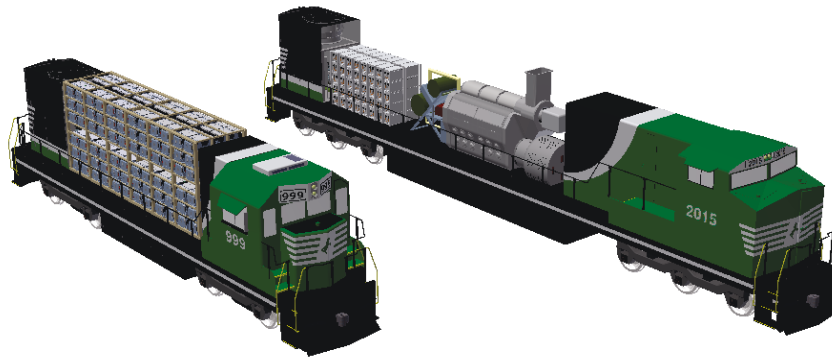U.S. Department of
Transportation

**Federal Railroad
Administration**

Hybrid Locomotive for Energy Savings and Reduced Emissions

Office of Research,
Development
and Technology
Washington, DC 20590

REPORT DOCUMENTATION PAGE

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13. ABSTRACT (Maximum 200 words)
Norfolk Southern Corporation (NS) and Pennsylvania State University tested several different battery systems in hybrid locomotives. Advanced lithium-ion battery technology was the only kind that displayed the capacity to perform in heavy switching or local service. Testing proved hybrid locomotives could reduce emissions and save fuel, sometimes in significant amounts. However, even with the best assumptions taken into consideration, these locomotives would require high annual operating subsidies.

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METRIC/ENGLISH CONVERSION FACTORS

ENGLISH TO METRIC

LENGTH (APPROXIMATE)

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

AREA (APPROXIMATE)

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

MASS - WEIGHT (APPROXIMATE)

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

VOLUME (APPROXIMATE)

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

TEMPERATURE (EXACT)

$[(x-32)(5/9)]$ °F = y °C

METRIC TO ENGLISH

LENGTH (APPROXIMATE)

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

AREA (APPROXIMATE)

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

MASS - WEIGHT (APPROXIMATE)

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

VOLUME (APPROXIMATE)

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

TEMPERATURE (EXACT)

$[(9/5) y + 32]$ °C = x °F

QUICK INCH - CENTIMETER LENGTH CONVERSION

Inches: 0 1 2 3 4 5

Centimeters: 0 1 2 3 4 5 6 7 8 9 10 11 12 13
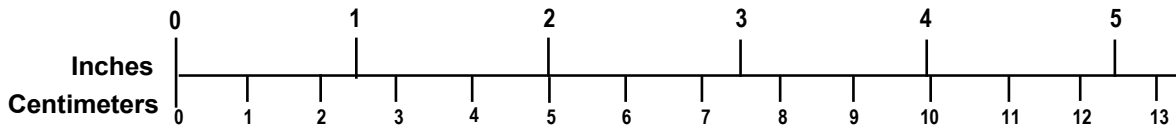
QUICK FAHRENHEIT - CELSIUS TEMPERATURE CONVERSIO

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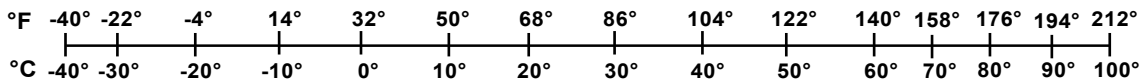
For more exact and or other conversion factors, see NIST Miscellaneous Publication 286, Units of Weights and Measures. Price $2.50 SD Catalog No. C13 10286

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Executive Summary

From April 2014 to December 2015, Norfolk Southern Corporation (NS) continued the project it started in 2008 to develop the NS 999 battery electric switcher locomotive by moving the unit to Roanoke, VA, for use in switcher service. NS found the lead-carbon batteries currently installed on the NS 999 had approximately 50% of expected capacity and could not complete a full shift of switcher duty. After about 3 months of service, several electrical parts on the NS 999 failed while the unit was charging. Failure analysis was underway at the time of this research project.

The Federal Railroad Administration (FRA) sponsored the study through continued laboratory testing of two other battery chemistries for use in both switcher and road service locomotives. Testing of a high-capacity lead-carbon battery string for switcher use at NS showed that this battery better withstood simulated switcher duty than previously tested lead-carbon batteries did. Pennsylvania State University (Penn State) tested an advanced-chemistry lithium-ion battery pack for use on both a switcher and road locomotive. This testing showed that the lithium-ion pack provided significant energy storage and would be suitable for more rigorous switching duties, local service, and road use. Penn State also characterized the lithium-ion pack with Hybrid Pulse Power Characteristic (HPPC) testing and capacity tests. Using this information, Penn State created a hybrid locomotive model that shared the load between a diesel engine and the lithium-ion pack. The model allowed dynamic braking energy to recharge the battery pack. Penn State checked the model's accuracy by comparing the model's results to hardware tests using the lithium-ion pack. NS then used this model to run a designed experiment that showed a hybrid locomotive could reduce emissions of pollutants. However, the resulting fuel savings do not offset the capital cost of the battery pack; so, each hybrid locomotive would need a large annual subsidy.

1. Introduction

Wide fluctuations in diesel fuel costs and advances in battery energy storage technology have prompted renewed interest in electric locomotives and hybrid locomotive systems. In switching service, a battery Energy Storage System (ESS) would allow for a zero-point source emission locomotive in non-attainment areas while a line-haul (road) hybrid would reduce emissions and improve efficiencies by an estimated 8–15% in some freight applications. The Norfolk Southern Corporation (NS) strategic research plan was to develop a battery electric switcher locomotive as an ESS research platform with the ultimate goal of developing a road hybrid locomotive capable of recovering dynamic braking energy by means of an ESS.

1.1 Background

Project Work 2008-2010

In 2008, NS began to develop a prototype battery powered all-electric switcher locomotive that used an array of 1,080 conventional 12-volt lead-acid batteries. NS unveiled the all-electric battery powered switcher locomotive, NS 999, at its Juniata locomotive shop in Altoona, PA, on September 28, 2009.

Figure 1. NS 999 under test at Rose Yard in Altoona, PA

Operating the NS 999 switcher locomotive identified numerous challenges associated with charging and discharging long strings of lead-acid batteries. Poor battery management caused large variations in individual battery voltage and State of Charge (SoC) across the battery strings. The voltage and SoC variations resulted in premature battery failure, reduced reliability and lower locomotive horsepower. Due to the premature battery failures, initial testing of the NS 999 was concluded in March 2010, and the ESS was disassembled in February 2011.

Project Work 2011-2013

Follow-up work in 2011 through 2013 focused on testing solutions to several shortcomings identified from initial NS 999 field trials. These included redesign of the Battery Management

System (BMS), exploration of alternative battery technologies and repackaging of the energy storage system to improve maintenance and battery thermal issues (seen in laboratory testing).

To support the test program, design and construction of an NS battery test laboratory, or Hybrid Locomotive Simulator (HLS), was completed in November 2011. The HLS included BMS design enhancements and a new battery technology to be tested prior to reassembling the locomotive. Comprehensive full-scale (charge/discharge cycle testing of two 700v battery strings) laboratory testing combined with energy modeling was initiated to understand and optimize battery performance for both switcher and road service duty cycles.

The new battery technology was a lead carbon battery developed by Axion Power International Inc., referred to as the Axion pack hereafter. This battery technology removes the sulfation failure mode occurring from poor battery management, which reduced the expected life of the conventional lead acid batteries in the original NS 999. Further, the battery's higher dynamic charge acceptance appeared to offer a greater opportunity to capture the dynamic brake energy with less energy fade and a longer projected service life.
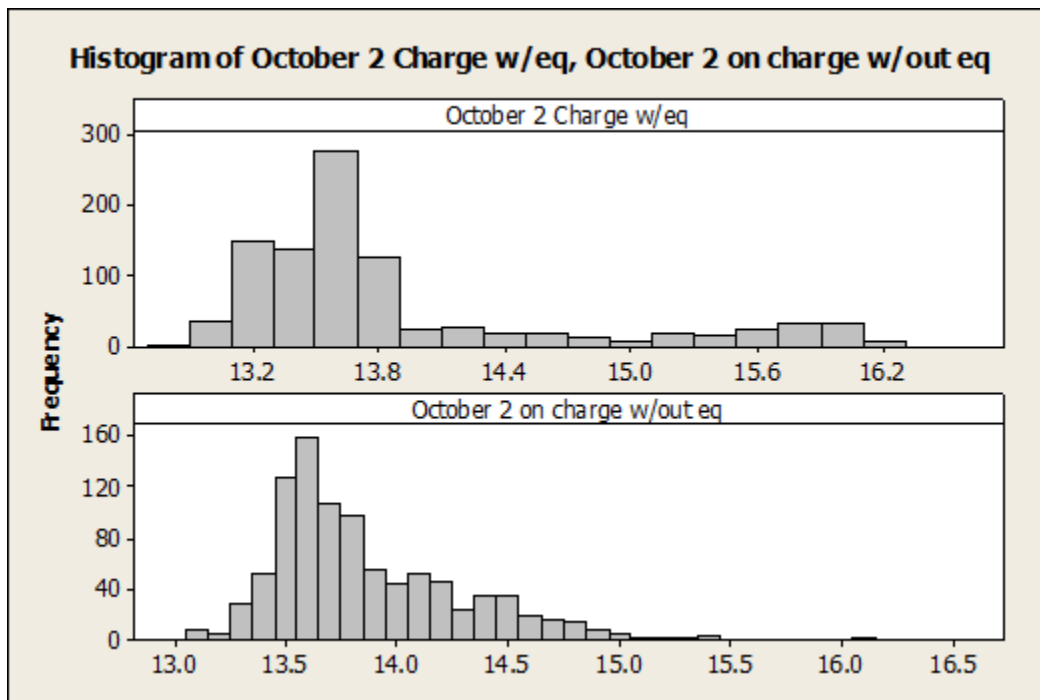
Figure 2. NS 999 traditional lead-acid battery voltage variation across a string of 54 batteries after charging. Top histogram (w/ equalization). Bottom histogram (w/o equalization)

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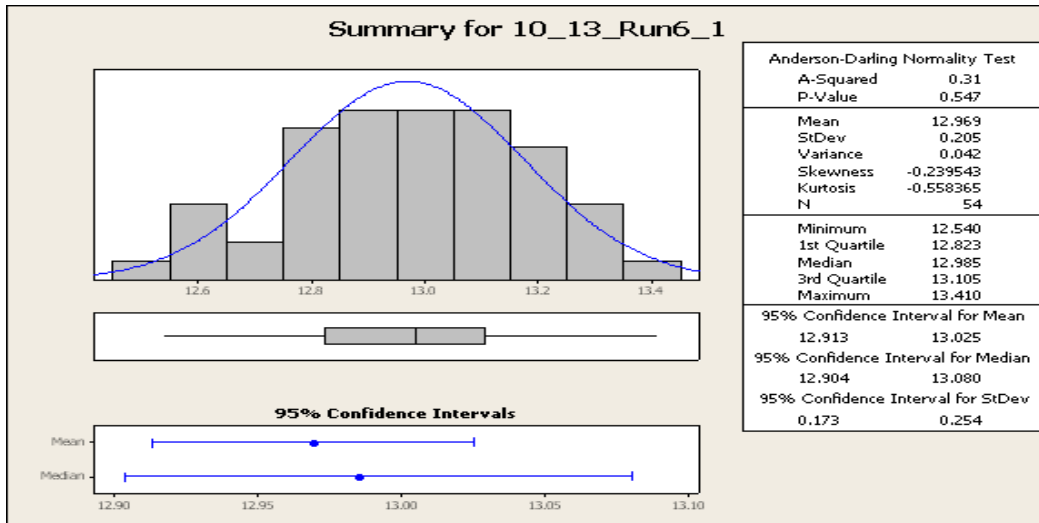
Figure 3. HLS lead carbon battery voltage variation across a string of 54 batteries after charging

The approach to the redesign of the NS 999 battery packaging was to design a packaging system that utilizes passive cooling based on current industrial Uninterruptible Power Supply (UPS) designs that can then be ruggedized for the railroad environment. IntraPack Corp, a leader in stand-by power battery systems, designed and manufactured the battery trays, and DropBox, Inc, a custom ISO container modification specialist, designed and manufactured the battery container to hold the battery trays.

Figure 4. NS 999 battery ISO container manufactured at DropBox, Inc.

Project Work 2014

The NS 999 rebuild at the Juniata locomotive shop was completed in October 2014, and the battery switcher returned to Rose Yard in Altoona, PA, during the fourth quarter of 2014 for initial testing. After testing, the locomotive was placed in revenue service in the NS Roadway Material Yard in Roanoke, VA. The NS 999 has been in operation in this service since February 2015.

Figure 5. Battery ISO container in place on NS 999

Figure 6. IntraPack battery trays in place on NS 999

Figure 7. NS 999 charge and discharge testing at Juniata locomotive shop

In parallel to NS 999 rebuild efforts and continued HLS testing, NS worked with researchers at the Penn State Battery Application Technology Testing & Energy Research Laboratory (BATTERY) for exploration into and testing of "next generation" battery technologies, such as lithium-ion variants and nickel metal hydride, for the road hybrid locomotive application.

For full-scale road hybrid battery testing at BATTERY, NS selected the Corvus Energy AT6500 Energy Storage Modules (6.5kWh) featuring Dow Kokam's Lithium Nickel Manganese Cobalt (NMC) polymer cells. The Corvus Modules are a viable candidate for a road hybrid due to their favorable combination of energy density, cycle life, advanced BMS and industrial experience with hybrid marine watercraft. After selection of the Corvus battery, preliminary work began into the development of a locomotive model that would be used in hybrid locomotive Software in the Loop (SIL) computer simulations and Hardware in the Loop (HIL) battery testing using actual locomotive duty cycles.

1.2 Objectives

The general objective of this project is to continue the FRA grant activities initiated under Agreements FR-RRD-0015-10-01-00 through FR-RRD-0015-10-01-04, of researching the feasibility and ultimate development of a hybrid battery powered road locomotive.

Specific objectives for the grant period include:

1. Continuing to operate the NS 999 switcher locomotive in revenue service to trend capacity and efficiency for comparison to diesel engines. Thus far, the NS 999 reliability has proven poor; largely due to non-battery systems including choppers, insulated-gate bi-polar transistor (IGBT) and cooling system failures. The NS 999 prototype provides a unique opportunity to further study and define the technical challenges and long-term

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economics of battery-based energy storage systems. Ultrabattery testing – underway since December 2014 will continue. Thus far, the East Penn UltraBattery has tested with higher capacity, lower variation, and higher efficiency (resulting in less heating) then previously proposed systems.

2. Continuing laboratory testing of a 104-kWh string of 16 Corvus Energy AT6500 48V Li-NMC battery modules, hereafter referred to as the Corvus string. It includes:

   A. Accelerated switcher cycle testing. Findings will be compared against the results obtained from previous evaluations of advanced lead-carbon battery technologies in terms of charge/discharge efficiencies, battery/cell variations, heat loads generated, etc. This item has been updated to run between 6 and 8 strings of Corvus AT6500 battery modules against defined switcher load profiles. Coupled with the capacity testing this should give an indication of the feasibility of the Corvus system in an electric switcher locomotive. The series of tests will include the ability of the batteries to achieve this service as the battery modules age.

   B. Hybrid Pulse Power Characterization testing (HPPC) of the Corvus string to further define the ideal operating range and potential for battery overheating by estimating the instantaneous resistance at various states of charge.

   C. Additional capacity checks to confirm the manufacturer's energy ratings for the Corvus string, noting cell variations and its influence on the overall useable energy. This test will be repeated as the Corvus string is tested to define life cycle degradation.

   D. Accelerated line-haul cycle testing using representative load profiles ("drive cycle") derived from event recorder data in revenue service. Testing will explore various hybrid configurations (diesel engines), ESS size and utilization strategies. This task has also been updated to include running a Design of Experiment (DoE) including a full factorial of five different variables including: temperature, charge/discharge power, number of strings, two different load profiles, and gain (range of State of Charge and the speed at which the hybrid controller allows the batteries to change SoC). This DoE will include 32 different runs with two replicates or an estimated 64 runs to optimize application of the Corvus string and define potential deficiencies. The end points of the DoE will be run first for evaluation prior to completing all the runs and replicates. This line-haul testing is also known as HIL testing and SIL simulations.

1.3 Overall Approach

To further development of a zero-point source emission battery electric switcher the Corvus string will be tested using the previously developed "advanced switcher cycle." Integration of these more energy dense batteries onto a switcher platform will allow more onboard capacity and less downtime due to recharging. Other switcher activities will be continued operation of the NS 999 and HLS testing of the East Penn UltraBattery.

To determine viability of a road hybrid locomotive, NS and the Penn State BATTERY lab will perform HPPC tests to assess the effectiveness of the Corvus string. From these tests a battery model can be developed and integrated with the previously created locomotive model for SIL computer simulations. With the SIL model we can simulate various road hybrid locomotive scenarios to determine the most viable configurations. Ultimately the battery model within the road hybrid SIL model will be "replaced" with the physical Corvus string and tested under the same conditions to determine fidelity between the computer simulations and physical cycling of the battery. If the fidelity is high, we can use the SIL as a surrogate for time consuming (1 run is approximately 30 hrs) physical testing.

With SIL and HIL results NS will determine the viability of a road hybrid locomotive. The analysis will include sections dedicated to energy recovery, emissions reductions and a financial analysis.

1.4 Scope

The work contained within and performed during the grant period pertains to North American freight railroads. Load profiles, locomotive characteristics and engineering considerations have been developed with this specific industry in mind. Due to the flexible design of the test protocols, HIL and SIL models modifications can be made to accommodate other rail segments if given the appropriate inputs.

2. NS 999 Operation and HLS Testing

2.1   NS 999 Operation

The Juniata locomotive shop completed construction of the second-generation NS 999 in September 2014. After a brief checkout in Altoona Yard, NS moved the unit to the Roanoke Roadway Material Yard in the 1st quarter of 2015. NS researchers checked and recorded data for 2 months while the locomotive was in use.

During cold weather, the Axion pack had less capacity than it had shown during the previous laboratory testing. NS began charging the unit for one-hour at mid-shift to try to extend the unit's run time to complete an entire shift. However, the Axion pack could not complete an entire shift even with the mid-shift charge or with warmer weather. NS estimated the Axion pack capacity was at approximately 50% of expected, but could not quantify the exact capacity because the unit's software lacked a standardized capacity test.
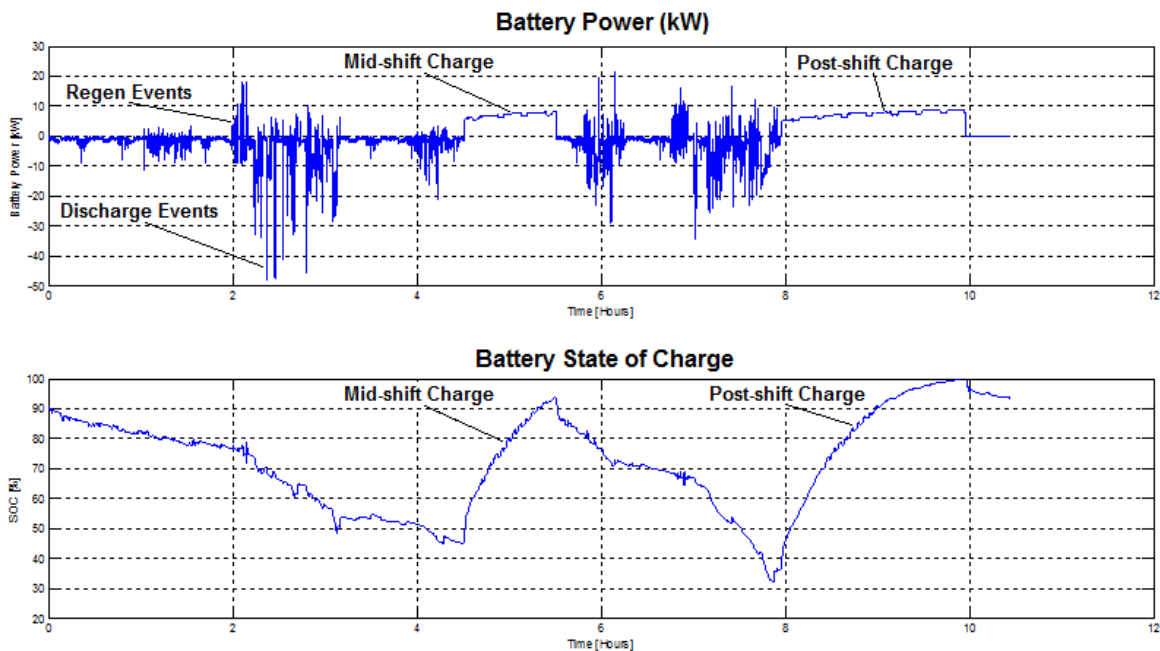

Figure 8. NS 999 material yard switching load profile

After completing 22 switcher shifts, several electrical parts on the NS 999 failed while the unit was charging. A ruptured cooling line that leaked coolant onto the high-voltage bus likely caused the part failures, but a power surge from severe electrical storms in the area may have also caused the failures. Several improvements were made to the control software during the unit's repairs:

- Doubling the BMS CAN bus speed to fix a communication problem

- Adding an improved state-of-charge (SoC) algorithm

- Adding a standardized capacity test (20-amp discharge) similar to the laboratory tests

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Capacity testing after the repairs and upgrades showed the control software intermittently disabled strings to protect the equipment. This prompted further investigation, which found possible shorts within three of the battery trays and other potential issues with the power electronics. Analysis of these problems is still underway.

2.2   HLS Testing

To address runtime issues with the NS 999, NS sought out a higher capacity lead-carbon battery. As a result, NS began testing a string of East Penn UltraBatteries in the Roanoke HLS. In 2015, The UltraBattery string completed about 425 (9900kWh) simulated switcher shifts. The testing has shown low within-string voltage variation and double the capacity compared with other lead-carbon batteries previously evaluated. These results make the UltraBattery a strong candidate for use in the current switcher service but not for more rigorous switcher service.

Figure 9. HLS outfitted with East Penn UltraBattery string

3. Penn State University Testing

3.1 Accelerated Switcher

The purpose of the Accelerated Switcher cycle is to estimate the battery run-time in a switcher locomotive. It consists of simple charges and discharges that simulate the NS 999 in service. The cycle repeats until the battery has reached its lower voltage or SoC limit.
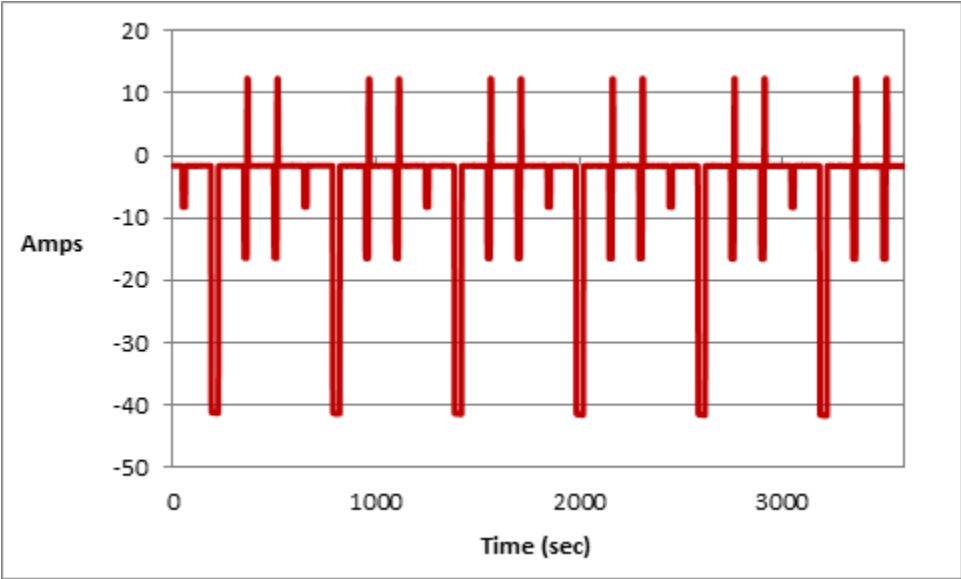

Figure 10. Graph demonstrating typical Accelerated Switcher cycle current demand
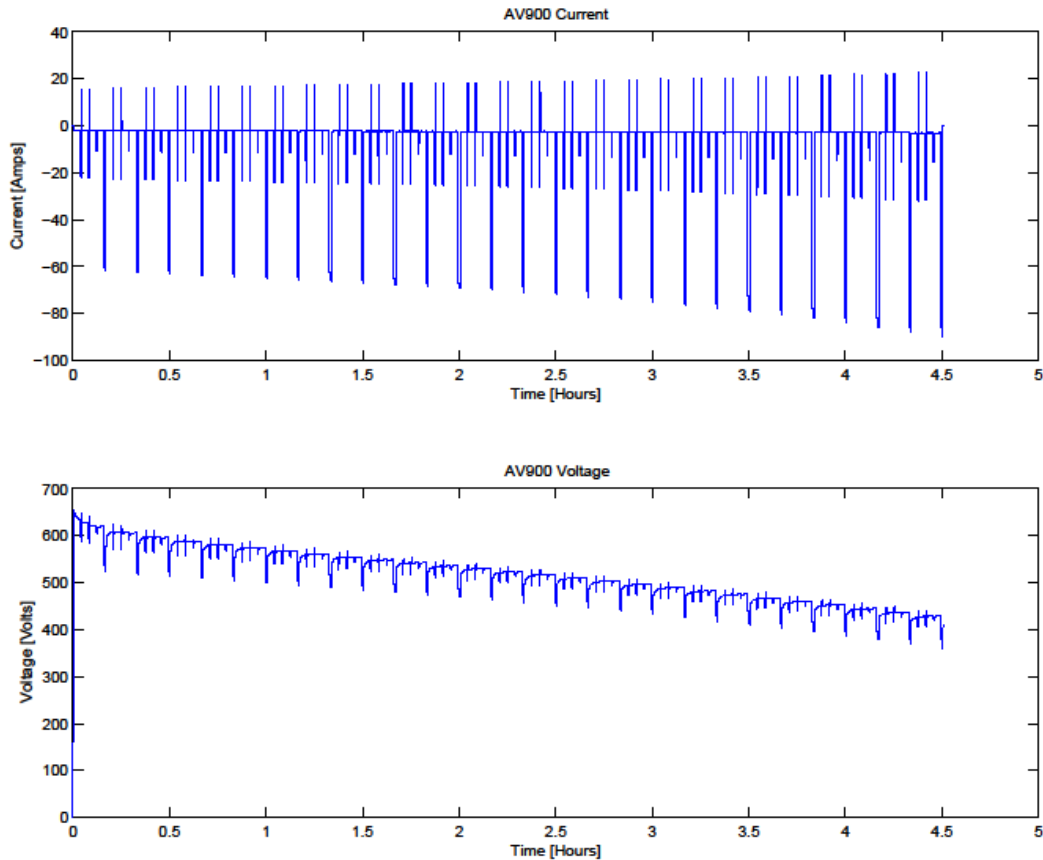
Figure 11. AV900 current and voltage output during Corvus battery pack Advanced Switcher cycling

Previous Accelerated Switcher testing with the Axion pack yielded 4.5 hours of total runtime. This result is nearly identical with the runtime seen in NS 999 field service. Testing of the Corvus pack produced a runtime of 26 hours in Advanced Switcher testing. With this runtime, the NS 999 could complete a full day of switching without need of a recharge instead of the single shift that it can complete with lead-carbon packs. The Corvus pack may allow for more power and energy demanding switching service such as hump yard switching or even "local service" traveling around a city switching industry customers.

3.2   Hybrid Pulse Power Characterization

Hybrid Pulse Power Characterization testing is intended to determine dynamic power capability over the device's useable voltage range using a test profile that incorporates both discharge and regenerative pulses. The primary objective of this test is to establish, as a function of depth-of-discharge, the discharge power capability and the regenerative power capability.
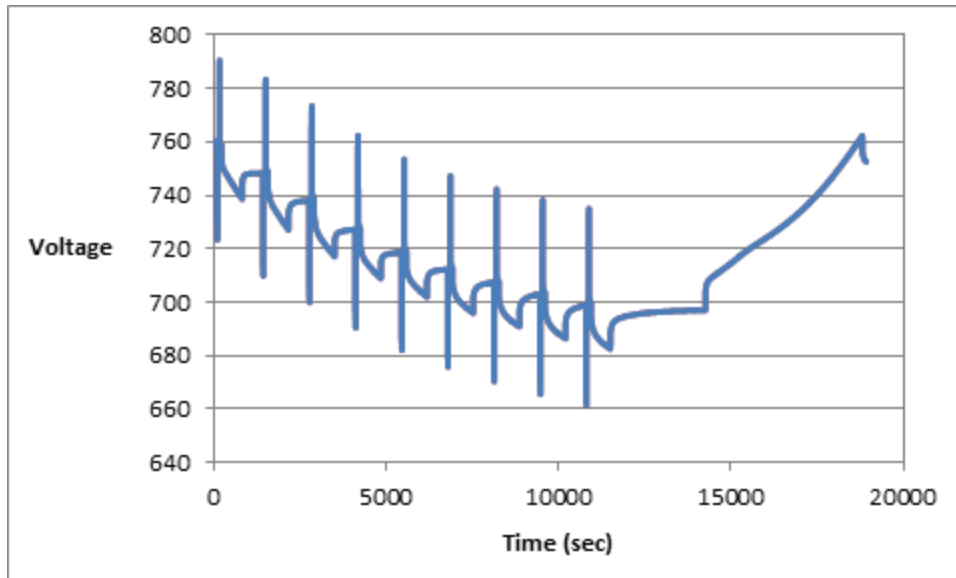
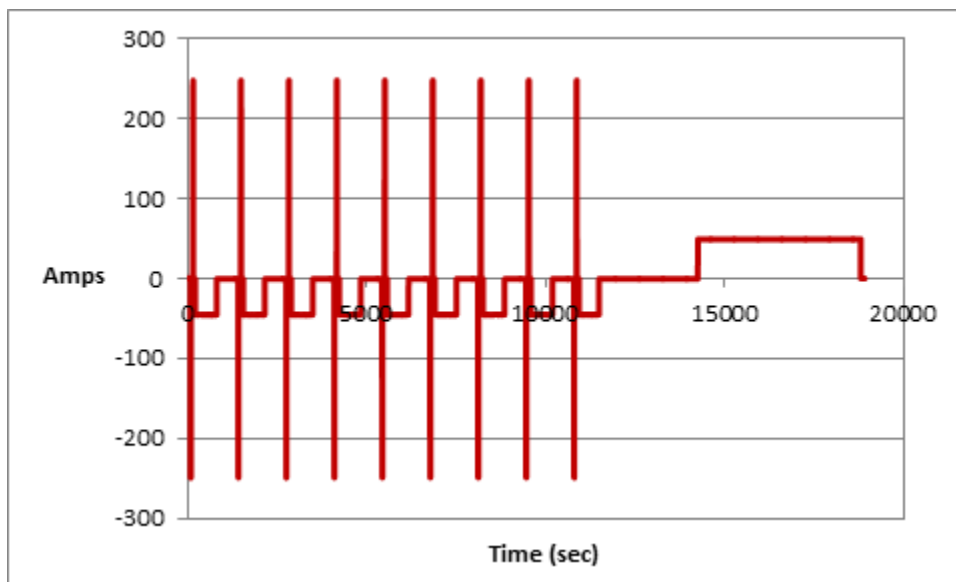**Figure 12. Corvus voltage during HPPC test**

Figure 13. Corvus amperage during HPPC test

The voltage response curves are then used to derive the fixed (ohmic) cell resistance and cell polarization resistance as a function of state-of-charge. The resistance measurements will be used to evaluate resistance degradation during subsequent life testing and to develop hybrid battery performance models for vehicle systems analysis [1]. Penn State used the information from this test to develop the battery model used with the hybrid locomotive model.

3.3 Capacity Tests

Penn State performed multiple capacity tests on the Corvus pack during 2015 to record the capacity loss, or State of Health (SoH), as it degraded over time. Corvus reported the pack's capacity at 150 A-hrs (at 100% Depth of Discharge [DoD]). Penn State's tests did not confirm

that capacity. However, Penn State limited the previous charge to about 93% SoC to prevent overcharging the battery.
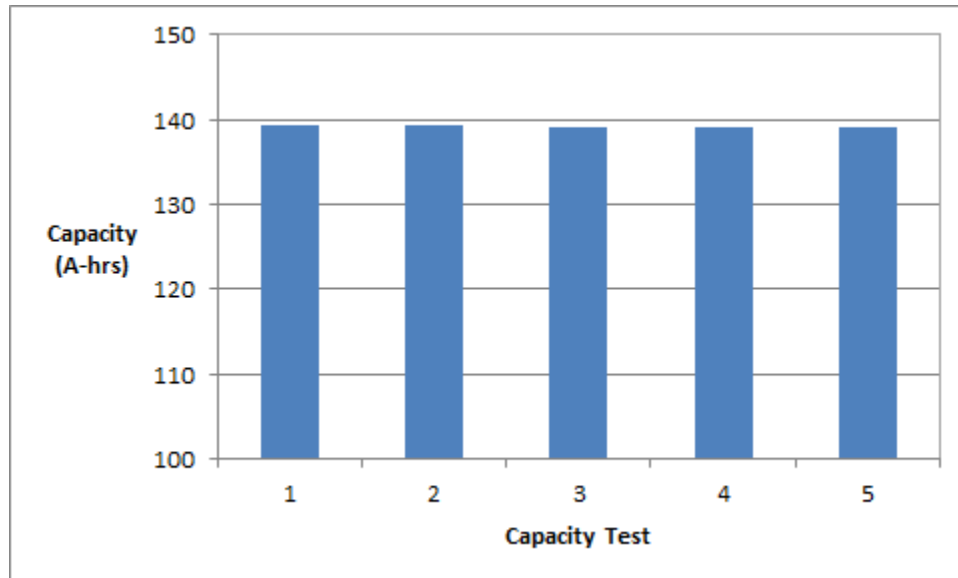

Figure 14. Corvus battery pack capacity test results

3.4   SIL and HIL

Due to multiple unpredictable full battery charge and discharge cycles over the course of a multi-day road hybrid locomotive duty cycle an accurate generic drive cycle is difficult to develop. The two categories of testing that can be conducted to simulate a road hybrid locomotive are software-in-the-loop and hardware-in-the-loop testing.

SIL is used as a development tool for locomotive/battery control logic and also is used as a benchmark for HIL testing. In other words, matching results from SIL and HIL validates both the integrity of the computer model and the proper functioning of the hardware setup. A SIL simulation is to be used to analyze the effectiveness of the control logic and as performance index that the HIL tests are expected to match. HIL test reports are to be used to validate the functionality of all of the systems working together. HIL results also are used to give a close estimate to the battery performance in a real-world application.

3.4.1 SIL Software Setup

The MATLAB/Simulink environment was used as the main tool to develop the locomotive powertrain model to be used in simulation. Power demand and time are the only inputs into the model. This power demand is the culmination of actual data obtained from locomotives in operation. The power demand over various drive cycles was provided by NS for the development of the power split control algorithms. Figure 15 shows the highest level of the model with power demand as the single input and output power from the three forms of energy transmission (diesel generator, battery, and dynamic brake) included.
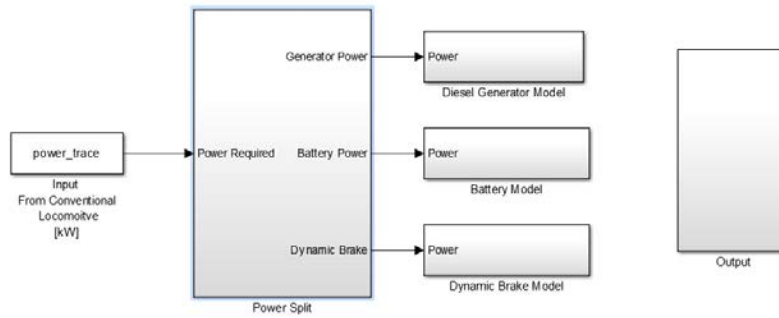
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Figure 15. Top-level of locomotive powertrain model

Power-split Model

As the power demand is input into the power split model a forward looking control (FLC) algorithm is initiated. The control method applied here is to operate the battery in a steady state manner. This means the control method should command the battery to output a constant current as often as possible. The logic here is to recognize discharge and charge cycles, and then apply a constant current over that cycle to reach either a discharge or charge respectively. This FLC is used to operate the battery in a fashion that decreases negative SoH effects that occur in aggressive control strategies while also resulting in minimal fuel consumption.
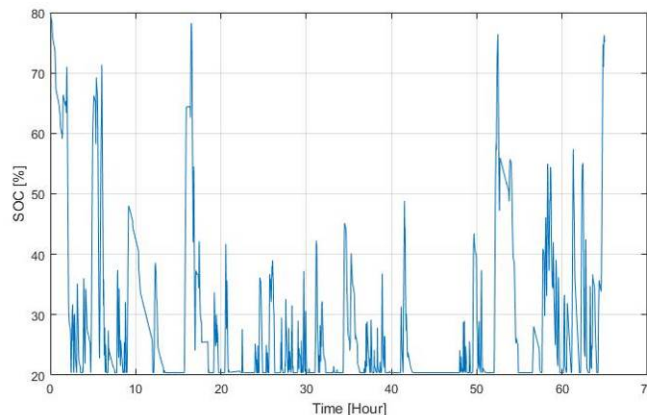

Figure 16. FLC fully discharges the battery with steady state battery operation

In observing the SoC over the simulation, FLC effectively discharges the battery completely just as each discharge cycle ends, rather than quickly discharging and sitting at a minimum SoC, which is an issue with the other control methods. Charge cycles are also more effective as often the power profile allows for charging at a maximum rate. This allows all possible available regenerative energy to be captured by the ESS.

The proper functionality of the steady state battery operation is more easily seen in Figure 17. This is a visual of the current command over a small-time window.
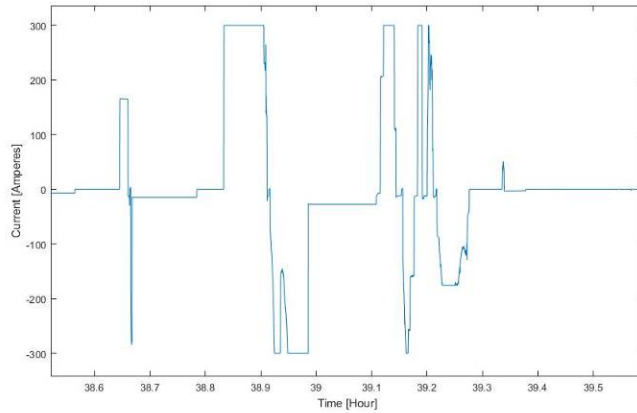
Figure 17. FLC logic commands a series of constant current cycles to operate the battery in a steady state manner

FLC recognizes charge and discharge events and commands an average current over the cycle to operate the battery in a steady state manner. The benefit of this can be seen in the much lower negative effect on battery SoH. This is achieved by eliminating rapid charge and discharge cycling as well as commanding constant current levels during these cycles.

Table 1. FLC performance metrics

Potential Discharge Energy	34.04 MWhr (1636.6 gallons of diesel)
Potential Regenerative Energy	8.107 MWhr
Energy Offset by Battery	3.58 MWhr (172.35 gallons of diesel)
Energy Captured	3.08 MWhr
Generator Diesel Consumption	1458.7 gallons of diesel
SoH Loss	0.1983%

Diesel Generator Model

The diesel generator model accounts for all power demanded that the battery cannot meet. The diesel generator will fill the excess power demand that the battery does not output. Power in kW from the generator is translated into fuel consumption for later use in comparison of the effect on fuel consumption of each control strategy.

Battery Model

A simple linear battery model was used for software-in-the-loop simulations. The model consists of lookup tables based on the data from HPPC battery characteristic tests and from Corvus that were used in hardware-in-the-loop simulation. The battery model is necessary to test that commanded battery output from the controller is as expected before implementing battery hardware. It was not in use under HIL testing.

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Dynamic Brake Model

Dynamic braking provides the method of capturing kinetic energy under braking for storage in the ESS. The dynamic braking model simply monitors all negative power demands. Negative power corresponds to braking scenarios that, without hybridization, would be wasted in the form of thermal energy. Energy captured from dynamic braking charges the battery for later use [2].

3.4.2 HIL Hardware Setup

Corvus string

Figure 18 shows the battery system enclosed in an ESPEC ETC-200L chiller for simulation of thermal management. The battery model being used is the Corvus AT6500-250. The battery modules are arranged in a 16-module series element configuration.

Figure 18. Corvus battery system enclosed in ESPEC chiller

AV900

The AV900 Electrical Loading Device gives the hardware simulation the capability to meet battery power output capabilities. This machine is capable of operating continuously up to 1000 Amps, at 1000 Volts, and up to 250 kW. The AV900 has the benefit of having automatic cutoff switches in the case of power outage or operation exceeding load capabilities

Component Interface

The key component in this setup is the Simulink Real-Time Target with communication to both the AV900 and battery system. There is then also a high power/high voltage interface between both the AV900 and battery system which is monitored and controlled by the Simulink Real-Time Target.
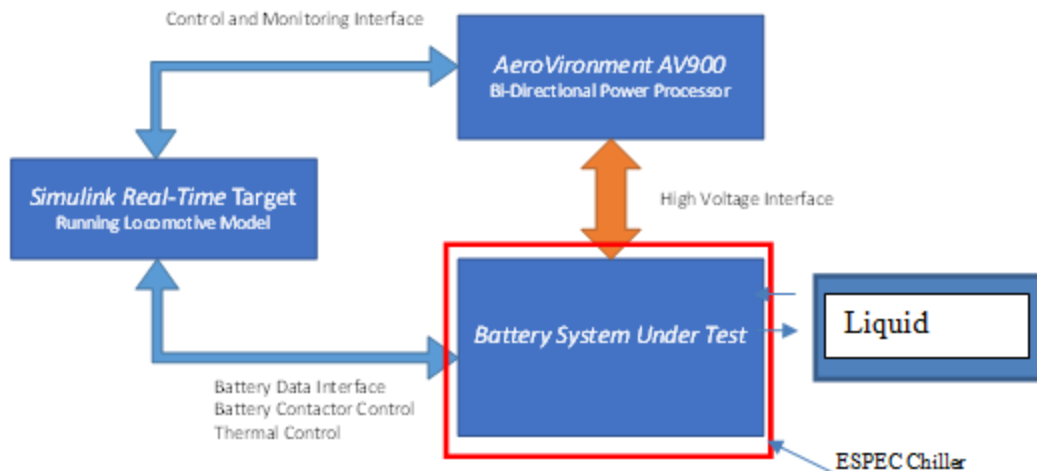
Figure 19. Interface diagram of HIL testing station

3.4.3 Results

Penn State performed a series of tests to compare the results of HIL and SIL simulations. Factors included in the tests were:

- Allowable battery DoD (SoC range)
- Two load profiles
- Ambient temperature

Analysis of the results showed that the SIL model was sufficiently accurate to use as a proxy for further work. Discrepancies between the SIL and HIL primarily resulted from:

- Minor differences between the simulation's BMS and the real pack's BMS
- Temperature effects on the Corvus pack's ability to charge and discharge, which the SIL model does not consider.

These discrepancies cause the hybrid locomotive model slightly to overstate real-world performance.

3.5 Hybrid Locomotive Analysis

Using the hybrid locomotive model, NS conducted a full factorial design of experiment to find the ideal number of battery strings and best battery operating range. Factors included in the simulations were:

- Power factor (number of battery strings)
- Allowable battery DoD (SoC range)
- Route (hilly or flat), which provided load profile

To prevent terrain for a route from unduly influencing the results, each route consisted of a round-trip between origin and destination. Blocks in the experiment removed undue influence

from train handling and dispatching. Blocks used data from an intermodal train from each route. Including center points, the designed experiment consisted of 72 simulations.

The four primary outputs used to analyze the results were:

1. Calculated battery life in years (assumed number of trips each year)

2. Gallons of fuel saved (calculated with data from a typical Tier 0 4,000-hp road locomotive)

3. kWH to recharge the pack to initial value at the end of each round trip

4. Pounds of emissions prevented (calculated with data from a typical Tier 0 4,000-hp road locomotive)

Using the first three outputs, NS calculated an Effective Uniform Annual Cost (EUAC) for each run to determine the financial impact. EUAC was calculated with a battery cost of $1250/kWh and a fuel cost of $3.00/gallon. The cost estimate of the battery pack was determined using the typical 2015 cost of a Li-NMC pack adding a BMS, cooling system and packaging (typically 50%). The cost of capital used in the calculations was 10%. Expenses such as additional electrical components and control system upgrades necessary for hybridization were not included in the EUAC. As a result, the calculated EUAC understates the costs of an actual hybrid locomotive.

Analysis of the experiment showed that variable settings that produced the best financial results did not correspond to the best reductions in emissions and vice versa. The analysis also showed that power factor and load profile (route) were the key variables. In hilly terrain, more dynamic brake energy is available to recharge the battery, which reduces emissions and fuel use but also reduces battery life with more frequent cycling. Similarly, a higher power factor and larger SoC range allows more dynamic brake energy to be recovered, which reduces emissions and fuel use but increases the initial battery cost and reduces its life with deeper discharges.
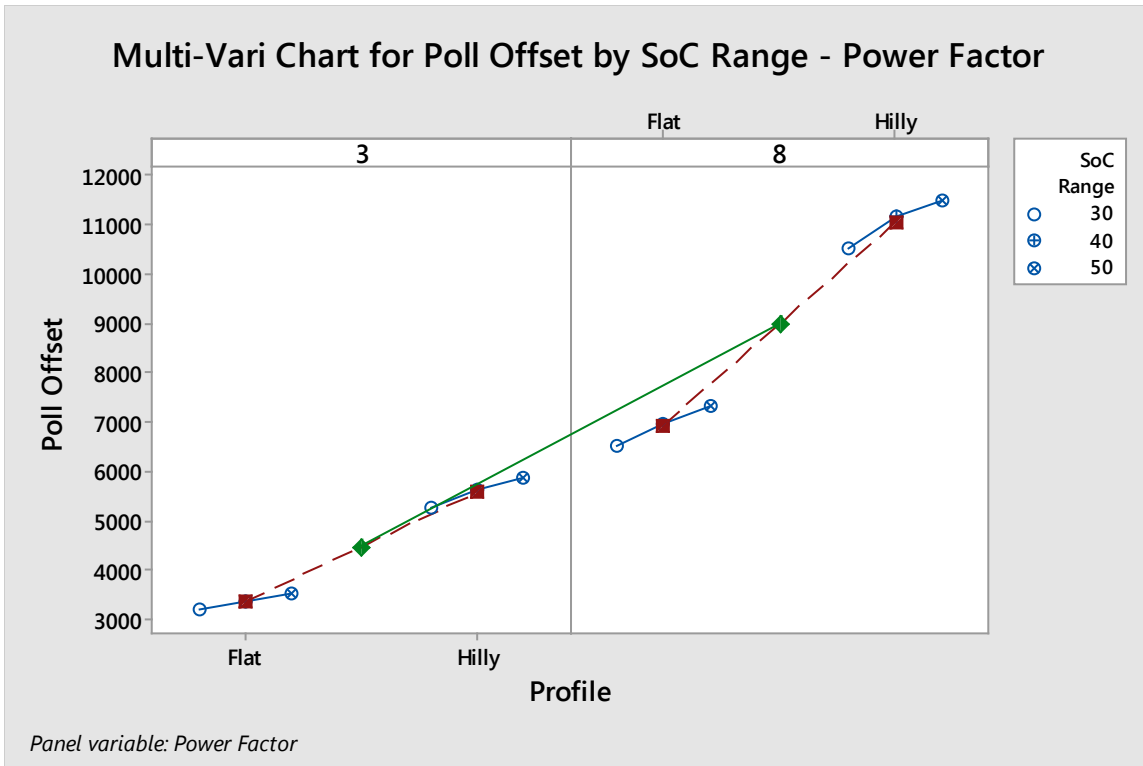
Figure 20. Multi-Vari chart displaying annualized CO_2 pollution (lbs.) offset

Figure 21 shows that the capital cost of the battery pack cannot be recovered at current prices for fuel and batteries. The overall trend in the figure indicates that a smaller battery (lower capital costs) operating over a longer period of time (fewer cycles in flat terrain yields longer battery life) is more economic than a larger battery pack recovering greater amounts of dynamic brake energy.
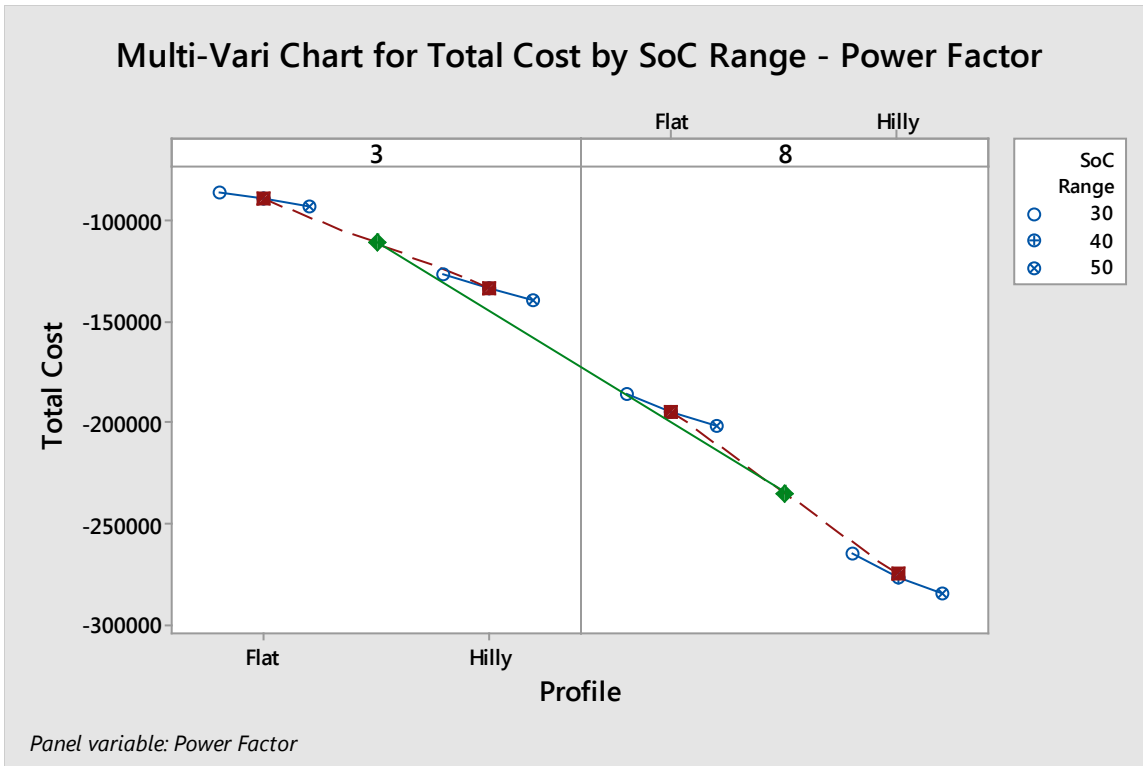
20

Figure 21. Multi-Vari chart displaying annualized battery cost

NS created a response surface to identify "break even" points where the annualized cost of the battery pack was offset by fuel savings. Figure 22 uses the best-case hybrid locomotive simulation and the calculated annualized cost at a given fuel and battery cost. Note that this "break even" analysis does not consider the cost of the additional power electronics and control system modifications that would be needed to build a hybrid locomotive.
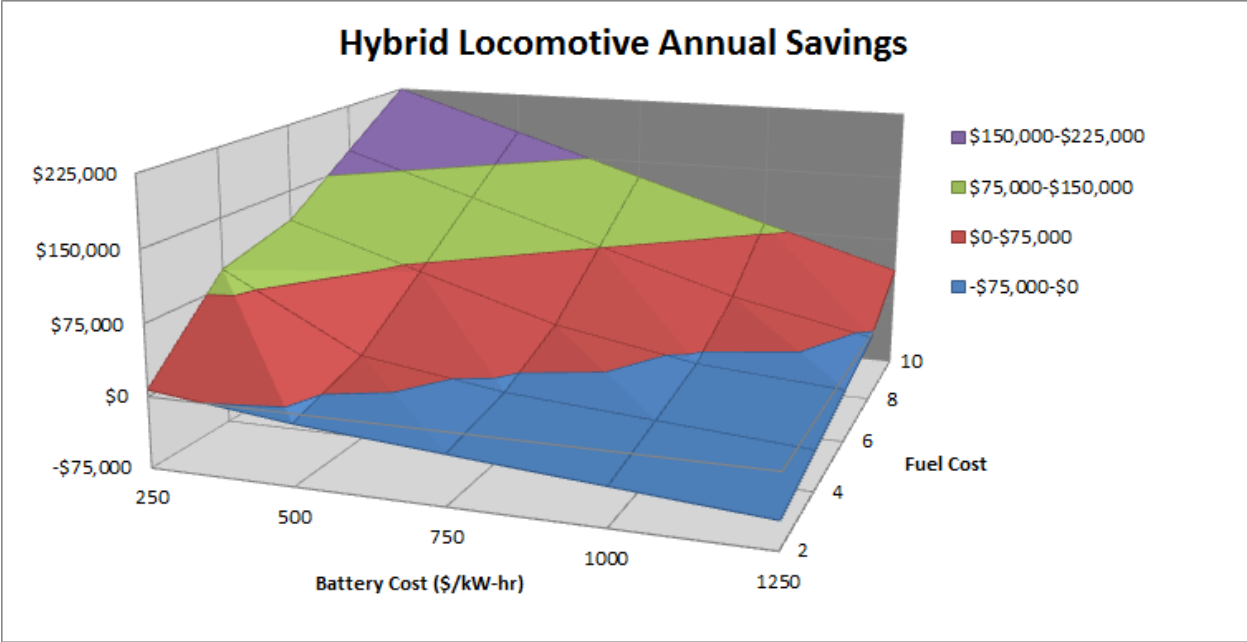
Figure 22. Surface plot displaying effects of varying battery cost and fuel cost vs. annualized savings due to hybridization

4. Conclusion

Based on the work detailed in this report, Norfolk Southern Corporation (NS) concluded that a battery switcher that could meet railroad operating demands must use an advanced lithium-ion battery technology. This was the only battery technology tested that displayed the capacity to perform in heavy switcher or local service. However, the estimated cost for such a unit would exceed $1 million in batteries alone and was not economically justifiable.

Also, based on the work detailed here, NS concluded hybrid locomotives would not be feasible at this time. Testing proved hybrid locomotives could reduce emissions and save fuel, sometimes in significant amounts. However, even with the best assumptions taken into consideration, these locomotives would require high annual operating subsidies.

5. References

1. U.S. Department of Energy Vehicle Technologies Program. *Battery Test Manual For Plug-in Hybrid Electric Vehicles*. March 2008.

2. Wilson, Andrew. *Power Management Control Optimization of a Hybrid Electric-Diesel Locomotive.* ASME Joint Rail Conference 2016. JRC2016-5777.

Abbreviations and Acronyms

BATTERY	Battery Application Technology Testing & Energy Research Laboratory
BMS	Battery Management System
DoD	Depth of Discharge
DoE	Design of Experiment
ESS	Energy Storage System
EUAC	Equivalent Uniform Annual Cost
FLC	Forward Looking Control
FRA	Federal Railroad Administration
HIL	Hardware in the Loop
HLS	Hybrid Locomotive Simulator
HPPC	Hybrid Pulse Power Characteristic
IGBT	Insulated-gate Bipolar Transistor
NMC	Nickel Manganese Cobalt
NS	Norfolk Southern Corporation
SIL	Software in the Loop
SoC	State of Charge
SoH	State of Health
UPS	Uninterruptible Power Supply