BNSF ZERO-AND NEAR ZERO-EMISSION FREIGHT FACILITIES PROJECT (ZANZEFF) DATA ACQUISITION SUPPORT

BNSF Contract Number BF 10015561

TOPICAL REPORT:
BATTERY ELECTRIC LOCOMOTIVE CONSIST

SwRI Project 03.24318

Prepared for:
BNSF Railway Company
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Fort Worth, TX 76131

Prepared by:
Garrett Anderson

MAY 2021

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This project was supported by the “California Climate Investments” (CCI) program.

Flexible Solutions for Freight Facilities is part of California Climate Investments, a statewide initiative that puts billions of Cap-and-Trade dollars to work reducing greenhouse gas emissions, strengthening the economy, and improving public health and the environment — particularly in disadvantaged communities.

DESIGN AND DEVELOPMENT DEPARTMENT
POWERTRAIN ENGINEERING DIVISION

TABLE OF CONTENTS

BNSF ZERO-AND NEAR ZERO-EMISSION FREIGHT FACILITIES PROJECT 1

TABLE OF CONTENTS iii

LIST OF FIGURES iv

LIST OF TABLES vi

LIST OF ACRONYMS vii

ACKNOWLEDGEMENTS viii

EXECUTIVE SUMMARY ix

Table ES1. Key Statistics for BEL Hybrid Consist Operation from January to April, 2021 x

1.0 INTRODUCTION 1

2.0 BACKGROUND 2

3.0 CONSIST SPECIFICATIONS 3

3.1 Tier 4 Locomotive Specifications 3

3.2 BEL Specifications 4

4.0 LOCOMOTIVE DATA ACQUISITION SYSTEM 8

5.0 BEL OPERATIONS 10

5.1 Trip Characterization 11

5.2 Daily Usage 14

5.3 Fuel & Energy Consumption 18

5.4 BEL Pure Electric Range 23

5.5 Calculated Fuel Savings and Emissions Reductions 24

6.0 MAINTENANCE & REPAIRS 32

7.0 SUMMARY 33

Attachment A 1

SwRI’s Reporting Requirements - Locomotives 1

Attachment B 1

Failure Analysis of Battery modules and Battery String Controller 1

Attachment C 1

Maintenance 1

LIST OF FIGURES

Figure ES1. BEL Hybrid Consist used for ZANZEFF Field Trial ix
Figure ES2. Elevation Profile of Route used for BEL Consist Evaluation. ix
Figure 1. Types of Equipment Instrumented 2
Figure 2. Image of BEL Hybrid Consist 3
Figure 3. Engine Emissions Label for BNSF 3965 4
Figure 4. Engine Emissions Label for BNSF 3940 4
Figure 5. Image of BEL Locomotive 4
Figure 6. BEL Charging Station in Stockton, CA 5
Figure 7. Image of Charging Port and Charger Connector on BEL Locomotive 6
Figure 8. Image of BEL While Charging at the BNSF Stockton Momorn Yard 6
Figure 9. Data Acquisition System Installed on BNSF 3965 8
Figure 10. IOT Diagram 9
Figure 11. Map of Route Between Barstow and Stockton, CA 10
Figure 12. Elevation Profile of the Stockton-Barstow Route 11
Figure 13. Scatter Plot of Distance Traveled for Each Train 12
Figure 14. Scatter Plot of Average Speed for Each Train 12
Figure 15. Scatter Plot of Duration for Each Train 13
Figure 16. Scatter Plots of Stops Per Mile for Each Train 13
Figure 17. Scatter Plot of Time Stopped for Each Train 14
Figure 18. Notch Duty Cycle for BNSF 3940 for Duration of 3-Month Study (Idle Not Shown) 16
Figure 19. Notch Duty Cycle for BNSF 3965 for Duration of 3-Month Study (Idle Not Shown) 16
Figure 20. Net Traction Horsepower Duty Cycle for BEL for Duration of 3-Month Study 17
Figure 21. BNSF 3940 Hours Spent Idling by Day for 3-Month Study 18
Figure 22. BNSF 3965 Hours Spent Idling by Day for 3-Month Study 18
Figure 23. Plot of Fuel Level, Cumulative Dispensed Fuel, and Final Fuel Level for Each Fueling Event 19
Figure 24. Plot of BEL Initial SOC for Each Train During Field Trial 20
Figure 25. BEL Final SOC for Each Train During Field Trail 21
Figure 26. Energy Dispensed During Each Observed Charge Event During 3-Month Field Trial 21
Figure 27. Cost of Each Charge Event Observed During 3-Month Field Trial 22
Figure 28. Duration of Each Charge Event Observed During 3-Month Field Trial 22
Figure 29. Percentage of BEL Energy into the Battery from the Wayside Charger 23
Figure 30. BEL SOC, Speed, and Power vs Distance used to Estimated Range of Locomotive Under Load 24
Figure 31. Diagram Overview of BEL Fuel and Emissions Reduction Estimation Approach 24
Figure 32. Percent Fuel Reduction for BEL Consist for Each Train 26

Figure 33. Plots Showing Altitude, SOC, Speed, and Estimated Fuel Reduction for 3-24 BAR-STO Train Traveling from Bartow, CA to Stockton, CA 26
Figure 34. Plots Showing Altitude, SOC, Speed, and Estimated Fuel Reduction for 3-24 BAR-STO Train Traveling from Stockton, CA to Bartow, CA 27
Figure 35. Estimated CO_2 Reduction for BEL Consist for Each Train 28
Figure 36. Estimate NO_x Emission Reduction Versus Estimated Fuel Reduction 28
Figure 37. Estimated Hydrocarbon Emission Reduction Versus Estimated Fuel Reduction 29
Figure 38. Estimate PM Emission Reduction Versus Estimated Fuel Reduction 29
Figure 39. General Trend of PM Rate and BSPM vs Gross Power 30
Figure 40. Estimated CO Emission Reduction for BEL Consist for Each Train......................... 31

LIST OF TABLES

Table ES1. Key Statistics for BEL Hybrid Consist Operation from January to April, 2021 x
Table 1. Specification for Wabtec Tier 4 Locomotives. 3
Table 2. Advertised Specification for Wabtec BEL. 5
Table 3. Daily Statistics 15
Table 4. Cumulative Net Tractive Power for 3-Month Period for All Locomotives in BEL Consist 15
Table 5. Table of BEL Charging Statistics 20

LIST OF ACRONYMS

BEL	Battery Electric Locomotive
CARB	California Air Resources Board
CO	Carbon Monoxide
CO_2	Carbon Dioxide
GPS	Global Positioning System
HP	Horsepower
LTE	Long-Term Evolution
MQTT	Message Queuing Telemetry Transport
NO_X	Oxides of Nitrogen
O_2	Oxygen
RPM	Revolutions per Minute
SJVAPCD	San Joaquin Valley Air Pollution Control District
SOC	State of Charge
SwRI	Southwest Research Institute
THC	Total Hydrocarbons
US-EPA	United States Environmental Protection Agency
ZANZEFF	Zero and Near Zero Emission Freight Facilities

ACKNOWLEDGEMENTS

The project would like to acknowledge:

- California Air Resources Board (CARB) Mobile Source Control Division for funding this project to investigate Zero and Near Zero Emission Freight Facilities (ZANZEFF) at the BNSF Intermodal Yard.
- This project was supported by the "California Climate Investments" (CCI) program.

> *Flexible Solutions for Freight Facilities is part of California Climate Investments, a statewide initiative that puts billions of Cap-and-Trade dollars to work reducing greenhouse gas emissions, strengthening the economy, and improving public health and the environment — particularly in disadvantaged communities.*

- San Joaquin Valley Air Pollution Control District (SJVAPCD).
- Staff at BNSF's Barstow, CA and Stockton, CA Intermodal Yards.
- Dave Desanzo, John Madonna, and Justin Norris with Wabtec for DAQ integration, troubleshooting, and installation in Erie, PA and throughout the duration of the project.
- Jacob Guerra with SwRI for data acquisition system design, construction, and validation.

EXECUTIVE SUMMARY

This Topical Report summarizes datalogger monitoring of a battery electric locomotive (BEL) hybrid consist from January to April 2021. The consist was made up of two Tier 4 Wabtec ET44C4 diesel locomotives and a single BEL, as shown in Figure ES1.

Figure ES1. BEL Hybrid Consist used for ZANZEFF Field Trial

The BEL was designed to produce the same tractive power as a Tier 4 diesel locomotive. All locomotives in the consist used a modified version of Wabtec's Trip Optimizer algorithms so they could operate in a coordinated manner as if it were a single hybrid vehicle. The BEL battery system has a nameplate capacity of 2,400 kW-hr and is capable of being typically charged in 8 to 9 hours.

The consist was used and monitored on 17 round trips during this period along a route between Barstow, CA and Stockton, CA, about 375 miles each direction. This route was chosen because it traverses the San Joaquin Valley and contains both mountains and relatively flat plains to evaluate the performance of the BEL consist. The elevation of this route is shown in Figure ES2 with various cities along the route. This plot demonstrates the varied topography which maximizes opportunities for regenerative braking.

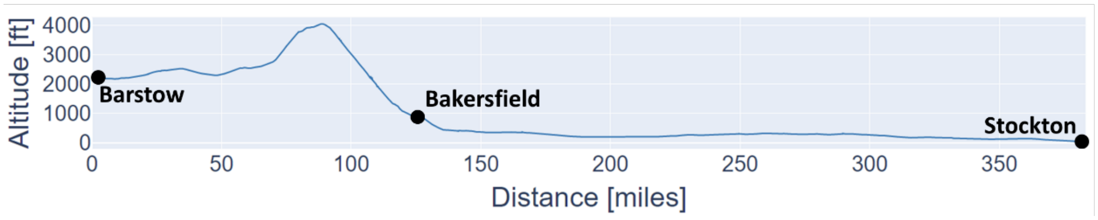


Figure ES2. Elevation Profile of Route used for BEL Consist Evaluation.

Performance of the BEL consist was evaluated by comparing it to a virtual diesel consist using simulations. In other words, the team was interested in "how would the locomotives on that same train have performed if the BEL was not included." This eliminated the need to correct for differences in train make up, ambient temperature, train speed, and other parameters that affect trip fuel consumption. This virtual diesel consist was made up of two diesel locomotives.

One important finding was that the BEL consist was able to reduce fuel consumption by an average of 12 percent throughout the 3-month field trial. Other important statistics are presented in Table ES1.

Table ES1. Key Statistics for BEL Hybrid Consist Operation from January to April, 2021

Days of Operation	64 days
Average Daily Usage	10.3 hours
Round Trips	17 trips
Distance Traveled	12,800 miles
Fuel Consumed	63,400 gallons
Fuel Reduction*	12%
CO_2 Reduction*	12%
PM Reduction*	3%
NO_X Percent Reduction*	8%
CO Percent Reduction*	3%
Total Hydrocarbons percent Reduction*	3%

*Percentage reductions consider diesel locomotive consist made up of two T4 diesel locomotives as a baseline.

1.0 INTRODUCTION

This report supports BNSF's grant from the San Joaquin Valley Air Pollution Control District (SJVAPCD). The SJVAPCD, in partnership with BNSF Railway (BNSF), received funding for the Flexible Solutions for Freight Facilities Project (Project) through the California Air Resources Board (CARB) Mobile Source Control Division's Zero and Near Zero Emission Freight Facilities (ZANZEFF) solicitation. The Project entailed demonstrating zero-and near zero emissions cargo handling equipment in Stockton and San Bernardino, California, and in rail service between Stockton and Barstow, California.

SwRI supported BNSF Railway in the Project, by taking on the responsibility for the "purchase, installation, and maintenance of data logging or other data collection equipment" as detailed in Appendix F "Data Collection Requirements" of the CARB ZANZEFF grant solicitation. Appendix A of this report includes the list of items for data collection and associated primary responsibility for the locomotive phase of the ZANZEFF project.

2.0 BACKGROUND

SwRI supported the ZANZEFF project by collecting data on locomotives, rubber tire gantry crane (RTG), side pick cargo handler, and drayage trucks with examples shown in Figure 1.

Figure 1. Types of Equipment Instrumented

3.0 CONSIST SPECIFICATIONS

The BEL consist was made of three locomotives. Two of the locomotives were 4,500 HP Tier 4 Wabtec ET44C4 diesel locomotives. The third was the BEL, with the road number GECX 3000. This consist is shown in Figure 2.

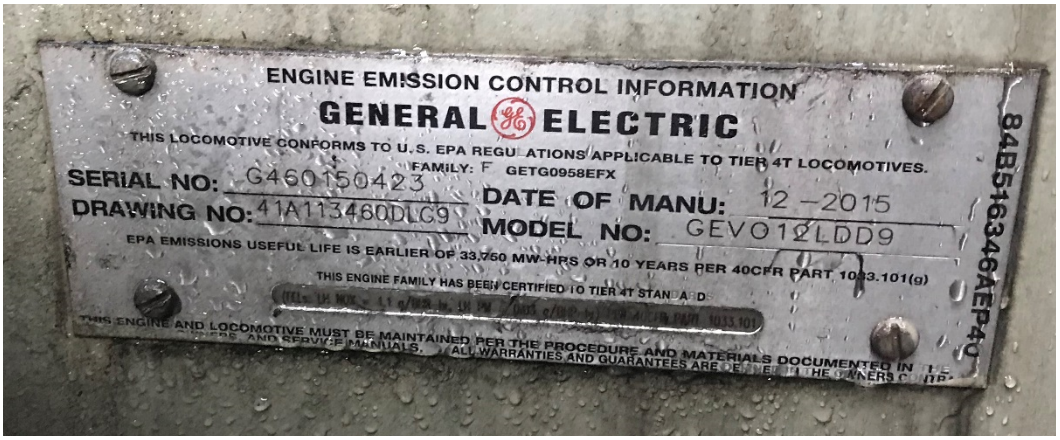
Figure 2. Image of BEL Hybrid Consist

3.1 Tier 4 Locomotive Specifications

The diesel locomotives were Tier 4 Wabtec ET44C4 locomotives. These locomotives were modified to interact with the BEL, but their engine operation was unchanged from a production Tier 4 locomotive. The specifications for these two locomotives are presented in ***Table 1***. Images of the emissions labels are shown in Figure 3 and Figure 4.

Table 1. Specification for Wabtec Tier 4 Locomotives.

Model	ET44C4
No. of Axles	6 (4 powered)
Weight	432,000 lbs.
Emissions	USA EPA T4
Horsepower (gross)	4,500 HP (3,356 kW)
Horsepower (tractive)	4356 HP (3,255 kW)
Max. Speed	75 mph
Total Fuel	5,300 gal
Useable Fuel	4,800 gal
Engine Model	GEVO12-LDD



ENGINE EMISSION CONTROL INFORMATION

GENERAL ELECTRIC

THIS LOCOMOTIVE CONFORMS TO U.S. EPA REGULATIONS APPLICABLE TO TIER 4T LOCOMOTIVES.

FAMILY: F GETG0958EFX

SERIAL NO: G460150423

DATE OF MANU: 12 – 2015

DRAWING NO: 41A113460DLG9

MODEL NO: GEVO12LDD9

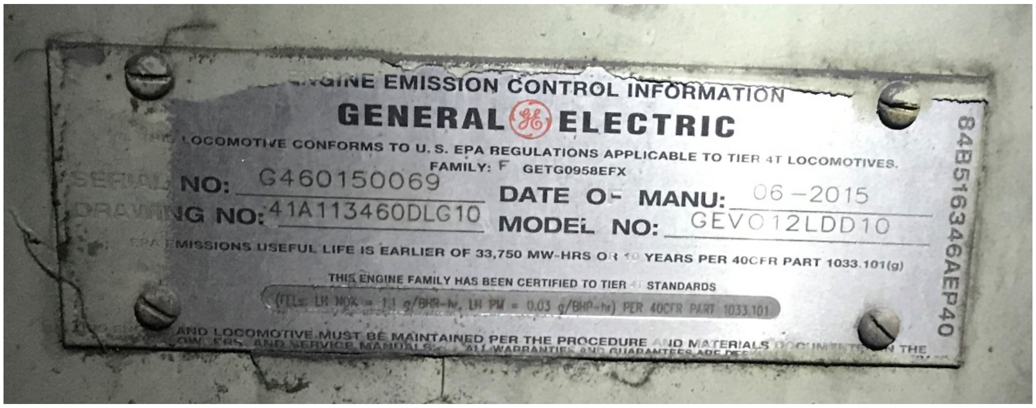
EPA EMISSIONS USEFUL LIFE IS EARLIER OF 33,750 MW-HRS OR 10 YEARS PER 40CFR PART 1033.101(g)

THIS ENGINE FAMILY HAS BEEN CERTIFIED TO TIER 4T STANDARDS

THIS ENGINE AND LOCOMOTIVE MUST BE MAINTAINED PER THE PROCEDURE AND MATERIALS DOCUMENTED IN THE [illegible] AND SERVICE MANUALS. ALL WARRANTIES AND GUARANTEES ARE [illegible] THE OWNERS [illegible]

84B516346AEP40

Figure 3. Engine Emissions Label for BNSF 3965



ENGINE EMISSION CONTROL INFORMATION

GENERAL ELECTRIC

THIS LOCOMOTIVE CONFORMS TO U.S. EPA REGULATIONS APPLICABLE TO TIER 4T LOCOMOTIVES.

FAMILY: F GETG0958EFX

SERIAL NO: G460150069

DATE OF MANU: 06 – 2015

DRAWING NO: 41A113460DLG10

MODEL NO: GEVO12LDD10

EPA EMISSIONS USEFUL LIFE IS EARLIER OF 33,750 MW-HRS OR 10 YEARS PER 40CFR PART 1033.101(g)

THIS ENGINE FAMILY HAS BEEN CERTIFIED TO TIER 4T STANDARDS

(FELs: LH NOX = 1.1 g/BHR-hr, LH PM = 0.03 g/BHP-hr) PER 40CFR PART 1033.101

[illegible] AND LOCOMOTIVE MUST BE MAINTAINED PER THE PROCEDURE AND MATERIALS [illegible] THE [illegible] AND SERVICE MANUALS. ALL WARRANTIES AND GUARANTEES ARE [illegible]

84B516346AEP40

Figure 4. Engine Emissions Label for BNSF 3940

3.2 BEL Specifications

Figure 5 shows the BEL locomotive developed by Wabtec for the ZANZEFF project. Table 2 gives the specification on GECX 3000, the BEL.

Figure 5. Image of BEL Locomotive

Table 2. Advertised Specification for Wabtec BEL.

Energy Source	Lithium-ion batteries
No. of Axles	6 (4 Powered)
Weight	418,000 lbs.
Emissions	Reduces train's emissions by 10%
Duration @ Rated Output	30 to 40 minutes
Rated Output	4400 hp
Charging	Wayside charging and regenerative braking
Energy Capacity	2,400 kW-hrs.
Thermal Management	Air cooled
Maximum Speed	75 mph

The BEL was charged at the BNSF Mormon Yard in Stockton, CA with a custom charger that was installed at that facility and is shown in Figure 6. The charger consists of safety systems, a smart meter, and a crane to assist operators. The crane is the tall portion of the station shown in Figure 6.

Figure 6. BEL Charging Station in Stockton, CA

The BEL was charged using 480V three phase AC power. The connector is a non-standard connector when compared to other electric vehicles. This connection can be seen in Figure 7. The large, heavy nature of it necessitated the lift seen in Figure 6.

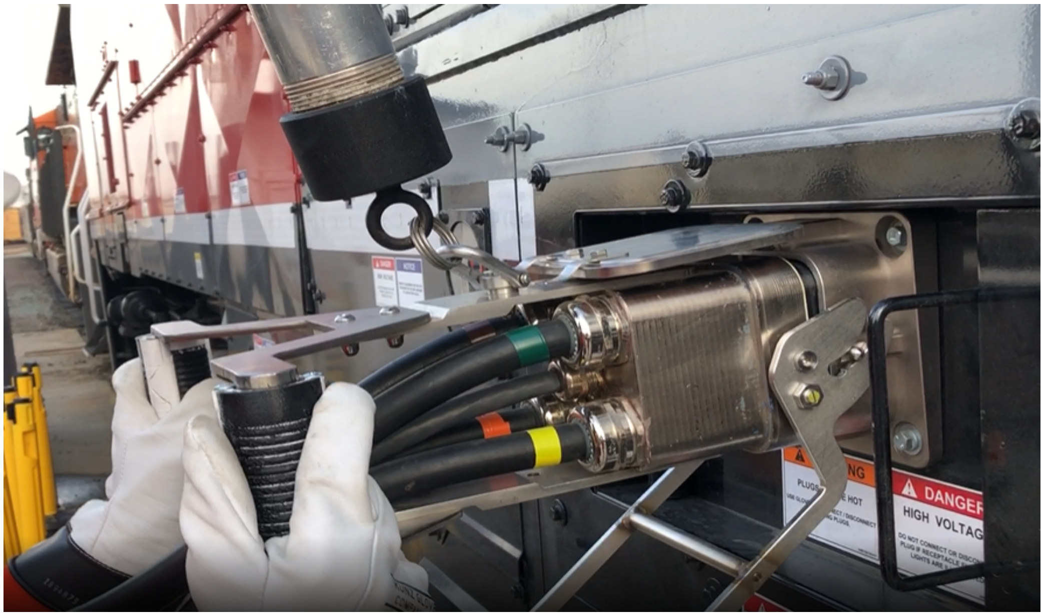


Figure 7. Image of Charging Port and Charger Connector on BEL Locomotive

The BEL is charged with AC power. The rectification of the AC power occurs on the locomotive. The DC power is then passed through an inverter to charge the batteries. This process can take up to 11 hours to complete depending on locomotive state of charge. The BEL is shown during one of its charge events in Figure 8.

Figure 8. Image of BEL While Charging at the BNSF Stockton Momorn Yard

The BEL consist also had several modifications to the Wabtec Trip Optimizer logic over the course of the demonstration. Trip Optimizer is often described as a smart cruise-control system for trains that optimizes locomotive operation based on route restrictions, operating conditions, and train make up. Modifications to this system were made by Wabtec to incorporate the BEL performance characteristics into this optimization. This enabled the consist to operate in a coordinated fashion so that the consist would function as a hybrid vehicle.

The BEL consist acts somewhat like a hybrid vehicle. Its architecture most closely mimics a parallel hybrid architecture. Most of these types of hybrid vehicles are coupled through the transmission or some other gearbox in the driveline. The BEL consist differs in that it is coupled at the rail, but most of the same limitations of this architecture still apply to the BEL consist. The largest of these limitations is that it can only charge from wayside power or while performing regenerative braking. There is not direct coupling from the Tier 4 diesel locomotives to the BEL battery management system to provide charging power.

4.0 LOCOMOTIVE DATA ACQUISITION SYSTEM

A SwRI data acquisition (DAQ) system was installed on each locomotive in the consist. This system interacted with the locomotive interface gateway (LIG).

The DAQ was housed in a rugged case that fit under the rear seat in the cab of the locomotive. Each DAQ consisted of a rugged computer, LTE router equipped with GPS, 74V inverter, and a 24V backup power supply. The DAQ installed system in the cab on BNSF 3965 can be seen in Figure 9.

Figure 9. Data Acquisition System Installed on BNSF 3965

Data was collected from each locomotive through the LIG. The LIG provides a Class D messaging interface that allowed for a predefined set of messages to be queried from the locomotive at a rate of 1 Hz. The LIG interface is defined in AAR Standard S-9356.

The parameters that were collected from the diesel locomotives were standard parameters defined by the BNSF LIG data dictionary. These included items like throttle, notch, DB notch, speed, acceleration, gross horsepower, auxiliary horsepower, tractive effort, fuel level, and GPS coordinates. The parameters collected from the BEL were a mix of custom and standard messages.

The custom messages were BEL specific parameters such as state of charge, BEL specific auxiliary loads, and charger power.

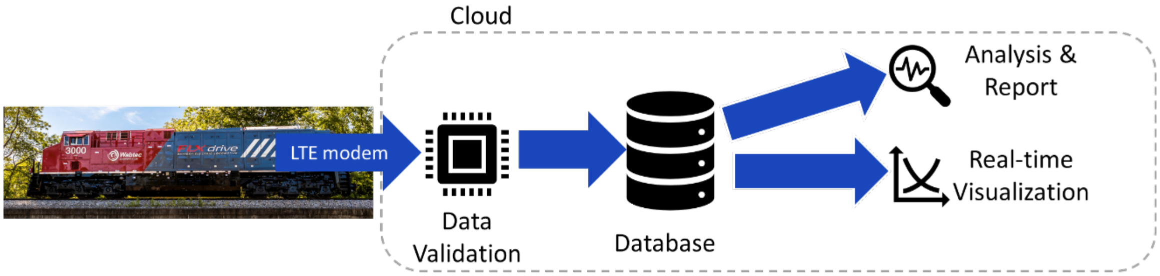


Figure 10. IOT Diagram

Figure 10 shows a diagram of the data flow from the BEL consist. The data collected from each locomotive was stored locally and simultaneously published to the cloud through a Message Queuing Telemetry Transport (MQTT) messaging scheme. This scheme is common for many IOT applications where bandwidth may be limited or intermittent. These messages were then processed and inserted into a database for real time monitoring and further analysis.

5.0 BEL OPERATIONS

The BEL consist was evaluated on a route between Barstow and Stockton, California. The route is approximately 375 miles one way and is shown in Figure 11. The consist typically made 2 to 3 of these round trips per week.

Figure 11. Map of Route Between Barstow and Stockton, CA

The geography along the route made it well suited for the BEL consist evaluation. The elevation profile of the route can be seen in Figure 12. The mountains provided opportunities for high power regenerative braking for long durations. This is important to understand for development of the battery thermal management system. The long flat plain in the valley provided another extreme in geography. This portion of the trip allowed for quantification of the fuel efficiency gains and associated air pollution reductions that could be realized through normal starting and stopping of the train along the route.

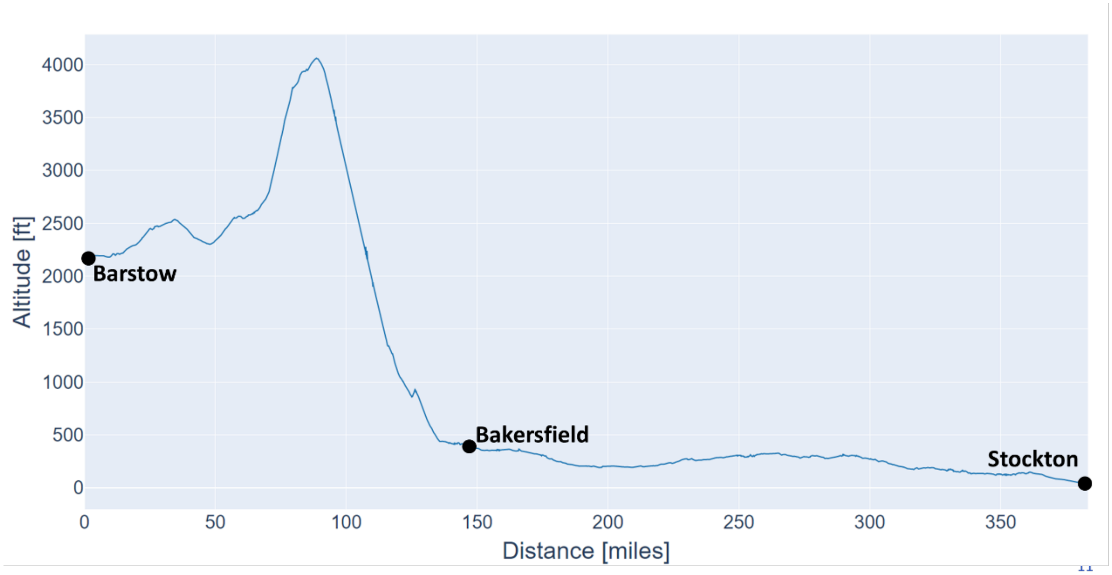


Figure 12. Elevation Profile of the Stockton-Barstow Route

5.1 Trip Characterization

A total 18 round trips were made by the BEL consist. The first round trip was made in December 2020. This trip was used to verify BEL consist and DAQ operation to ensure a successful field trial. The remaining 17 round trips were used for this analysis. These trips were conducted during the period from January – April 2021. Each train was characterized with the following statistics: One train in each direction made a round trip.

- Distance
- Average speed
- Stops per mile
- Duration per trip
- Time Stopped

Appendix A of this Topical Report lists the parameters to be measured and reported, as detailed in *Appendix F "Data Collection Requirements" of the ZANZEFF grant solicitation.* The remainder of Section 5 of this report covers those parameters.

The distance each train traveled was calculated from the locomotive reported speed based upon wheel speed. The median speed for the consist was calculated on a second-by-second basis. This was then integrated to calculate the distance that the consist traveled. Wheel speed was chosen as the basis for distance calculation because the GPS signal was not consistently reliable when traveling through the mountains and several tunnels along the route.

The calculated distance for each train is show in Figure 13. The average distance traveled for each train was 375 miles. The small differences seen in the data can be attributed to building the train, moving into sidings, and positioning in various yards throughout each trip.

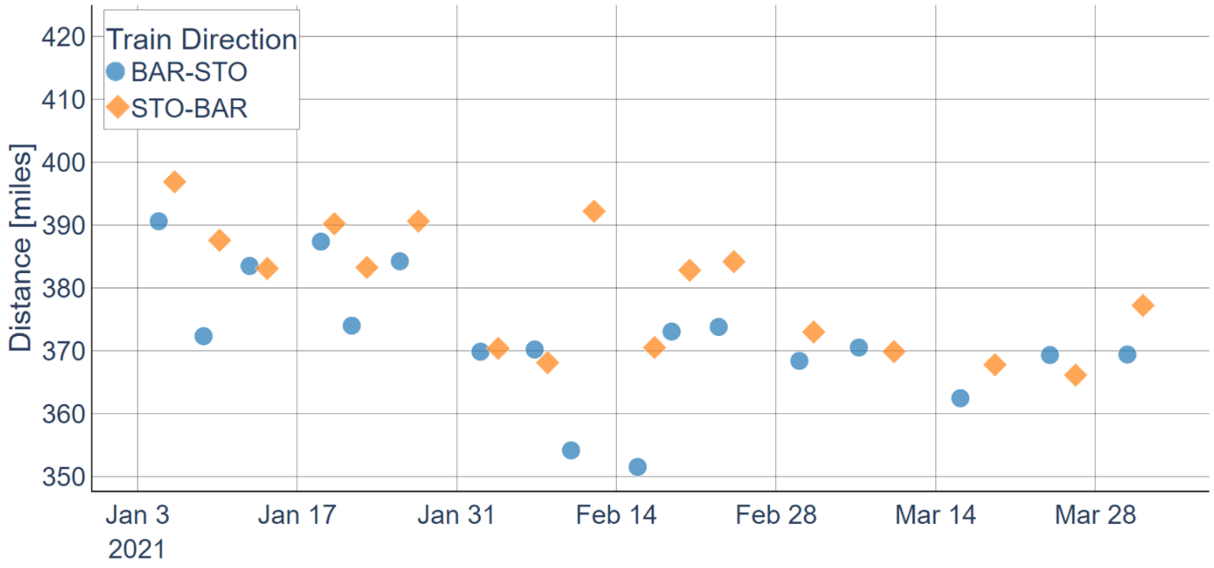


Figure 13. Scatter Plot of Distance Traveled for Each Train

The average speed for each train is shown in Figure 14. The speed was averaged for the duration of each trip for the consist. The consist speed was calculated by taking the median speed of each locomotive on a 1 Hz basis prior to averaging for the trip. The average speed for all trains was 16 mph.

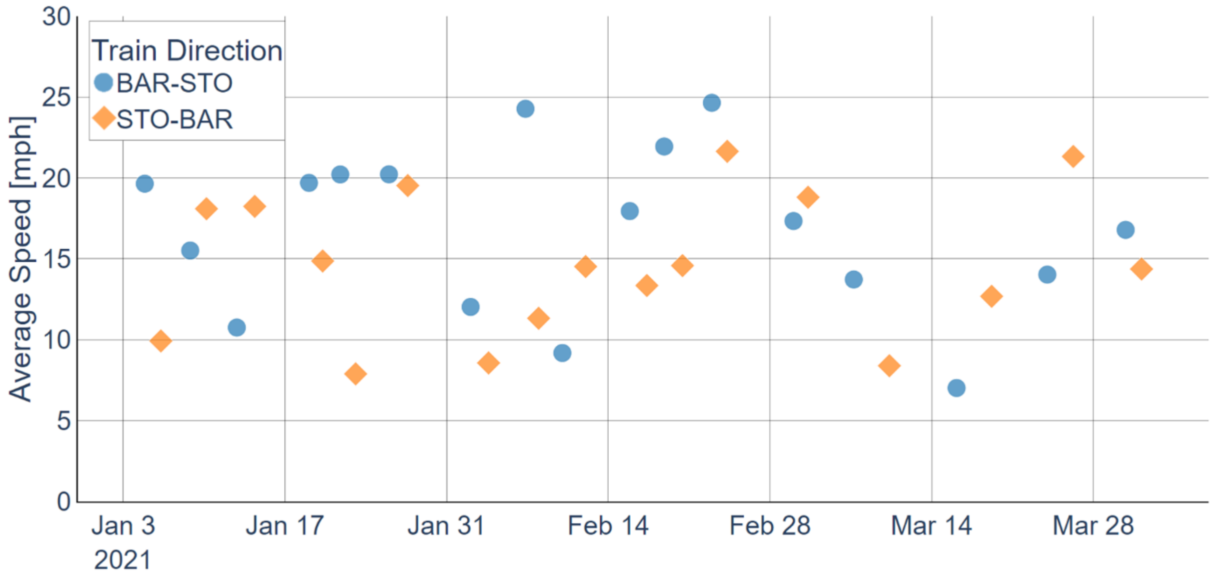


Figure 14. Scatter Plot of Average Speed for Each Train

The duration for each train was manually determined by evaluating GPS data and train speed. The start of the trip was specified to be the moment the train began accelerating out of the origin yard. This was typically rounded to within the nearest minute interval prior to leaving. The end of the trip was defined by the train stopping within the destination yard.

The duration of each train is show in Figure 15. The average duration for each train during the 3-month monitoring period was 27 hrs. The maximum duration was 52 hours. This was one of several outliers that were caused by other train derailments, crew scheduling, and other train traffic.

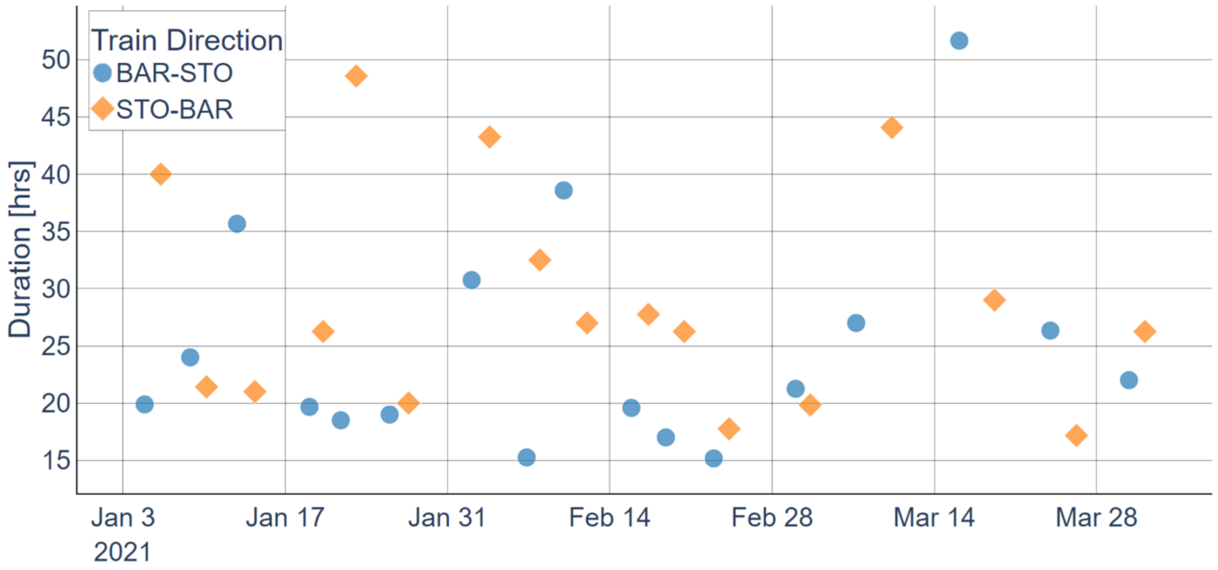


Figure 15. Scatter Plot of Duration for Each Train

Figure 16 shows that the average stopping frequency for all trains was 0.12 stops/mile. The maximum stops per mile was 0.27 stops/mile. This aspect of the operation was heavily impact by other train traffic because typically the BEL consist was assigned to a lower priority train. The lower priority resulted in a higher number of stops than a high priority train.

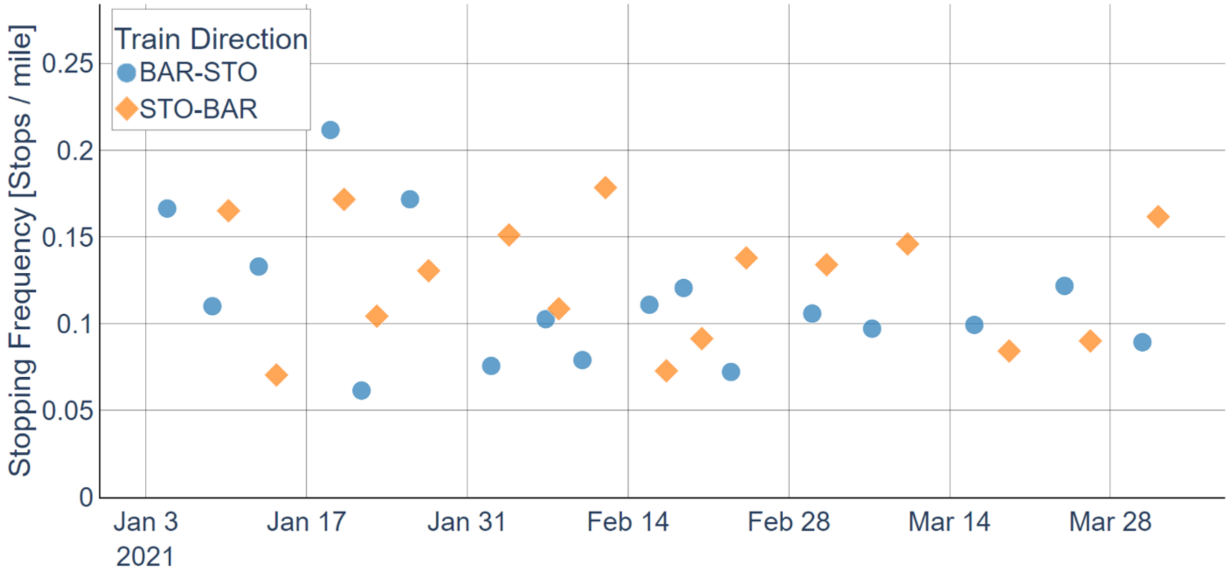


Figure 16. Scatter Plots of Stops Per Mile for Each Train

Figure 17 shows the amount of time stopped during each trip. On average, the train spent 14.3 hours stopped, but this was heavily impacted by the same aspects of train operation mentioned earlier. The maximum time stopped was 39 hours. While these outliers are not typical of the normal trip, they are important, and represent edge cases that a BEL must tolerate in its day-to-day operation. Many of these long duration stops were not necessarily planned for in the BEL design. Early in the demonstration, and in cooperation with BNSF, Wabtec established a manual procedure to turn the BEL locomotive off if a stop was more than a few hours long, so that the batteries were not consumed by auxiliary loads, and that the BEL auxiliary battery SOC did not go below a threshold value which would render the BEL inoperative until it was charged. This procedure arguably biased the results, but it was agreed that auxiliary power load management during extended stops was a needed feature of future BEL products, and as such, this could be best implemented on GECX 3000 by simply shutting off the BEL during these extended stops.

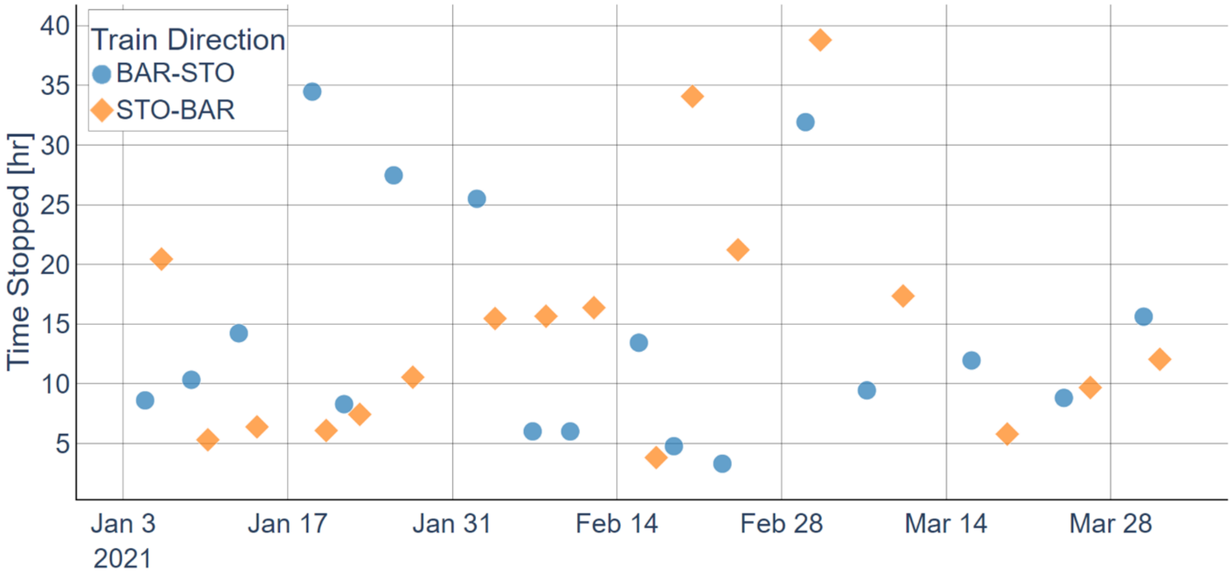


Figure 17. Scatter Plot of Time Stopped for Each Train

5.2 Daily Usage

Several daily statistics were calculated to capture the complete locomotive behavior that include time during and between trips for this specific route. This data is summarized in ***Table*** 3.

The locomotive was projected to be used 263 days of the year. The locomotives were considered as utilized for the day if they spent any time in revenue service. The date range considered was from the departure of the first train to the arrive of the last train for this field trial. This includes periods where the train was delayed while in service.

Table 3. Daily Statistics

Start Date	1/4/2021
End Date	4/2/2021
Total Days	89
Days Used	64
Total Hours Used	909
Average Daily Usage	10.3 hours/day
Extrapolated Annual Hourly Usage	3770 hours / year
Extrapolated Annual Days Used	263 days/year

The cumulative net tractive megawatt-hour readings were collected from the two Tier 4 locomotives throughout the project. The BEL was not equipped with this parameter because of its prototype nature. The BEL tractive megawatt-hours were calculated by integrating the positive net traction horsepower throughout the entire project. These values are reported in ***Table*** 4.

Table 4. Cumulative Net Tractive Power for 3-Month Period for All Locomotives in BEL Consist

	BNSF 3965	BNSF 3940	GECX 3000
Traction MWhr Start	7775	8780	0
Traction MWhr End	8149	9137	98
Traction MWhr Change	374	357	98
Average Daily Traction Energy [MWhr]	4.2	4.0	1.1

The duty cycle for each locomotive in the consist is shown in Figures 18-20. The duty cycle for the two diesel locomotives is presented as a notch duty cycle and only includes time that the engine is running. Therefore, this does not include AESS shutdowns and Battery Saver events. Note that these duty cycles are impacted by the BEL consist-specific Trip Optimizer. The time at idle was omitted for each of these locomotives because of its large difference in magnitude. However, the diesel locomotives idled for 76% of the time the engine was running.

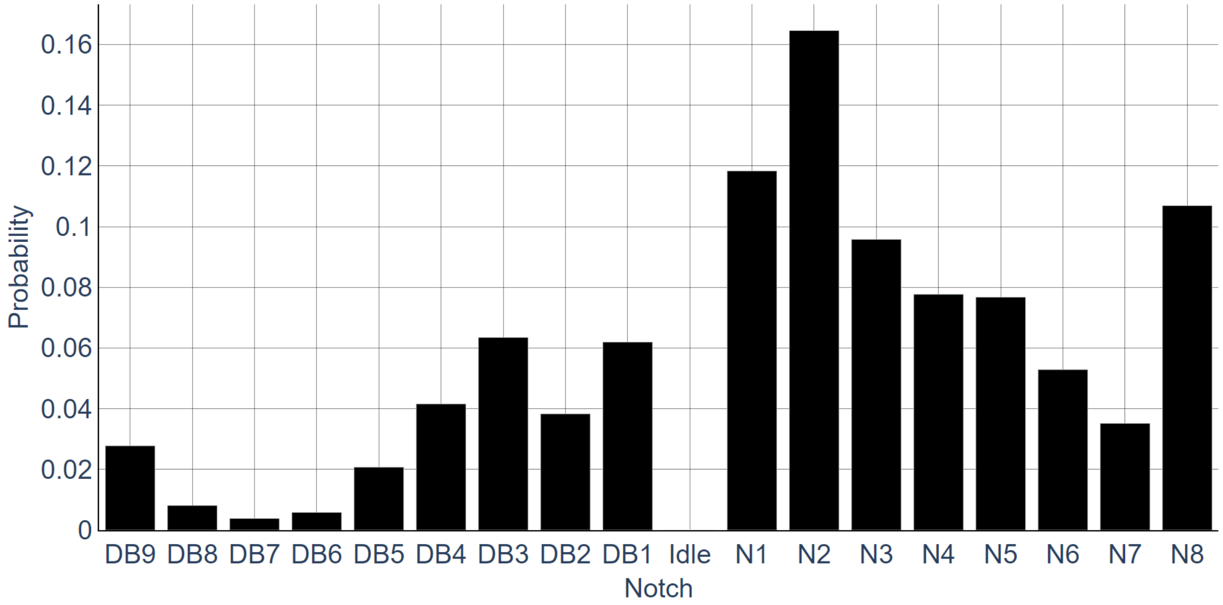


Figure 18. Notch Duty Cycle for BNSF 3940 for Duration of 3-Month Study (Idle Not Shown)

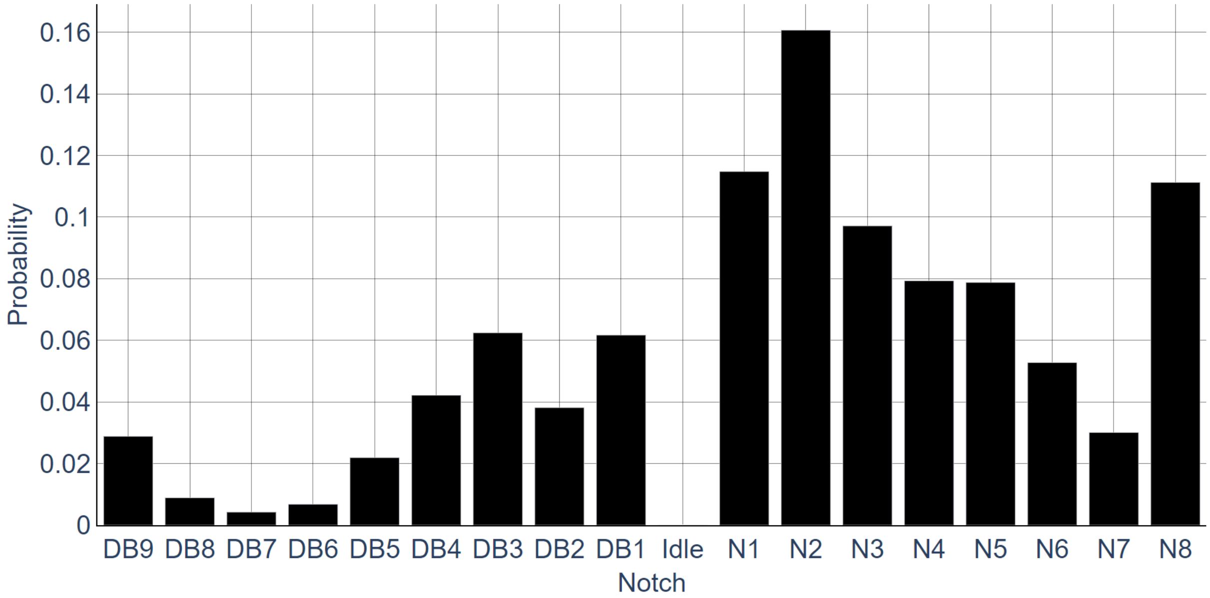


Figure 19. Notch Duty Cycle for BNSF 3965 for Duration of 3-Month Study (Idle Not Shown)

The duty cycle for the BEL is presented as a function of net traction power and is shown in Figure 20. Net traction power was used for this locomotive because the relationship between notch and traction power was not deterministic as it is on the diesel locomotives. Note that positive power in Figure 20, to the right of zero on the x-axis, represents work performed by the BEL to pull the train. The negative power in Figure 20, to the left of zero on the x-axis, represents energy recovery and battery charging during dynamic braking, when the locomotive is used to slow the train down.

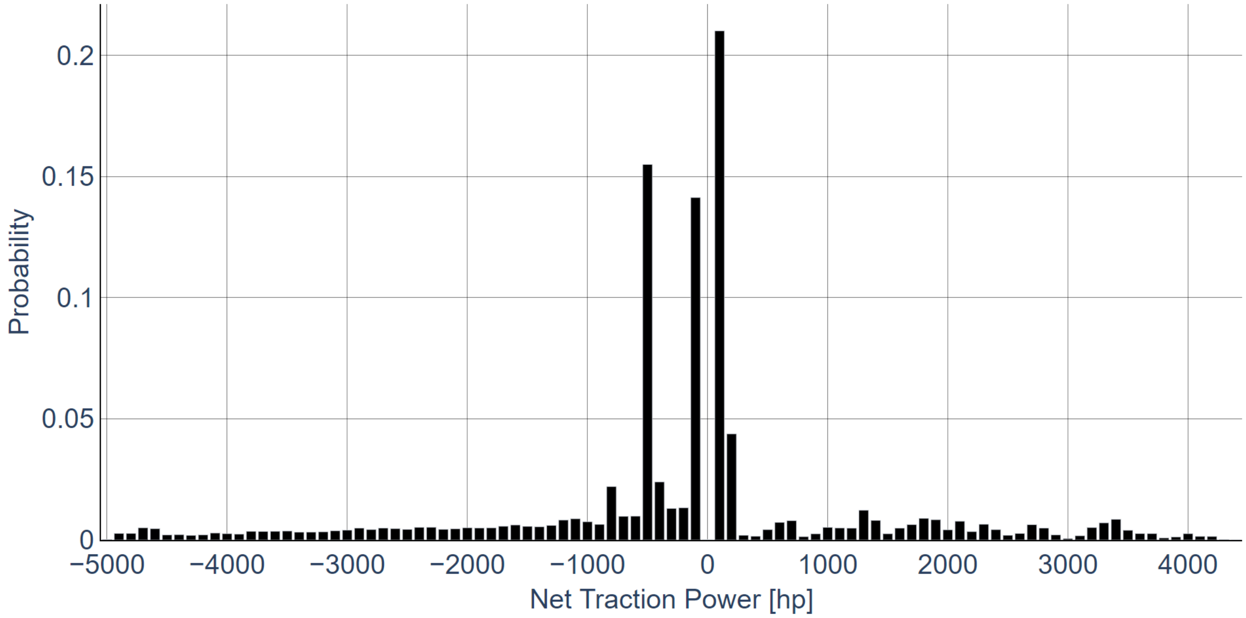


Figure 20. Net Traction Horsepower Duty Cycle for BEL for Duration of 3-Month Study

The hours spent idling was a significant portion of the operating time. Engine idle time for the two Tier 4 diesel locomotives was defined as any period where the engine speed was greater than 0, train speed was less than 0.5 miles per hour, and both DB and Throttle notch position are 0. The diesel locomotives spent an average of 11 hours per day idling. This results in about 28 gallons of fuel consumed per day while idling. The time spent idling each day is presented in Figure 21 and Figure 22. There are some days that exceed 20 hours of idle time. These days are most likely attributed to personnel suspending AESS while occupying the cab to keep the heater functioning on a cold day.

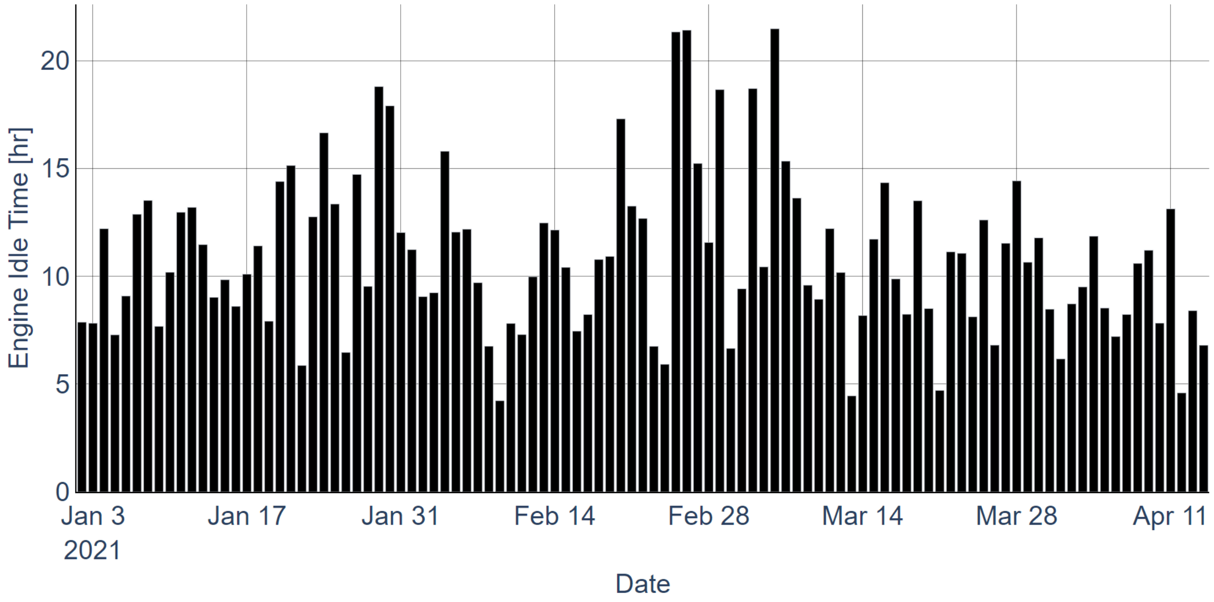


Figure 21. BNSF 3940 Hours Spent Idling by Day for 3-Month Study

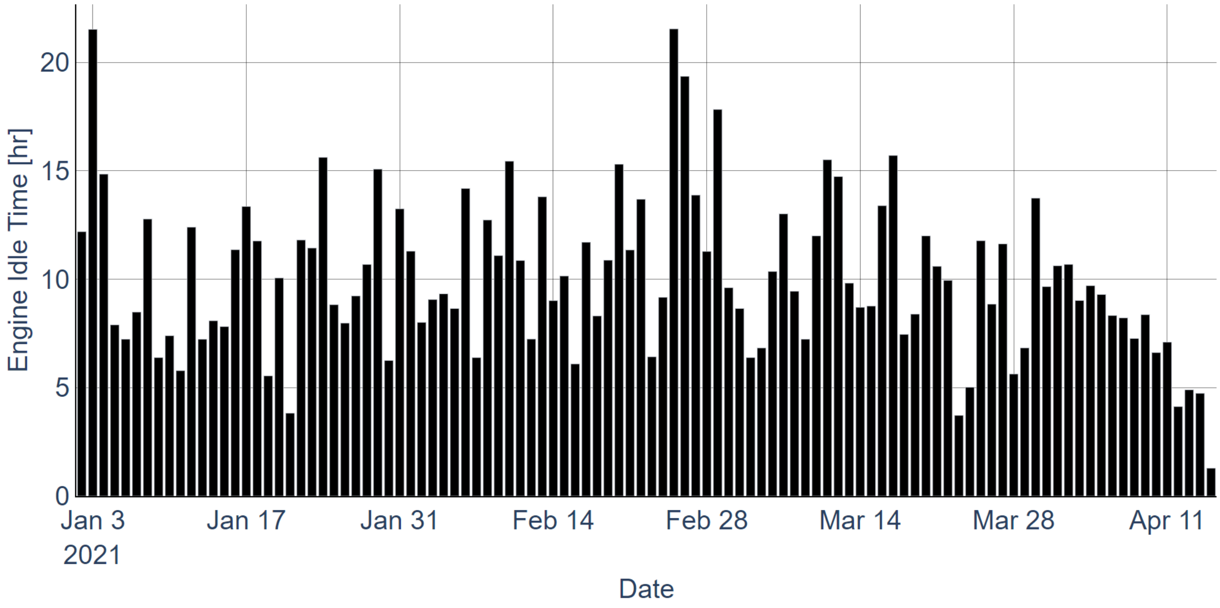


Figure 22. BNSF 3965 Hours Spent Idling by Day for 3-Month Study

5.3 Fuel & Energy Consumption

The diesel fuel and charge energy were monitored for all locomotives during this study. The fueling data for the two Tier 4 diesel locomotives was supplied by BNSF from their fueling logs. All charging data was acquired from a sub-meter supplying the wayside charger electricity at Stockton.

The diesel locomotives consumed a total of 63,400 gallons of fuel during the field trial. All fueling events occurred while the consist was in Bartow, CA. The locomotives were filled 20 times with average dispensed fuel of 1600 gallons per locomotive. The fueling data for the consist is shown in Figure 23.

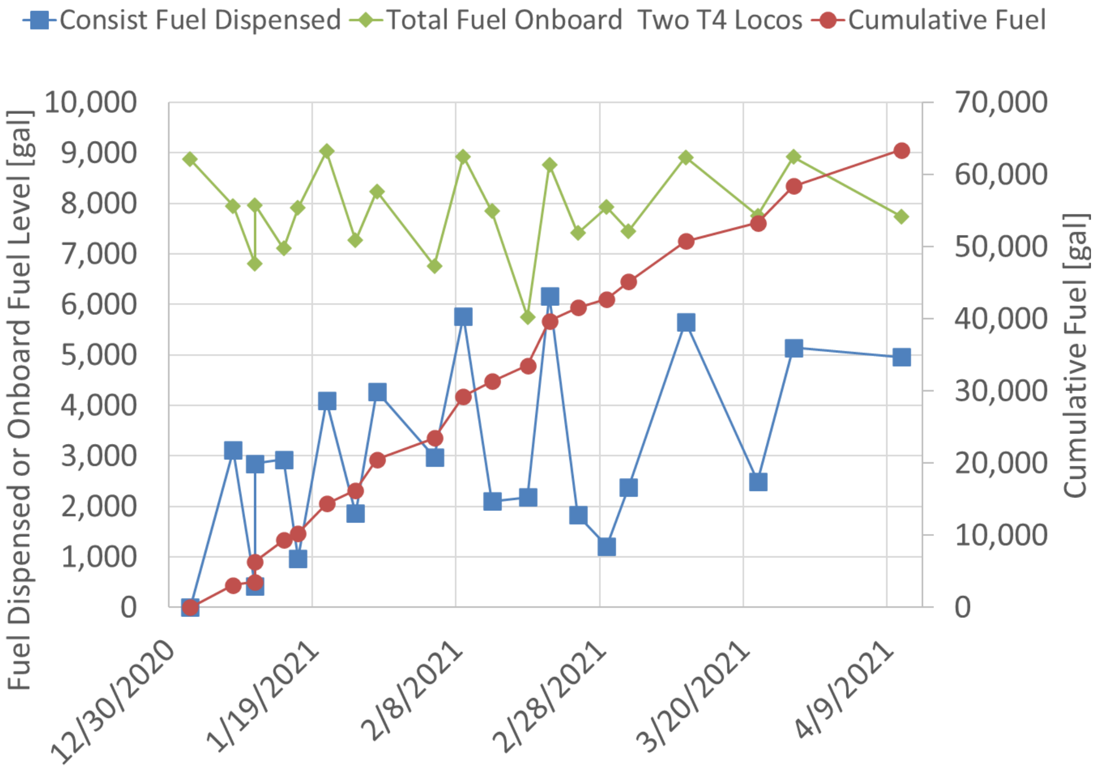


Figure 23. Plot of Fuel Level, Cumulative Dispensed Fuel, and Final Fuel Level for Each Fueling Event

The average cost of diesel fuel for the first quarter of 2021 was $2.735 per gallon. This was determined by averaging the ULSD highway price per gallon in California for the first 3 months of the year obtained from U.S. Energy Information Administration (EIA) and removing the road taxes from it (since it is off road diesel which is not subject to road tax). With this average fuel price, the cost of the diesel dispensed during this 3-month study was $2.735/gallon x 63,400 gallons, which equals $173,400.

It should be noted that the consist fuel level began the trial 1,100 gallons higher than it ended the study. This is depicted by the green line with diamonds in Figure 23. This amount of fuel was added to the cumulative fuel dispensed at the last fueling event.

The BEL locomotive was charged with the wayside charger in Stockton 17 times during this trial. These charge events ranged in duration from 1 to 11 hours. These charge events did not always result in a final SOC of 100 percent. While this was the intent, it was not always possible due to operational constraints of the railroad. The average SOC at the end of charging was 79 percent.

Table 5. Table of BEL Charging Statistics

Charge Events	17
Total Time Charging	148 hours
Average Initial SOC @ Start of Charge	20%
Average Final SOC @ End of Charge	79%
Average Change in SOC	59%
Average Charge Duration	8.7 hours
Energy Dispensed	26,200 kW-hr
Average Electricity Unit Cost	$0.1869 / kW-hr
Electricity Cost	$4,895

While the average SOC at the end of charging was less than 100 percent, this does not reflect the typical behavior. The data presented in Figure 24 shows the initial SOC for each train. The initial SOC for the STO-BAR trains essentially equals the final SOC from each charge event. Half of these STO-BAR trains had a departure SOC higher than 95 percent, and most trains departing Stockton had an initial SOC higher than 80 percent.

The average SOC departing Stockton was biased low due to two relatively low charging events. The 1-14 and 2-20 STO-BAR trains had initial SOCs of 36 percent and 9 percent. The average initial SOC with these two trains omitted is 93%. The reasons for these outliers were driven by operational delays preventing the opportunity to fully charge.

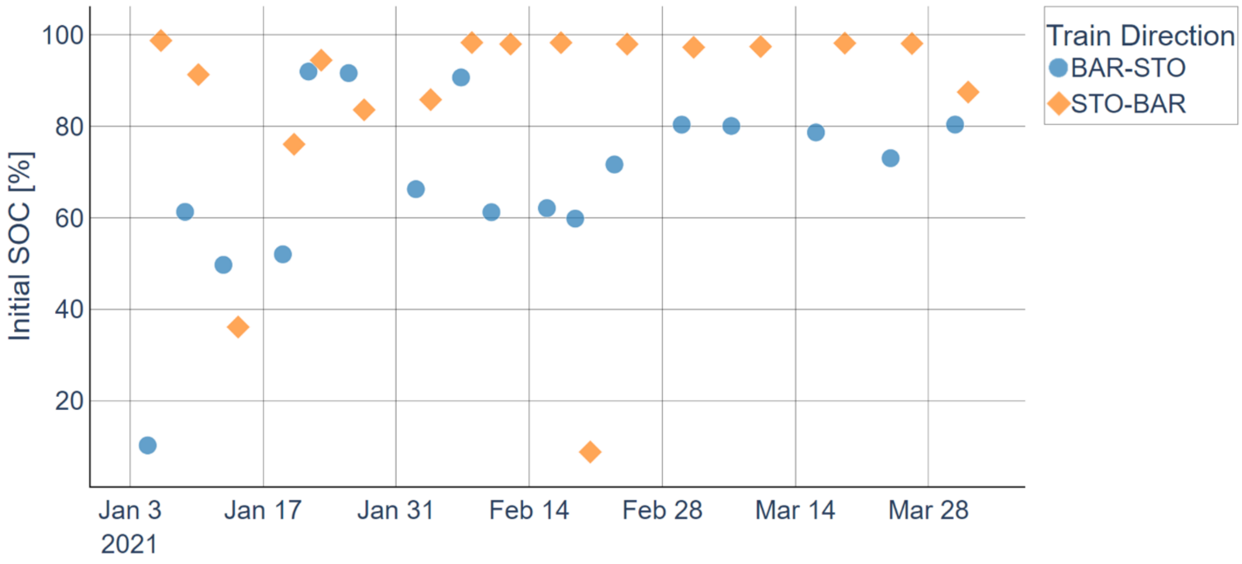


Figure 24. Plot of BEL Initial SOC for Each Train During Field Trial

The final state of charge for each train was heavily dependent upon train direction. This is driven by geography. The trains arriving into Barstow, CA had a higher final SOC because they had a large opportunity for regenerative braking near the end of the trip due to the downhill portion through the mountains.

The geography from Bakersfield North to Stockton is very flat. The only opportunities for regenerative braking during this portion of the trip are when the train stops. As a result, trains arriving into Stockton generally had a low SOC, which was planned, so that the BEL could accept the most energy possible from the wayside charger.

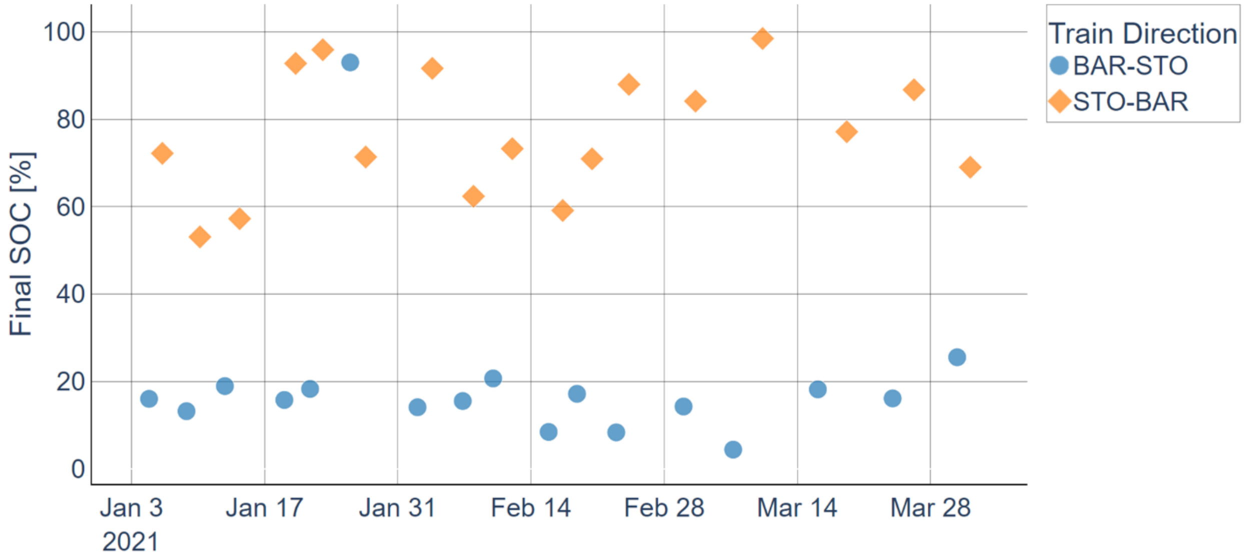


Figure 25. BEL Final SOC for Each Train During Field Trail

During most charge events the BEL was typically charged with between 1500 and 2000 kW-hrs of electricity, as seen in Figure 26. These "typical" charge events cost between $300 to $400 as shown in Figure 27, using the average price of electricity at the Stockton charger of $0.1869 / kW-hr.

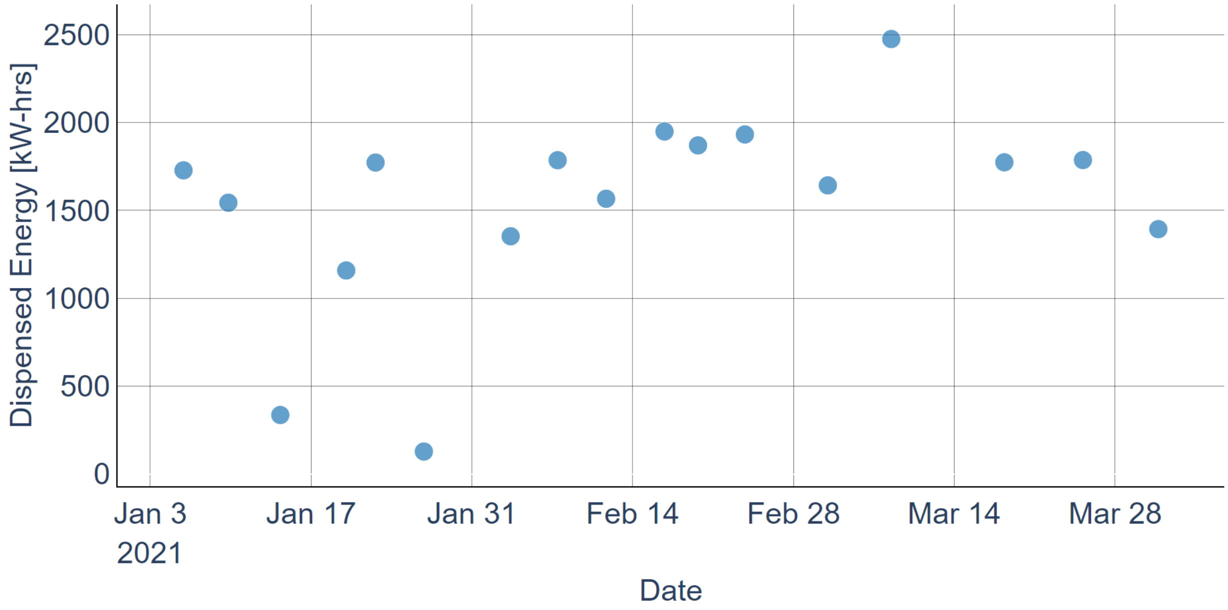


Figure 26. Energy Dispensed During Each Observed Charge Event During 3-Month Field Trial

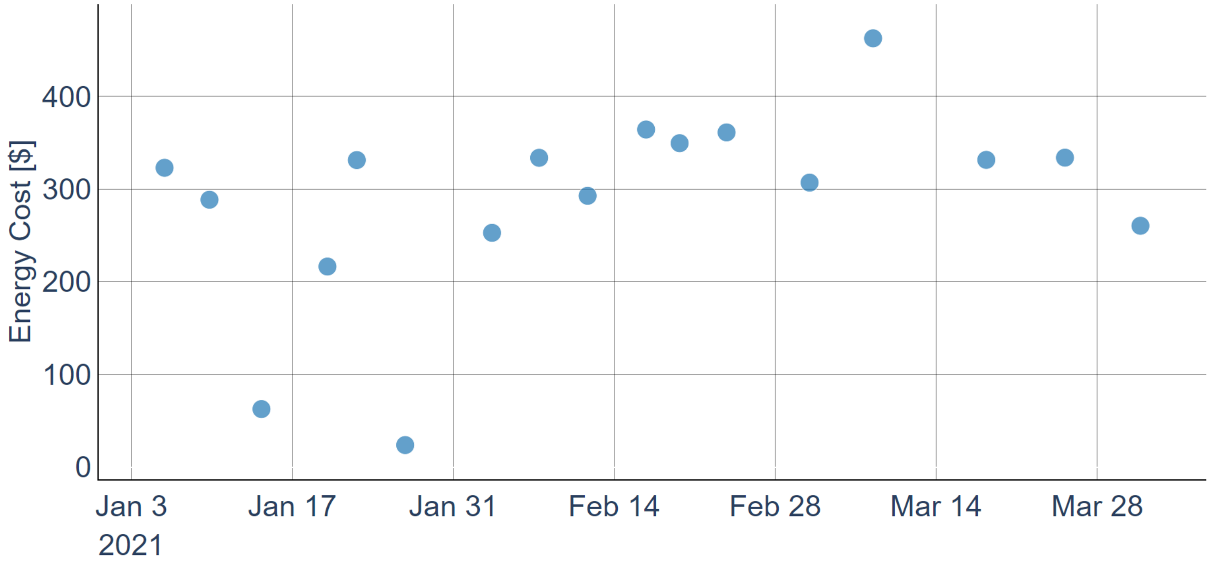


Figure 27. Cost of Each Charge Event Observed During 3-Month Field Trial

The charging duration varied considerably as seen in Figure 28. Note this is the actual duration of charging – with electricity flowing. The exact reason for this variation is unknown. The charging strategy was likely impacted by initial SOC, final SOC, battery temperature, and ambient temperature to work within the constraints.

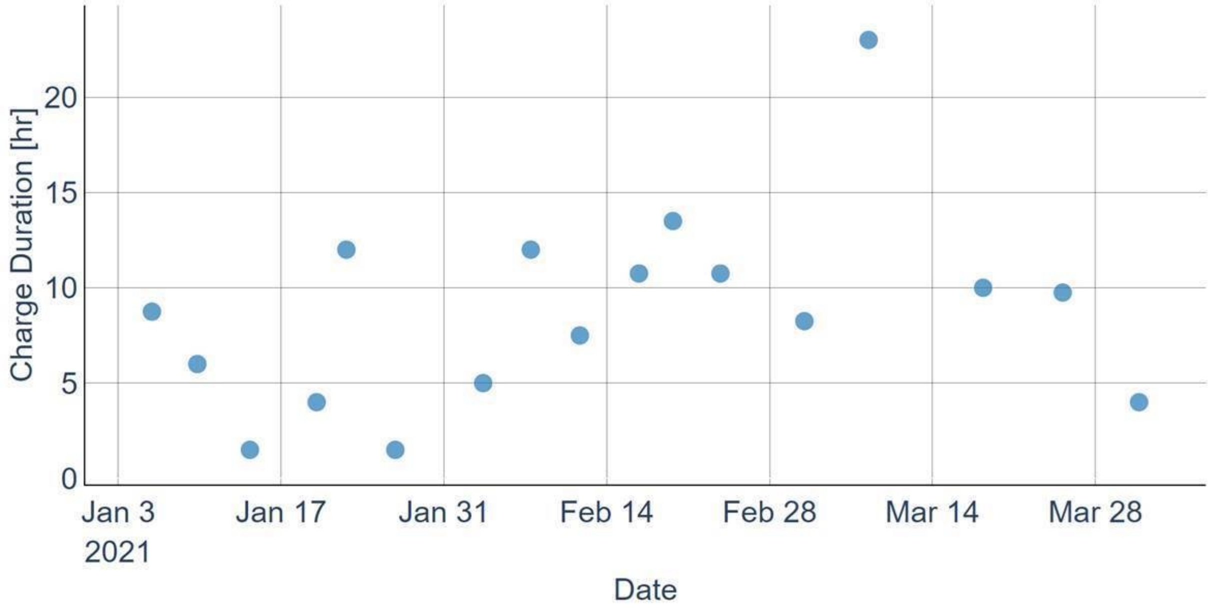


Figure 28. Duration of Each Charge Event Observed During 3-Month Field Trial

The final aspect of the battery charging was the source of the energy. The BEL can acquire energy from wayside power or regenerative braking. The data presented in Figure 29 shows what percent of the BEL energy into the battery for each round trip that was charged from wayside power.

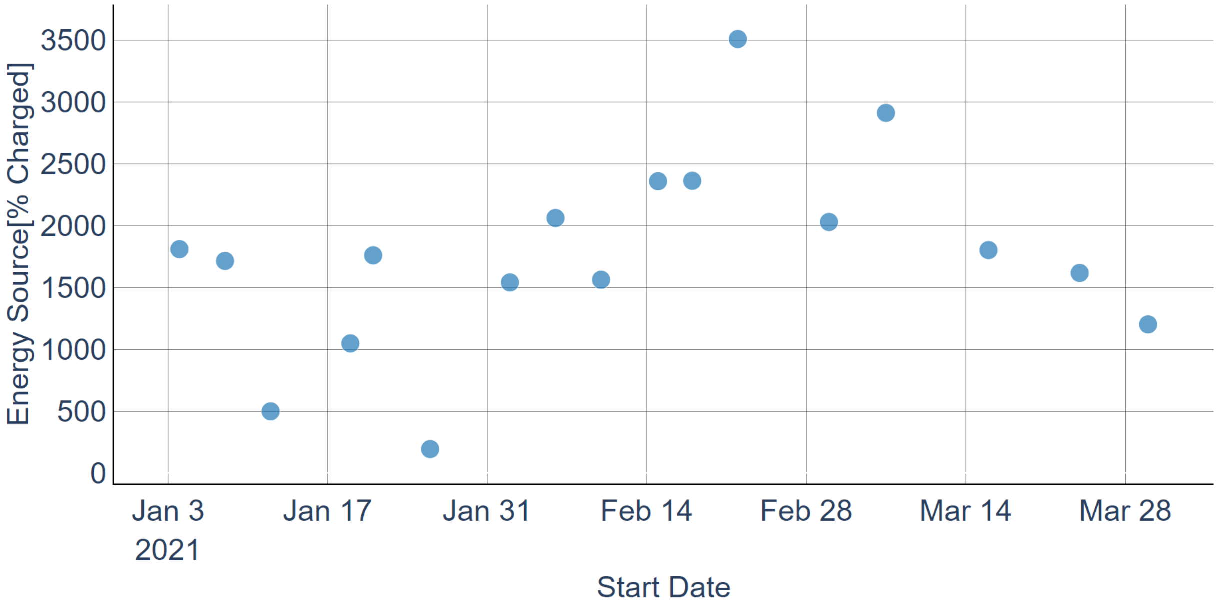


Figure 29. Percentage of BEL Energy into the Battery from the Wayside Charger

5.4 BEL Pure Electric Range

One aspect of the BEL performance is its potential range to pull freight in a battery-only or pure electric mode. The data presented in Figure 30 is from January 10, 2010, when the BEL was used solely to pull the train out of the Stockton yard, without tractive support from the two Tier 4 locomotives. The initial SOC was 85 percent, and the final SOC was 19 percent 36 miles later when the train made a routine stop and Trip Optimizer was configured for normal BEL operation. The final SOC is at the lower range of the usable SOC allowed by Wabtec for the BEL.

The duration for this BEL-only traction operation was an hour and fifteen minutes. This is longer than the Wabtec-advertised time of 30 to 40 minutes at full horsepower. However, the duration and distance for this estimate will be dependent up train make up, power demand, speed profile, and track elevation.

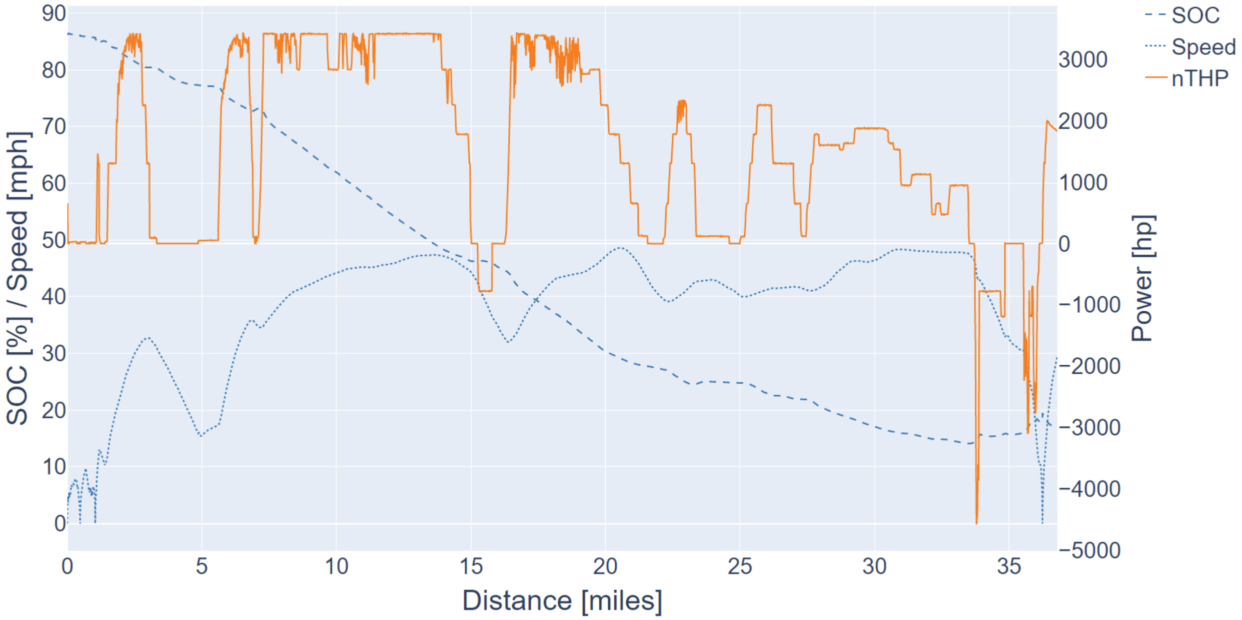


Figure 30. BEL SOC, Speed, and Power vs Distance used to Estimated Range of Locomotive Under Load

5.5 Calculated Fuel Savings and Emissions Reductions

The calculation of the BEL impact on fuel and emissions reductions was evaluated by comparing it to a model of a virtual diesel consist. This approach was used because it was not possible to perform a direct comparison between two identical trains on the same day. Accounting for differences in train makeup, ambient temperature, speed, and auxiliary loads would be very difficult if not impossible.

The simulation approach was based upon 1 Hz data from three locomotives within the consist. A high-level diagram of the approach is shown in Figure 31. There are four major steps for this approach that include establishing the power requirement of the BEL consist at each 1-second interval during a trip, mapping it to a virtual consist, estimating locomotive fuel consumption, and integration of the data.

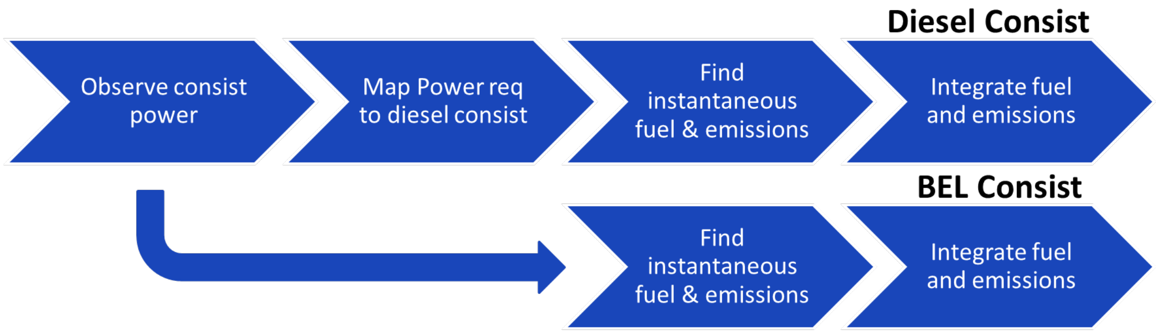


Figure 31. Diagram Overview of BEL Fuel and Emissions Reduction Estimation Approach

The power demand for the BEL consist was determined by summing the power for each locomotive within the BEL consist on a second-by-second basis. Gross horsepower was used for the two diesel locomotives. The BEL power contribution was estimated in a different manner because it does not have a direct equivalent to gross horsepower. The BEL net tractive horsepower was used as the basis for its power contribution. An alternator efficiency of 95.5 percent was assumed to estimate the BEL gross horsepower contribution to the BEL consist.

The BEL consist power requirement was then mapped to a virtual diesel consist that was made up of two Tier 4 diesel locomotives, without the BEL. The assumption was made that the power split evenly between the two locomotives to make the same power as the BEL consist. If the BEL consist exceeded the maximum power of the two Tier 4 locomotives, it was assumed that the excess power demand was met with the same brake specific fuel consumption or emissions at rated power.

The fuel consumption and the emissions for the two Tier 4 diesel locomotives were based on Wabtec test data from 8 different Tier 4 locomotives which were averaged to develop a single table based upon gross horsepower. This table included fuel rate, NO_X, PM, THC, and CO. Each of the parameters were linearly interpolated based upon gross horsepower at each time step.

The last step in the process is to integrate the 1 Hz fuel rate and emission rates for both consists for each train. A trapezoidal integration was used to complete this step.

Figure 32 shows the percent fuel reduction for the BEL consist for each train. The average fuel savings during the field trial was 12 percent. Note that these values do not take into account wayside charging. The highest reduction observed for a single train was 19 percent. The lowest was 4 percent. There is also a large difference based upon train direction. This is due to the geography of the route. Barstow is about 2,150 ft higher in elevation than Stockton. Despite having a lower state of charge when leaving Barstow, the train has an overall larger amount of stored energy when considering both potential energy (train mass and elevation change) and stored battery energy.

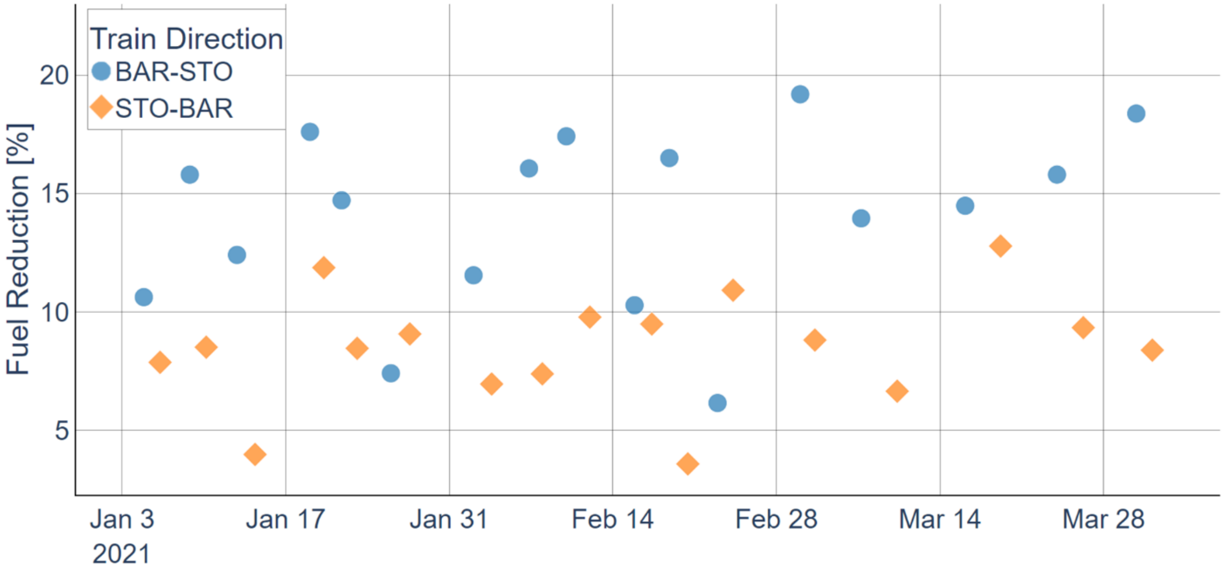


Figure 32. Percent Fuel Reduction for BEL Consist for Each Train

Understanding the difference in geography helps to understand why fuel is saved differently along the route. Figures Figure 33 and Figure 34 show elevation, speed, SOC, and estimated fuel reduction versus the distance traveled for that train. Figure 33 is for the 3-24 BAR-STO train. Figure 34 is for the 4-1 STO-BAR train.

Figure 33. Plots Showing Altitude, SOC, Speed, and Estimated Fuel Reduction for 3-24 BAR-STO Train Traveling from Barstow, CA to Stockton, CA

Both trains gain a significant amount of fuel savings when accelerating upon the start of the trip. The SOC starts high during this portion of the trip, and the BEL can contribute work.

This represented about half of the estimated savings for the April 1 STO-BAR train in Figure 34. The other period where large fuel savings are realized is just after crossing the mountain, where dynamic-brake recharges the BEL so that it can again contribute work.

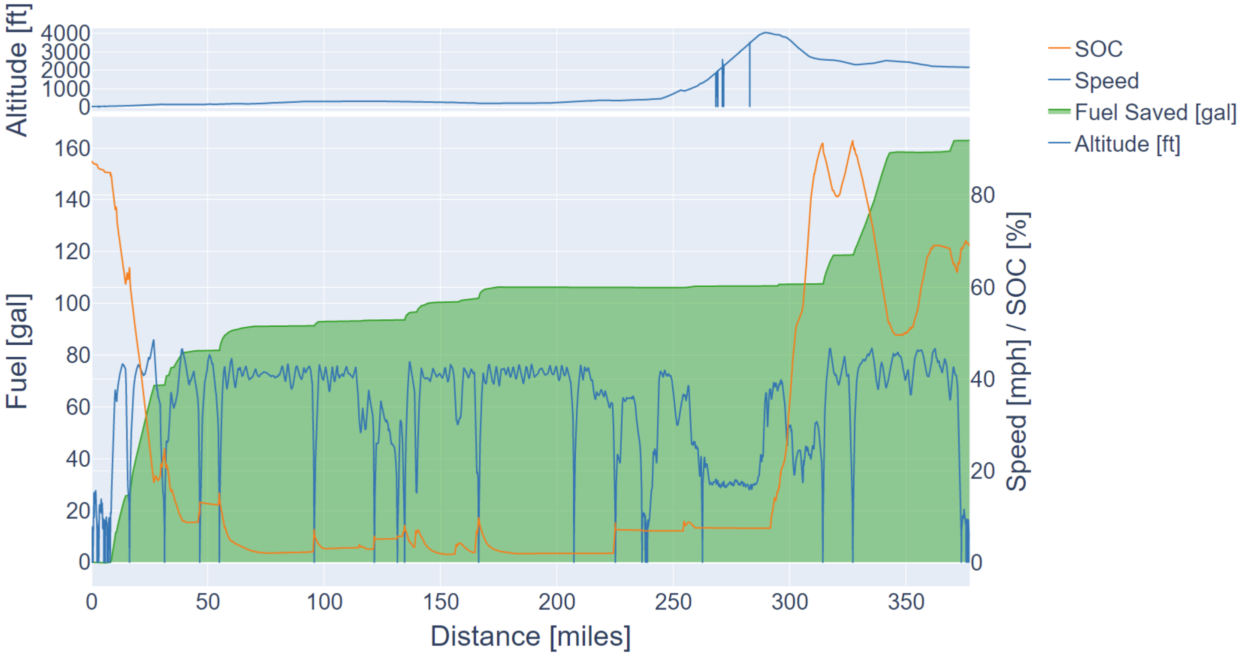


Figure 34. Plots Showing Altitude, SOC, Speed, and Estimated Fuel Reduction for 3-24 BAR-STO Train Traveling from Stockton, CA to Barstow, CA

Some fuel reductions were realized from unplanned train stops, but there are differences depending on the direction of the train. There is a slight grade down Northbound from Bakersfield to Stockton. This means that each stop Northbound provides more regenerative braking opportunity and less energy needed to accelerate again. The opposite is true when leaving Stockton Southbound on a slight uphill grade toward Bakersfield. Each stop provides less regenerative braking and requires more energy when accelerating.

Reductions in fuel consumption were the focus for the optimization of the BEL Trip Optimizer control algorithms, but exhaust emissions reductions were also expected with reductions in fuel consumption. Emissions reductions for CO_2, CO, PM, THC, and NO_X were estimated using the same approach as was used for calculating fuel savings.

CO_2 reductions were estimated directly from reductions in fuel consumption. It was assumed that 22.2 lbs. of CO_2 would not be generated for every gallon of fuel not consumed[1]. This results in an overall 12 percent reduction in CO_2 for the field trial. This results in an estimated reduction of 86 metric tons of CO_2 during the field trial. Results for each train are shown in Figure 35.

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[1] EPA Emission Facts, “Average Carbon Dioxide Emissions Resulting from Gasoline and Diesel Fuel,” EPA420-F-05-001, February 2005.

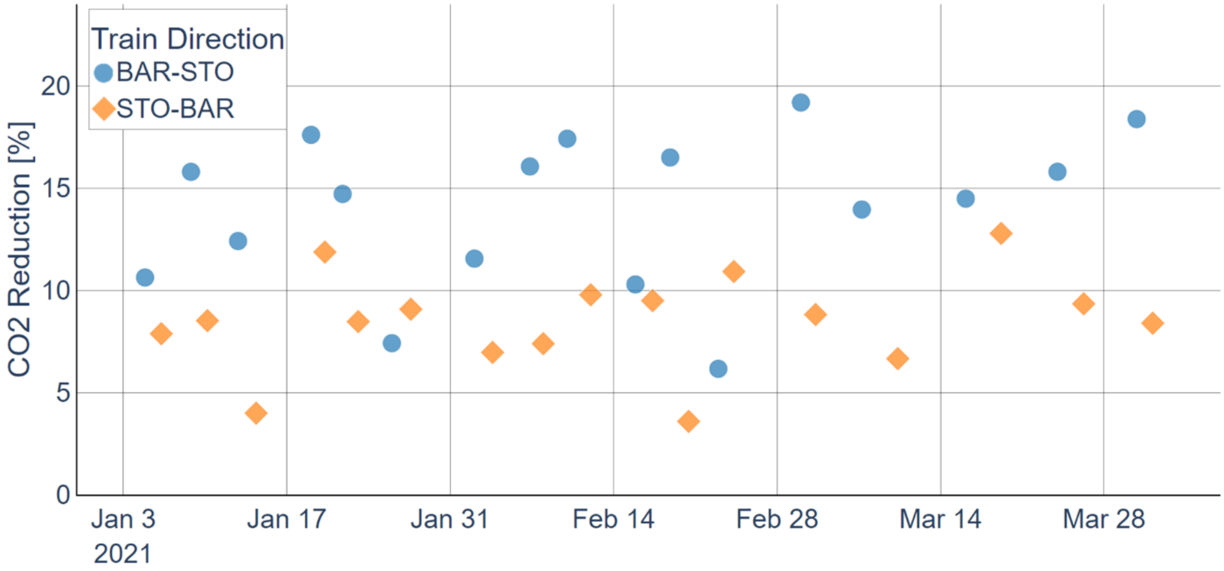


Figure 35. Estimated CO_2 Reduction for BEL Consist for Each Train

The reduction in total hydrocarbon (THC) and NO_X emissions correlated well with the reduction in fuel consumption. The results for these two estimates are shown in Figure 36 and Figure 37. The average NO_X reduction was 8 percent, and the average THC reduction was 3 percent

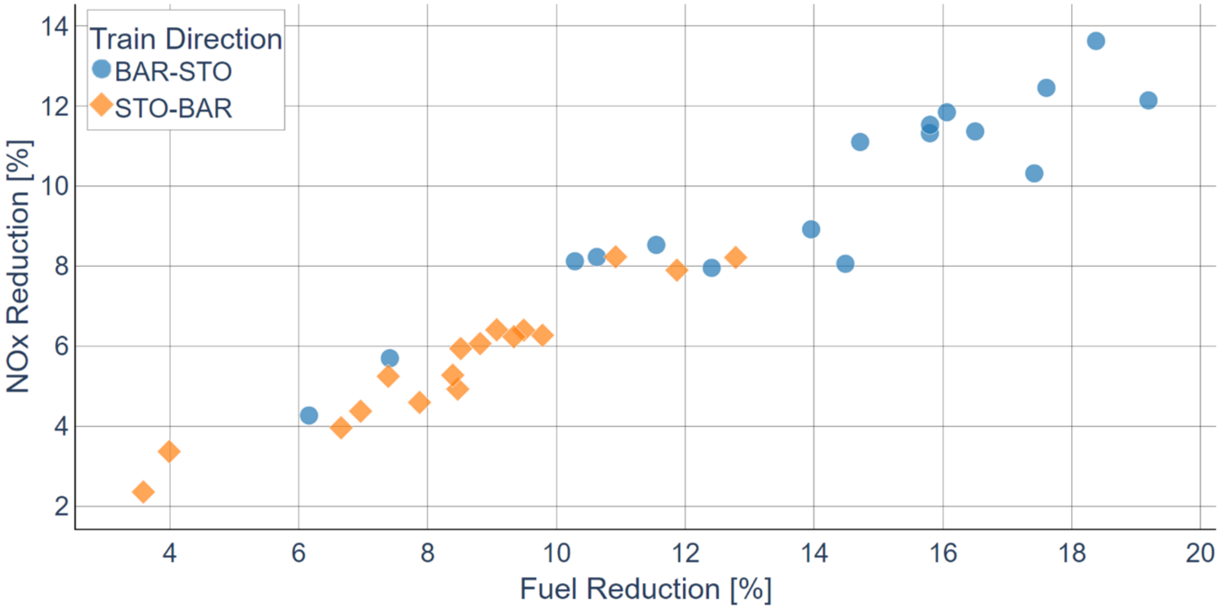


Figure 36. Estimate NO_x Emission Reduction Versus Estimated Fuel Reduction

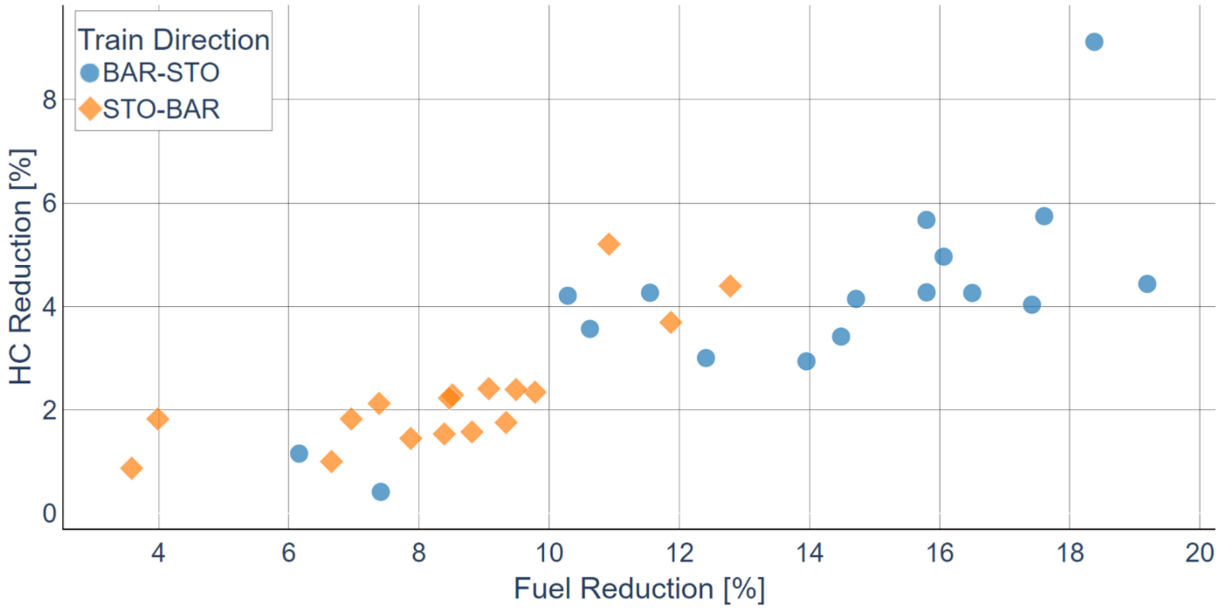


Figure 37. Estimated Hydrocarbon Emission Reduction Versus Estimated Fuel Reduction

The estimated reduction for PM did not always correlate with the reduction in fuel consumption. The BEL consist may have slightly increased PM emissions for a few trains, but it did reduce PM emissions by 3 percent on average. While this may seem counter intuitive, it is possible to explain this behavior. PM results are presented in Figure 38.

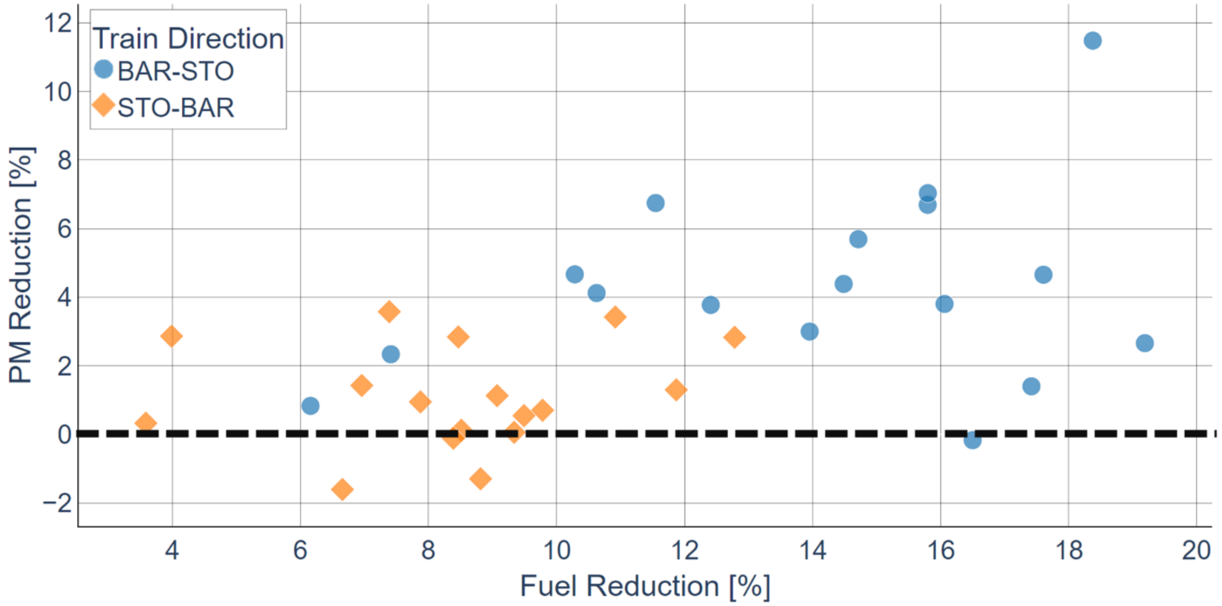


Figure 38. Estimate PM Emission Reduction Versus Estimated Fuel Reduction

The BEL algorithms were optimized to reduce fuel consumption. Reductions of exhaust emissions were not considered and were assumed to decrease with a decrease in fuel consumption. However, not all the emissions are linear with power. PM mass emissions rate can increase with a reduction in power as seen in Figure 39, where moving from 2,500 BHP down to 1,250 BHP results in an increase in PM g/hr. The BEL biased diesel locomotive power demand for some trains toward a lower power condition, which led to a higher PM mass rate. This resulted in higher PM emissions for the trip.

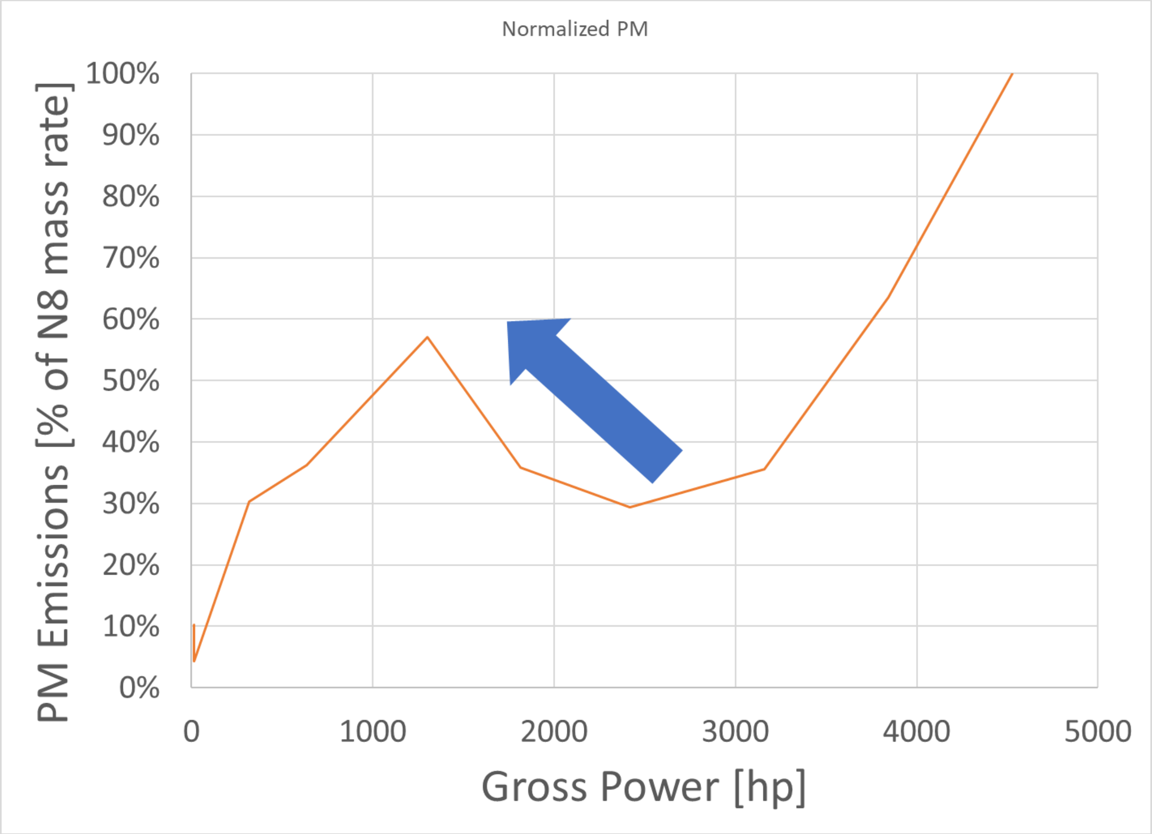


Figure 39. General Trend of PM Rate and BSPM vs Gross Power

CO emissions showed similar trends to PM emissions. In three cases, CO emissions for a train were increased slightly. This can be seen in Figure 40. The reasons for this behavior are the same reasons as the increase in PM emission. The average reduction for CO emissions was 3 percent.

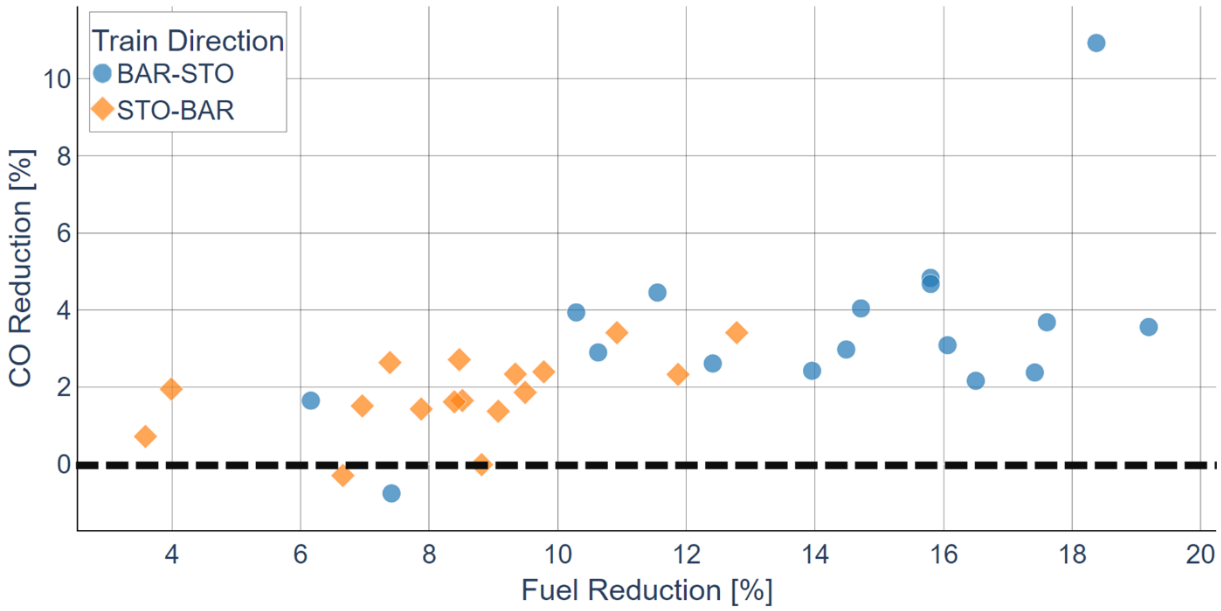


Figure 40. Estimated CO Emission Reduction for BEL Consist for Each Train

6.0 MAINTENANCE & REPAIRS

Summaries of maintenance and repairs are provided in Attachments B and C. These summaries were provided by Wabtec and were included in the report for completeness.

There were no failures during the 3-month trial. However, several battery modules were replaced proactively due to the control system identifying potential faults. These modules were returned to Wabtec's offices in Erie, PA for teardown and analysis. All of these modules were replaced in Barstow, CA or Stockton, CA and did not interrupt train operation. Descriptions of replaced components and teardown findings are contained in Attachment B.

There was no planned maintenance that occurred during the 3-month trial. Normal maintenance was conducted immediately prior the start of the trial. If the trial were longer, normal maintenance would have been required. Descriptions of these potential maintenance items are provided in Attachment C.

7.0 SUMMARY

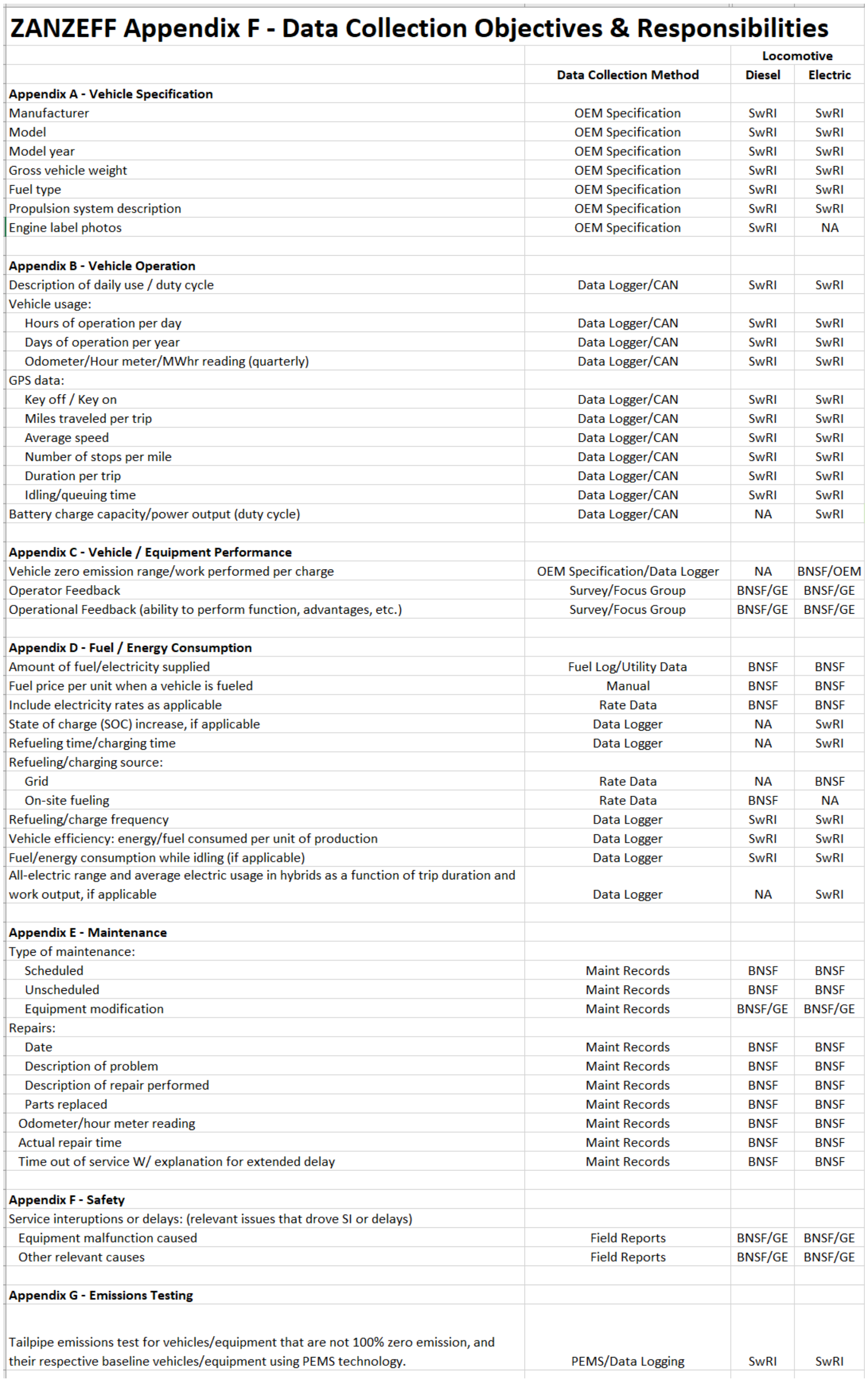
Data was logged for a 3-month period on the BEL consist. This data was used to predict overall fuel and emissions reductions by modeling an equivalent diesel consist. This consist was made up of the BEL plus two Wabtec 4,500 HP Tier 4 ET44C4 diesel locomotives.

The BEL consist made a total of 18 round trips from Barstow, CA to Stockton, CA. The maiden voyage ran from Dec 14th, 2020, to Dec 18th, 2020, to ensure all systems were functioning properly and to develop training documents for the wayside charging operations in Stockton. The maiden voyage was not included in the fuel and emissions analysis.

Data for the BEL consist was collected for 17 round trips from Barstow, CA to Stockton CA for a total of 12,800 miles. During this time, 63,400 gallons of fuel were consumed for a total fuel cost of $173,400. The BEL was charged with 26,200 kW-hrs. of electricity. This electricity cost $4,895.

The estimated fuel savings of the BEL was 12 percent throughout the study. This is a reduction of 8,600 gallons of fuel in a 3-month period. Based on the fuel reduced, it is estimated that CO_2 emissions were reduced by 86 metric tons. In addition, the reduction in fuel consumption was estimated to have saved $23,500. This resulted in a net savings of about $18,600 over the demonstration period of 3 months.

Attachment A
SwRI's Reporting Requirements - Locomotives



ZANZEFF Appendix F - Data Collection Objectives & Responsibilities

		Locomotive	
	Data Collection Method	**Diesel**	**Electric**
Appendix A - Vehicle Specification			
Manufacturer	OEM Specification	SwRI	SwRI
Model	OEM Specification	SwRI	SwRI
Model year	OEM Specification	SwRI	SwRI
Gross vehicle weight	OEM Specification	SwRI	SwRI
Fuel type	OEM Specification	SwRI	SwRI
Propulsion system description	OEM Specification	SwRI	SwRI
Engine label photos	OEM Specification	SwRI	NA
Appendix B - Vehicle Operation			
Description of daily use / duty cycle	Data Logger/CAN	SwRI	SwRI
Vehicle usage:			
Hours of operation per day	Data Logger/CAN	SwRI	SwRI
Days of operation per year	Data Logger/CAN	SwRI	SwRI
Odometer/Hour meter/MWhr reading (quarterly)	Data Logger/CAN	SwRI	SwRI
GPS data:			
Key off / Key on	Data Logger/CAN	SwRI	SwRI
Miles traveled per trip	Data Logger/CAN	SwRI	SwRI
Average speed	Data Logger/CAN	SwRI	SwRI
Number of stops per mile	Data Logger/CAN	SwRI	SwRI
Duration per trip	Data Logger/CAN	SwRI	SwRI
Idling/queuing time	Data Logger/CAN	SwRI	SwRI
Battery charge capacity/power output (duty cycle)	Data Logger/CAN	NA	SwRI
Appendix C - Vehicle / Equipment Performance			
Vehicle zero emission range/work performed per charge	OEM Specification/Data Logger	NA	BNSF/OEM
Operator Feedback	Survey/Focus Group	BNSF/GE	BNSF/GE
Operational Feedback (ability to perform function, advantages, etc.)	Survey/Focus Group	BNSF/GE	BNSF/GE
Appendix D - Fuel / Energy Consumption			
Amount of fuel/electricity supplied	Fuel Log/Utility Data	BNSF	BNSF
Fuel price per unit when a vehicle is fueled	Manual	BNSF	BNSF
Include electricity rates as applicable	Rate Data	BNSF	BNSF
State of charge (SOC) increase, if applicable	Data Logger	NA	SwRI
Refueling time/charging time	Data Logger	NA	SwRI
Refueling/charging source:			
Grid	Rate Data	NA	BNSF
On-site fueling	Rate Data	BNSF	NA
Refueling/charge frequency	Data Logger	SwRI	SwRI
Vehicle efficiency: energy/fuel consumed per unit of production	Data Logger	SwRI	SwRI
Fuel/energy consumption while idling (if applicable)	Data Logger	SwRI	SwRI
All-electric range and average electric usage in hybrids as a function of trip duration and work output, if applicable	Data Logger	NA	SwRI
Appendix E - Maintenance			
Type of maintenance:			
Scheduled	Maint Records	BNSF	BNSF
Unscheduled	Maint Records	BNSF	BNSF
Equipment modification	Maint Records	BNSF/GE	BNSF/GE
Repairs:			
Date	Maint Records	BNSF	BNSF
Description of problem	Maint Records	BNSF	BNSF
Description of repair performed	Maint Records	BNSF	BNSF
Parts replaced	Maint Records	BNSF	BNSF
Odometer/hour meter reading	Maint Records	BNSF	BNSF
Actual repair time	Maint Records	BNSF	BNSF
Time out of service W/ explanation for extended delay	Maint Records	BNSF	BNSF
Appendix F - Safety			
Service interuptions or delays: (relevant issues that drove SI or delays)			
Equipment malfunction caused	Field Reports	BNSF/GE	BNSF/GE
Other relevant causes	Field Reports	BNSF/GE	BNSF/GE
Appendix G - Emissions Testing			
Tailpipe emissions test for vehicles/equipment that are not 100% zero emission, and their respective baseline vehicles/equipment using PEMS technology.	PEMS/Data Logging	SwRI	SwRI

Attachment B
Failure Analysis of Battery modules and Battery String Controller

The Wabtec Battery Electric Locomotive (BEL) did not experience any road failures during the demonstration. However, seven of the battery modules and two battery string controllers were changed out as a precaution. The changes were made after monitors on each module alerted the control system of a potential failure. Following is a description of the observed faults and the analysis to determine the root cause of the potential fault.

Table F1 – Battery Module Removal Summary

Date	Serial Number	Observations	Root Cause	Locomotive Resolution
January 7, 2021	MAAEL20112002	Module open wire fault	Inconclusive- estimated to be loose wires	Replaced module, locomotive performance restored
January 14, 2021	MAAEL20041001	Module periodic voltage out of range fault	Inconclusive- estimated to be loose wires	Replaced module, locomotive performance restored
February 9, 2021	MAAEL19345001	Module open wire fault	Inconclusive- estimated to be loose wires	Replaced module, locomotive performance restored
February 15, 2021	MAAEL20079004	Module periodic temperature out of range fault	Inconclusive- estimated to be loose wires	Replaced module, locomotive performance restored
March 3, 2021	MAAEL20013004	Control Card self-test failed – open wire fault	Inconclusive – could not duplicate in lab	Replaced module, locomotive performance restored
March 11, 2021	MAAEL20015002	Control Card self-test failed – open wire fault	Inconclusive- estimated to be loose wires	Replaced module, locomotive performance restored
March 19, 2021	MAAEL20010004	Control Card self-test failed – open wire fault	Inconclusive- estimated to be loose wires	Replaced module, locomotive performance restored

Modules MAAEL20112002 and MAAEL2004101 were dis-assembled at the same time and analyzed for their faults. The modules were inspected on January 26, 2021. Neither unit had any visible evidence of improperly installed or damaged pins or ring terminals. There was no visible wire damage.

Bolted connections were checked to verify that they had been torqued correctly. Seven connections in module MAAEL20112002 and three connections in module MAAEL2004101 were identified as having low torque values compared to the minimum required torque for these connections.

The manufacturing instructions were reviewed for these bolted joints. Tooling used to install these bolted joint connections have torque settings to apply the correct amount of torque to each connection. However, there was no formal process to check and verify that the actual torque applied to each connection met the specification.

A test was conducted to determine whether the bolt torque truly affects the “loose wire” alarm in the system. The test demonstrated that the connections simply required contact to be made to avoid a loose wire alarm. Therefore the “loose wire” alarm may not have adequately captured a potential failure even though the alarms did trigger before any true module failures occurred.

Module MAAEL19345001 was replaced and inspected for an open wire fault similar to module MAAEL20112002. Faults occurred with this module when open wire self-tests were conducted in the field on the locomotive.

The errors were able to be replicated in the test lab when the module was being analyzed. The fault was more prevalent during temperature cycling tests. No loose wires were found, but the voltage sensor was re-tightened. This resolved the problem. The sensor loosened during additional testing, but the fault did not recur. This indicates the sensor connection was not the true root cause of the faults. Investigations are continuing to determine the actual root cause.

Module MAAEL20079004 was changed because of a temperature out-of-range indication. The module was subjected to temperature cycling in the test lab, and the condition was able to be reproduced. The temperature sensor appeared to be working properly. Loose bolted connections were found in the module similar to those found in the first two modules described above, but in a different location.

Table F2 – Battery String Controller Module Removal Summary

February 16, 2021	BAAEL2018307	Positive Contactor Self-Test	Possible software setting error	Replaced module, locomotive performance restored
March 26, 2021	BAAEL2018302	Positive Contactor Self-Test	Possible software setting error	Replaced module, locomotive performance restored

Both Battery String Control Modules had the same failures. These were both located in the same position on the locomotive, so it is believed that the faults were caused by an incorrect software setting in the prototype software which caused timing of some of the contactor functions to be slightly out of specification from the settings. Like the battery modules, no actual failures occurred during operations, and the control modules were replaced as a precaution.

During the final run of the locomotive, one battery module and one battery string controller encountered faults. These faults were cleared, and the units were not replaced. Upon inspection after the locomotive was returned to the Wabtec facility in Erie, PA, all battery and battery string control modules were operating properly.

Attachment C
Maintenance

The Wabtec Battery Electric Locomotive (BEL) did not require any scheduled or unscheduled repairs which removed the locomotive from service. Some modification and repairs were made to the unit just prior to the unit going into service and during layovers between runs.

Prior to the locomotive entering service, the unit was inspected and found to require two minor repairs. The "F" stencil needed to be added to the front of the locomotive, and the handrail colors needed to be high contrast compared to the car body. They were repainted white.

Seven battery modules and two battery string controllers were changed throughout the demonstration period. All changes were precautionary measures driven by system alerts. The changes were completed prior to any potential component or mission failures. The modules were changed during the layover period between train runs at the Barstow, CA facility so that the locomotive was always available for planned runs.

There was no planned scheduled maintenance for the locomotive during the demonstration period. Regular maintenance would be required if the locomotive had operated for a longer period. This maintenance would include air filter changes and routine maintenance of the brake rigging. There is less regular maintenance required on this locomotive because there is no engine, engine support systems or alternator on the unit.