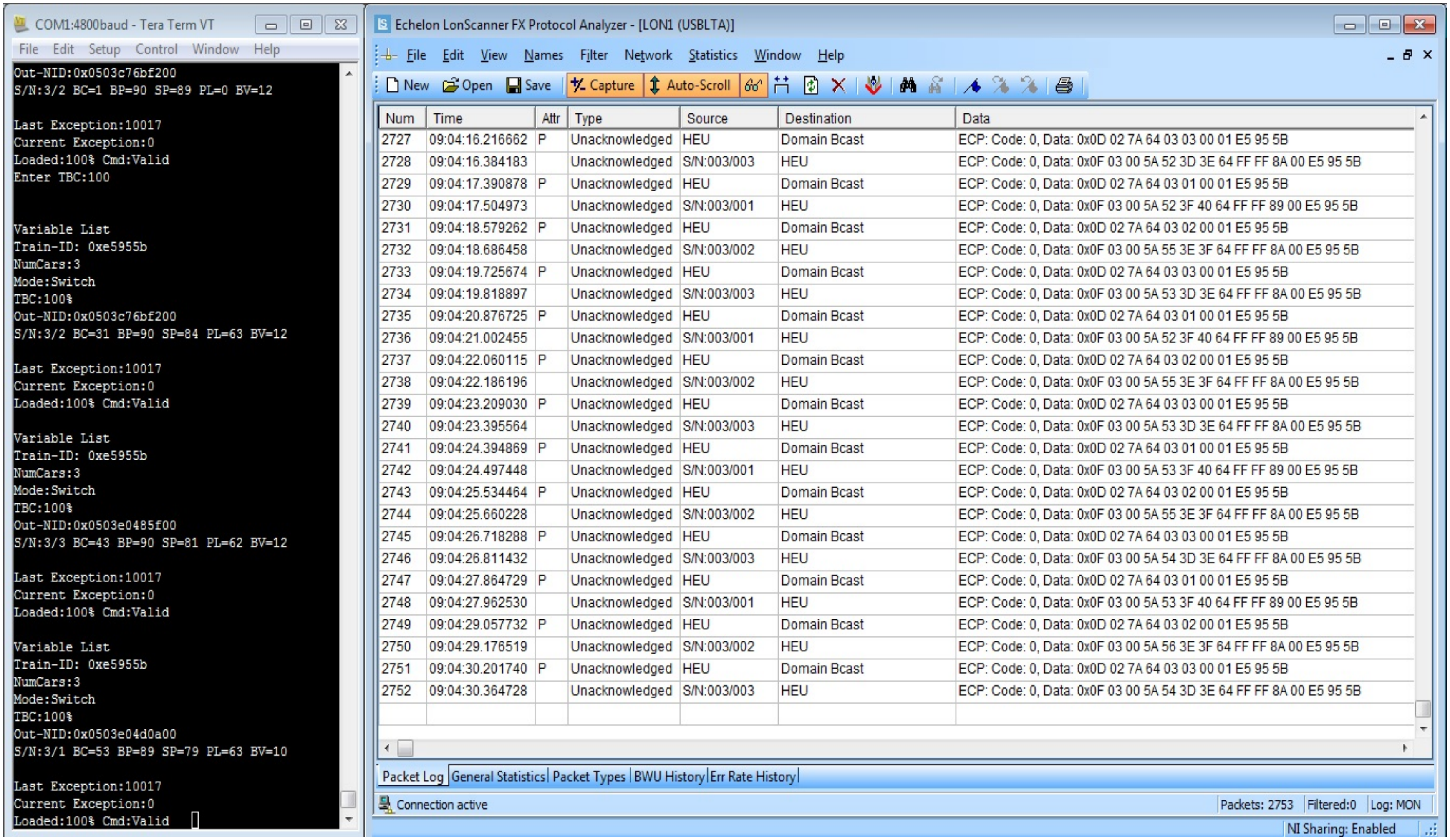


Figure 9-4 – HEU Simulator GUI (left) and Network Monitor (right)

9.3 Car ID Read/Write

The Car ID Module was designed to store Car ID information on an EEPROM and perform sequencing. The Comm Module communicates with the EEPROM using the I^2C protocol, which was bit-banged in software. Functions were created in the Comm Module to read data from and write data to the EEPROM. Figure 9-5 shows an example of Car ID reading and writing operations testing. The terminal emulator was also used extensively for testing the read and write operations by manipulating written data and confirming that the read data would update accordingly. SA connected a terminal emulator to the Comm Module, requested the Comm Module to read the contents of the Car ID, displayed them to the terminal, and instructed the Comm Module to write new information to the Car ID. The EEPROM can be configured to protect from write operations as needed.

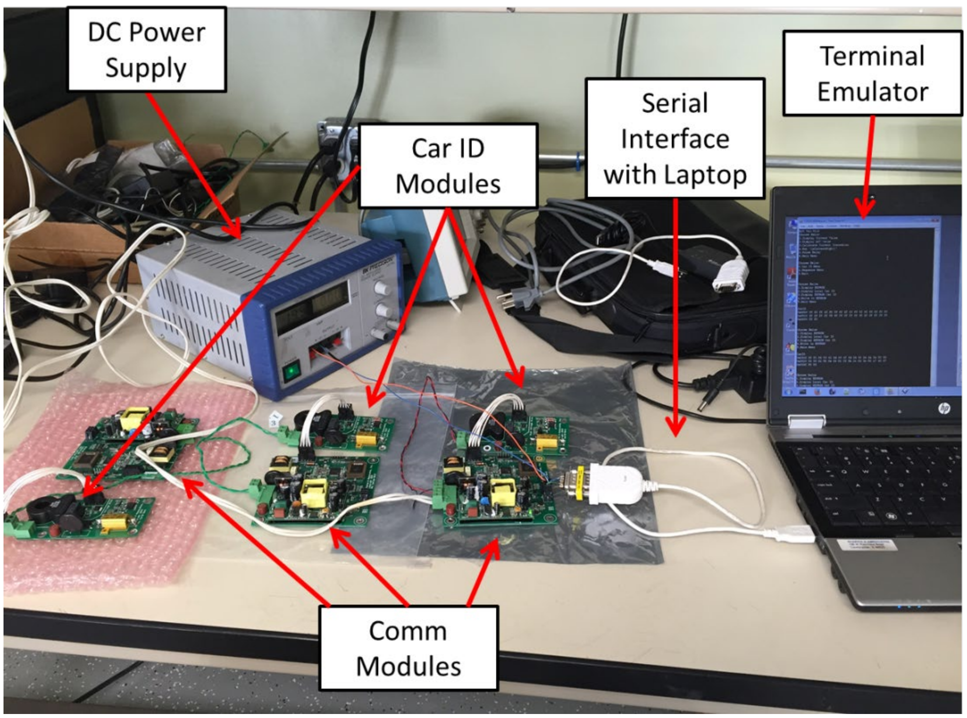


Figure 9-5 – Testing Car ID Read and Write Operations

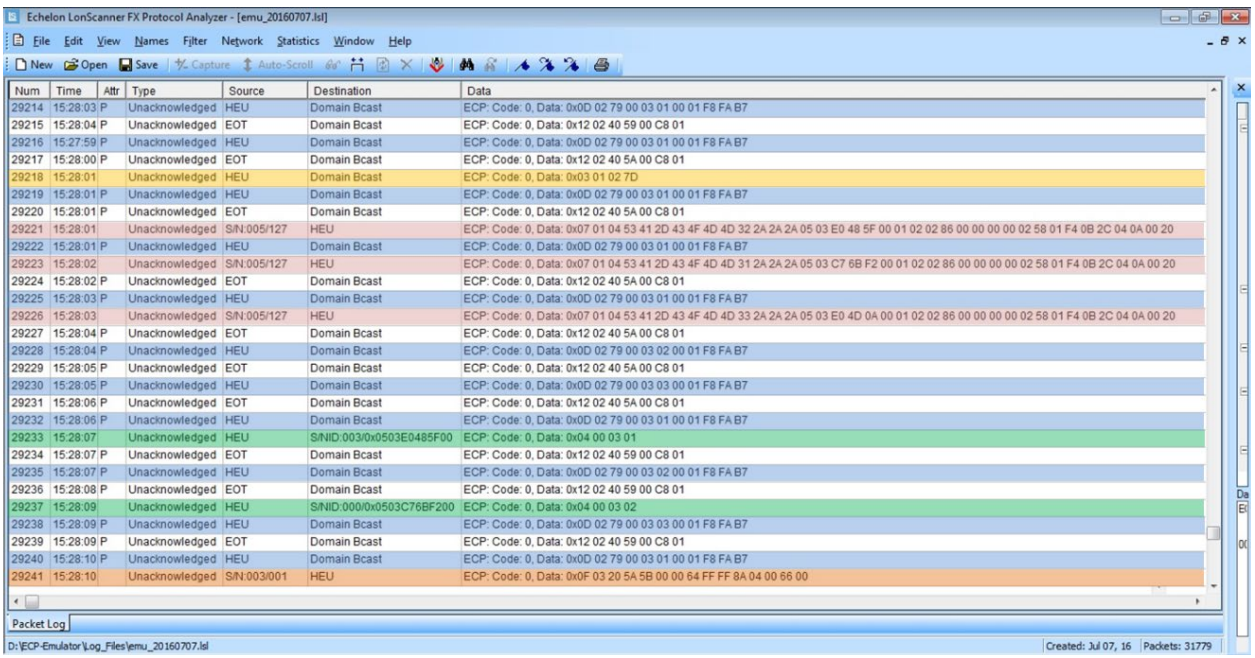
9.4 Train Building

Train building testing was performed using multiple Comm Modules and the HEU simulator, then it was validated by monitoring network communication.

The simulator can send the "Device Info Request" Message to all devices on the network. SA could monitor the network, relate the responses ("Car Static Info" message) from each Comm Module to respective car information. Each response would be sent at different times, which confirmed the randomizing feature. The HEU simulator was programmed to create a CCD database with this information and could then assign appropriate network addresses based on a first-response priority. Thereafter, a Comm Module would respond with its new S/N address. The process was repeated several times to ensure the ECP address allocation changed with train builds. Devices with assigned addresses would also not respond to further device info requests. Testing also confirmed that Comm Modules cannot be assigned a new address unless ECP restarts or the HEU Simulator commanded the device to unlock its address.

Figure 9-7 shows part of a screenshot from the LonScanner Protocol Analyzer network monitor that was taken during a train-build procedure. The analyzer monitors network traffic and records each message in this program. The program lists the time the message was received by the analyzer, the type of message, the priority attribute, the message source, the message destination, and the message contents. For comprehension, certain addresses and message contents were given aliases, which can be seen under the headers (Source, Destination, and Data). Under the source and destination headers, "HEU" represents the HEU Simulator (S/N: 1/2), the EOT is a NYAB EOT (S/N: 2/1), and there are three CCDs listed by their respective S/N address (initial for all S/N: 5/127). Also, messages are colorized by their IDs: "HEU Beacon" is blue, "EOT Beacon" is white, "Device Info Control/Query" is yellow, "Device Info (CCD)" is red, "Assign Node ID" is green, and "CCD Status Response" is orange. Messages are also labeled to the left of the image.

Using this example, the train-build starts with the "Device Info Control/Query" message (yellow) sent from the HEU simulator. Each CCD subsequently responds with its device information "Device Info (CCD)" (red). The HEU simulator then organizes all of the devices based on their Neuron® IDs into a database and designates unique S/N addresses to each (not shown). The HEU simulator then assigns each device its S/N address by sending "Assign Node ID" messages (green) to all three CCDs. Before the last CCD is sent the "Assign Node ID" message (not seen in this screenshot), the first CCD (S/N: 3/1) responds to the HEU beacon (blue) with its "CCD Status Response" message (orange).



Num	Time	Attr	Type	Source	Destination	Data
29214	15:28:03	P	Unacknowledged	HEU	Domain Bcast	ECP: Code: 0, Data: 0x0D 02 79 00 03 01 00 01 F8 FA B7
29215	15:28:04	P	Unacknowledged	EOT	Domain Bcast	ECP: Code: 0, Data: 0x12 02 40 59 00 C8 01
29216	15:27:59	P	Unacknowledged	HEU	Domain Bcast	ECP: Code: 0, Data: 0x0D 02 79 00 03 01 00 01 F8 FA B7
29217	15:28:00	P	Unacknowledged	EOT	Domain Bcast	ECP: Code: 0, Data: 0x12 02 40 5A 00 C8 01
29218	15:28:01		Unacknowledged	HEU	Domain Bcast	ECP: Code: 0, Data: 0x03 01 02 7D
29219	15:28:01	P	Unacknowledged	HEU	Domain Bcast	ECP: Code: 0, Data: 0x0D 02 79 00 03 01 00 01 F8 FA B7
29220	15:28:01	P	Unacknowledged	EOT	Domain Bcast	ECP: Code: 0, Data: 0x12 02 40 5A 00 C8 01
29221	15:28:01		Unacknowledged	S/N:005/127	HEU	ECP: Code: 0, Data: 0x07 01 04 53 41 2D 43 4F 4D 4D 32 2A 2A 2A 05 03 E0 48 5F 00 01 02 02 86 00 00 00 00 02 58 01 F4 0B 2C 04 0A 00 20
29222	15:28:01	P	Unacknowledged	HEU	Domain Bcast	ECP: Code: 0, Data: 0x0D 02 79 00 03 01 00 01 F8 FA B7
29223	15:28:02		Unacknowledged	S/N:005/127	HEU	ECP: Code: 0, Data: 0x07 01 04 53 41 2D 43 4F 4D 4D 31 2A 2A 2A 05 03 C7 6B F2 00 01 02 02 86 00 00 00 00 02 58 01 F4 0B 2C 04 0A 00 20
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 9-6 – Network Monitor Log of Train-Building Process

Num	Time	Attr	Type	Source	Destination	Data
29214	15:28:03	P	Unacknowledged	HEU	Domain Bcast	ECP: Code: 0, Data: 0x0D 02 79
29215	15:28:04	P	Unacknowledged	EOT	Domain Bcast	ECP: Code: 0, Data: 0x12 02 40
29216	15:27:59	P	Unacknowledged	HEU	Domain Bcast	ECP: Code: 0, Data: 0x0D 02 79
29217	15:28:00	P	Unacknowledged	EOT	Domain Bcast	ECP: Code: 0, Data: 0x12 02 40
29218	15:28:01		Unacknowledged	HEU	Domain Bcast	ECP: Code: 0, Data: 0x03 01 02
29219	15:28:01	P	Unacknowledged	HEU	Domain Bcast	ECP: Code: 0, Data: 0x0D 02 79
29220	15:28:01	P	Unacknowledged	EOT	Domain Bcast	ECP: Code: 0, Data: 0x12 02 40
29221	15:28:01		Unacknowledged	S/N:005/127	HEU	ECP: Code: 0, Data: 0x07 01 04
29222	15:28:01	P	Unacknowledged	HEU	Domain Bcast	ECP: Code: 0, Data: 0x0D 02 79
29223	15:28:02		Unacknowledged	S/N:005/127	HEU	ECP: Code: 0, Data: 0x07 01 04
29224	15:28:02	P	Unacknowledged	EOT	Domain Bcast	ECP: Code: 0, Data: 0x12 02 40
29225	15:28:03	P	Unacknowledged	HEU	Domain Bcast	ECP: Code: 0, Data: 0x0D 02 79
29226	15:28:03		Unacknowledged	S/N:005/127	HEU	ECP: Code: 0, Data: 0x07 01 04
29227	15:28:04	P	Unacknowledged	EOT	Domain Bcast	ECP: Code: 0, Data: 0x12 02 40
29228	15:28:04	P	Unacknowledged	HEU	Domain Bcast	ECP: Code: 0, Data: 0x0D 02 79
29229	15:28:05	P	Unacknowledged	EOT	Domain Bcast	ECP: Code: 0, Data: 0x12 02 40
29230	15:28:05	P	Unacknowledged	HEU	Domain Bcast	ECP: Code: 0, Data: 0x0D 02 79
29231	15:28:06	P	Unacknowledged	EOT	Domain Bcast	ECP: Code: 0, Data: 0x12 02 40
29232	15:28:06	P	Unacknowledged	HEU	Domain Bcast	ECP: Code: 0, Data: 0x0D 02 79
29233	15:28:07		Unacknowledged	HEU	S/NID:003/0x0503E0485F00	ECP: Code: 0, Data: 0x04 00 03
29234	15:28:07	P	Unacknowledged	EOT	Domain Bcast	ECP: Code: 0, Data: 0x12 02 40
29235	15:28:07	P	Unacknowledged	HEU	Domain Bcast	ECP: Code: 0, Data: 0x0D 02 79
29236	15:28:08	P	Unacknowledged	EOT	Domain Bcast	ECP: Code: 0, Data: 0x12 02 40
29237	15:28:09		Unacknowledged	HEU	S/NID:000/0x0503C76BF200	ECP: Code: 0, Data: 0x04 00 03
29238	15:28:09	P	Unacknowledged	HEU	Domain Bcast	ECP: Code: 0, Data: 0x0D 02 79
29239	15:28:09	P	Unacknowledged	EOT	Domain Bcast	ECP: Code: 0, Data: 0x12 02 40
29240	15:28:10	P	Unacknowledged	HEU	Domain Bcast	ECP: Code: 0, Data: 0x0D 02 79
29241	15:28:10		Unacknowledged	S/N:003/001	HEU	ECP: Code: 0, Data: 0x0F 03 20

Figure 9-7 – Network Monitor Log of Train-Building Process with Message Labels

Part of train-build testing was performed without the Car ID Module, by programming static and unique Car information in the Comm Module. This ensured that train building worked independent of the Car ID Module. Once the Car ID Module was sufficiently tested, all Comm Modules were programmed without unique car information and tested for train building and Car ID read operation.

9.5 Car Sequencing

After confirming each Comm Module's and Car ID Module's hardware and software functioned independently, it was necessary to test multiple connected CCDs to validate the sequencing process at a system level. SA tested sequencing for all three Comm Modules and three Car ID Modules by testing all combinations of CCD ordering and testing different combinations of Comm Module and Car ID Module. The HEU simulator was programmed to send the necessary messages for sequencing and would display the results after sequencing was complete. The program was set up so that the user had complete control of all messages, which proved useful for ensuring CCDs only take the necessary actions at required times according to S-4200 and S-4230. Sequencing was verified for all Comm Modules and Car ID Modules.

9.6 Normal Operations

9.6.1 ECP

Aside from the special ECP functions outlined, testing was also performed to ensure proper brake control and normal system responses. Using fully assembled CCDs (Junction Box and CCD Manifold on pipe bracket), the HEU simulator was used to command normal operations for ECP. The user interface of the HEU simulator displayed CCD information from status messages and other train-wide configurations on a terminal emulator.

For example, after initializing the train (for ECP address assignment), SA would command the HEU simulator to change the TBC. This change would show up on the network and on the display. Brake cylinder could be visually observed for brake applications, and pressure gages were used to confirm the pressure readings (measured by Brake Controller pressure transducers and transmitted on the ECP line by the Comm Modules) seen on the network. Varying TBC would effectively change the BCP, and was easily verified this way. Network monitor logs were often exported to Microsoft® Excel workbooks to plot brake responses for all CCDs. This allowed SA to validate the BCP control criteria outlined in the S-4200. However, only one CCD responds to the HEU beacon with a status response at a time and the pressures relayed to the HEU only update once every polling cycle for any given CCD. For example, in a three-car train, pressure readings update to the network once every three seconds, even though the pressure transducers are being read by the CCD more often (the Brake Controller requests pressure transducer readings every 50 ms and the Comm Module requests pressures from the Brake Controller every 100 ms).

While the simulator monitors network communication with pressure readings, pressure readings were taken with a data acquisition unit (DAQ), SoMat eDAQlite, and external pressure transducers. By using a DAQ, SA could record pressure readings at a much higher sample rate and resolution than what is displayed on the network. Figure 9-8 shows ECP testing with the HEU simulator, the network monitor, and the DAQ.

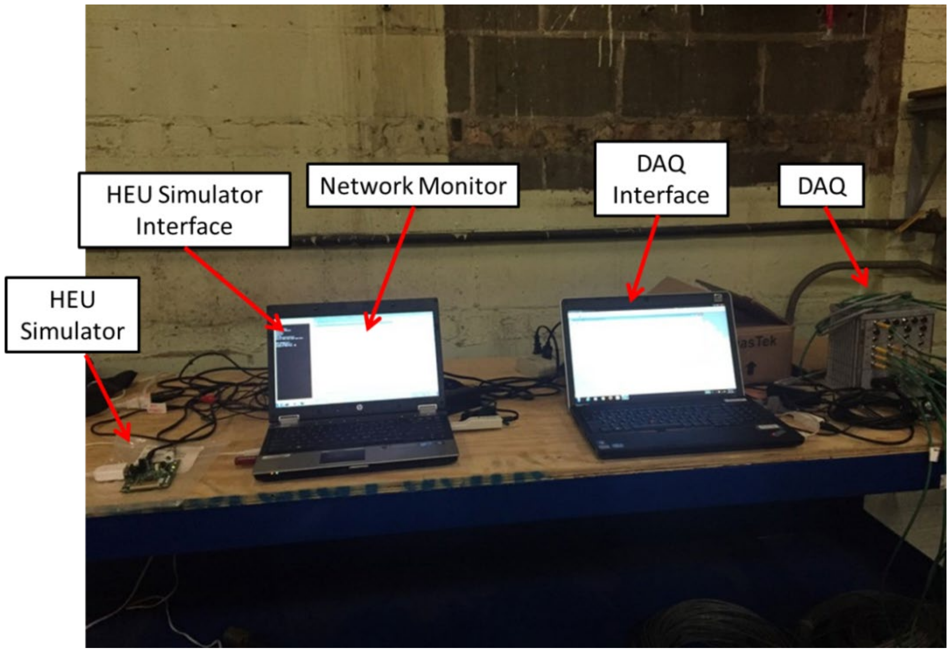


Figure 9-8 – ECP System Testing Using a DAQ

Figure 9-9 and Figure 9-10 show example plots from brake applications displaying three CCD's BCPs, which were collected from the DAQ. In both plots, TBC (purple in the plot) from the network log is synchronized and superimposed to show brake response times. Figure 9-9 shows three separate brake applications from a full release: Minimum Service Pressure (MSP), Full Service Pressure (FSP), and ECP emergency. Figure 9-10 shows a graduated brake application, from full release to full-service (10 percent increments), and a graduated release, from full service to fully released (10 percent decrements). As can be seen, all CCDs actuate the brakes similarly to each other, and respond appropriately to the TBC.

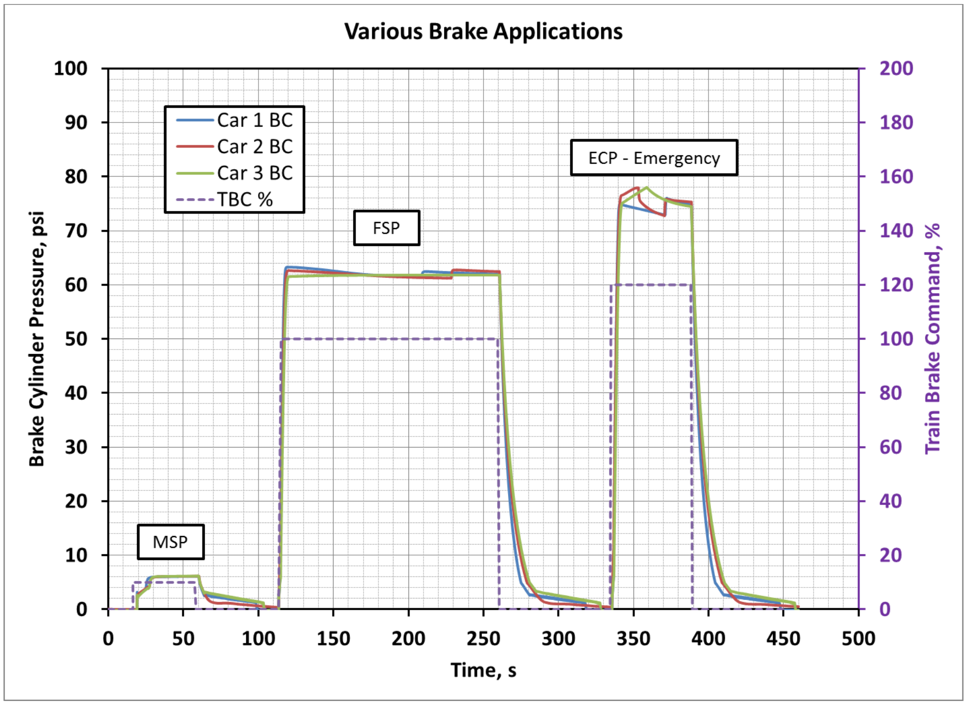


Figure 9-9 – Three ECP Brake Applications: MSP, FSP, and Emergency

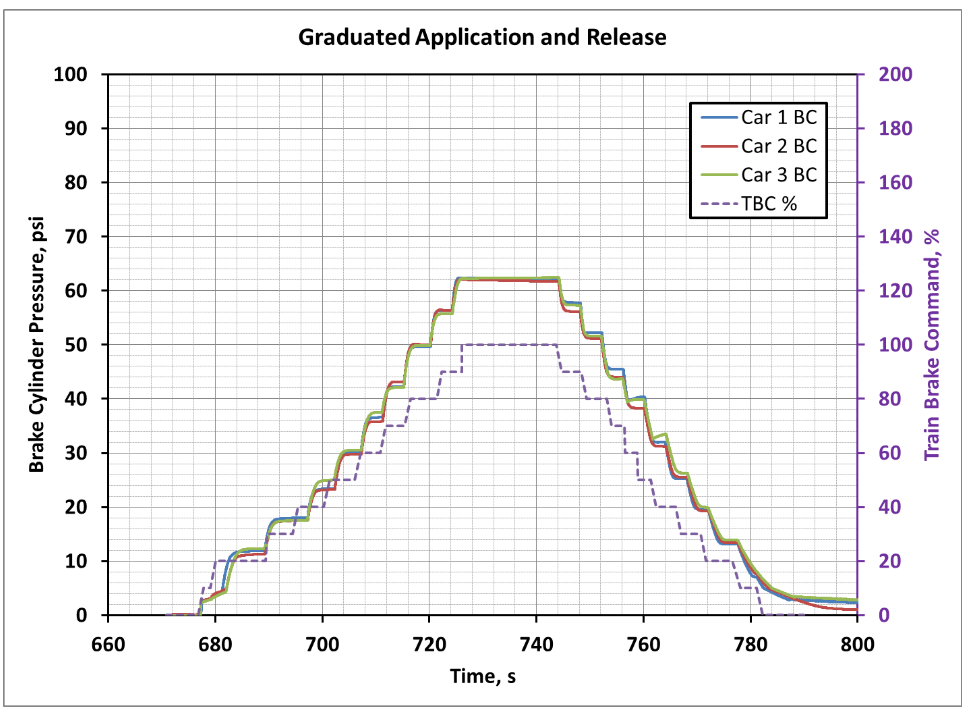


Figure 9-10 – Graduated Full Service Brake Application and Release

9.6.2 Pneumatic Emulation

Pneumatic emulation was tested by controlling the BPP from the locomotive control stand's brake handle (in the test stand) and monitoring the actions from the Brake Controller and CCD pneumatics. Figure 9-11 shows several brake applications in the pneumatic emulation mode. As shown in the plot, for each brake application, the BCP increases to the appropriate amount based on the BPP reduction.

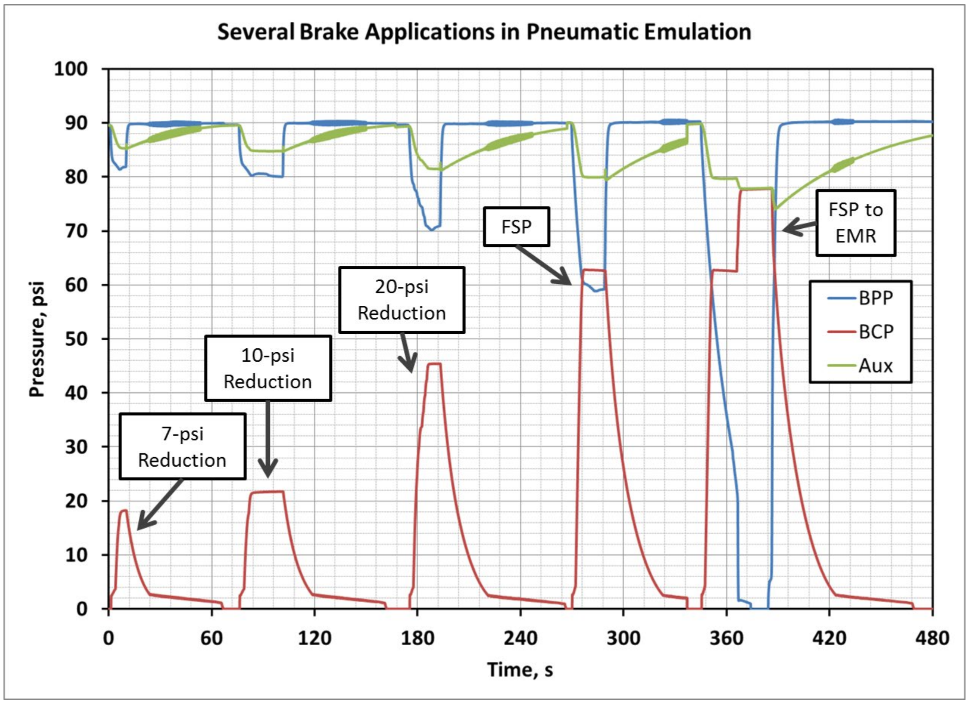


Figure 9-11 – Pneumatic Emulation Brake Applications

As part of the PPG testing, SA recorded measurements of the battery power consumed for various applications during pneumatic emulation.

9.7 Response to Faults

Fault testing was executed in two main phases, which were based on the priority of the fault. ECP faults are enumerated in the S-4200 and have defined priorities so that the system handles the most critical faults first. ECP faults fall in to two categories: critical and normal. Normal exceptions for the most part require no action and sometimes instruct the HEU to cut-out the faulty CCD. Critical exceptions can impede performance and lead to system degradation. Normal exceptions were tested with the Brake Controller communication utility, which could communicate with the Comm Module by simulating Brake Controller transmissions. SA used this communication utility to manipulate the pressures and battery voltage data that were sent to the Comm Module in order to force exceptions (e.g., Low Reservoir Exception and Incorrect BCP Exception). These tests successfully validated the normal exception faults. Critical exceptions were partially tested using this scheme also. To fully validate critical faults, however, critical faults were tested with multiple CCDs assembled in the ECP test rack.

Special routines were programmed in the HEU Simulator that allow SA access to further test fault responses. One such routine was used to stop HEU transmissions to elicit a Loss of Communication fault. Then, by monitoring network activity and brake applications, SA could validate the procedures were successfully implemented.

9.8 Battery Performance

An emulator CCD must be able to function for at least 48 hours [2]. Tests were conducted to verify the power requirements for emulation. SA verified this criterion for the stationary condition by powering a CCD emulator (i.e., Brake Controller only) with a fully charged battery and not interfering with it for at least 48 hours. After such time, SA performed a series of brake applications to which the emulator successfully responded.

SA continued to leave the emulator powered strictly through the battery, without external power, for at least 2 weeks. During this period, SA made various brake applications and releases in emulation at varying pressures. After this period, it was observed that the battery maintained a nominal charge, and the emulator's performance did not change.

9.9 PPG Integration

Tests were performed on the PPG to confirm its ability to recharge the battery during emulation mode. Tests were conducted for varying battery voltages and various brake applications, and data was collected to correlate the BCP with the power produced by the PPG. Additional tests were conducted to calculate energy dissipated by the battery without the PPG as compared to net energy dissipated with the PPG installed. Battery voltage and current from the battery to the Brake Controller were measured simultaneously. Their product (power) was integrated over time to determine net energy into or out of battery. All the PPG tests were performed using the same CCD and PPG. Current and voltage measurements were collected at high resolution (battery voltage at 0.5 mV, and current at 0.5 mA). Both measurements were also collected at high sample rates to ensure that Brake Controller functions were fully captured.

Figure 9-12 and Figure 9-13 show two sets of results from PPG testing: one without the PPG connected and the other with the PPG connected. Typically, the battery voltage did not change over any one particular test. The battery voltage for both of these tests was 12.50 V. Positive current is defined as the direction of current flow from the battery's positive terminal to the Brake Controller. Each figure shows current draw for a brake application and its corresponding release. A 20-psi brake pipe reduction was used in each case, resulting in about 40 to 45 psi cylinder pressure.

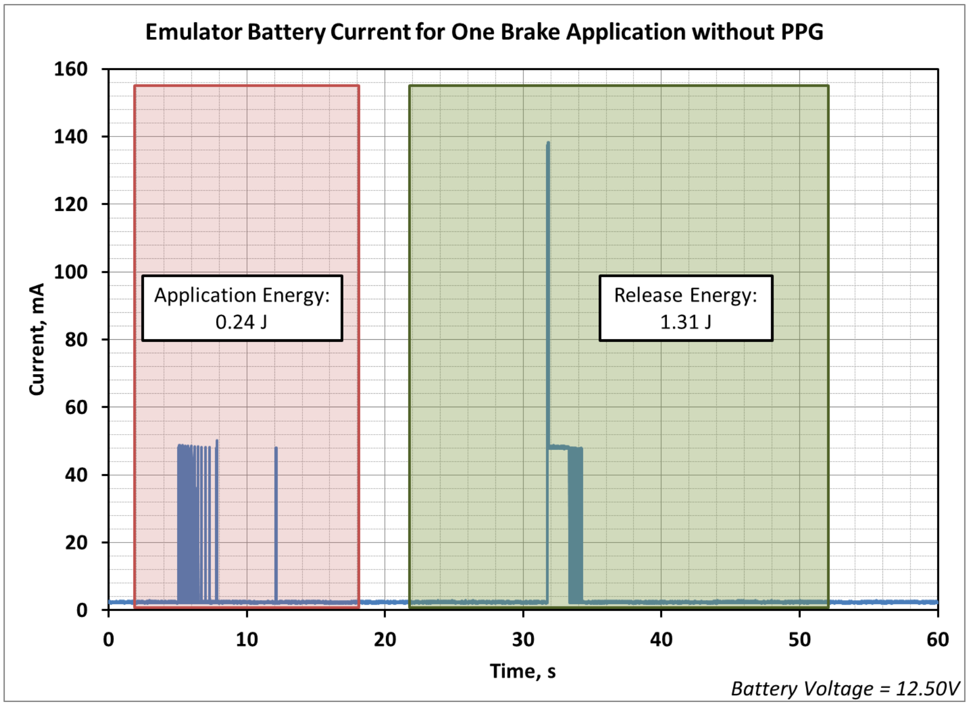


Figure 9-12 – CCD Emulator Battery Current and Energy Consumption Without PPG

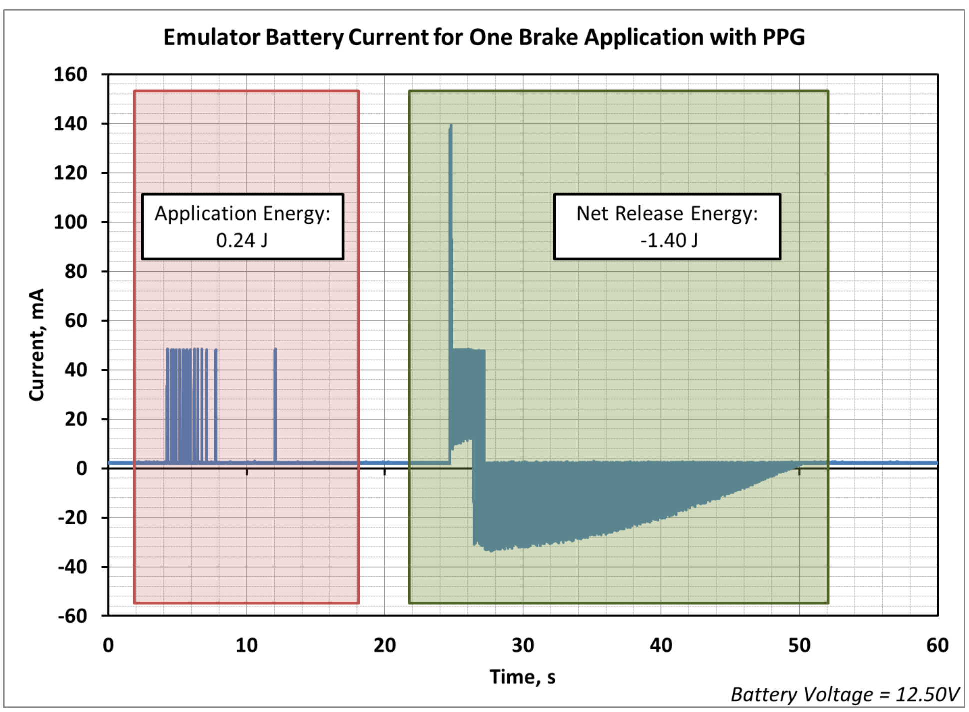


Figure 9-13 – CCD Emulator Battery Current and Net Energy Produced with PPG

All brake applications typically draw current in 50 mA pulses. The pulse width and number of pulses relate to the rate of pressure change in the brake pipe. Releasing brakes typically draws a 140-mA spike initially and then subsides. Standby mode is when the Brake Controller is performing minimal functionality, mainly periodic monitoring of the pressures. When there is no action taken by the Brake Controller, standby mode occurs regardless of whether brakes are currently applied. Typically, the current draw from standby is 2 mA. As seen in the plots, the standby current is 2 mA, the brake application current is 50 mA, and the release current is initially 140 mA and afterwards steady at 50 mA. Since the two brake applications shown in these figures are about the same magnitude, the duration of the current draw is similar. After a brake release without the PPG, the current stabilizes to the steady-state current. However, with the PPG, modulated negative current is produced before stabilizing to steady-state. According to the defined polarity, negative current flow shows that energy is being provided from the PPG, through the Brake Controller's charging circuit, to the battery.

In each test (with and without the PPG), the energy drawn by the Brake Controller to apply brakes was 0.24 J. The energy required to release the brakes, without the PPG, was 1.31 J. In the test with the PPG, the net energy drawn by the Brake Controller to release the brakes was negative 1.40 J, indicating that 1.4 J was returned to the battery. Thus, for a single brake application and release cycle, the PPG is able to recharge the battery with slightly more than one Joule of energy. These energy calculations do not include standby energy, which (at 2 mA) amounts to about 25 mW, or 1.5 J per minute. Since brake application and release cycles occur much less frequently than every 40 seconds, the PPG system cannot be relied upon to provide battery recharging indefinitely.

These test results show that the PPG provides net energy to the battery during a cycle of applying and releasing the brakes, but cannot completely compensate for the standby power that is consumed over time. However, the standby power consumption is very low: on the order of 25 mW, which is equivalent to about 1.5 amp-hours per month for the 12.5 V battery. Therefore, during normal pneumatic brake operation, the PPG can be expected to provide more than enough energy to cover the active braking functions, thus extending the amount of time the CCD can run in emulator mode without external charging. In fact, laboratory testing confirmed that after 2 weeks of standby operation, the system still functioned normally and battery voltage remained at its full 12.5 V.

9.10 Summary of System Testing Results

In a laboratory setting, SA tested the new emulator CCD to validate normal operation, brake applications, interoperable communication, and fault detection. SA verified that the hardware used in the CCD could perform the functions of both an ECP CCD and a pneumatic emulator. This meant testing both circuit boards of the dual-board scheme: the Brake Controller for brake operations and emulation, and the Comm Module for ECP processes.

The Brake Controller was shown to effectively control the brakes, in conjunction with the CCD manifold (e.g., pneumatic relays and worm-plate), as evidenced by the BCP response to BPP reduction in emulation mode and by changing TBC in ECP mode. The effective brake control response to changing TBC also confirmed the communication between the Brake Controller and Comm Module. Whether by monitoring changes in the brake pipe or receiving a brake command, the Brake Controller appropriately operated pneumatic valves to change the air in the brake cylinder. In emulation, the brake response was compared to conventional pneumatic brake responses. In ECP, the brake response was compared to the S-4200 criteria for brake control. The testing was conducted with the PPG confirmed the charging circuit operates as intended.

The Comm Module was shown to operate satisfactorily as a CCD in an ECP system. By using the HEU Simulator device to transmit HEU messages and by monitoring network communication, it was verified that the Comm Module performs the necessary ECP functions in all tested modes.

In initialization mode, train-building was verified in a multiple car ECP system by monitoring the network transmissions between each Comm Module and the HEU simulator. All message transactions were scrutinized to ensure each byte in each message was accurate. When prompted by the HEU simulator to send car information, each device responds accordingly with the appropriate device information. By viewing the device information contents, SA could confirm the communication between the Comm Module and Car ID module, since the device information is coded in the Car ID module. To further emphasize this point, SA rearranged the Comm Modules and Car ID modules for all combinations to ensure that the device information that was reported by the Comm Module would change according to which Car ID module it was connected to. Also, as a consequence from a successful build, the Comm Module would respond to messages sent to its new S/N address.

Using a similar method, car sequencing was verified through network communication. Sequencing hardware, such as the current sensor and shunt, was tested on its own and in a multiple CCD ECP system. The results of a sequencing event could be seen on the network and on the HEU simulator GUI. By observing the network and HEU simulator GUI, it was confirmed that sequencing was implemented successfully, such that each CCD would accurately determine its position based on the S-4200 sequencing procedure. These tests also show the Car ID module satisfies its requirements.

As indicated in Section 9.6 of this report, brake operations were confirmed by observing the brake cylinder response to varying TBCs sent by the HEU simulator. By comparing the amount of cylinder pressure to the TBC and to the S-4200 criteria for brake control, brake functionality for the CCD (Comm Module and Brake Controller) was confirmed. Additionally, changing certain car information, such as weight, and cutting-in or cutting-out a particular CCD further confirmed specific functionality of brake control.

Handling and detection of exceptions and faults were tested and validated by inducing a fault in the system. When a fault was induced on a specific CCD, the CCD would transmit a fault-specific exception message on the network. This might be followed by some action depending on the type of fault, notably for system critical faults such as Loss of Communication or Loss of Brake Pipe. By monitoring network communication for exception messages and observing how the CCD responds to a specific fault, exception detection was confirmed. Similarly, faults would be resolved to validate the requirements for clearing exceptions. Inducing additional faults to an already fault-induced CCD confirmed the hierarchy established in S-4200 and validated how a CCD is supposed to handle multiple faults. As stated, CCDs are required to take an action after a critical fault is detected. This can either be cut-out the CCD or perform an ECP emergency, respectively depending on whether the fault is isolated to a single CCD or experienced on multiple devices. By monitoring network communication and observing brake operations, all combinations of normal and critical faults were tested.

PPG operation and battery compliance were confirmed through testing. Without any external charging, the emulator was able to function from a fully charged battery after 48 hours. Furthermore, it continued to function optimally throughout an extended period of 2 weeks.

Performance testing was conducted to determine how much energy the PPG actually contributes to the battery. It was found that the PPG can fully compensate the energy consumed for brake applications, but charging the battery depends on how often and for how long brake applications are executed.

10. Plan for Service Demonstration of ECP Emulator

Though many of the S-4200 and S-4230 requirements were demonstrated in a laboratory setting during this phase, field testing is necessary to confirm the remaining requirements. One such requirement that could not be fully tested in a lab is interoperability. SA has demonstrated some interoperability by testing its CCD and a NYAB CCD (EP-60) on the same ECP network with the testing devices and environment mentioned earlier. To fully comply with the interoperability requirements, it must be demonstrated that this CCD successfully operates in an ECP train with equipment from multiple manufacturers. Specifically, this CCD must operate in an ECP train with another manufacturer's HEU, PSC, CCDs, and EOT. The remaining ECP equipment does not need to come from a single manufacturer, but the equipment must be S-4200 compliant already.

This would require an ECP-equipped locomotive, car(s) with ECP CCD, and an ECP-compatible EOT device. All tests conducted in the lab to validate the ECP requirements should be performed again to further validate interoperability. Below is a representative list of functionality testing for a field demonstration.

Table 10-1 – Representative Test Matrix for Field Demonstration

	ECP MODE
INTIALIZATION	• Train build • Car sequencing
RUN	• Graduated application to full service • Graduated release • Emergency application and release/recovery • Pneumatic backup (low brake pipe pressure, emergency) • Response to HEU requests for information
SWITCH	• Operate without trainline power • Graduated applications and releases • Emergency and pneumatic backup
CUT-OUT	• Release of brake cylinder pressure • No response to HEU brake commands • Pneumatic backup
	ECP Faults
Car-level Faults	• Low brake cylinder pressure • Stuck brake • Low battery • Low reservoir pressure
Train-level Faults	• Response to loss of brake pipe pressure • Response to loss of HEU beacon
	EMULATION MODE
• Minimum application and release • Partial application and release • Full service application and release • Graduated application to full service and release • Emergency application and release	

SA can conduct such the service tests on Indiana Northeastern Railroad (IN). At IN's facility in Hudson, IN, there is an NYAB ECP system equipped GP-40 locomotive (DOTX-2000) that has been previously used for various field tests conducted by SA for FRA projects, including the Advanced Concept Train which featured ECP brakes on all five of its cars.

The proposed plan would be to perform field tests using three emulator CCD equipped freight cars. Testing will be separated into two parts: ECP and emulation. For ECP testing, the test consist will be the DOTX-2000, three emulator CCD equipped cars, multiple NYAB CCD equipped cars, and multiple Wabtec CCD equipped cars. An ECP EOT will be attached to the last car to complete the ECP network. For emulation testing, the test consist will be the DOTX-2000 locomotive, three emulator CCD equipped cars, and multiple conventional freight cars.

11. Conclusion

Electronically controlled pneumatic (ECP) brakes can improve safety, train handling, and improve other factors of performance for freight trains. Realizing an industry wide implementation with existing standalone ECP technologies faces obstacles, including installation costs and not being backwards compatible with conventional brake systems. Since standalone ECP equipped cars cannot be used in conventional trains, their effectiveness is limited.

Overlay-type ECP Car Controlled Devices (CCD) overcome this problem by containing two different systems, which allows them to perform in an ECP train and a pneumatic train. However, the emulator CCD, an alternative integrated one-system solution, was developed by ZefTron. The emulator CCD can operate in both ECP and conventional trains, which overcomes one of the major issues with standalone ECP. Emulation can make it easier to implement ECP for the entire U.S. fleet of railcars. This technology was developed before the ECP standards were finalized. In a previous effort, SA performed a cost-benefit analysis on the emulation technology for industry implementations.

This effort called for updating the existing ECP Emulator technology for industry compliance with the AAR MSRP S-4200 and S-4230 standards. SA built upon the technology developed by ZefTron to modernize the emulator CCD concept. To fully develop a compliant system, SA redesigned the emulator CCD using modern electronics in a sustainable design. In addition, to optimize the system and comply with the power requirements, the CCD was configured into two physically separate circuit boards: the Comm Module performed ECP communication and basic operations, and the Brake Controller performed brake operations in ECP and emulation modes.

The Comm Module was developed around an Echelon Smart Transceiver PL3150 microcontroller. The Brake Controller was developed around a TI MSP 430 microcontroller. As a result of new hardware, the existing software for the emulator device was completely rewritten for the new dual-board configuration.

Through comprehensive testing of the new hardware and software, the updated emulator satisfied a majority of the ECP requirements that could be tested in a laboratory setting. These tests include validating the initialization processes (e.g., train-building, car sequencing), normal operations (e.g., brake applications, diagnostics), and fault detection and error handling. The remaining requirements were not completely validated, but they were set out for laboratory testing, have been implemented in software and preliminarily tested.

However, not every test that is required to fully demonstrate compliance can be conducted in a laboratory setting. One feature of ECP that cannot easily be tested in SA's laboratory setting is interoperability with other ECP manufacturer's equipment. By developing the emulator software and hardware to comply with the S-4200 and S-4230 standards, the emulator can operate with other manufacturer's ECP equipment. For completeness, SA has determined that a service demonstration would provide evidence that the emulator completely satisfies the interoperability ECP requirements. SA has outlined a series of tests that should be used to confirm the emulator's industry readiness.

SA also recommends quantifying the battery and PPG more extensively. For various applications and at varying battery voltages, the PPG will extend the battery's charge and emulator operation without the need of an external power supply. Performing additional tests for the full range of the battery’s capacity and analyzing the net energy gains for more brake application cycles would greatly improve the PPG model and advance the emulator’s design.

12. References

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Appendix A.
ECP CCD Requirements from S-4200

Table A-1 – S-4200 Requirements Applicable to CCD, and Associated Test Procedures

Paragraph of S-4200	Summary of CCD requirement	Test procedure	Results
3.9	Car ID module must be tied to car (not CCD).	In a one car train, note the reporting mark in the Device Info (CCD) message. Replace the Comm Module and confirm the vehicle reporting mark stays the same in the Device Info (CCD) message.	Passed
4.2.3	CCDs must wake up and begin to cut-in within 2 seconds of seeing ≥100 VDC on the ECP trainline.	Start with trainline power turned off, CCD in sleep mode, and brake in emulator mode. Apply 105 VDC to the ECP trainline and confirm that a (randomly selected) CCD transitions from sleep mode to low power mode within 2 seconds.	Passed
4.2.3 (cont'd)	Train makeup: CCD must communicate with HEU to update ECP S/N address during initialization.	Set up a three car train. Turn power on. Send a Device Info Query message to all devices. Confirm that each CCD responds with a Device Info (CCD) message containing unique information specific to that CCD and Car ID module combination. Send an Assign Node message to each CCD with a unique S/N address. Confirm that each CCD subsequently responds to HEU Beacons with a CCD Status Response message according to its newly assigned S/N address.	Passed

Paragraph of S-4200	Summary of CCD requirement	Test procedure	Results
4.2.3.1	Provide sequencing capability. Determine sequential position of each vehicle (CCD) in the train consist with an accuracy of +/- 0 vehicles.	Initialize a three car train so that each CCD has an ECP address. Broadcast a Train Sequencing Command message with Prepare for Sequencing bit set. Turn off power, and clear the trainline bit in the HEU Beacons. Turn power to 24V. Send a Train Sequencing Command message with Reset Pulse Count bit set. Send a Vehicle Sequence Command with Connect Load bit set to first CCD in database (first S/N address). Confirm that CCD responds with a Vehicle Sequence Status (Applied) message and then with a Vehicle Sequence Status (Removed) message. Repeat sending a Vehicle Sequence Command message to the remaining CCDs. Confirm each CCD responds accordingly with two Vehicle Sequence Status messages—first with the Load Applied bit, and then with the Load Removed bit. Send a Train Sequencing Command (Stop Pulse Count) message. Send a Vehicle Sequence Info Query (Update Position) message to each device. Confirm that each device responds accordingly with a Vehicle Sequence Info message containing its correct position in the train. Send a Train Sequencing Command (End Sequencing). Confirm normal operation resumes.	Passed
4.3.2.1	Network communication diagnostic testing support: Maintain record of CRC error counts Reset count upon start-up and when commanded by HEU Report to HEU when count exceeds threshold specified by HEU	Monitor the CCD Status Response message for proper value of CRC Error Count Threshold bit. Check upon system startup (count reset to zero), during normal operation, after command from HEU to reset the CRC error count, and after command from HEU changing the value of the CRC Error Threshold. These HEU commands are sent in the Train Dynamic Configuration message.	Passed
4.3.5	Minimum service TBC shall be at 10%. Default value for minimum service BCP is 7 psi, but other value can be provided in car ID.	Delete minimum BCP (MSP) setting from Car ID module. This forces CCD to use default value. Apply minimum brake application in ECP mode. Confirm that TBC is 10% (shown on HEU display and in HEU Beacon message). Confirm that BCP is 7 psi. Repeat test with a value of 10 for MSP in Car ID module. Confirm that BCP develops to 10 psi.	Passed

Paragraph of S-4200	Summary of CCD requirement	Test procedure	Results
4.3.6.1	CCD shall supply BCP corresponding to the train NBR transmitted by the HEU.	Initialize train as loaded. Do not explicitly change NBR (use default value). Apply full service ECP brake (TBC = 100%). Confirm that BCP at each car corresponds to the value of FSP (full service pressure), as given by FSP = NBR * W / C where NBR = 12.8% (default train net braking ratio), W is loaded car weight and C is braking constant. Car loaded weight and braking constant are programmed into the Car ID Module. Change NBR to 10% with Train Dynamic Configuration message. Release and reapply full service ECP brake and confirm that BCP at each car corresponds to its calculated FSP.	Passed
4.3.7	Full service BCP (FSP) is calculated by CCD based on car weight (W), train net braking ratio (NBR), and C (brake constant for car). FSP = NBR * W / C. Car empty weight, loaded weight and brake constant are programmed into the Car ID Module. Additional algorithms define limiting values (minimum and maximum) for FSP.	Initialize train as loaded and TBC = 0%. Apply MSP ECP Brake (TBC = 10%). Confirm that each car applies brake per its Car ID Module MSP. Apply FSP (100%). Confirm each car applies brake per Weight, NBR, and C. Change train load to empty. Repeat an MSP brake application to confirm the pressure does not change. Repeat an FSP application to confirm the pressure changes according to the load.	Passed
4.3.9	CCDs must be capable of responding to an empty/load (E/L) command directed to an individual CCD as well as a train empty/load command. Each CCD must determine its own car loading value upon initialization, and update its value, if appropriate, whenever new load data information becomes available.	Initialize train as loaded. Send a CCD Dynamic Configuration to a particular CCD with E/L status to 255 (maintain car weight). Check CCD Status Response for 100% Car Load. Change E/L status in CCD Dynamic Configuration to 50%. Check CCD Status Response for 50%. All other CCDs should report 100% still. Change HEU Beacon E/L fields to both Empty. All CCDs should report 0% in the Status Response.	Passed

Paragraph of S-4200	Summary of CCD requirement	Test procedure	Results
4.3.13.3	Warning to engineer whenever CCD cuts out on emulator-equipped car without stuck brake protection.	Command a car's brake to cut out (from HEU interface). Monitor message traffic and confirm that the affected CCD sends a CCD cutout message to the HEU with status field bits 0 and 1 set (=1), and other bits cleared (=0). Bit 4 cleared indicates stuck brake protection is not active, which is the case for the emulator CCD.	Passed
4.3.14.1	Battery power. A CCD with fully charged battery must be capable of operating at least 4 hours (in ECP mode) on battery power alone.	While in ECP run mode, disconnect power supply to ECP trainline. Confirm that CCDs continue to operate normally in ECP mode for at least 4 hours.	Passed
4.3.14.2	Low power mode, commanded by HEU. Power consumed by CCD, including battery charger, limited to 10 W peak. In low power mode, the average consumption of a CCD over any 15-minute period is limited to 5 W.	Monitor and record power consumption of CCD during ECP mode operation. Confirm that power never exceeds 10 W. Identify operation with highest power consumption. Command low power mode (Train Dynamic Configuration message). Monitor power consumption of CCD during maximum power consumption activity (as previously identified) and confirm that average power over any 15-minute period never exceeds 5 W. Command normal power mode (Train Dynamic Configuration message) and confirm that CCD reverts to normal power mode. Confirm that CCD enters low power mode upon initial power-up and reverts to normal power mode if no low power mode command is received within 2 minutes.	Passed: Maximum power is 4 W (transition from low to normal power mode, very short duration). Message transmittal uses 3 W (for about 0.1 seconds). Average power consumption in normal power mode is 0.7 W. Average power consumption in low power mode is 0.5 W.

Paragraph of S-4200	Summary of CCD requirement	Test procedure	Results
4.3.17	Shutdown (battery conservation) mode. In shutdown mode, a CCD turns off to conserve battery power. Operation, from both trainline and battery power, is ceased and BCP is released.	1) From ECP run mode, remove trainline power. Confirm that CCD remains active (using battery power) and responds to HEU brake commands. With brake application in effect, turn off HEU. Confirm that 1 hour later, the CCD enters shutdown mode, releasing cylinder pressure. 2) From ECP run mode, remove trainline power. Confirm that CCD remains active (using battery power) and responds to HEU brake commands. With brake application in effect, turn off HEU and reduce the brake pipe (at service rate) to zero. Confirm that CCD enters shutdown mode, releasing cylinder pressure, within 2 minutes. 3) From ECP run mode, remove trainline power. Confirm that CCD remains active (using battery power) and responds to HEU brake commands. With brake application in effect, command CCD to cutout, then turn off HEU. Confirm that CCD immediately enters shutdown mode, releasing cylinder pressure. 4) From ECP run mode, remove trainline power. Confirm that CCDs remain active (using battery power) and respond to HEU brake commands. With brake application in effect, enter the ECP Cutout operating mode, then turn off HEU. Confirm that all CCDs immediately enter shutdown mode, releasing cylinder pressure.	Passed
4.3.18.3	CCD status message shall include BC pressure (psig), car hand brake status, trainline power status, etc. Compare to 5.4.3 of S-4230 Intratrain Communication Specification, which specifies the format of the CCD Status Response message.	Confirm through network log while polling CCDs	Passed

Paragraph of S-4200	Summary of CCD requirement	Test procedure	Results
4.3.22.1	CCD shall indicate to HEU (as part of its Device Info (CCD) message) whether the car has hand brake apply/release sensing and/or control.	Confirm the bits 4, 5, and 6 are cleared in the Device Info (CCD) message.	Passed
4.4	General priority hierarchy implemented for Exception codes. When in an emergency, CCD's shall suppress all exception messages, except Critical Losses. Exception-Clear messages are always allowed.	Connect the Brake Controller communication utility to the Comm Module. Reduce BPP to 40 psi or less. Confirm that the Loss of Brake Pipe Pressure Exception message is sent. Send a battery voltage of 2 V to the Comm Module through the communication utility. Confirm that the Low Battery Exception message is not sent. Restore the BPP above 65 psi. Confirm that the Low Battery Exception message is sent.	Passed
4.4.2.2.1	Loss of HEU Beacon	Start with a one car train. Stop HEU Beacon transmissions for one CCD for at least 6 seconds. Confirm the CCD maintains current brake application and sends a Loss of HEU Beacon Exception message.	Passed
4.4.2.7.3	CCD detects that its transceiver is generating uncontrolled signal transmissions and shuts off its transceiver and cuts itself out.	N/A	Echelon confirmed, via email to SA, that PL3150 hardware is not susceptible to the uncontrolled transmission problem that existed in previous transceiver model(s).
4.4.3.3	Loss of BPP	Start with a one car train. Reduce BPP to 40 psi or less. Confirm that the Loss of Brake Pipe Pressure Exception message is sent.	Passed

Paragraph of S-4200	Summary of CCD requirement	Test procedure	Results
4.4.4.1	System Critical Loss – Multiple CCDs See Critical Fault State Diagram, Fig. A-1, for schematic representation of System Critical Loss logic (S-4200 paragraphs beginning with 4.4.4).	1) For a multiple car train, stop HEU transmissions for at least 6 seconds. Confirm that all CCDs send a Loss of HEU Beacon Exception message, and then immediately do an emergency application. 2) For multiple car train, reduce BPP to 40 psi or less. Confirm all CCDs send a Loss of Brake Pipe Pressure Exception message and immediately do an emergency application.	Passed
4.4.4.1	Multiple CCDs—Non Fault	1) For a two-car train, reduce the BPP to 40 psi. Confirm both CCDs send a Loss of BPP Exception message and immediately do an emergency application. 2) For a three-car train. Pneumatically cutout one CCD. Reduce the BPP to 40 psi. Confirm that two CCDs send the Loss of BPP Exception messages, and all three CCDs do an emergency application. 3) For a two-car train, stop the HEU communication. Wait 6 seconds. Confirm that the Loss of HEU Beacon Exception messages are sent and that the CCDs do an emergency application.	Passed

Paragraph of S-4200	Summary of CCD requirement	Test procedure	Results
4.4.4.1.1	Critical Loss Relay	1) Initialize a three-car train. Apply a TBC of 50%. Pneumatically cutout the second CCD. Isolate the second CCD from the train by disconnecting the trainline from that CCD and connecting the trainline from the first CCD directly to the third CCD. Wait 11 seconds and confirm that the second CCD cuts-out and releases its brakes. Reduce the BPP to 40 psi. Confirm that CCD #1 and CCD #3 go to a self-initiated emergency application. Reconnect the trainline to the second CCD. Confirm that the Critical Loss Relay Exception message is sent and that the second CCD goes into emergency. 2) Initialize a three-car train. Stop all HEU communication. Confirm that Loss of HEU Beacon Exception messages are sent. Confirm that all CCDs self-initiate emergency. Wait 5 seconds. Confirm that a Critical Loss Relay Exception message is sent from each CCD every 5 seconds for the next 60 seconds. 3) For multiple car train, reduce BPP to 40 psi or less. Confirm all CCDs send a Loss of Brake Pipe Pressure Exception message and immediately do an emergency application. Wait 15 seconds and confirm that the Critical Loss Relay Exception messages are sent every 5 seconds. Send the HEU Beacon with TBC of 120%. Wait another 15 seconds to confirm no Critical Loss Relay Exception messages are sent. 4) For multiple car train, reduce BPP to 40 psi or less. Confirm all CCDs send a Loss of Brake Pipe Pressure Exception message and immediately do an emergency application. Wait 15 seconds and confirm that the Critical Loss Relay Exception messages are sent every 5 seconds. Send the Train Dynamic Configuration message with the Reset Fault Logic bit set. Wait another 15 seconds to confirm no Critical Loss Relay Exception messages are sent.	Passed

Paragraph of S-4200	Summary of CCD requirement	Test procedure	Results
4.4.4.2	Isolated Critical Loss	1) Initialize a three-car train. Pneumatically cutout two of the three cars. Reduce the BPP to 40 psi. Confirm that the Loss of Brake Pipe Pressure Exception message is sent only from the CCD that is still pneumatically cut-in. Wait 5 seconds. Confirm that the CCD reports itself cutout in its CCD Status Response message. 2) Initialize a three-car train. Apply the brakes (e.g., 50%). Isolate CCD #2 by connecting the trainline from CCD #1 directly to CCD #3. Wait 11 seconds. Confirm that CCD #2 releases its brakes, indicating that it has cut itself out.	Passed
4.4.6	CCD Detects Low Reservoir	Connect Brake Controller communication utility to Comm Module. In switch or run mode, send a reservoir pressure of 45 psi to the Comm Module through the communication utility. Confirm that the Low Reservoir Exception message is sent. Send a reservoir pressure of 75 psi to the Comm Module. Confirm that the Low Reservoir Exception Cleared message is sent.	Passed
4.4.10	CCD Detects Low Battery	Connect Brake Controller communication utility to Comm Module. In switch or run mode, send a battery voltage of 2 V to the Comm Module through the communication utility. Confirm that the Low Battery Exception message is sent. Send a battery voltage of 4 V to the Comm Module. Confirm that Low Battery Voltage Exception Cleared message is sent.	Passed

Paragraph of S-4200	Summary of CCD requirement	Test procedure	Results
4.4.12	CCD Detects Incorrect BCP. Message is sent to HEU, including indication of BCP high, cannot apply, or stuck brake.	1) Connect Brake Controller communication utility to Comm Module. In switch or run mode, command TBC to 10%. After 2 seconds, confirm that the Incorrect BCP Exception message is sent with “Cannot Apply” field set. Send a BCP of 0 psi to the Comm Module using the communication utility. Confirm that the Incorrect BCP Exception Cleared message is sent. 2) In switch or run mode, command TBC to 10%. In less than 2 seconds, send a BCP of 7 psi to the Comm Module using the communication utility. Command TBC to 0%. After 5 seconds, confirm that the Incorrect BCP Exception message is sent with “Stuck Brake” field set. Send a BCP of 0 psi to the Comm Module. Confirm that the Incorrect BCP Exception Cleared message is sent. 3) In switch or run mode, command TBC to 50%. Send a BCP message with 7 psi to the Comm Module using the communication utility. Command TBC to 10%. After 10 seconds, confirm that the Incorrect BCP Exception message is sent with “BCP High” field set. Send BCP of 7 psi to Comm Module. Confirm that the Incorrect BCP Exception Cleared message is sent. 4) Cutout the individual Comm Module. Repeat step 2. Confirm that the Stuck Brake Exception message is sent instead of the Incorrect BCP Exception.	Passed
4.4.14	CCD detects empty/load command mismatch	Develop a special command in the HEU simulator that sends a one-time HEU Beacon with one E/L command field set to 1 and the other E/L command field set to 0. Initialize train. Send this special mismatch HEU Beacon. Confirm that the CCD Status Response messages sent indicate a mismatch in the Car Load field and that the CCDs do not change their Car Weight.	Passed
4.4.15.1	CCD detects car ID fault.	In one of the Junction Boxes, install a Car ID with default values in all of the fields. Initialize train. Confirm the Car ID Exception Message is sent.	Passed

Paragraph of S-4200	Summary of CCD requirement	Test procedure	Results
4.5	Train ID - Crosstalk Mitigation	Develop a special command in the HEU simulator that sends a one-time crosstalk HEU Beacon with a different Train ID. Initialize train. Confirm CCDs respond to initial Train ID HEU Beacons. Send one special crosstalk HEU Beacon. Confirm that the CCD Status Response messages sent indicate that a crosstalk has occurred with the Train ID from the crosstalk message. Confirm CCDs respond to normal HEU Beacons.	Passed
5	Environmental Requirements for CCD Temperature: -50 to +150 °F in all humidity conditions Shock and Vibration: 0.4 g rms, 1 Hz to 150 Hz, with 3 g peaks in 1 Hz to 100 Hz range in all three axes; and a 10 g peak longitudinal shock impulse.	N/A	Not included in project scope.

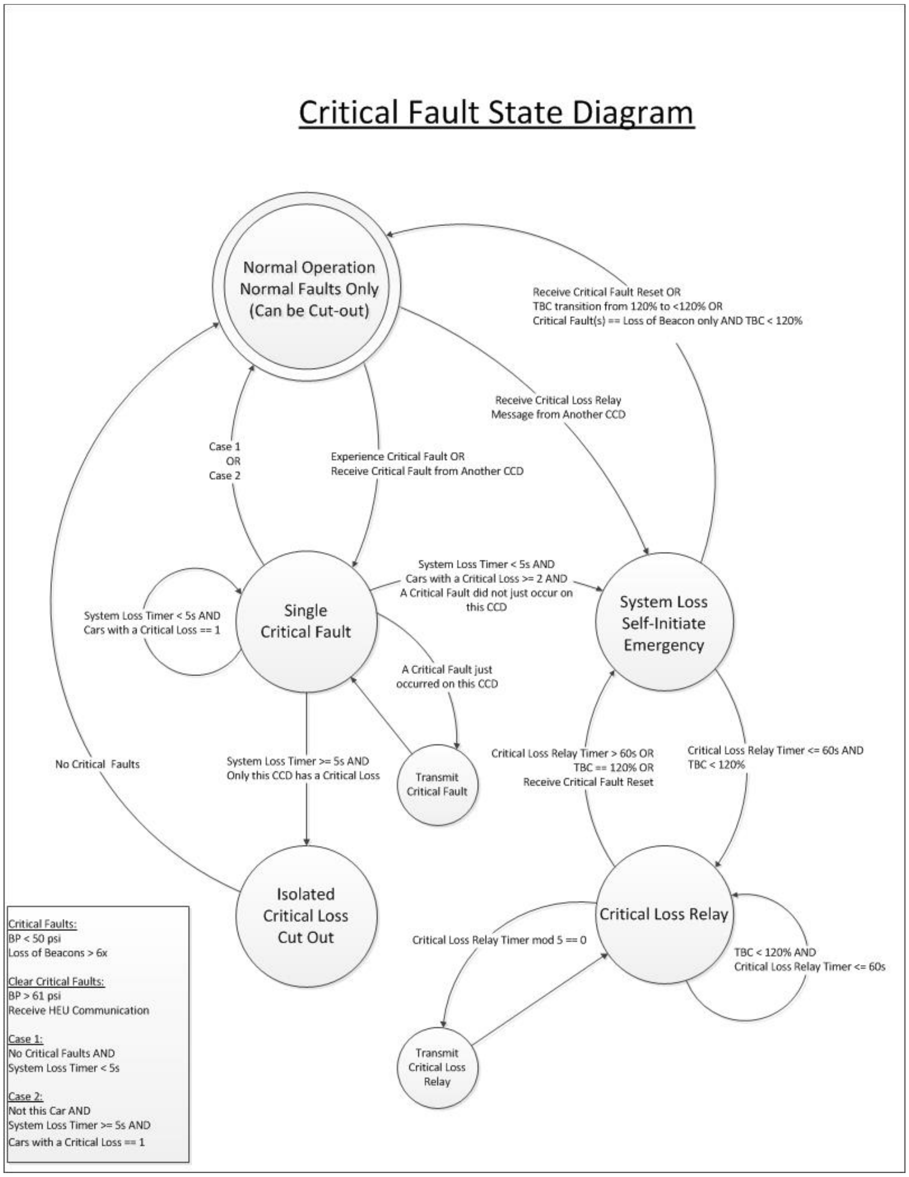

Figure A-1 – Critical Fault State Diagram

Abbreviations and Acronyms

S-4200	AAR MSRP Section E-II, Electronically Controlled Pneumatic (ECP) Cable-Based Brake Systems – Performance Requirements
S-4230	AAR MSRP Section E-II, Intratrain Communication Specification for Cable-Based Freight Train Control Systems
AC	Alternating Current
ADC	Analog to Digital Converter
AAR	Association of American Railroads
BC	Brake Controller
BCP	Brake Cylinder Pressure
BPP	Brake Pipe Pressure
CCD	Car Controlled Device
Comm	Communication (Module)
DAQ	Data Acquisition Unit
DC	Direct Current
ECP	Electronically Controlled Pneumatic (Brakes)
EEPROM	Electrically Erasable Programmable Read-Only Memory
EOT	End of Train (ECP)
EEPROM	Electrically Erasable Programmable Read-only Memory
EMR	Emergency Application
E/L	Empty/load
FRA	Federal Railroad Administration
FSP	Full Service Pressure
GE	General Electric
GETS	GE Transportation Systems
GUI	Graphical User Interface
HEU	Head End Unit
IN	Indiana Northeastern Railroad
I^2C	Inter-Integrated Circuit (Bus)
MSRP	Manual of Standards and Recommended Practices

MSP	Minimum Service Pressure
NBR	Net Braking Ratio
NPV	Net Present Value
NYAB	New York Air Brake
PCP	Pneumatically Controlled Pneumatic (Brakes)
PPG	Pneumatic Power Generator
Psi	Pounds per Square Inch
PLT	Power-Line Transceivers
PSC	Power Supply Controller
PCB	Printed Circuit Board
SPI	Serial Peripheral Interface (Bus)
SA	Sharma & Associates, Inc.
S/N	Subnet/Node (Address)
TBC	Train Brake Command
TTCI	Transportation Technology Center, Inc.
USB	Universal Serial Bus
WFA	Western Fuels Association