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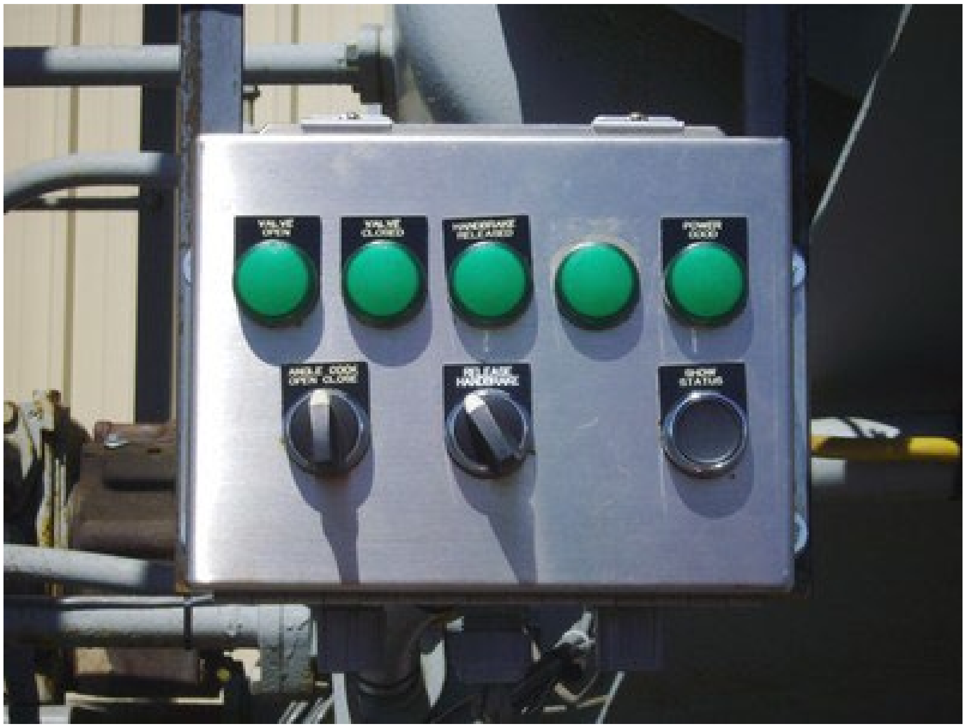
Development of Locomotive Power Freight Car Electrical Power Supply System (EPSS): Method of Electrical Power Distribution on Freight Trains



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14. ABSTRACT
The Federal Railroad Administration (FRA) previously demonstrated advanced, remotely controlled, electro-mechanical systems, such as hand brakes, angle cocks, and cut levers that can contribute to increased safety and improved efficiency of freight railroad operations. The main impediment to implementation of such devices is the lack of reliable and continuous electrical power on freight cars. The objectives of this project were to develop a preliminary design/architecture for a cost-effective, scalable and robust, electrical power supply system (EPSS) for railroad freight cars, and to develop a prototype. EPSS developed under the project derives its power from the train's locomotive, which is transformed to alternating current (AC) power and is distributed to the cars via a standardized, hard-wired configuration. Sharma & Associates, Inc. tested the prototype EPSS system at the Transportation Technology Center (TTC). The test successfully demonstrated the overall viability and performance of the prototype EPSS on a small consist which included a locomotive and two freight cars.

15. SUBJECT TERMS
Electrical power supply system, EPSS, Electrically Driven Set & Release Hand Brakes, EDHB, Hand brake release sensors, HBRS, remote controlled angle cocks, RCAC, remote controlled cut levers, RCCL, remote release hand brake, RCHB, alternating current, AC

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METRIC/ENGLISH CONVERSION FACTORS

ENGLISH TO METRIC

LENGTH (APPROXIMATE)

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

AREA (APPROXIMATE)

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

MASS - WEIGHT (APPROXIMATE)

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

VOLUME (APPROXIMATE)

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

TEMPERATURE (EXACT)

[(x-32)(5/9)] °F = y °C

METRIC TO ENGLISH

LENGTH (APPROXIMATE)

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

AREA (APPROXIMATE)

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

MASS - WEIGHT (APPROXIMATE)

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

VOLUME (APPROXIMATE)

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

TEMPERATURE (EXACT)

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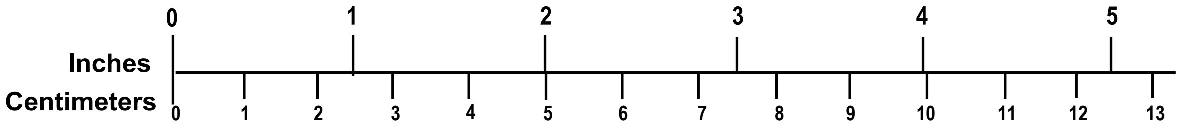
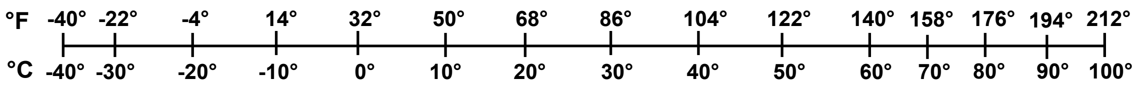
QUICK INCH - CENTIMETER LENGTH CONVERSION



QUICK FAHRENHEIT - CELSIUS TEMPERATURE CONVERSION



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) has demonstrated the feasibility of several advanced devices that can reduce the risks associated with the manual operation of devices such as hand brakes, angle cocks, and cut levers. The design of the prototype devices improves worker safety with hand brake release sensors (HBRS), remote controlled hand brakes (RCHB), remote controlled cut levers (RCCL), remote controlled angle cocks (RCAC), and electronic piston travel indicators. Demonstrations of these prototype devices showed that to successfully integrate remote controlled devices on all cars of a freight train, a sufficient amount of electrical power must be available along the entire train. Designing and installing such an electrical supply system can provide the necessary power to operate these devices and create opportunities for other beneficial advanced devices such as Electrically Driven Set & Release Hand Brakes (EDHB), Global Positioning System (GPS) equipment, equipment monitoring sensors for hazardous material release, accident/collision notification sensors, freight car intrusion and tampering sensors, derailment notification sensors, wireless sensor networks, etc. The existing Electronically Controlled Pneumatic (ECP) power line has no provision to provide any power beyond what is required by the ECP components.

From September 2011 through July 2013, FRA awarded Sharma & Associates, Inc. (SA) a project to develop an electrical power supply system (EPSS) for freight cars using the locomotive(s) in the train as the source of power for these safety devices. SA accomplished the reported work at its engineering laboratory and the Transportation Technology Center (TTC), Pueblo, CO. The prototype EPSS supplied 240 V alternating current (AC) inverted from the 74 VDC power provided by industry standard locomotives. AC was chosen down the train-line to reduce power loss down the train line and to make the power supply more flexible. With respect to powering devices down along the train, it is easier and more cost effective to transform AC to direct current (DC) than it is DC to AC at the device level.

Design requirements for the EPSS include compliance with industry/electrical/electronic standards, cost effectiveness, scalability to long trains, and the ability to be maintained with no specialized training of railway personnel.

Researchers reviewed the American Public Transportation Association (APTA), Association of American Railroads (AAR) and Passenger Rail Investment and Improvement Act (PRIIA) specifications that were primarily related to existing equipment and infrastructure. In terms of electrical specifications, the above standards pertain to either hotel power on passenger equipment or multiple unit (MU) connection systems for locomotives and are not directly related to the requirements of the EPSS system. The AAR's S-4200 Electronically Controlled Pneumatic (ECP) Cable-Based Brake Systems – Performance Requirements specification was found to have some relevance. However, it was determined that, for EPSS, a specification similar to S-4270 ECP Brake System Configuration Management would have to be developed. In other standards, general requirements such as Good Manufacturing Practices (GMP) and compliance with the National Electric Code (NEC) and Institute of Electrical and Electronics Engineers (IEEE) standards were found to be of value.

To design the prototype EPSS, a mathematical model of a freight car with installed devices and an associated electrical system were developed. The representative car was equipped with one EDHB, two RCCL, two RCAC, a data collection system and one monitoring system. This model assisted with the calculation of nominal power requirements for one car equipped with designated devices. The nominal power required for this configuration was determined to be 376 W. With consideration to the efficiency of electrical circuits and devices (assumed 80 percent), the power needed was estimated to be 470 W.

Assuming that this was the only active car and was the last car in a 150-car train and accounting for line losses and other non-active devices and sensors installed along the train, a power supply with a nominal capacity of 600 W would be required in the locomotive. A supply of 600 W would seriously limit the capabilities of the system to provide power for more than a single car, so this size was determined to be an absolute minimum requirement. SA conducted additional research to determine a functional supply capacity that would provide a balance between locomotive capacity and system capability. Based on this research, the EPSS design power supply capacity was set at 4 kW, and locomotive EPSS inverter size, power line gage and inter-car connectors were selected. It was calculated by the model that in a 150-car train, a maximum of 8 lead cars or 2 trailing cars may have all the devices activated simultaneously, where the cars are equipped as described above.

After the completion of the EPSS modeling and power estimation task, the prototype EPSS design was developed. The research team installed electrical system components RCAC and remote release hand brake (RRHB) on a locomotive and two freight cars at the TTC, in Pueblo, CO. EPSS's operability was tested on the TTC test tracks with the three-vehicle consist in motion and at rest. To verify the EPSS system model, voltage calculations at key locations were compared with those measured and recorded in these tests. The measured voltage and current data showed minimal electrical potential losses during the test. The power supply system and the battery boxes of the short train maintained charge during and after the application of the advanced devices and the traversing of miles of track.

This test demonstrated the overall viability and performance of the prototype EPSS in a short test train.

To further evaluate the EPSS under more demanding environments, such as in revenue service and on longer trains, a larger configuration should be built and tested. Additionally, specifications for the design, operation and maintenance of interchange-worthy EPSS systems need to be developed. Finally, a standard universal DC access battery box and charger system to integrate into any EPSS equipped vehicle for use by suppliers of monitoring and control devices needs development to allow for easier adoption of the advanced devices.

1. Introduction

To further the advancement of electrically powered safety devices on freight cars, the Federal Railroad Administration's (FRA) Office of Research, Development and Technology (RD&T) awarded a contract to Sharma & Associates, Inc. (SA) to research and develop a cost-effective freight car electrical power supply system (EPSS). This system supplies electrical power to batteries, sensors, control systems, actuators, communication and tracking devices, etc. for increased operational safety.

1.1 Background

To increase safety and improve efficiency of switching operations, FRA's RD&T sponsored projects to demonstrate electro-mechanical designs of these devices that also included on-board monitoring and control. For example, hand brake release sensors (HBRS), remote controlled hand brakes (RCHB), remote controlled cut levers (RCCL), remote controlled angle cocks (RCAC), and electronic piston travel indicators were installed on five cars and successfully demonstrated.

These demonstrations identified that to successfully implement remote-controlled devices on freight cars then enough electrical power must be available. Designing and installing such an electrical power system can provide the necessary power to these devices and create opportunities for other beneficial advance devices such as Electrically Driven Set & Release Hand Brakes (EDHB), Global Positioning Systems (GPS) equipment, equipment monitoring sensors for security, equipment monitoring sensors for hazardous material release, accident/collision notification sensors, freight car intrusion and tampering sensors, derailment notification sensors, wireless sensor networks, etc.

It is understood that Electronically Controlled Pneumatic (ECP) braking systems that are currently entering the market have limited power availability and that the ECP systems would need significant specification and design changes to be able to supply sufficient power for additional devices apart from ECP's needs.

Therefore, the main impediment for universal implementation of electrically powered safety devices/systems on freight cars is the lack of reliable and continuous electrical supply. If, indeed, electrical power could be made available on freight cars, it would greatly increase safety and efficiency in freight operations. It would allow for the implementation of an abundance of safety and efficiency improvement devices, such as:

1. HBRS
2. RCHB or EDHB
3. RCCL
4. RCAC
5. GPS equipment
6. Equipment monitoring sensors for security
7. Equipment monitoring sensors for hazardous material release
8. Accident/collision notification sensors

9. Freight car intrusion and tampering sensors
10. Electronic piston travel indicators
11. Derailment notification sensors
12. Wireless sensor network

Some of the devices listed above were installed and demonstrated during previous projects, and show potential for immediate benefit upon their implementation if sufficient power is made available.

Further, to ensure reliability and sufficiency of power, the EPSS's electrical power source must be from in-train locomotives, and not from less reliable car-mounted devices such as mechanical bearing generators, solar cells, energy harvesters, or piezo-electric devices.

This report describes the project's objectives and the process that the SA team followed in the development of the prototype EPSS design, the EPSS design itself, and the results of the demonstration and testing of the prototype EPSS.

1.2 Objectives & Scope

The project consisted of two major objectives. The first objective was to develop architecture and preliminary specifications for a cost effective and robust EPSS, deriving its power from in-train locomotives, which can be used via a standard, hard-wired configuration on freight railroad cars.

The second objective was to design a representative EPSS system to be installed on a short consist and evaluate the designs' viability and performance via full scale, albeit limited due to train length, implementation.

To achieve these objectives, researchers identified six major tasks outlined below:

- Develop a profile of the power requirements for a set of representative advanced devices installed on a freight car and on a 150-car train
- Assess power availability and supply methods/paths in modern locomotives
- Review electrical power design standards and communication protocols used in freight, transit, and commuter train systems
- Develop an electrical circuit and performance model of EPSS
- Design a prototype EPSS
- Equip one locomotive and two cars with the prototype EPSS system and a nominal set of advanced devices and conduct demonstration tests evaluate the prototype EPSS design

1.3 Overall Approach

To accomplish the project objectives, SA reviewed the advanced devices and their power requirements. This was then followed by review of the power availability in the locomotives. A review took place of the various railway industry standards for electrical power transmission in a train. An electric circuit and performance model was then developed to determine the needed power for a given number and placement of advanced devices in a train. This was then used to design and select the electrical cable to minimize the power losses during transmission and the drop-off junction boxes. A prototype was developed and tested in the laboratory followed by a field test using a locomotive as a power source and several freight cars with advance devices installed.

1.4 Organization of the Report

This reports outlines the EPSS design specifications, including the voltage and power, and standards for revision in Section 2. Section 3 discusses the EPSS installation and demonstration test. Section 4 provides observations of the work conducted and recommendations for further research.

2. EPSS Design Specifications

To develop an overall estimate of the electrical power required for a freight car/train EPSS system, individual device level power needs were determined. These were used for developing an EPSS power model. Once the power requirement was defined, a reliable source of supply was identified on the locomotive. A review of various industry standards and practices occurred during the development of EPSS component and system level design. The following subsections discuss this.

2.1 Estimating Advanced Device Power Requirements

The average train consist is around 150 cars long. An average car length is assumed to be 60 ft. (9,000 ft. for a 150-car train). Only one car or one coupling location (two freight car ends) is powered at any given time. The power required by the EPSS system should be readily available from most commonly utilized locomotives without requiring significant rework, costs, or additions to the locomotive based electrical systems. The most relevant devices considered would not consume significant power until activated by a crew member. Because feedback would also be provided locally (and remotely if desired), the operator would remain in that location until the completion of operations at that location. Thus, all the primary power consumers would be active on only one car or at one location at any given time. For this analysis, these power consumers included a remote-controlled set and release hand brake, 2 angle cocks, 2 cut-levers, 2 carbody accelerometers, and wheel set journal bearing temperature and acceleration sensors—which were all assumed to be active at the same time—and 150 cars away from the nearest locomotive (i.e., power source), thus taking into account all power losses to that point.

2.1.1 Power Consumption Profile for Advanced Devices

The following list details the devices, on a per car basis, considered for this task along with their associated power requirements and other pertinent information.

Hand Brake Release Sensors (HBRS)

Current HBRS are passive devices and consume little power. However, equipment to monitor the output of this device or provide visual feedback of the status of this sensor consumes power. The amount of power required varies depending on the equipment selected to monitor the sensor. If a simple visual indicator is used, the power consumption would be approximately 1.2 W (i.e., 0.6 W each for one indicator on each side of the car). Indicators would be illuminated only momentarily during device operations or when requested by operators to both reduce energy requirements as well as increase the time between component failures. If monitoring or data collection equipment were used, the additional power requirement would be covered under other devices listed below.

Remote Controlled Release Hand Brakes (RHB)

This particular type of hand brake requires approximately 12 W of power for actuation to release the brake. Actuation time is less than 10 seconds and energy consumption is small compared with devices with longer durations of operation. Status is indicated via release sensors as detailed above.

Electrically Driven Set & Release Hand Brakes (EDHB)

The EDHB is a hand brake that can be operated either traditionally in manual mode, or electronically via crew accessible control enclosures mounted on the car near the hand brake. For manual operation, no electrical power is required. For operation in remote mode, the current design requires approximately 120 W of power. Future designs might require more power to shorten cycle times. Current cycle times are around 2 minutes for an application and 2 minutes for a release, and thus energy consumption is relatively high for these devices. The power consumption of the visual indicator showing hand brake status is included in the 120 W value.

Remote Controlled Cut Levers (RCCL)

These devices are relatively low energy consumers because they only require approximately 12 W to actuate and are actuated for short durations.

Remote Controlled Angle Cocks w/Heater (RCACH)

The RCAC is available in two versions: one that includes an internal heater (RCACH) to maintain gear train lubrication viscosity during cold ambient temperatures and another without a heater (RCAC). The version without a heater requires 12 W to actuate. The version including a heater can require as much as 36 W during actuation if the heater is energized—the heater is controlled independently by a thermostat inside the valve actuator and draws 24 W even when the angle cock is not activated. The valve open and close cycles each require power for approximately 6 seconds. The valve closes in the 6 seconds of power draw for actuation. However, the valve open cycle takes considerably longer due to a long pause that is inserted in the middle of the 6 second actuation power draw cycle to allow for air brake system pressure equalization. Cycle times are the same for the heated valve and the valve without a heater. However, the heater can potentially be active continuously depending on air temperatures thereby increasing continuous electrical load by 24 W.

Global Positioning System (GPS) Equipment

GPS receiver systems can provide benefits when used in centralized asset tracking. Power requirements for GPS receivers vary widely, but devices requiring less than 2 W are common. Because of the limited benefit of this device alone, it is not included in the power requirement calculation.

Security Monitoring System (SMS)

Monitoring systems for security breach detection and notification typically have similar power requirements to those for general purpose monitoring systems. As there are no standard systems in use, power requirements can vary widely between systems with different functionality requirements.

Hazardous Materials Release Monitoring Sensors (HazMatMS)

Monitoring systems for release detection and notification of hazardous materials typically have similar power requirements to those for general purpose monitoring systems.

Collision Notification Sensors (CNS)

CNS and systems are primarily located at either end of a train. The head end unit could be powered directly by the auxiliary power system in the locomotive. The tail end unit could be powered by a system such as EPSS. Additional equipment is required to notify personnel of an impending problem so that action can be taken when and where appropriate. The CNS and additional equipment have power requirements comparable to general purpose monitoring systems.

Freight Car Intrusion & Tampering Sensors (ITS)

Freight car intrusion and tampering sensors and associated notification equipment are included under SMS.

Derailment Notification Sensors (DNS)

DNS data can be transmitted to personnel for appropriate action. The communication system would have the larger power requirement and are included in the General Monitoring System section.

Wireless Sensor Networks (WSN)

Wireless sensor networks will have a power value as a part of a data collection and/or monitoring system. Power requirements are covered in the General Monitoring System section.

General Monitoring System (GMS)

A general purpose monitoring system generally requires less than 20 W. This estimate includes 5 W for an embedded computer system and 15 W for all associated sensors and communication equipment. Systems dedicated to the task of data collection require even less power as they do not need to include local status indicators, and do not require communication links for immediate transfer of information. Normally, for a data collection system, 10 W should provide ample power.

Based on the above information and the requirement assumptions, Table 1 lists the devices and their associated power requirements for which the EPSS should accommodate.

Table 1 – Power requirements for EPSS devices per freight car

Device/Quantity	Power Requirements	Comments
EDHB / 1	250 **W**	Current design requires only 120 W; however, excess power requirement was added to allow for future EDHB enhancements.
RCCL / 2	12 W x 2 = **24 W**	There are two of these devices per car and although it would be unlikely that they would both be active on the same car simultaneously, two of them could be activated simultaneously at the coupling point between two cars.
RCACH / 2	36 W x 2 = **72 W**	There are two of these devices per car and although it would be unlikely that they would both be active on the same car simultaneously, two of them could be activated simultaneously at the coupling point between two cars.
Data collection system / 1	**10 W**	General purpose data collection system
Monitoring system / 1	**20 W**	General purpose monitoring system
		Total Power Required: 376 W

As shown in Table 1, the total power requirement for a single car equipped with this list of equipment is 376 W. Assuming a conservative 80 percent power conversion efficiency, the required power supplied to a single car is approximately 470 W.

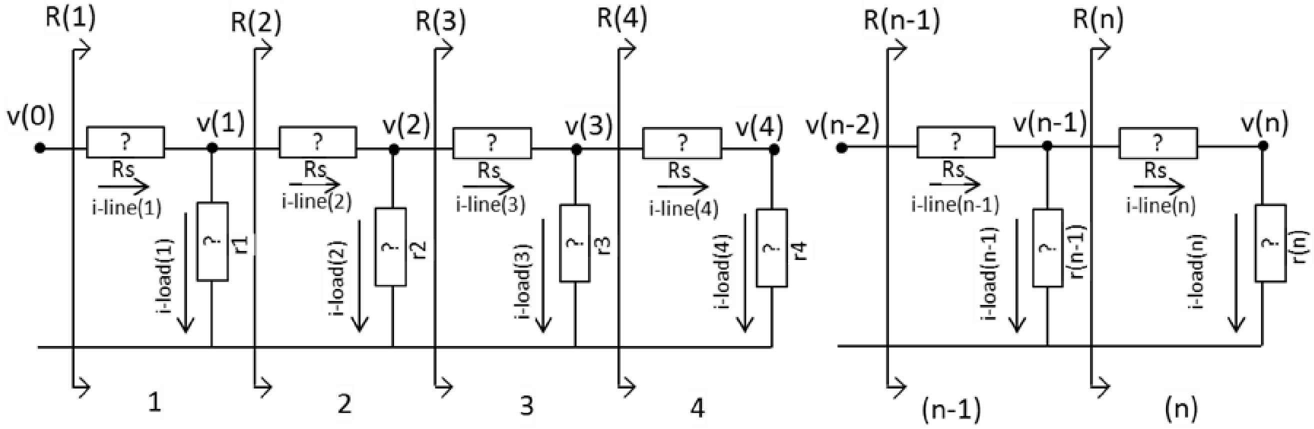
2.1.2 EPSS Electrical Power System Model

To determine the locomotive power supply/delivery requirement, the system was mathematically modeled. The model is based on the schematic shown in Figure 1. For modeling simplicity, the system is treated as a direct current (DC) system with purely resistive loads that consume a constant power independent of the voltage present. The actual alternating current (AC) system used is generally considered more efficient, and an improvement over the more conservative DC model calculations.

The notation used in the Figure 1 schematic is:

- v(x) = the voltage present at the leading end of car number x in a consist.
- Rs = the resistance of the train line wire for the length of the car plus the resistance of the EPSS connector between cars.
- Pr(x) = the electrical power required by car number x in the consist.

- R(x) = the total resistance of the system from point x to the tail end of the consist, assuming the train is disconnected at point x so the forward-looking resistance is not present.
- i-load(x) = load current for car number x in the consist.
- i-line(x) = sum of i-loads from x through remainder of the consist.
- The primary constraint of the model is power, therefore as the train line voltage decreases the load current increases to keep the power constant per load. The “?” marks in the drawing indicate the effective resistance calculated by the model to maintain the power.



Constraints:

Pr(1) = Pr(2) = Pr(3) = Pr(4) = Pr(n-1) = Pr(n)

Rs = (2*Rw*avgCarLength) + (2*Rc): (wire resistance + connector resistance)

Figure 1 – EPSS basic electrical model

2.1.3 EPSS Modeling Scenarios

Note, the number of devices that can be powered by EPSS are not always limited by the power available, but also due to the wire resistance of the train line. The following modeling scenarios were done with 4 kW supply.

Because not all devices are activated manually, additional modeling was performed to evaluate the performance of the EPSS for a device that actuates automatically and consumes the greatest power. One particular device, the RCACH was the target of this additional modeling. This device includes an integral heater that is automatically switched on and off based on the temperature of the valve. The simultaneous activation of all angle cock heaters would draw too much load for the proposed power line system to handle. Therefore, additional modeling was conducted to determine the maximum angle cock heater load the proposed power supply system could provide. It was determined from this modeling that the proposed system could simultaneously power angle cock heaters on up to 21 cars of a 150 car consist, even if these cars were at the end of the train. More cars could be powered if the cars were closer to the locomotive end. Additional studies may be required to research alternatives to the current angle cock with a heater to be used in conjunction with the proposed EPSS.

Another extreme scenario considered is a 150-freight car consist with each freight car having an EDHB, 2 RCACs, and 2 RCCLs. With this configuration, the proposed system could simultaneously power all devices on any three freight cars, including those at the tail end of the train. More cars could be powered if the cars were closer to the locomotive end.

Freight car monitoring systems were also considered in these additional modeling scenarios. For 1 scenario a consist of 150 freight cars, where each freight car is equipped with an EDHB, 2 RCACs, and 2 RCCLs is assumed. The result of this scenario indicates that a maximum of 20 freight cars at the tail end of the consist can have active monitoring systems with the system reserving the capacity to power all advanced devices on 1 car or at a single coupling location at the tail end of the consist.

A generic scenario was also considered where it was assumed that a 150 freight car consist is made up of freight cars all having identical electrical requirements. Given this hypothetical consist the system can only supply 13 W continuously to each car if all cars require the same power. Many devices have only an intermittent power draw, and batteries could be used to provide this additional requirement above the 13 W. Batteries can be continuously charged from EPSS with only a small amount of power.

2.2 EPSS Supply Voltage and Power

SA chose the system supply voltage to be 240 VAC nominal. This electric potential was chosen to optimize safety, system efficiency and reduce costs. Higher voltages reduce losses from wire resistance, but are more hazardous, potentially more expensive, and prone to problems due to dielectric breakdown. The voltage chosen is also commonly used in North America and facilitates the use of over-the-shelf components in the system.

As stated earlier, the model includes 150 cars and a locomotive, with the active car being the farthest (150th car) from the closest power source. This model is a very conservative case as this position has the least power available due to losses in the train line between the locomotive power source and this location.

The model indicates that to be able to supply 470 W to the 150th car of the modeled consist, the locomotive must be able to supply at least 530 W to compensate for the losses of the power line.

To improve system capabilities and to allow systems on multiple cars to be operated simultaneously, the proposed power supply size was increased to 3,600 W. This supply level allows the maximum functionality of the EPSS without significant modifications to the locomotive electrical system.

Based on the above information, the locomotive power supply is designed to be able to deliver a minimum of 3,600 W at 240 VAC. The system uses the locomotive’s 72 VDC electrical source, approximately 4,000 W (55A @ nominal 72 VDC), as input, if the inverter is fully loaded.

The power line wire size needed to supply this power was determined to be 8 AWG. This size provides a good tradeoff between cost, current capacity, and resistance. This wire size will allow 80 A capacity based on wire and cable rated for a maximum of 90 °C (194 °F). This capacity is much higher than required, but the overriding factor in sizing the wire was the line resistance that can create extremely large losses when lengths equivalent to a 150 car train are involved. A larger wire would provide lower losses and better efficiencies, but at a much greater financial cost. A resistance of 0.6282 mΩ/ft was used in the model and obtained from commercially available information.

The connector contact resistance was assumed to be 0.2 mΩ based on other commercially available connectors for similar current capacities. Section 2.4 shows the actual connector chosen for EPSS.

2.2.1 EPSS Power Supply Choice: Auxiliary System

Once minimum power requirements for the system were estimated, SA interviewed experts in locomotive electrical systems to understand methods of generating or extracting the required power from a locomotive. These interviews provided valuable information and allowed for a simplified path forward for EPSS.

The most important information obtained from the interviews was that most locomotive electrical systems are very similar and that commonly used locomotives have three sources of electrical power. These three power sources are an integral part of all commonly operated locomotives regardless of manufacturer and are as follows:

1. **The main traction generator/alternator**, which is the source of electrical power used for locomotive tractive effort.
2. **The companion alternator**, which is typically used to generate electricity for powering cooling fans and traction motor blowers, etc.
3. **The auxiliary generator**, which is used to charge the locomotive batteries and provide power for all remaining locomotive electrical systems including cab instrumentation and controls.

All these systems could generate electrical power for the proposed EPSS. However, based on the requirements of the system, it was determined that the most appropriate power source is the auxiliary system.

The EPSS's power source connects to the locomotive battery circuit like most of the other locomotive electrical systems. With this arrangement, the EPSS can provide power along the train at all times, as long as the batteries maintain charged.

The overall power requirements of the proposed system are low enough that installing an EPSS to an existing locomotive will not overload the auxiliary generator.

2.3 EPSS Standards and Specification Review

SA performed a comprehensive investigation into various industry standards and recommended practices to identify any specifications, design practices and hardware that could be transferred and used as is or with little modification in the EPSS. This exercise also helped in identifying areas that must be addressed when an eventual EPSS standard is developed.

SA reviewed the Association of American Railroads' (AAR), American Passenger Transit Agency's (APTA) and Passenger Rail Investment and Improvement Act's (PRIIA) documents for information that would be applicable to EPSS such as inter-car connectors, inter-car cables and conductors, train-line communications, connectors and receptacles, junction box design and other items that would provide a good design history, and a starting point for EPSS determination.

The following passenger related documents were identified as having potential applicability:

- APTA RP-E-016 “Recommended Practice for 480 VAC Head End Power System” [1]
- APTA RP-E-017 “Recommended Practice for 27-Point Control and Communication Train-lines for Locomotives and Locomotive-Hauled Equipment” [2]
- APTA RP-E-018 “Recommended Practice for 480 VAC Head End Power Jumper and Receptacle Hardware” [3]
- PRIIA Spec.305 for both single level passenger cars and locomotives [4]

AAR’s Manual of Standards and Recommended Practices was also reviewed. The following may be applicable:

- S-4210 ECP Cable-Based Brake System Cable, Connectors, and Junction Boxes–Performance Specification [5]
- S-4220 ECP Cable-Based Brake DC Power Supply–Performance Specification [6]
- S-4230 Intratrain Communication Specification for Cable-Based Freight Train Control Systems [7]
- S-4250 Performance Requirements for ITC-Controlled Cable-Based Distribution Power Systems [8]
- S-4260 ECP Brake and Wire Distributed Power Interoperability Test Procedures [9]
- S-4270 Brake System Configuration Management [10]

Existing commercially available freight ECP brake system hardware was inspected. The method of how and where these systems obtained their power was also investigated. This information was used for selecting and designing EPSS equipment.

Summary of Findings

Any EPSS should generally comply with ECP’s S-4210 [5]; however, EPSS cannot comply with this specification in its entirety. One exception is the connector design because EPSS connectors cannot be allowed to mate with ECP connectors. In addition, physical interference should be avoided between EPSS hardware and ECP hardware. S-4210 specifies connector mounting location envelopes and related information for the ECP system. Similar location and space envelopes should be utilized for EPSS in a manner where both systems can coexist.

EPSS should comply with S-4220, Section 2.1 [6], which addresses the input voltage of the power supply. EPSS will need a specification similar to S-4220, Sections 2.2 through 2.6, for defining the output of the power supply, albeit with a different voltage than ECP. The EPSS should completely comply with S-4220, Sections 3 and 4, of the same standard, which address electromagnetic compatibility and environmental specifications, respectively.

Lastly, a specification similar to S-4270 [10] regarding management procedures should be developed for EPSS because the hardware sections could be applicable, even though the software sections would be irrelevant.

2.4 System Overview

The presented system design is a result of compromises between cost and functionality to maintain a system with a reasonable chance of widespread industry adoption. Figure 2 shows the prototype EPSS system overview. It shows the general locations of the EPSS inverter, power disconnect, connectors, locomotive end boxes, train-line, freight car junction boxes and advanced device power taps.

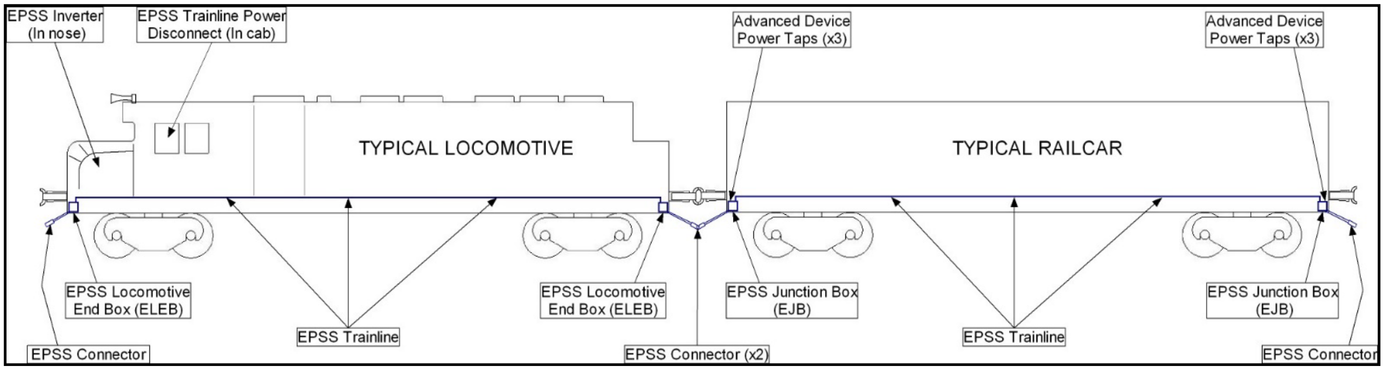


Figure 2 – Prototype EPSS system overview

The central component of the EPSS is the locomotive supply of power. The standard EPSS inverter will provide 240 VAC from the nose of the locomotive. This supply provides manufacturers with flexibility in the design of advanced devices. It is anticipated that most devices will require low voltages and consume little power. The 240 VAC provided by the EPSS can reliably be reduced via several different currently available technologies. For devices that can benefit from higher voltages, such as the EDHB, the higher voltage can be obtained without the use of boost converters. The higher train-line voltage also reduces losses caused by the resistances of the train line electrical conductors and connections.

A 4-kW inverter was determined sufficient for the prototype EPSS system. However, a 5-kW inverter was chosen as the power supply because it is commercially available off-the-shelf and better priced than a 4-kW inverter. The inverter outputs a pure 60 Hz 240 VAC sine-wave and is powered by the standard locomotive auxiliary electrical system. In future applications, the electrical connection of the inverter might vary per locomotive model, but generally will be connected to the load-side of the main battery disconnect switch of the locomotive. This will prevent the system from draining the locomotive batteries during locomotive storage periods. The inverter input wiring is protected from overload by an overcurrent protection device.

The 240 VAC inverter output wiring is also protected by a circuit breaker. This circuit breaker serves two purposes. First, the breaker provides protection for the train-line wiring in the event of an overcurrent condition. Second, the breaker allows the inverter to be electrically disconnected from the EPSS train-line circuit, which will be necessary for multiple unit (MU) operations. The breaker is mounted in a readily accessible location in the locomotive cab.

The train-line electrical circuit is constructed with 8 AWG stranded copper wire. The wiring is enclosed in liquid-tight flexible metallic conduit the entire length of the system (train). The 8 AWG wire is the same gauge used by the existing ECP system and provides a good compromise between system cost and functional capability.

Each car is equipped with two EPSS Junction Boxes (EJB), and the locomotive is equipped with two EPSS Locomotive End Boxes (ELEB). These boxes are located near the ends of the vehicles and are placed opposite the location envelope for the ECP end-of-car box. This location allows easy interconnection between cars as well as allowing system interoperability with the existing ECP system.

The locomotive and car junction boxes are slightly different designs. The ELEB for locomotives includes only the junction required to facilitate connecting the end-of-car EPSS connector to the EPSS train-line. The standard EJB for cars, as shown in Figure 3, includes three fused external connectors as attachment points to the EPSS system, referred to as taps. The EPSS taps are fused to prevent a malfunctioning device from interfering with the remainder of devices connected to the train line. Manufacturers of advanced devices will be required to develop their devices in compliance with the EPSS tap connector specification, thereby allowing the devices to quickly and interchangeably connect to the EPSS and utilize the benefits it provides. With two EJBs on each car, the system provides connection points for up to six advanced devices. T type adapters are available for extending the connection capability if needed. However, it is not anticipated that more than six connection points will be regularly required.

Figure 3 – EPSS junction box

Both cars and locomotives interconnect using a modified version of the AAR standard ECP connector, as shown in Figure 4. The connector provides an electrical connection that has already proven to be reliable and capable of withstanding the harsh environmental conditions of commercial railroad operations. The modification of the connector prevents accidental interconnection between the EPSS and ECP system.

Figure 4 – EPSS connector

3. EPSS Full Scale Checkout

3.1 EPSS Installation

The EPSS prototype was installed on a small test consist. The test consist included a locomotive, a tank car, and a covered hopper car. SA installed the system with assistance from the Transportation Technology Center (TTC).

The locomotive was equipped with the EPSS inverter and an EPSS supply disconnect for the inverter. Both pieces of equipment were installed in the nose of the locomotive as shown in Figure 5. The EPSS train-line disconnect was installed in the locomotive cab near the entry door for the short hood compartment, as shown in Figure 6. An ELJB was installed in the sub-floor area beneath the cab, as shown in Figure 7. ELEBs were installed at both ends of the locomotive opposite the coupler from the standard ECP box mounting location. Figure 8 and Figure 9 show the ELEBs mounted on the locomotive short hood and long hood ends, respectively.

Figure 5 – EPSS inverter (left) and supply disconnect

Figure 6 – EPSS train-line disconnect

Figure 7 – EPSS locomotive junction box

Figure 8 – Locomotive end box on short hood end

Figure 9 – Locomotive end box on long hood end

Both the hopper car and the tank car were equipped with EJBs at each end. EPSS power connector pigtails were attached to each of the EJBs. The boxes at each end were connected with flexible metallic electrical conduit which protects the EPSS wiring. Figure 10 through Figure 13 show the EJB installations. The hopper and tank cars were also equipped with a battery box at each end of the car. The battery boxes included two 12 VDC sealed lead-acid (SLA) batteries connected in series to provide a 24 VDC power source for the already installed advanced devices. Also included in the battery boxes was a battery charger to charge the batteries with power from the EPSS train-line. Finally, push button control boxes were installed on the two test cars for controlling the advanced devices.

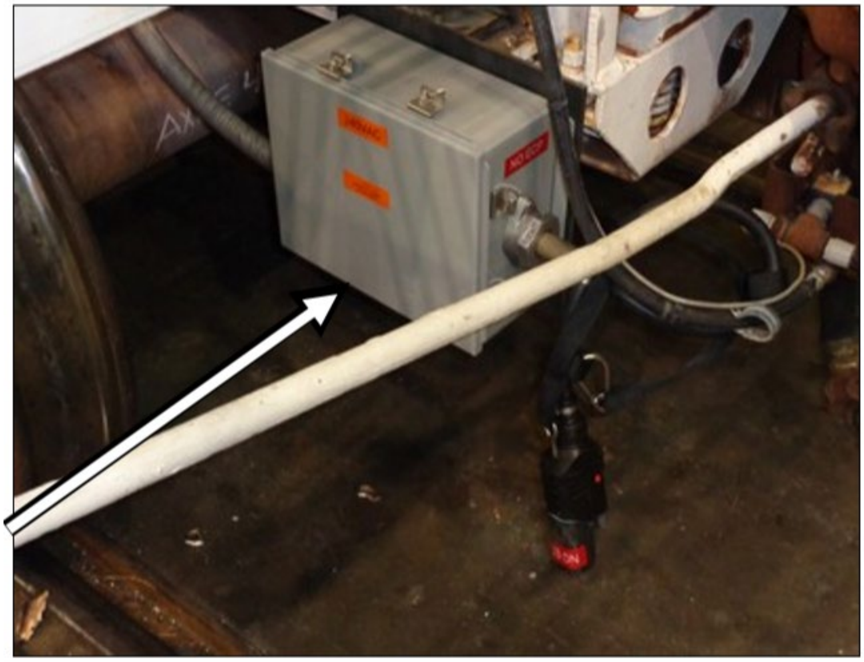


Figure 10 – EPSS junction box on the A-end of the tank car

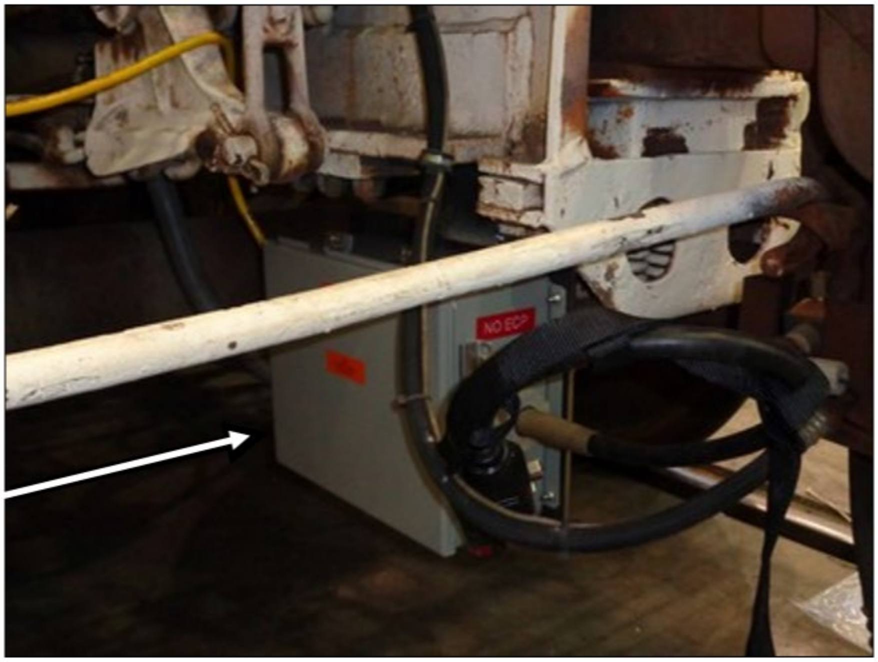


Figure 11 – EPSS junction box on the B-end of the tank car

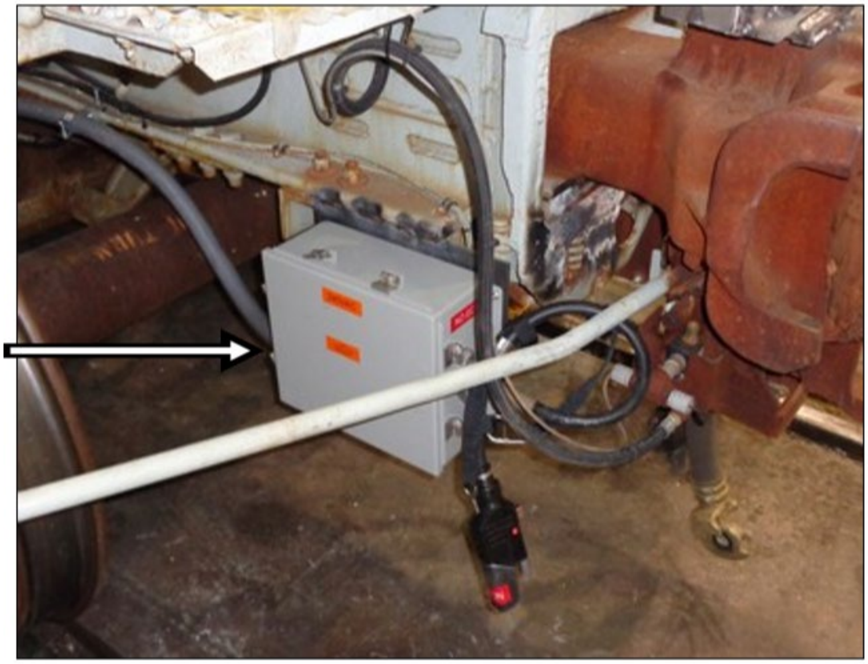


Figure 12 – EPSS junction box on the A-end of the hopper car

Figure 13 – EPSS junction box on the B-end of the hopper car

3.2 EPSS Demonstration Test

The goal of this test was to quantify the working capabilities of the EPSS. The requirements to satisfy this test were:

1. The battery boxes must maintain adequate charge throughout the test.

2. An appropriate amount of power must be supplied to each advanced device for it to perform effectively.

Observations of how the EPSS system operates for a locomotive plus a two car consist were recorded during the test. Any other factors that presented concern were recorded.

In May 2013, the EPSS was tested at the TTC following a previously submitted test plan. Testing began with assembly of the three EPSS equipped vehicle train. With the locomotive short-hood leading the train, the long-hood end of the locomotive was coupled to the B-end of the hopper car, and the A-end of the hopper was coupled to the A-end of the tank car. The assembled consist was initially located outside the Passenger Services Building (PSB).

After the test consist was assembled, the EPSS power connecters were mated between the locomotive and the hopper car, and then between the hopper car and the tank car. The power supply to the EPSS inverter was then switched on to supply the inverter with the required 74 VDC from the locomotive auxiliary electrical system. Once the inverter was initialized and stabilized, the EPSS train-line disconnect was switched on to supply the 240 VAC power to the EPSS train-line.

Before conducting the on-track testing, baseline EPSS voltages and current readings were recorded and are shown in Table 2. The baseline battery voltage measurements were made with the EPSS on and with no advance device active. The advanced devices installed on the test consist were operated and video footage of the operations was recorded. The advanced devices that were operated were all four of the RCACs on the two freight cars, and a remote release hand brake (RRHB) with release sensor, that was located on the tank car.

Table 2 – EPSS baseline measurements

Car / Locomotive	Measurement Location	Train-line Voltage	Train-line Current	Battery Voltage
Locomotive	Short Hood	239.9 VAC	0.0 A	-
	Long Hood	239.9 VAC	0.3 A	-
Hopper Car	B-end	239.9 VAC	0.3 A	27.6 VDC
	A-end	239.9 VAC	0.3 A	29.4 VDC
Tank Car	A-end	239.9 VAC	0.2 A	27.3 VDC
	B-end	239.9 VAC	0.2 A	29.7 VDC

Following the baseline measurements and advanced device operations, the test consist was moved under its own power at slow switching speeds from the initial location outside the PSB to the 9.1 mile long Transit Test Track (TTT) loop. Once on the TTT, a track conditioning run (TCR) was performed which involves traveling the entire TTT loop at a speed of 30 mph. After the TCR was complete, the test consist was moved at a speed of 40 mph to the tangent section on the backside of the TTT. While the test consist was stopped on the backside tangent, a second set of EPSS voltage and current measurements were recorded and the same advanced devices were again operated. Table 3 shows these measurements.

Table 3 – EPSS secondary measurements

Car / Locomotive	Measurement Location	Train-line Voltage	Train-line Current	Battery Voltage
Locomotive	Short Hood	239.8 VAC	0.0 A	-
	Long Hood	239.8 VAC	0.2 A	-
Hopper Car	B-end	239.8 VAC	0.2 A	27.6 VDC
	A-end	239.8 VAC	0.2 A	29.4 VDC
Tank Car	A-end	239.8 VAC	0.2 A	27.5 VDC
	B-end	239.8 VAC	0.2 A	29.7 VDC

After the second set of measurements was recorded, the test consist completed a lap and a half of the TTT at 40 mph. The test consist was then returned to the initial location outside the PSB at slow switching speeds. With the test consist relocated to the initial location, a final set of EPSS voltage and current measurements was recorded. Table 4 shows these measurements. Additionally, the same advanced devices were once again operated.

Table 4 – EPSS tertiary measurements

Car / Locomotive	Measurement Location	Train-line Voltage	Train-line Current	Battery Voltage
Locomotive	Short Hood	239.8 VAC	0.0 A	-
	Long Hood	239.8 VAC	0.4 A	-
Hopper Car	B-end	239.8 VAC	0.4 A	27.6 VDC
	A-end	239.7 VAC	0.4 A	29.4 VDC
Tank Car	A-end	239.8 VAC	0.2 A	27.3 VDC
	B-end	239.7 VAC	0.3 A	29.7 VDC

After all the critical measurements were recorded and the advanced devices were successfully operated, the EPSS was shut down. First, the EPSS train-line was disconnected at the locomotive using the EPSS train-line disconnect. Following the train-line disconnection, the EPSS supply disconnect was used to disconnect the 74 VDC power from the EPSS inverter. Finally, the locomotive was powered down.

With the EPSS completely powered off, the voltages of the batteries in the battery boxes were recorded. The battery voltages shown are less than when the EPSS is turned on. This is an indicator of the effect of the charging being accomplished by the EPSS. Table 5 shows these measurements.

Table 5 – EPSS battery voltage measurements

Car	Measurement Location	Battery Voltage
Hopper Car	B-end	25.6 VDC
	A-end	26.1 VDC
Tank Car	A-end	25.9 VDC
	B-end	26.3 VDC

Using the baseline readings for the EPSS supply voltage, the EPSS electrical modeling software was configured and executed. The results of the model were then used for comparison to the voltages and currents measured during testing.

3.2.1 Data Analysis and Model Validation

The test consist traveled an approximate total of 28 miles during demonstration/testing at speeds between 30 and 40 mph. Speeds greater than 40 mph were not attempted out of concerns for safety related to the known on-track performance of the test cars above that speed. Both the tank car and the hopper car have previously demonstrated significant hunting (i.e., dynamic lateral instability) behavior at speeds above 40 mph in other testing.

The advanced devices operated normally at all stages during testing. This indicates that the electrical connections between the batteries and the advanced devices remained intact throughout testing. It also signifies that the batteries did not deplete during testing.

For reference, Table 6 shows the nominal measurements obtained during the testing and the accuracy range of the Fluke 337 meter utilized.

Table 6 – Measurement accuracies

Nominal Measurement	Accuracy Range
24 VDC	±0.74 VDC
240 VAC	±2.9 VAC
0.4 A (AC)	±0.5 A (AC)
24 VDC	±0.74 VDC

As previously noted, the battery voltages measured with the EPSS powered down are lower than the voltages measured with the system active. This confirms that the batteries were being charged by the system. The battery charger system actively controls the amount of energy being delivered to the batteries to avoid overcharging or overheating. Because of this control, the voltage measured at the batteries when connected to an active charger will vary depending on the charge state of the batteries. This is evident in the data by the varying differences between the measured battery voltages with the EPSS shut down versus when the EPSS is active (Table 3 through Table 5).

Table 7 lists these voltage differences for the four battery boxes on the test consist. The EPSS Active voltages presented are the final voltage measurements recorded after the completion of the demonstration (from Table 4).

Table 7 – Battery voltages at rest and during EPSS charging

		Measured Battery Voltage (VDC)		
Test Car	End of Test Car	EPSS Active	EPSS Powered Down	Voltage Difference (VDC)
Hopper Car	B	27.6	25.6	2.0
	A	29.4	26.1	3.1
Tank Car	A	27.3	25.9	1.4
	B	29.7	26.3	3.4

The measured train-line voltages remained mostly consistent throughout the length of the test consist. This agrees with expectations, due to the short length of the test train.

A Fluke model 337 clamp-meter was used for all electrical measurements. The Fluke 337 has a specified current measurement accuracy of ± (2% + 0.5 A) and a voltage measurement accuracy of ± (1% + 0.5 V) when measuring AC sources. The specified AC accuracy ratings are applicable for the 60 Hz signal output of the EPSS inverter. The meter has a specified voltage measurement accuracy of ± (1% + 0.5 V) when measuring DC sources. The primary reason for using the Fluke 337 meter is the ability to measure current without interrupting the current loop. However, the inductive method for measuring current in the Fluke 337 is less accurate than inline measurements taken with other equipment. At this early stage in testing, it was important to be able to test the system while it remained intact and powered up. In addition, significant deviations in voltage and current values from the EPSS inverter are not expected due to the limited length of the test consist. At this stage in the project, obtaining more accurate inline measurements was both cost prohibitive and offered little value. Future evaluations should include more accurate inline measurements.

The model of the EPSS consist was developed before the system was designed and was meant to offer an approximation of the system. To this extent, the model treats each car as a singular electrical load. However, the actual consist, as installed, presents two electrical loads per car—one at each end—to the EPSS train-line. Measurements were taken where wires were easily accessible, which is not where the model predicts values. Figure 14 shows a simplified version of the model compared to the actual assembled test consist. Even with the differences, the measured values remain meaningful when analyzed appropriately. Based on such an analysis, the electrical current measurements taken during testing remain consistent with the model, given the accuracy of the measuring device.

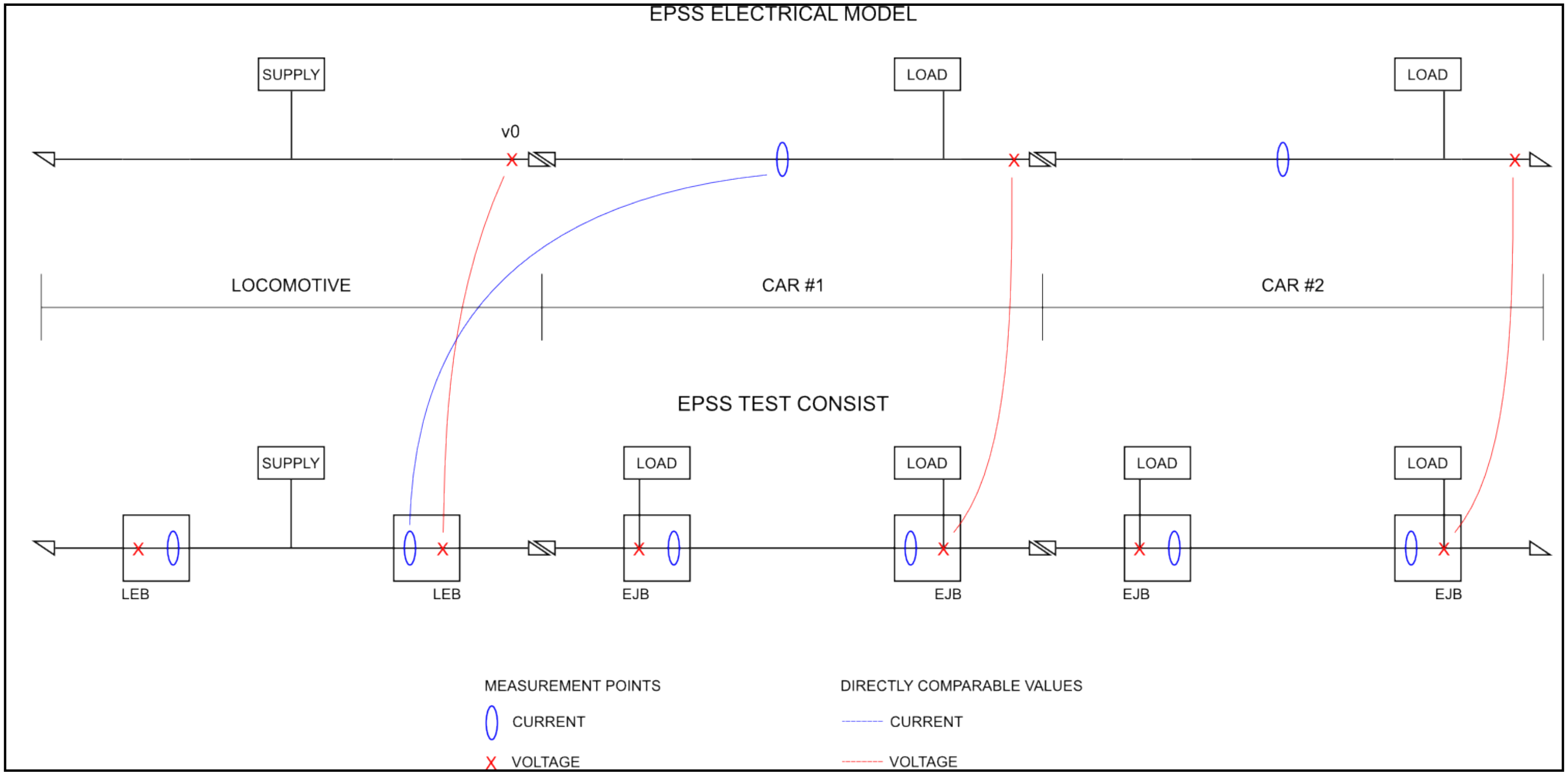


Figure 14 – **EPSS model compared to the EPSS test consist**

4. Conclusions and Recommendations

An EPSS system can supply a sufficient charge to battery systems on each car that allows for bursts of electrical power when demanded from safety devices. Also, there is enough EPSS electrical power to effectively utilize monitoring and control switching components (i.e., EDHB, RCCL, RCAC, etc.) in any number of configurations on each car. These findings have potentially significant safety benefits for the railroad industry.

SA's research additionally found the following:

- ECP systems cannot supply sufficient electrical power to freight cars for demands other than for braking use.
- On longer trains, an EPSS system cannot support utilization of advanced devices while continuously monitoring every car unless a battery-type interface exists which the EPSS system can keep charged.
- It is not possible to apply all EDHBs on a 150 freight car train at the same time when using a locomotive as the sole electrical supply vehicle because too much current would be required; however, if a battery-type interface exists on each car that EPSS will keep charged, it may be possible to apply all 150 EDHBs simultaneously because the EDHB requires a relatively short burst of power that can be provided from the batteries.
- The test confirms that the auxiliary generator should provide sufficient power for the EPSS requirements. Though some power distribution concerns must be considered, choosing a different locomotive power supply means for EPSS would be less favorable.
- The APTA, AAR, and PRIIA specifications reviewed primarily relate to existing equipment and infrastructure. In terms of electrical specifications, most relate to either house power on passenger equipment or MU connection systems for locomotives. Both of these purposes have specific requirements which are mostly unrelated to the requirements of the EPSS system. Because these systems are designed for very different purposes, the specifications will be different. Only general requirements such as Good Manufacturing Practices, National Electric Code compliance, Institute of Electrical and Electronics Engineers compliance, and similar specifications could be shared among the systems. Certain specifications will need to be developed specifically for EPSS to work in conjunction with the adoption of requirements currently utilized in other implementations.
- Demonstration and testing of the EPSS validated the theoretical predictions of the model for the system, albeit for a very limited version of the proposed system. The results of the demonstration combined with the validated model predictions suggest a need for system build-out (longer-train), harsher environmental, and more detailed monitoring/testing of EPSS during in-situ operations.

There are currently several advanced devices developed and many more being conceptualized. However, presently no reliable, cost effective systems for powering these devices on railroad freight cars exist. These devices have the potential to greatly impact railroad operations by increasing safety and efficiency. The EPSS provides the freight rail industry with the ability to add these advanced devices to railroad freight cars. Additionally, with a standard EPSS system, capable of powering advanced devices, in place manufacturers will be able to more cost-effectively develop new devices to further enhance freight railroad operations. As designed, and with limited further development, EPSS will provide this stable, reliable and convenient system for powering devices mounted to railroad freight cars.

There is a need to further develop and test the prototype architecture and specifications of EPSS, on a larger scale (longer train), and to continue to develop the system model and improve its accuracy for future use in designing EPSS for even longer trains. Additionally, the measurement of the system's functionality with the train in motion is needed. And a standard interface or transition from the train-line power to any device application such as sensors or remote controlled devices needs to be standardized for easy implementation. Therefore, future work should include the development of a standard universal DC access battery box and charger system to integrate into any EPSS equipped vehicle for use by suppliers of monitoring and control sensors/devices.

5. References

1. American Public Transportation Association, "15. Recommended Practice for 480 VAC Head End Power System," APTA PR-E-RP-016-99, 1999.
2. American Public Transportation Association, "16. Recommended Practice for 27-Point Control and Communication Trainlines for Locomotives and Locomotive-Hauled Equipment," APTA PR-E-RP-017-99, 1999.
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9. Association of American Railroads Manual of Standards and Recommended Practices Electronically Controlled Brake Systems S-4260, "ECP Brake and Wire Distributed Power Interoperability Test Procedures."
10. Association of American Railroads Manual of Standards and Recommended Practices Electronically Controlled Brake Systems S-4270, "Brake System Configuration Management."

Abbreviations and Acronyms

ACRONYMS	EXPLANATION
AC	Alternating Current
APTA	American Passenger Transit Agency
AWG	American Wire Gauge
A	Ampere
AAR	Association of American Railroads
CNS	Collision Notification Sensors
DNS	Derailment Notification Sensors
DC	Direct Current
ECP	Electrically Controlled Pneumatic
EDHB	Electrically Driven Set & Release Hand Brakes
EJB	Electrically Powered Supply System Junction Box
ELEB	Electrically Powered Supply System Locomotive End Box
ELJB	Electrically Powered Supply System Locomotive Junction Box
EPSS	Electrically Powered Supply System
EPTI	Electronic Poston Travel Indicators
FRA	Federal Railroad Administration
GMS	General Monitoring System
GPS	Global Positioning System
GMP	Good Manufacturing Practices
HBRS	Hand Brake Release Sensor
HazMatMS	Hazardous Materials Release Monitoring Sensors
Hz	Hertz
IEEE	Institute of Electrical and Electronic Engineers
ITS	Intrusion & Tampering Sensors
MU	Multiple Unit
NEC	National Electric Code
RD&T	Office of Research, Development and Technology
Ω	Ohm
PRIIA	Passenger Rail Investment and Improvement Act
PSB	Passenger Services Building

ACRONYMS	EXPLANATION
RCAC	Remote Controlled Angle Cocks
RCACH	Remote Controlled Angle Cock with Heater
RCCL	Remote Controlled Cut Levers
RCHB	Remote Controlled Hand Brakes
RRHB	Remote Release Hand Brake
SLA	Sealed Lead-Acid
SMS	Security Monitoring System
SA	Sharma & Associates, Inc.
TCR	Track Conditioning Run
TTC	Transportation Technology Center
TTT	Transit Test Track
VAC	Voltage Alternating Current
VDC	Voltage Direct Current
W	Watt
WSN	Wireless Sensor Networks