CERTIFICATION TESTING OF UNITED STATES DEPARTMENT OF ENERGY ATLAS TRAIN – S-2043 FINAL REPORT

for the United States Department of Energy

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Proprietary Report

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Executive Summary

As part of the United States Department of Energy (DOE) Atlas Railcar Project, the Atlas and Buffer railcars were developed to meet the need for future large-scale rail transport of spent nuclear fuel and high-level radioactive waste. The DOE collaborated with the United States Naval Nuclear Propulsion Program (NNPP) to purchase a rail escort vehicle (REV) for use the in the Atlas train project. Between 2018 and 2023, MxV Rail, a subsidiary of the Association of American Railroads (AAR), performed single- and multiple-car certification testing and modeling on these railcars. Tests were performed in several locations including the Transportation Technology Center (TTC) in Pueblo, Colorado; the Pueblo Chemical Depot (PCD) in Pueblo, Colorado; BNSF railroad tracks between Avondale, Colorado, and Folsom, New Mexico; and Union Pacific (UP) railroad tracks between Avondale, Colorado, and Scoville, Idaho.

Testing and modeling were performed according to the certification requirements in the AAR *Manual of Standards and Recommended Practices (MSRP)*, Standard S-2043, "Performance Specification for Trains Used to Carry High-Level Radioactive Material (HLRM)."[1] The work was performed as part of Phases 4 (single-car) and 5 (multiple-car) under DOE Contract 89243218CNE000004/P00022. The REV single-car test program was performed by MxV Rail, under contract from NNPP via Bechtel Plant Machinery, Inc. and Vigor Works, LLC. This report summarizes the steps undertaken to obtain Standard S-2043 certification for the Atlas train and is intended to demonstrate compliance with the Standard, as required by Standard S-2043 paragraph 9.0.

The test train consisted of a leading buffer railcar, a 12-axle cask railcar, a trailing buffer railcar, and a REV. The 12-axle cask railcar, known as Atlas, is equipped with fittings to accommodate cradles and end stops designed to allow the railcar to carry various casks used for the transportation of spent nuclear fuel and high-level radioactive waste. Depending on test requirements, the Atlas railcar was loaded with either the minimum test load (198,975 pounds) or the maximum test load (490,400 pounds). The buffer railcars were four-axle flatcars with permanent loads attached to achieve a gross rail load of 263,000 pounds. The REV was a four-axle car with facilities for personnel to escort the shipment.

During the course of testing, two modifications were made to improve car performance. The design of the attachment of the truck centerplates to the Atlas span bolsters was changed from a welded connection to a bolted connection to eliminate cracking. The wheel tread profile on the train was changed from AAR-1B narrow flange to AAR-2A narrow flange to improve curving performance. In addition, during single car tests with the Atlas car, a stiffer prototype primary pad was used to improve hunting performance but later replaced with the original production pad because the production pad provided a better balance of hunting and curving performance.

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1.0 INTRODUCTION

As part of the United States Department of Energy (DOE) Atlas Railcar Project, the Atlas and Buffer railcars were developed to meet the need for future large-scale rail transport of spent nuclear fuel and high-level radioactive waste. The DOE collaborated with the United States Naval Nuclear Propulsion Program (NNPP) to purchase a rail escort vehicle designed and tested by the NNPP. Between 2018 and 2023, MxV Rail, a subsidiary of the Association of American Railroads (AAR), performed single- and multiple-car certification testing and modeling on these railcars. Tests were performed in several locations including the Transportation Technology Center (TTC) in Pueblo, Colorado; the Pueblo Chemical Depot (PCD) in Pueblo, Colorado; BNSF railroad tracks between Avondale, Colorado, and Folsom, New Mexico; and Union Pacific (UP) railroad tracks between Avondale, Colorado, and Scoville, Idaho.

The testing and modeling were performed to determine whether the train meets the requirements for certification according to the AAR *Manual of Standards and Recommended Practices (MSRP)*, Standard S-2043, "Performance Specification for Trains Used to Carry High-Level Radioactive Material," revised 2017 (S-2043).[1] This report provides summaries of the analysis and test reports with sufficient detail to demonstrate compliance with Standard S-2043. The work was performed as part of Phases 4 (single-car) and 5 (multiple-car) under DOE Contract 89243218CNE000004/P00022. The REV single-car test program was performed by MxV Rail, under contract from NNPP via Bechtel Plant Machinery, Inc. (BPMI) and Vigor Works, LLC (Vigor).

2.0 OBJECTIVE

The objective of this report is to summarize the analysis reports, test reports, and other documentation required by Standard S-2043, paragraph 9.1 with sufficient detail to demonstrate compliance with Standard S-2043.

3.0 ATLAS TRAIN DESCRIPTION

The test train included the following vehicles:

- IDOX 20002 Buffer car
- IDOX 10001 Atlas cask car
- IDOX 20001 Buffer car
- IDOX 30001 Rail Escort Vehicle (REV)

The buffer cars, cask car, and REV represent at least one of each type of railcar that an anticipated consist would employ to transport various casks used for the transportation of spent nuclear fuel and high-level radioactive waste. The following subsections contain a description of each of the cars.

The three railcar types use Swing Motion® trucks (Figure 1) supplied by Amsted Rail. Each truck uses two wheelsets with AAR type K axles and AAR-2A narrow flange wheels. To improve curving performance of the train in revenue service curving tests, MxV Rail replaced the AAR-1B narrow flange profiles with AAR-2A narrow flange profiles during the multiple car test program. The change in wheel tread profile is described in detail in Section 4.2. Narrow flange wheels were specified for these cars because the increased gage clearance allowed more lateral movement for better performance. The trucks were specially designed to use a polymer element between the bearing adapter and the side frame, thereby giving the truck a passive steering capability. Figure 2 shows a bearing adapter pad.

During the Atlas railcar single car testing program, MxV Rail tested the car with a total of four primary suspension pad models. The pads are made from chlorosulfonated polyethylene (CSM) and are categorized by the Shore D durometer hardness value. The car arrived with CSM 58 production pads, ASF-Keystone part number 10522A, and these pads were found to have the best balance of curving and hunting performance. All the test results presented in this report used CSM 58 pads.

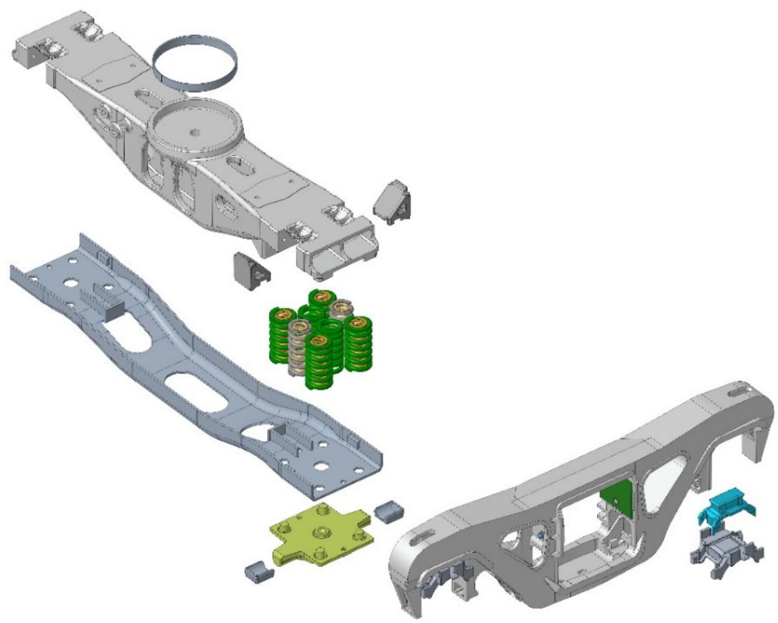

Figure 1. Exploded view of Swing Motion® truck

Figure 2. Bearing adapter pad used on the Atlas, Buffer cars, and the REV

3.1 Atlas Railcar Description

The Atlas railcar is a 12-axle span bolster railcar built by Kasgro Rail Corporation and completed in February 2019. The car is equipped with fittings to accommodate cradles and end stops designed to allow the railcar to carry various casks used for the transportation of spent nuclear fuel and high-level radioactive waste. The railcar deck is supported on two span bolsters. Each span bolster rests on three (3) two-axle trucks. Figure 3 shows the railcar with the minimum test load installed. Table 1 lists the railcar dimensions, and Table 2 shows the truck configuration used for testing. The secondary suspension is made up of special springs in a non-AAR-standard configuration.

Figure 3. IDOX 10001 during testing with minimum test load

Table 1. Atlas railcar dimensions

Dimension	Value
Length over pulling faces	78 feet 1 1/4 inches
Length over strikers	73 feet 5 1/4 inches
Span bolster spacing	38 feet 6 inches
Axle spacing on trucks	72 inches
Distance between adjacent truck centers	10 feet 6 inches
Coupler length	37 inches
Cushion unit length	15 inches

Table 2. Atlas railcar configuration

Component	Description	
Secondary suspension springs at end trucks (A,B,D,E)	(2) 1-94, (2) 1-95, (2) 1-96, (4) 1-97, (4) 1-92, (4) 1-99	
Secondary suspension springs at middle trucks (C,F)	(2) 1-88, (2) 1-89, (2) 1-90, (4) 1-91, (4) 1-92, (2) 1-93, (4) 1-99	
Primary suspension	Adapter Plus pads, ASF-Keystone part number 10522A	
Side frames	F9N-10FH-UB	
Bolsters	B9N-714N-HJ	
Side bearings	Miner TCC-III 60LT	
Friction wedge, composition faced (four per truck)	ASF-Keystone Part number 48446	
Bearings and adapters	AAR Class K 6 1/2 x 9 bearings with 6 1/2 x 9 Special Adapter ASF-Keystone Part number 10523A	
Center bowl plate	Metal Horizontal Liner	
	End Truck Average	Middle Truck Average
Minimum test load spring nest height measured May 19, 2023	8.98 inches	9.20 inches
Maximum test load spring nest height measured June 30, 2022	8.30 inches	8.30 inches
	Actual weight on rail used during testing	
TTC scale weight empty car measured April 1, 2019	222,050 (lbs.)	
TTC scale weight minimum test load measured June 6, 2022	421,025 (lbs.)	
TTC scale weight maximum test load measured July 12, 2022	712,450 (lbs.)	

The convention for wheel and truck identification is shown in Figure 4. The B-end of a typical railroad freight car is normally the end with the hand brake, but because the Atlas railcar has two hand brakes, the railcar manufacturer designated and stenciled the B-end. The right and left sides of the railcar are designated from the perspective of standing at the B-end and looking toward the A-end of the railcar. Axles are numbered starting from the B-end. For axle numbers greater than nine, the locations are stenciled with letters descending from Z.

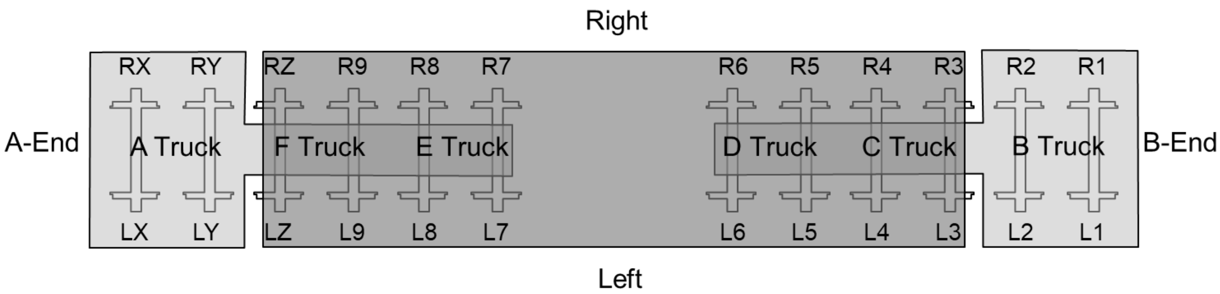

Figure 4. Axle and side naming convention

3.2 Buffer Railcar Description

The S-2043 compliant buffer railcar is a four-axle flatcar with a permanently attached steel plate load. In 2019, Kasgro completed manufacture of two prototype buffer cars, IDOX 20001 and IDOX 20002, which were delivered for Standard S-2043 testing alongside the Atlas cask railcar program.

The buffer railcar trucks use two Koni 04A 2032 vertical dampers to control the vertical motion of the railcar suspension. Table 3 lists the car's dimensions, and Figure 3 shows the general arrangement drawing of the car. Table 4 shows the truck configuration used for testing.

Table 3. IDOX 20001 and 20002 Buffer railcar dimensions

Dimension	Value
Length over pulling faces	66 feet, 4 5/8 inches
Length over strikers	61 feet, 8 5/8 inches
Truck center spacing	44 feet 6 inches
Axle spacing on trucks	72 inches
Coupler length	43 inches
Cushion unit length	15 inches

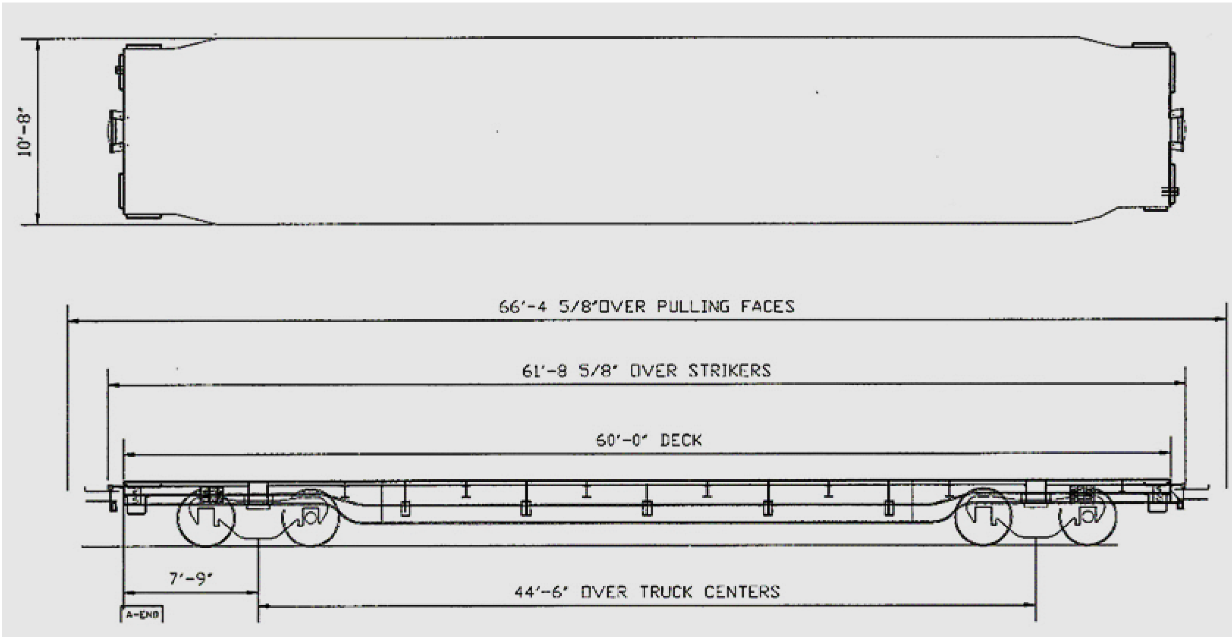

Figure 5. IDOX 20001, 20002 Buffer railcar arrangement drawing

Table 4. IDOX 20001, 20002 Buffer railcar truck configuration

Component	Description	
Secondary suspension	Five D7 outer coils, five D6 inner coils, five D6A inner inner coils, two 49427-1, two 49427-2	
Primary suspension	Adapter plus pads, ASF part number 10522A	
Side bearings	Miner TCC-III 60LT	
Friction wedge	Amsted part number 1-9249	
Bearings and adapters	K class 6 ½ x 9 bearings with 6 ½ x 9 special adapter ASF Part number 10523A	
Center bowl plate	Metal horizontal liner	
Vertical hydraulic dampers	KONI damper 04a 2032	
Side frames	F9N-10FH-UB	
Bolsters	B9N-714N-FS	
	A-end truck average	B-end truck average
Spring nest height IDOX 20001	7.66 inches	7.69 inches
Spring nest height IDOX 20002	7.78 inches	7.84 inches
TTC scale weight – June 2, 2022 IDOX 20001	131,725 pounds	131,800 pounds
TTC scale weight – June 2, 2022 IDOX 20002	131,050 pounds	131,725 pounds

3.3 Rail Escort Vehicle Description

The REV is a four-axle car built by Vigor to house personnel during shipments. Figure 6 shows the general arrangement elevation drawing of the REV, and the basic car dimensions are listed in Table 5. The REV uses 100-ton Swing Motion® trucks from Amsted Rail. Amsted Rail designed the trucks to use primary pads to improve steering performance and vertical KONI dampers (model 04A 2032) to control carbody motion. The REV car's truck configuration is summarized in Table 6. The REV has a light rail load (no personnel, empty water and diesel fuel tanks) of 175,000 pounds and a gross rail load (full complement of personnel, full water and diesel fuel tanks) of 185,000 pounds. For the REV testing, two different railcars were used. For single-car testing, an early NNPP/BPMI REV unit was used, unit number VWXX-800, and the testing was done under a Vigor contract with MxV Rail. That work was reported in references 11 through 15. The Phase 5 multiple-car testing was performed using the DOE-owned REV, IDOX 30001. Unless otherwise indicated, this report will describe the DOE REV.

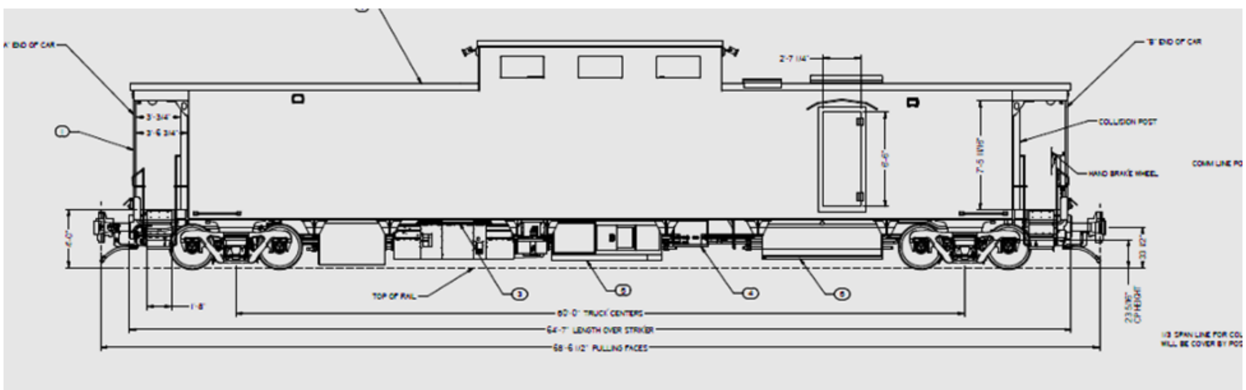

Figure 6. IDOX 30001 REV general arrangement

Table 5. REV dimensions

Dimension	Value
Length over pulling faces	68 feet 11 inches
Truck center spacing	50 feet
Axle spacing	72 inches
Coupler length (pin to coupling line)	43 inches
Cushion unit travel	10 inches

Table 6. IDOX 30001 REV configuration

Component	Description	
Secondary suspension	Five 52596-1 outer coils, five D7 inner coils, five D6A inner inner coils, two 49427-1 outer control coils, two 49427-2 inner control coils	
Primary suspension	Adapter plus pads, ASF part number 10522A	
Side bearings	Miner TCC-III 80LT	
Friction wedge	Amsted part number 1-9249	
Bearings and adapters	K class 6 1/2 x 9 bearings with 6 1/2 x 9 special adapter ASF part number 10523A	
Center bowl plate	Metal horizontal liner	
Vertical hydraulic dampers	KONI damper 04A 2032	
Side frames (AAR design feature code)	F9N-10FH-UB	
Bolsters (AAR design feature code)	B9N-714N-FS	
	A-end truck	B-end truck
Loaded spring nest height	8.06 inches (average)	8.06 inches (average)
TTC scale weight - June 6, 2022 (Partial Load)	89,675 pounds	87,450 pounds

4.0 DESIGN CHANGES

During the course of testing, two modifications were made to improve car performance. The design of the attachment of the truck centerplates to the Atlas span bolsters was changed from a welded connection to a bolted connection to eliminate cracking (Section 4.1). To improve curving performance (Section 4.2), the wheel tread profile on the train was changed from the narrow-flange version of AAR-1B (standard when cars were built) to the narrow-flange version of AAR-2A (standard adopted in 2020). In addition, during single car tests with the Atlas car, a stiffer prototype primary pad was used to improve hunting performance but later replaced with the original production pad design because the production pad provided a better balance of hunting and curving performance.

4.1 Atlas Span Bolster to Truck Centerplate Connection

In December 2020, cracked tri-span bolster center plate welds were found during track performance testing. In January 2021, Kasgro sent welders to the TTC to remove the defects and reweld the center plates. After all weld repairs, MxV Rail personnel performed a non-destructive examination (NDE) of the repair welds, and the welds were found to be acceptable with no cracks. In June 2022, MxV Rail's Rail Vehicle Maintenance (RVM) department inspected the Atlas railcar, the Buffer railcars, and the REV. One crack was found in the B-truck centerplate (one of the centerplates repaired in 2020) on the left side of the Atlas railcar, parallel to the rail. In July 2022, the DOE, Kasgro, and MxV Rail made plans to repair the crack while the consist was parked for the installation of the instrumented wheelsets. Figure 7 shows the crack defect.

Figure 7. Atlas railcar: (left) Crack is on left side of centerplate, B-Truck; (right) Close-up

During Kasgro's repairs to the weld cracks discovered in June 2022, additional defects were found in the tri-span bolster base material. The DOE, Kasgro, and MxV Rail agreed that both tri-span bolsters be shipped back to Kasgro. To avoid future cracking issues, Kasgro changed the attachment method for the six centerplates to the two Atlas railcar tri-span bolsters. Based on the original build drawings, the former attachment method was to use four bolts and weld the centerplates on each side, to the trispan base material. The revised method, which was used for the remaining dynamic tests regarding the Atlas railcar, used a standard AAR (S-207) 12-bolt arrangement plus one tack weld between each bolt head and the centerplate base material, so the bolts cannot back out (Figure 8). The revised method has no welds to the trispan base material. These modifications were completed, and the two (2) new tri-span bolster assemblies were shipped to MxV Rail and delivered at the end of August 2022. As of the most recent inspection in October 2023, following the demonstration test run, the new span bolsters and centerplates show no cracking defects. Kasgro submitted the design change titled "Trispan Static Analysis" to Equipment Engineering Committee (EEC) for M-975 approval in June 2023.

Figure 8. Revised 12-bolt centerplate mounted to replacement Atlas tri-span bolster (no welds to trispan)

4.2 Wheel Tread Profile

The first revenue service test (Standard S-2043, paragraph 6.3) was performed in October 2022. The train encountered rail profile conditions during the revenue service test that caused curving issues not observed during single car tests. The wheel profile was changed from AAR-1B narrow flange to AAR-2A narrow flange to address the problem. The AAR-1B wheel profile was the standard when the railcars were built, but the AAR-2A replaced AAR-1B as the standard in 2020. In June 2023, the revenue service 10-degree curve test was repeated with AAR-2A narrow flange profiles, and the test showed improved performance.

In October 2022, the train, with the Atlas railcar loaded with the minimum test load, traveled from Avondale, Colorado, to the 10-degree curve at Milepost 274 of the BNSF's Twin Peaks subdivision (Alps curve). During these tests, truck side L/V ratios on the Atlas and REV exceeded the S-2043 criterion in many of the 4-degree or tighter curves between Trinidad, Colorado and the siding at Folsom, New Mexico. The siding at Folsom is about 10-miles beyond the Alps curve. Although we focus on the Alps Curve herein, the behaviors modeled will apply to the other exceptions as found on nearby curves in the Twin Peaks Sub.

MxV Rail used the vehicle dynamics models developed and validated during the design and the single car testing phases of the S-2043 process to investigate several possible solutions to reduce the truck side L/V ratios. The potential solutions investigated include:

- Changing pedestal lateral and longitudinal clearances in the trucks
- Changing truck center plate friction
- Changing primary suspension longitudinal stiffness

- Changing primary suspension lateral stiffness
- Changing from the AAR-1B narrow flange wheel profiles to the AAR-2A narrow flange wheel profile

Based on modeling results the only solution that appeared to have a potentially significant effect on vehicle curving performance was replacing the AAR-1B narrow flange wheel profile with the AAR-2A narrow flange wheel profile.[2,3] Figure 9 shows the difference between how the two wheel-tread profiles (blue) contact the outside rail in the Alps curve (red). The AAR-1B has two distinct points of contact between the wheel and rail, one on the tread and one on the flange, with nearly 1.4 inches in between where no contact occurs. Two contact points limit the steering forces that are generated by the wheelset.[4] The reduced steering forces are not adequate to rotate the trucks and axles into the proper position to best negotiate the curve. The AAR-2A has single point contact with the high rail of the Alps curve, allowing for larger steering forces that result in a better position of the trucks and axles, thereby improving the steering performance.

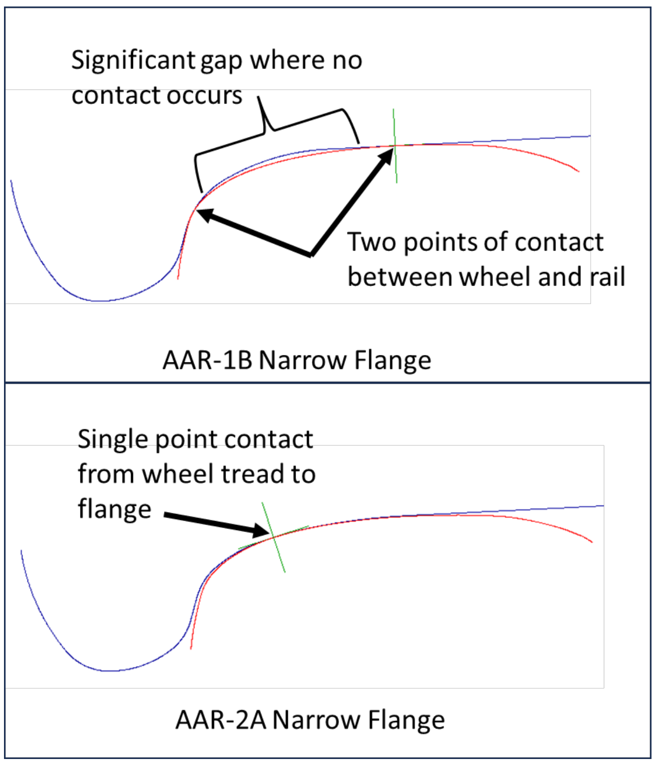

Figure 9. Comparison of the contact conditions of the AAR-1B narrow flange and the AAR-2A narrow flange wheel profiles on the outside rail profile measured in the Alps curve

Changing from the AAR-1B narrow flange wheel profile to the AAR-2A narrow flange wheel profile significantly improved the test results. Figure 10 shows:

- A histogram of the track curves between Trinidad and the Alps curve
- The number of curves where the REV did not meet the truck side L/V ratio criterion with AAR-1B narrow flange wheel profiles

- The number of curves where the REV did not meet the truck side L/V ratio criterion with AAR-2A narrow flange wheel profiles

The truck-side L/V ratio results shown were measured while traveling south with the REV's instrumented truck leading (B-ends of the cars leading). During this portion of the test, the REV did not meet the truck side L/V ratio criterion for two out of 88 total curves with the AAR-2A narrow flange profile, indicating a significant improvement over AAR-1B narrow flange profile in which the REV did not meet the criterion for 30 out of 88 total curves.

The tests with AAR-2A profiles were conducted several months after the tests with AAR-1B profiles. Wheel-rail friction conditions can also affect curving performance, but friction conditions were similar for the two tests. Average friction measured on October 26, 2022, (the day after the AAR-1B test) was 0.44 (top of low rail), 0.53 (top of high rail), and 0.29 (gage face of high rail). Average friction measured on June 27 and 29, 2023, (the days of AAR-2A test) was 0.44 (top of low rail), 0.49 (top of high rail), and 0.35 (gage face of high rail). Simulations showed that the truck side L/V ratio curving performance was more sensitive to wheel and rail shape than wheel-rail friction conditions.

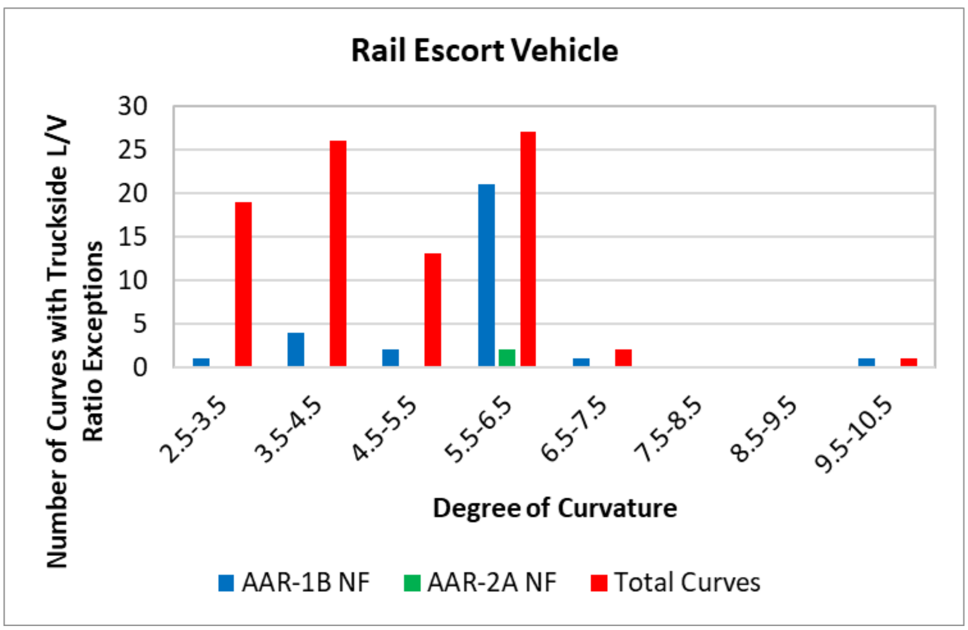

Figure 10. REV truck side L/V ratio curving performance going from Trinidad to the Alps curve with the B-end leading

Figure 11 shows a plot of the truck side L/V ratios for the Atlas railcar while it operated in the Alps curve for B-end leading southbound runs in buff and A-end leading northbound runs in draft. These runs were performed with AAR-1B narrow flange profiles and repeated with AAR-2A narrow flange profiles. Eight operating permutations exist for each wheel profile on this curve: north versus south travel direction, A-end versus B-end oriented toward the south, and buff or draft in-train forces). However, only two of the eight were captured before stopping the AAR-1B tests. Therefore, only the Northbound, Draft, B-End South results and Southbound, Buff, B-End South results will be compared in Figure 11. Based on these exceptions measured with the AAR-1B narrow flange profile, testing was suspended following these test runs to begin investigation of the issue. For this portion of the runs performed, the graph shows that the Atlas railcar did not meet the truck side L/V ratio criterion for any of the runs with the AAR-1B narrow flange profile, but it did meet the criterion for all the runs shown (2 of 8 permutations) with the AAR-2A narrow flange profile. The highest truck side L/V ratio for each run, regardless of wheel profile, occurred on the high rail side of the train.

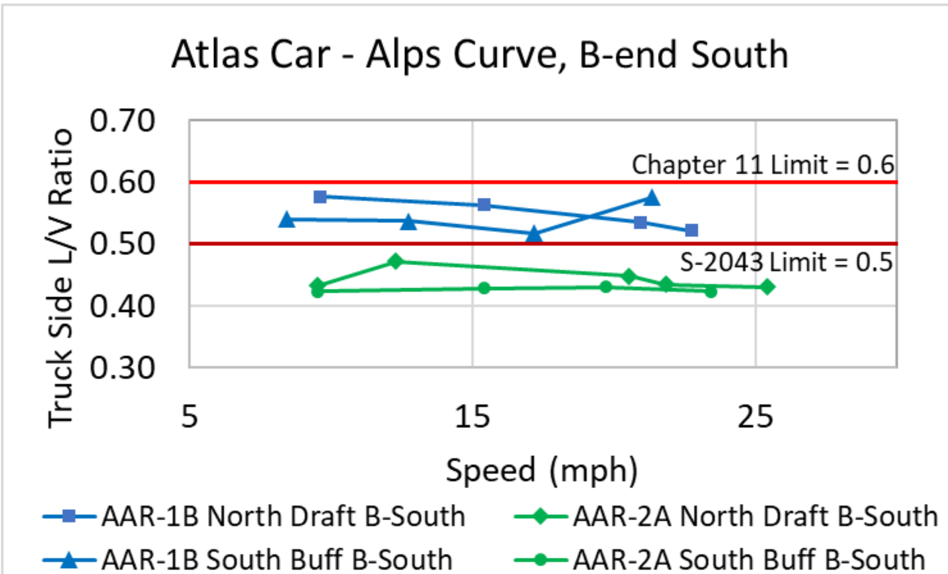

Figure 11. Comparison of Atlas railcar truck side L/V ratios with AAR-1B narrow flange wheel profiles and with AAR-2A narrow flange wheel profiles in the Alps test curve

5.0 OVERVIEW OF SINGLE-CAR AND MULTIPLE-CAR TEST REPORTS

The completion of Standard S-2043 requirements is documented as follows:

- Atlas
  - P-17-021 Revised 12-14-2017, S-2043 *Certification: Preliminary Simulations of Kasgro-Atlas 12-Axle Cask Car*[5]
  - P-21-037, *S-2043 Certification Tests of United States Department of Energy Atlas Railcar Design Project 12-Axle Cask Car*[6]
  - P-21-049, *Atlas Railcar Post Test Analysis Report*[7]
- Buffer
  - P-17-023 Revised 11-20-2017, *S-2043 Certification: Preliminary Simulations of Kasgro Buffer Railcar*[8]
  - P-20-032, *AAR Standard S-2043 Single-Car Certification Tests of U.S. Department of Energy Atlas Railcar Design Project Buffer Railcar*[9]
  - P-21-013, *Buffer Railcar Post Test Analysis Report*[10]

- REV
  - Vigor Design Report 2760-DR-001, revision 2, dated September 6, 2016, with Addendum, revision 0, dated October 12, 2016[11]
  - P-15-029, *S-2043 Certification: Preliminary Simulations of Vigor Industrial LLC Rail Escort Vehicle*[12]
  - Test Report for the REV Structural Test, revision B, dated July 22, 2019[13]
  - P-21-016, *Single-Car S-2043 Certification Tests of Vigor Works Rail Escort Vehicle*[14]
  - P-21-018, *Rail Escort Vehicle Post Test Analysis Report*[15]
- Multiple Car Test Reports
  - P-23-030, *Certification Testing of United States Department of Energy Atlas Train Multiple Car Test Report*[16]
  - P-23-031, *United States Department of Energy Atlas Train Multiple Car Post-Test Analysis Report*[17]
- Maintenance Information
  - Atlas and Buffer Car: *Standardized Inspection of Department of Energy Railcars for Transport of Spent Nuclear Fuel and High-Level Waste*[18]
  - REV: *REV Operations and Maintenance Manual*[19]

5.1 Atlas

The preliminary simulations were performed according to Standard S-2043, paragraph 4.3 as part of the railcar design phase before the prototype car was built. The results of the preliminary simulation were submitted to the AAR as part of the preliminary design review package. To verify that the model accurately represents the vehicle as tested and as required in Standard S-2043, paragraph 8, the test results have been compared to the preliminary dynamic analysis predictions and revised model predictions in report P-21-049.

Simulation predictions were made using inputs created with measured track geometry. MxV Rail's experience has shown that simulations with measured track geometry produce better predictions of car performance than are obtained with analytic track inputs created with mathematical functions. Because the measured track geometry inputs contain short wavelengths that cause spurious peaks in the data, the 50-millisecond and 3-foot analysis windows described in AAR Chapter 11 and Standard S-2043 are used when analyzing data to produce the most realistic results.

As originally equipped with chlorosulfonated polyethylene (CSM) 58 primary pads, the Atlas railcar with a minimum test load did not meet the Standard S-2043 single-car dynamic test requirement for hunting (Standard S-2043, paragraph 5.5.7). The hunting tests were the first tests to be performed, and the testing process was paused to solve the hunting problem. During the troubleshooting tests, the railcar met the hunting requirements with stiffer CSM 70 primary suspension pads, and all the remaining dynamic tests were completed with these pads. With the stiffer pads, the car performance met the hunting requirements but not all the curving requirements. After reviewing the available data with the AAR EEC, MxV Rail performed additional troubleshooting and found that the CSM 58 pads provided the best balance between the curving and the hunting performance results.

The testing data was used to 1) revise the preliminary multi-body vehicle dynamics models that had used CSM 58 pads and 2) modify the revised model into one that used the CSM 70 primary pads. Both revised models showed good alignment with most relevant testing data, such as wheel loads, although comparisons showed some variation between the predicted behavior and the tested behavior. Regimes with existing CSM 70 pad test data were re-modeled using CSM 70 pads to demonstrate the model was validated. These regimes were also modeled with CSM 58 pads to show the change in performance with the final pad. In addition to simulations performed to replicate the conducted tests, numerous other simulations were performed to estimate the car's behavior in conditions that are not easily tested, such as buff and draft curving, rail lubrication, and the effect of worn components.

Like the earliest tests, the revised model of the car equipped with CSM 58 pads did not meet the criterion for the standard deviation of lateral carbody acceleration in the hunting regime. In addition, criteria were not met for other simulation-only regimes, including curving with single rail perturbation with 3-inch amplitude and curving with various lubrication conditions. However, in most circumstances, the model was more conservative than the test results and is indicative of the actual performance.

The EEC approved the Atlas single car test results in a letter from Nichole Fimple to Patrick Schwab dated April 29, 2022. The EEC considered that the hunting with the CSM 58 adapter pad was mild and did not represent a safety concern. Additionally, the test conditions that produced hunting will not be encountered in service because the car would be limited to less than 50 mph per AAR Operating Transportation (OT) circular OT-55[20] when in high-level radioactive material (HLRM) service, 15 mph below the speed where these vehicles become unstable. The performance in the Truck Twist Equalization regime was accepted by the EEC because the requirement was severe, and the performance of the Atlas railcar was reasonable in light of the car's acceptable performance in other regimes. Table 7 shows a summary of the test results and the model predictions for the Atlas railcar.

Table 7. Atlas railcar summary results

Standard S-2043 Section	Met/Not Met		
	Preliminary Simulations CSM 58 pads	Revised Simulations CSM 58 pads	Test Result and Details if Not Met
5.2 Nonstructural Static Tests			

Standard S-2043 Section	Met/Not Met		
	Preliminary Simulations CSM 58 pads	Revised Simulations CSM 58 pads	Test Result and Details if Not Met
4.2.1/5.2.1 Truck Twist Equalization	Met	Not Simulated	Not Met with CSM 58 pads **Minimum Test Load:** Wheel load at 50% during 2″ drop condition. Wheel load at 43% during 3″ drop condition. **Maximum Test Load:** Wheel load at 43% during 2″ drop condition. Wheel load at 29% during 3″ drop condition.
4.2.2/5.2.2 Carbody Twist Equalization	Met	Not Simulated	Met with CSM 58 pads
4.2.3/5.2.3 Static Curve Stability	Met	Not Simulated	Met with CSM 58 pads
4.2.4/5.2.4 Horizontal Curve Negotiation	Met	Not Simulated	Met with CSM 58 pads
5.4 Structural Tests			
5.4.2 Squeeze (Compressive End) Load	Met	Not Simulated	Met with CSM 58 pads
5.4.3 Coupler Vertical Loads	Met	Not Simulated	Met with CSM 58 pads
5.4.4 Jacking	Met	Not Simulated	Met with CSM 58 pads
5.4.5 Twist	Met	Not Simulated	Met with CSM 58 pads
5.4.6 Impact	Met	Not Simulated	Met with CSM 58 pads
5.5 Dynamic Tests			
4.3.11.3/5.5.7 Hunting	Met	Not Met At Minimum Test Load: Car unstable at speeds greater than 65 mph with KR wheel profiles Meets with Maximum Test Load	Not Met with CSM 58 pads At Minimum Test Load: Car unstable at speeds greater than 65 mph with KR wheel profiles Meets with Maximum Test Load
4.3.9.6/5.5.8 Twist and Roll	Met	Met	Not tested with CSM 58 pads – Met with CSM 70 pads
5.5.9 Yaw and Sway	Met	Met	Not tested with CSM 58 pads – Met with CSM 70 pads
5.5.10 Dynamic Curving	Not Met Max. Test Load Wheel L/V ratio 0.88, Limit=0.8, A-end and	Met	Met with CSM 58 pads – Not met with CSM 70 pads (0.81 Wheel L/V ratio)

Standard S-2043 Section	Met/Not Met		
	Preliminary Simulations CSM 58 pads	**Revised Simulations CSM 58 pads**	**Test Result and Details if Not Met**
	B-end lead, 39-ft. input		
4.3.9.7/5.5.11 Pitch and Bounce (Chapter 11)	Met	Met	Not tested with CSM 58 pads – Met with CSM 70 pads
4.3.9.7/5.5.12 Pitch and Bounce (Special)	Met	Not Simulated Truck center spacing close to Chapter 11 wavelength	Not tested
4.3.10.1/5.5.13 Single Bump Test	Met	Met	Not tested with CSM 58 pads – Met with CSM 70 pads
4.3.11.6/5.5.14 Curve Entry/Exit	Met	Met	Not tested with CSM 58 pads – Met with CSM 70 pads
4.3.10.2/5.5.15 Curving with Single Rail Perturbation	Not met **Empty with Ballast Load:** Wheel L/V ratio 0.96, Limit=0.8 Truck Side L/V ratio 0.52, Limit=0.5 **Loaded** 5.0-degree roll angle, Limit=4.0	Not met **Minimum Test Load** Carbody roll angle =4.2, limit=4.0 **Maximum Test Load** Carbody roll angle =4.7, limit=4.0	Minimum Test Load: Not met with CSM 70 pads (Wheel L/V ratio = 0.88, Limit = 0.8; Truck side L/V ratio = 0.50, Limit = 0.5), not tested with CSM 58 pads
4.3.11.4/5.5.16 Standard Chapter 11 Constant Curving	Met	Met	Not tested with CSM 58 pads – Not Met with CSM 70 pads: **Minimum Test Load:** Wheel L/V ratio = 0.86 95% Wheel L/V ratio = 0.66 **Maximum Test Load:** 95% Wheel L/V ratio = 0.63
4.3.11.7/5.5.17 Special Trackwork, No 7 Crossovers	Not Met **Loaded:** Truck side L/V ratio=0.52, Limit=0.5	Met	Not tested with CSM 58 pads – Met with CSM 70 pads on a No 10 crossover

<table>
<tr><th rowspan="2">Standard S-2043 Section</th><th colspan="3">Met/Not Met</th></tr>
<tr><th>Preliminary Simulations CSM 58 pads</th><th>Revised Simulations CSM 58 pads</th><th>Test Result and Details if Not Met</th></tr>
<tr><td>4.3.11.5 Curving with Various Lubrication Conditions</td><td>Not Met
Min Test Load with new profiles:
95% Wheel L/V ratio = 0.62 (Case 2), Limit=0.6
95% Wheel L/V ratio = 0.66 (Case 4), Limit=0.6
Min Test Load with worn profiles:
Truck Side L/V ratio = 0.56 (Case 1), 0.62 (Case 2), 0.61 (Case 4), Limit=0.5
95% Wheel L/V ratio = 0.68 (Case 2), 0.61 (Case 4), Limit=0.6
Max Test Load with worn profiles:
Truck Side L/V ratio = 0.56 (Case 1), 0.62 (Case 2), 0.61 (Case 4), Limit=0.5
95% Wheel L/V ratio = 0.68 (Case 2), 0.61 (Case 4), Limit=0.6</td><td>Not Met
Min Test Load with new profiles:
95% Wheel L/V ratio = 0.62 (Case 4), Limit=0.6
Min Test Load with worn profiles:
Truck Side L/V ratio = 0.53 (Case 1), 0.61 (Case 2), 0.58 (Case 4), Limit=0.5
95% Wheel L/V ratio = 0.64 (Case 2), Limit=0.6
Max Test Load with worn profiles:
Truck Side L/V ratio = 0.52 (Case 1), 0.60 (Case 2), 0.58 (Case 4), Limit=0.5
95% Wheel L/V ratio = 0.66 (Case 2), 0.61 (Case 4), Limit=0.6</td><td>Not required</td></tr>
<tr><td>4.3.12 Ride Quality</td><td>Met</td><td>Not Simulated</td><td>Not required</td></tr>
<tr><td>4.3.13 Buff and Draft Curving</td><td>Not Met
When coupled between other Atlas railcars under buff load Truck side L/V ratio=0.51, Limit=0.50</td><td>Met</td><td>Not required</td></tr>
<tr><td>4.3.14 Braking Effects on Steering</td><td>Met</td><td>Not Simulated</td><td>Not required</td></tr>
<tr><td>4.3.15 Worn Component Simulations</td><td>Not Met
Numerous criteria not met in dynamic curving and hunting regimes with several worn components. See reference 2 for details</td><td>Not Met
Hunting stability, maximum lateral acceleration standard deviation:
Worn CCSB low preload: 0.17
Worn primary pads, soft: 0.19
Worn primary pads, stiff: 0.20</td><td>Not required</td></tr>
</table>

5.2 Buffer

The buffer railcar met all Standard S-2043 single-car structural and dynamic test requirements.

Finite element analysis (FEA) simulations and structural test strain measurements showed that stresses accounted for less than 75 percent of the allowable stress, eliminating the requirement for FEA to be refined per Standard S-2043, paragraph 8.1. The largest difference between the measured and predicted stress was 23 percent based on a measured stress of -30 ksi (60 percent of yield) compared to a predicted stress of -24.3 ksi.

The revised model did not meet the criterion for peak-to-peak carbody lateral acceleration for the 39-foot wavelength inputs (1.38g, limit = 1.3g) or the 44.5-foot wavelength inputs (1.31g, limit = 1.3g) in yaw-and-sway simulations. In contrast, the buffer railcar met test requirements for yaw and sway, thereby indicating the model is conservative. The yaw-and-sway test is only performed with 39-foot wavelength inputs.

The revised modeling predictions did not meet the S-2043 criterion for truck side L/V ratio (0.52, limit = 0.5) in the curving with various lubrication conditions regime. This exception occurred for counterclockwise runs with Case 2 lubrication and the worn wheel profile at 12 and 24 mph. The Case 2 lubrication condition is a 0.5 coefficient of friction on the top of both rails and a 0.2 coefficient of friction on the gage face of the high rail. Simulations meet the S-2043 criteria for curving with various lubrication conditions during clockwise runs for this lubrication and profile case and for all runs with other lubrication and profile combinations.

Due to the small number of changes to the design of the buffer railcar since the original dynamic predictions were performed, only a small subset of the regimes were run with the revised dynamic model. These regimes were chosen because 1) they allowed for comparison with test data or 2) the original dynamic predictions for the regime were close to or did not meet the criteria.

Simulation predictions were made using inputs created with measured track geometry. MxV Rail's experience has shown that simulations with measured track geometry produce better predictions of car performance than those obtained with analytic track inputs created with mathematical functions. Because the measured track geometry inputs contain short wavelengths that cause spurious peaks in the data, the 50-millisecond and 3-foot analysis windows described in AAR Chapter 11 and Standard S-2043 are used when analyzing data to produce the most realistic results.

The EEC approved the Buffer car single car test results in a letter from Nichole Fimple to Patrick Schwab dated April 29, 2022. Table 8 shows a summary of test results and model predictions for the buffer car.

Table 8. Buffer railcar summary results

S-2043 Section	Met/Not Met		
	Preliminary Simulations	Revised Simulations	Test Result
5.2 Nonstructural Static Tests			
4.2.1/5.2.1 Truck Twist Equalization	Met	Not Simulated	Met
4.2.2/5.2.2 Carbody Twist Equalization	Met	Not Simulated	Met
4.2.3/5.2.3 Static Curve Stability	Met	Not Simulated	Met
4.2.4/5.2.4 Horizontal Curve Negotiation	Met	Not Simulated	Met
5.4 Structural Tests			
5.4.2 Squeeze (Compressive End) Load	Met	Not Required	Met
5.4.3 Coupler Vertical Loads	Met	Not Required	Met
5.4.4 Jacking	Met	Not Required	Met
5.4.5 Twist	Met	Not Required	Met
5.4.6 Impact	Met	Not Required	Met
5.5 Dynamic Tests			
4.3.11.3/5.5.7 Hunting	Met	Met	Met
4.3.9.6/5.5.8 Twist and Roll	Met	Met	Met
5.5.9 Yaw and Sway	Met	Not Met P-P Lat Accel 1.38 Limit=1.3	Met
5.5.10 Dynamic Curving	Met	Met	Met
4.3.9.7/5.5.11 Pitch and Bounce (Chapter 11)	Met	Met	Met
4.3.9.7/5.5.12 Pitch and Bounce (Special)	Met	Met	Met
4.3.10.1/5.5.13 Single Bump Test	Met	Not Simulated	Met
4.3.11.6/5.5.14 Curve Entry/Exit	Met	Not Simulated	Met
4.3.10.25.5.15 Curving with Single Rail Perturbation	Met	Met	Met
4.3.11.4/5.5.16 Standard Chapter 11 Constant Curving	Met	Not Simulated	Met
4.3.11.7/5.5.17 Special Trackwork	Met	Not Simulated	Met
4.3.11.5 Curving with Various Lubrication Conditions	Met	Not Met Truck Side L/V ratio 0.52, Limit=0.50	Not Required
4.3.12 Ride Quality	Met	Not Simulated	Not Required
4.3.13 Buff and Draft Curving	Not Met Truck Side L/V ratio 0.51, Limit=0.50	Met	Not Required
4.3.14 Braking Effects on Steering	Met	Not Simulated	Not Required
4.3.15 Worn Component Simulations	Met	Not Simulated	Not Required

5.3 Rail Escort Vehicle

Vigor contracted with MxV Rail to perform certification testing and modeling on its REV. Per this contract, MxV Rail performed characterization, static, and dynamic tests on the REV. Vigor and RailcarCO performed the structural tests on the REV. The single car tests used an early NNPP/BPMI railcar, VWXX-800, that had not yet been fitted with interior furnishings end equipment. The railcar was ballasted with sandbags to match the weight and center of gravity of the finished vehicle.

The secondary suspension of the REV was changed during the testing process. During dynamic tests with the original spring group, the suspension showed hard contact with the bolster-to-transom lateral stops during the yaw-and-sway tests. The spring group was changed to use softer main springs while adding inner control coils to provide more lateral damping to improve the yaw-and-sway performance. The nonstructural static tests were performed with the original spring group, consisting of four D7 outer coils, four D7 inner coils, four D6A inner-inner coils, and two 49427-1 outer control coils. All dynamic tests were repeated with the new spring group consisting of five 52596-1 outer coils, five D7 inner coils, five D6A inner-inner coils, two 49427-1 outer control coils, and two 49427-2 inner control coils. After the spring group was changed, all the modeling regimes listed in Standard S-2043, paragraph 4.3 were repeated for this report, with the exception of the 1- and 3-inch amplitude perturbations for the Curving with Single Rail Perturbation regime. Only the 2-inch amplitude was modeled because the results were compared to test data and only the 2-inch amplitude was tested.

The REV met test requirements during the hunting tests at speeds below 70 mph, but the lateral carbody acceleration standard deviation was 0.14g at 70 mph (limit = 0.13g). The simulation prediction for this regime was 0.13g, which met the criterion. Both test results and simulation predictions met criteria for other hunting metrics. The conditions that the car hunted in test will not be encountered in service because the car would be limited to less than 50 mph per AAR Operating Transportation (OT) circular OT-55[19] when in HLRM service, 20 mph below the speed where the vehicle becomes unstable.

The REV did not meet test requirements during the yaw-and-sway tests. The lateral peak-to-peak acceleration was 0.73g (limit = 0.60g) at 45 mph. The maximum lateral acceleration was 0.38g (limit = 0.35g) at 45 mph. The simulation predictions for 39-foot wavelength inputs showed the lateral peak-to-peak acceleration was 0.65, while the maximum lateral acceleration was 0.34g. Simulation predictions using 50-foot wavelength inputs showed 0.68g and 0.39g for lateral peak-to-peak and maximum lateral acceleration, respectively. The 39-foot wavelength inputs match the condition tested. Standard S-2043 also requires simulations be performed using inputs with wavelengths equal to the truck center spacing of the vehicle being evaluated (50 feet).

The simulation predictions did not meet the truck side L/V ratio criterion for the turnouts and crossovers regime. The simulations of the Number 7 (No. 7) crossover showed a maximum truck side L/V ratio of 0.53 (limit = 0.5). Criteria were met for other metrics in the No. 7 crossover. Criteria were met for all metrics for the turnouts and Number 10 (No. 10) crossovers simulated and tested.

Simulation predictions using standardized track geometry files were completed for ride quality simulations. While ride quality has no specific criteria, the accelerations, displacements, and wheel forces are compared to criteria in Standard S-2043 Table 4.1 “Dynamic analysis performance criteria.” Simulation predictions did not meet the maximum carbody vertical acceleration criterion at speeds of 55 mph and above for Class 4 track inputs. The maximum vertical acceleration was 0.66 g (limit = 0.6 g) at 60 mph. Criteria were met for other metrics using Class 4 inputs and all metrics for other inputs.

Simulation predictions for the “Curving with Various Lubrication Conditions” regime did not meet requirements. Simulation predictions for the Case 2 worn profile conditions showed the maximum 95th percentile wheel L/V ratios of 0.63 (limit = 0.6) and truck side L/V ratios of 0.53 (limit = 0.5). Case 2 friction is a coefficient of friction of 0.5 on both high rails and 0.2 on the gage face of the high rail.

Simulation predictions for worn component simulations with stiff primary pads showed maximum 95th percentile wheel L/V ratios of 0.62 (limit = 0.6) during constant curving simulations. Other metrics for this case, and all metrics for other worn component simulations, met criteria.

Table 9 shows a summary of test results and model predictions for the REV. Due to spring nest changes in the REV, pre-test simulations are not shown. Ride quality model and tests per International Organization for Standardization (ISO) Standard 2631[22] were also completed but are not covered in this table as there were no criteria to meet. The EEC approved the REV single car test results in a letter from Nichole Fimple to Jeff Cederberg dated June 21, 2022. The EEC cited that the hunting and yaw and sway results only slightly exceeded the limits and were not an issue for safety.

Simulation predictions were made using inputs created with measured track geometry. MxV Rail’s experience has shown that simulations with measured track geometry produce better predictions of car performance than those obtained with analytic track inputs created with mathematical functions. Because the measured track geometry inputs contain short wavelengths that cause spurious peaks in the data, the 50-millisecond and 3-foot analysis windows described in AAR Chapter 11 and Standard S-2043 are used when analyzing data to produce the most realistic results.

Table 9. REV summary results

Standard S-2043 Section	Met/Not Met	
	Revised Simulations	**Test Result**
5.2 Nonstructural Static Tests		
4.2.1/5.2.1 Truck Twist Equalization	Met	Met
4.2.2/5.2.2 Carbody Twist Equalization	Met	Met
4.2.3/5.2.3 Static Curve Stability	Met	Met
4.2.4/5.2.4 Horizontal Curve Negotiation	Met	Met

Standard S-2043 Section	Met/Not Met	
	Revised Simulations	Test Result
5.5 Dynamic Tests		
4.3.11.3/5.5.7 Hunting	Met	Not Met Standard deviation of lateral acceleration = 0.14g, limit = 0.13g
4.3.9.6/5.5.8 Twist and Roll	Met	Met
5.5.9 Yaw and Sway	Not Met Maximum peak-to-peak lateral acceleration = 0.65g, limit = 0.60g	Not Met Maximum lateral acceleration = 0.38g, limit = 0.35g Maximum peak-to-peak lateral acceleration = 0.73g, limit = 0.60g
5.5.10 Dynamic Curving	Met	Met
4.3.9.7/5.5.11 Pitch and Bounce (Chapter 11)	Met	Met
4.3.9.7/5.5.12 Pitch and Bounce (Special)	Met	Met
4.3.10.1/5.5.13 Single Bump Test	Met	Met
4.3.11.6/5.5.14 Curve Entry/Exit	Met	Met
4.3.10.25.5.15 Curving with Single Rail Perturbation	Met	Met
4.3.11.4/5.5.16 Standard Chapter 11 Constant Curving	Met	Met
4.3.11.7/5.5.17 Special Trackwork	Not Met Maximum truck side L/V ratio = 0.53, limit = 0.50	Met
4.3.11.5 Curving with Various Lubrication Conditions	Not Met 95th percentile single wheel L/V ratio = 0.63, limit = 0.6 Maximum truck side L/V ratio = 0.53, limit = 0.5	N/A
4.3.12 Ride Quality (Table 4.1 performance criteria)	Maximum carbody vertical acceleration (g) = 0.66, limit = 0.60	NA
4.3.13 Buff and Draft Curving	Met	N/A
4.3.14 Braking Effects on Steering	Met	N/A

5.4 Multiple Car Test Results

Multiple car testing and modeling were performed according to the certification requirements in Standard S-2043, paragraph 6. The test train consisted of a leading Buffer car, a 12-axle cask car, a trailing Buffer car, and a REV. Twenty-three sand cars were coupled behind the REV to provide additional braking because brakes on three of the four Atlas train railcars were cut out to allow for instrumented wheelset measurements. Except for the second revenue service 10-degree curve test and the demonstration test run, all tests were performed with AAR-1B narrow flange wheel profiles. After the first revenue service test in October 2022, the wheel tread profiles on the train were changed from AAR-1B narrow flange profiles to AAR-2A narrow flange profiles to improve curving performance as described in Section 4.2. In June 2023, a repeat of the revenue service 10-degree curve test using the AAR-2A narrow flange profiles showed improved performance. In September 2023, a demonstration test run using the AAR-2A narrow flange profiles was completed. Tests were performed in several locations including the Transportation Technology Center (TTC) in Pueblo, Colorado; the Pueblo Chemical Depot (PCD) in Pueblo, Colorado; BNSF railroad tracks between Avondale, Colorado, and Folsom, New Mexico; and Union Pacific (UP) railroad tracks between Avondale, Colorado, and Scoville, Idaho. Table 10 shows the test performed, the results of the tests, and data where criteria were not met.

Table 10. Multiple Car Test Summary Results

S-2043 Section	Critical Data (S-2043 Criteria and Loading Condition)	Met/Did not Meet
6.1 Dynamic Tests at the Controlled Test Site		
6.1.1.1 Stop Distance (Loaded)	The jerk rate did not match to within 0.5 mph/sec^2 from car to car during three of the 12 emergency and two of the 14 full-service application stop distance test runs.	Not Met
6.1.1.1 Stop Distance (Empty)	The Atlas railcar did not meet the wheel slip criterion (63.4%, limit = 15%) during a full-service braking run at 50 mph The jerk rate did not match to within 0.5 mph/sec^2 from car to car during two of the 16 emergency application stop distance test runs.	Not Met
6.1.1.2 Braking in Curves		Met
6.1.2 Hand Brake	No established criteria	NA
6.1.3 Buff and Draft Curving	Buffer railcar 20001 Maximum vertical acceleration = 0.94 g (limit = 0.9 g) Buffer railcar 20002 Maximum lateral acceleration = 1.77 g (limit = 0.75 g) Buffer railcar 20002 Maximum lateral peak to peak acceleration = 1.89 g (limit = 1.3 g)	Not Met
6.2 System Monitoring Tests		
6.2.1 System Functional Tests		Met
6.2.2 Failure Simulations		Met
6.3 Revenue Service Tests		
6.3.1 Turnouts, Crossovers		Met
6.3.1 Tight Curves: 12-degree curve at TTC		Met
6.3.1 Tight Curves: 10- and 12-degree curves at PCD		Met

S-2043 Section	Critical Data (S-2043 Criteria and Loading Condition)	Met/Did not Meet
6.3.1 Tight Curves: 10-degree curve at Alps, New Mexico	Atlas railcar maximum truck side L/V ratio = 0.53 (limit = 0.5)	Not Met
6.3.2 Class 2 Maintained Track (5 miles no better than FRA class 2)		Met
6.3.2 Class 2 Maintained Track (additional revenue service track)	Atlas railcar maximum truck side L/V ratio = 0.57 (limit = 0.5) Atlas railcar maximum wheel L/V ratio = 0.82 (limit = 0.8) REV maximum truck side L/V ratio = 0.55 (limit = 0.5)	Not Met
6.3.3 Ride Quality	No established criteria	NA
6.3.4 Demonstration run	No established criteria	NA

During stop distance testing with maximum test load, the car-to-car jerk rate variation did not match to within 0.5 mph/sec^2 from car to car during three of the 12 emergency stop distance runs and two of the 14 full-service application stop distance test runs. It is unclear how the exception to the jerk rate car-to-car match criteria will affect train operations or safety.

The Atlas railcar did not meet the wheel slip criterion (63.4 percent, limit = 15 percent) during a full-service stop distance braking run on wet rail at 50 mph with the minimum test load. The jerk rate did not match to within 0.5 mph/sec^2 from car to car during two of the 16 emergency application stop distance test runs. The exception to the wheel slip criterion occurred on only one run out of six emergency application test runs with the minimum test load.

During buff and draft curve testing, the Buffer railcars did not meet the maximum vertical (0.94 g, limit = 0.9 g), maximum lateral (1.77 g, limit = 0.75 g), and maximum lateral peak-to-peak (1.89 g, limit = 1.3 g) acceleration criterion for three runs. The exceptions were the result of extremely short duration acceleration events that were not representative of the gross motion of the railcars.

During the revenue service test with AAR-2A narrow flange wheels, the Atlas railcar did not meet the maximum truck side L/V ratio criterion (0.53, limit = 0.5) during the Alps 10-degree curve test. The exception occurred during a 10-mph northbound draft run with the B-end leading. After the completion of the test series, the test crew repeated the 10-mph run, and the maximum truck side L/V ratio met the criterion on the second run.

During revenue service testing with AAR-2A narrow flange wheels between Trinidad, Colorado, and the siding at Folsom, New Mexico, the Atlas railcar did not meet criteria in five curves, not including the 10-degree test curve. There was one single wheel L/V ratio exception (0.82, limit = 0.8) in a 6-degree curve. The remaining exceptions were truck side L/V ratio exceptions (worst = 0.57, limit = 0.5). Three 6-degree curves and one 4-degree curve had truck side L/V ratio exceptions. The number of individual truck side L/V ratio exceptions in each curve ranged from two to 45. These exceptions occurred in curves with ground rail profiles.

During revenue service testing with AAR-2A narrow flange wheels between Trinidad, Colorado, and the siding at Folsom, New Mexico, the REV did not meet truck side L/V ratio criterion in three 6-degree curves (worst=0.55, limit=0.5). The number of truck side L/V ratio exceptions in each curve ranged from one to eight.

Compared to the Chapter 11 maximum truck side L/V ratio criterion (0.6) (based on a free body diagram of an *unrestrained* rail[6]), the Standard S-2043 maximum truck side L/V ratio criterion (0.5) is very conservative for reasons that made a rail rollover very unlikely at these levels:

- In reality, a rail is restrained by adjacent trucks, assuming those trucks are applying lower lateral forces to the track than the subject truck.
- Rails are restrained by fasteners connecting the rails to the ties. For the Alps curve, these fasteners are elastic fasteners that apply significant restraint.

While the truck side L/V ratios measured on the Atlas and REV did not meet the Standard S-2043 criterion in some curves, they did meet AAR *MSRP*, Section C—Part II, Car Construction Fundamentals and Details, Design, Fabrication, and Construction of Freight Cars, Chapter 11, (Chapter 11) criterion in every case. The performance with AAR-2A narrow flange wheel profiles showed a dramatic improvement over the performance with AAR-1B narrow flange wheel profiles.

5.5 Post Test Modeling Results

Although the multiple car post-test modeling was suggested due to the results found during Multiple Car Testing, nothing within this section touches upon hypothetical effects of car-to-car interaction. Post-test modeling following multiple car tests is not necessarily required as part of the Standard S-2043 approval process. The train encountered rail profile conditions during the revenue service portion of multiple car tests that caused curving issues not observed during single car tests. The wheel profile was changed from AAR-1B narrow flange to AAR-2A narrow flange to address the problem. The AAR-1B wheel profile was the standard when the railcars were designed, and the AAR-2A replaced AAR-1B as the standard in 2020. The EEC Standard S-2043 task force requested that simulations of select single car test regimes be performed to evaluate how the wheel profile change affects other areas of performance where tests were already completed. A summary of the results of these simulations is presented in this section.

As described in Section 4.2, a revenue service test was performed in October 2022 with the Atlas train fitted with AAR-1B narrow flange profile wheels. During this test, MxV Rail measured the truck-side L/V ratios on the Atlas railcar and REV in many of the curves measuring 4-degrees or tighter that did not meet the Standard S-2043 criterion for the maximum truck side L/V ratio. To find a solution, several methods were investigated, but researchers ultimately determined that switching from wheels with AAR-1B narrow flange profiles to wheels with AAR-2A narrow flange profiles was the only viable solution.

The objective of the simulations described in this section is to compare the predicted individual (single car) performance of the Atlas car, the Buffer car, and the REV when configured with AAR-1B narrow flange (and KR) profile wheels with the performance predicted when those cars are configured with AAR-2A narrow flange profile wheels. The simulation regimes for each vehicle were selected as a result of a request from the EEC to perform follow-up modeling in areas where either the test or the modeling results of the car equipped with AAR-1B wheel profiles were borderline and could become problematic if switching over to AAR-2A profiles caused the performance to degrade.

The REV and Atlas railcar met the Standard S-2043 criteria for simulations of the Alps curve with the AAR-2A profiles but did not meet all criteria with the AAR-1B profiles. With the AAR-2A profile, the simulation predictions were slightly worse than predictions with the AAR-1B profile for the Atlas with minimum test load in No. 7 crossover (wheel L/V ratio = 0.51 compared to 0.49) and for the REV in the Class 4 ride quality simulations (standard deviation of lateral acceleration =0.14 g compared to 0.11 g). In all other regimes, simulations predictions with both profiles either both met criteria or were the same or better with the AAR-2A wheel profile.

The following tables summarize the modeling results for the empty Atlas railcar (Table 11), the Atlas railcar with minimum test load (Table 12), the Atlas railcar with maximum test load (Table 13), the Buffer railcar (Table 14), and the REV (Table 15).

Table 11. Simulation predictions - empty Atlas car

Standard S-2043 Section	Met/Not Met	
	Simulations Idealized AAR-1B Wheels (Idealized KR Hunting)	Simulations Idealized AAR-2A Wheels
5.5 Dynamic Tests		
4.3.11.3/5.5.7 Hunting	Met	Met
5.5.10 Dynamic Curving	Met	Met

Table 12. Simulation predictions, Atlas railcar with minimum test load

Standard S-2043 Section	Met/Not Met	
	Simulations Idealized AAR-1B Wheels (Idealized KR Hunting)	Simulations Idealized AAR-2A Wheels
5.5 Dynamic Tests		
Alps 10-degree Curve	Not Met CW Maximum truck side L/V ratio: = 0.74, limit = 0.50 CCW Maximum wheel L/V ratio: = 0.81, limit = 0.80 CCW Maximum truck side L/V ratio: = 0.75, limit = 0.50	Met
4.3.11.3/5.5.7 Hunting	Not Met Std dev carbody lateral acceleration (g): = 0.14, limit = 0.13	Met
5.5.10 Dynamic Curving	Met	Met

Standard S-2043 Section	Met/Not Met	
	Simulations Idealized AAR-1B Wheels (Idealized KR Hunting)	Simulations Idealized AAR-2A Wheels
4.3.11.7/5.5.17 Special Trackwork, No 7 Crossovers	Met	Not Met A-End Leading Maximum truck side L/V ratio: = 0.51, limit = 0.50 B-End Leading Maximum truck side L/V ratio: = 0.51, limit = 0.50

Table 13. Simulation predictions, Atlas railcar with maximum test load

Standard S-2043 Section	Met/Not Met	
	Simulations Idealized AAR-1B Wheels (Idealized KR Hunting)	Simulations Idealized AAR-2A Wheels
5.5 Dynamic Tests		
Alps 10-degree Curve	Not Met CW Maximum truck side L/V ratio: = 0.71, limit = 0.50 CCW Maximum truck side L/V ratio: = 0.73, limit = 0.50	Met
4.3.11.3/5.5.7 Hunting	Met	Met
5.5.10 Dynamic Curving	Met	Met
4.3.11.7/5.5.17 Special Trackwork, No 7 Crossovers	Met	Met

Table 14. Simulation predictions, Buffer car

Standard S-2043 Section	Met/Not Met	
	Simulations Idealized AAR-1B Wheels (Idealized KR Hunting)	Simulations Idealized AAR-2A Wheels
5.5 Dynamic Tests		
4.3.11.3/5.5.7 Hunting	Met	Met
5.5.10 Dynamic Curving	Met	Met

Table 15. Simulation predictions, REV

Standard S-2043 Section	Met/Not Met	
	Simulations Idealized AAR-1B Wheels (Idealized KR Hunting)	Simulations Idealized AAR-2A Wheels
5.5 Dynamic Tests		
4.3.11.3/5.5.7 Hunting	Met	Met

Standard S-2043 Section	Met/Not Met	
	Simulations Idealized AAR-1B Wheels (Idealized KR Hunting)	Simulations Idealized AAR-2A Wheels
5.5.9 Yaw and Sway	Not Met Peak-to-peak carbody lateral acceleration (g): = 0.83, limit = 0.60 Maximum carbody lateral acceleration (g): = 0.53, limit = 0.35	Not Met Peak-to-peak carbody lateral acceleration (g): = 0.71, limit = 0.60 Maximum carbody lateral acceleration (g): = 0.38, limit = 0.35
5.5.10 Dynamic Curving	Met	Met
4.3.10.25.5.15 Curving with Single Rail Perturbation	Met	Met
4.3.11.7/5.5.17 Special Trackwork, No 7 Crossovers	Not Met Maximum truck side L/V ratio: = 0.54, limit = 0.50	Not Met Maximum truck side L/V ratio: = 0.54, limit = 0.50
4.3.12 Ride Quality	Not Met Class 4 Track: Maximum carbody vertical acceleration (g): = 0.70, limit = 0.60	Not Met Class 4 Track: Std dev carbody lateral acceleration (g): = 0.14, limit = 0.13 Maximum carbody vertical acceleration (g): = 0.70, limit = 0.60

6.0 DEMONSTRATION RUN

The demonstration test run (DTR) was administered by MxV Rail directly with UP Railroad on a route between MxV Rail's test facility near Avondale, CO, and a junction that serves the DOE's Idaho National Laboratory (INL) near Scoville, ID. The test took place between September 5 and September 9, 2023. The DTR was completed successfully without performance issues on any of the four cars under test.

Two DOE personnel and two MxV Rail personnel, one of whom served as an official AAR observer, traveled aboard the REV for the duration of the DTR. Additionally, one MxV Rail employee followed the train by highway to create photo documentation of the test. The test team's credentials are summarized in Table 16.

Table 16. Test team for DTR

DTR Participant	Affiliation	Title/DTR Role
Patrick Schwab	DOE	Atlas Project Manager/REV Passenger
Michael Schultze	ORNL	R&D Staff, Transportation Security Specialist/REV Passenger
Matthew Wenger	MxV Rail	Senior Engineer III/REV Passenger/AAR Observer
Justin Penrod	MxV Rail	Lead Test Controller/REV Passenger
Brandon Morris	MxV Rail	Senior Engineer III/UAV Photographer

Figure 12 and Figure 13 depict the test train's outbound and return routes, respectively, totaling 1,471 miles roundtrip. The location markers in the route maps were recorded during train starts and periodically while moving by the REV car's TRANSCOM tracking system. Therefore, marker spacing may be interpreted as being indicative of the trains average speed (i.e., close marker spacing is indicative of numerous stops and/or low train speed). Additionally, the location markers are color coded so each day of the DTR has a unique marker color.

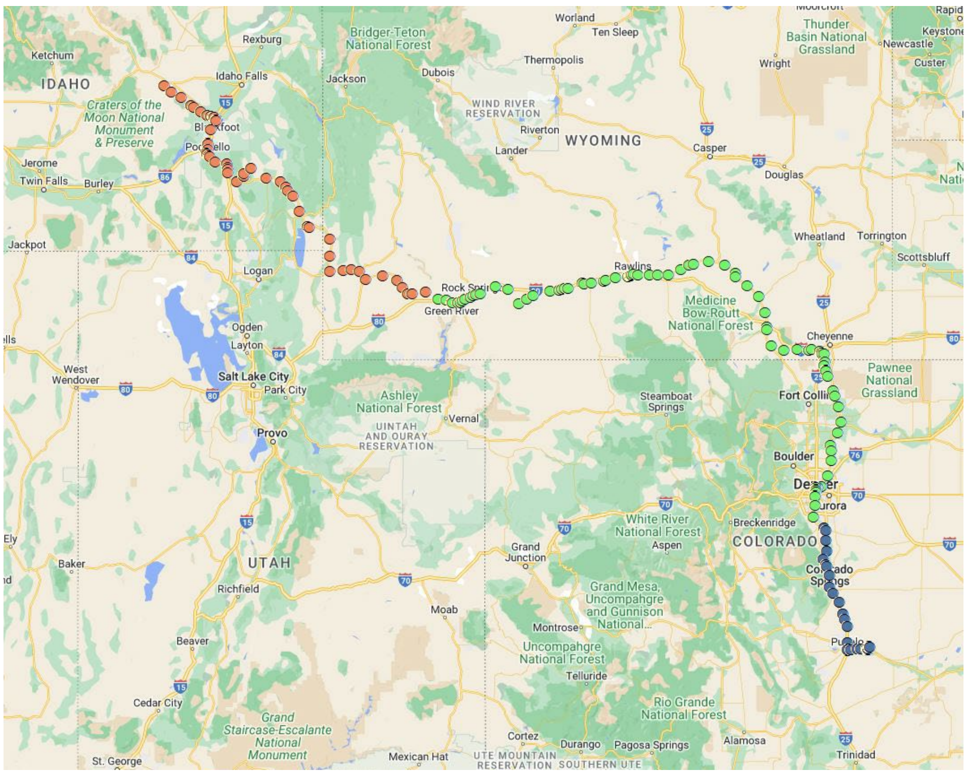

Figure 12. Outbound route of DTR as recorded by TRANSCOM system

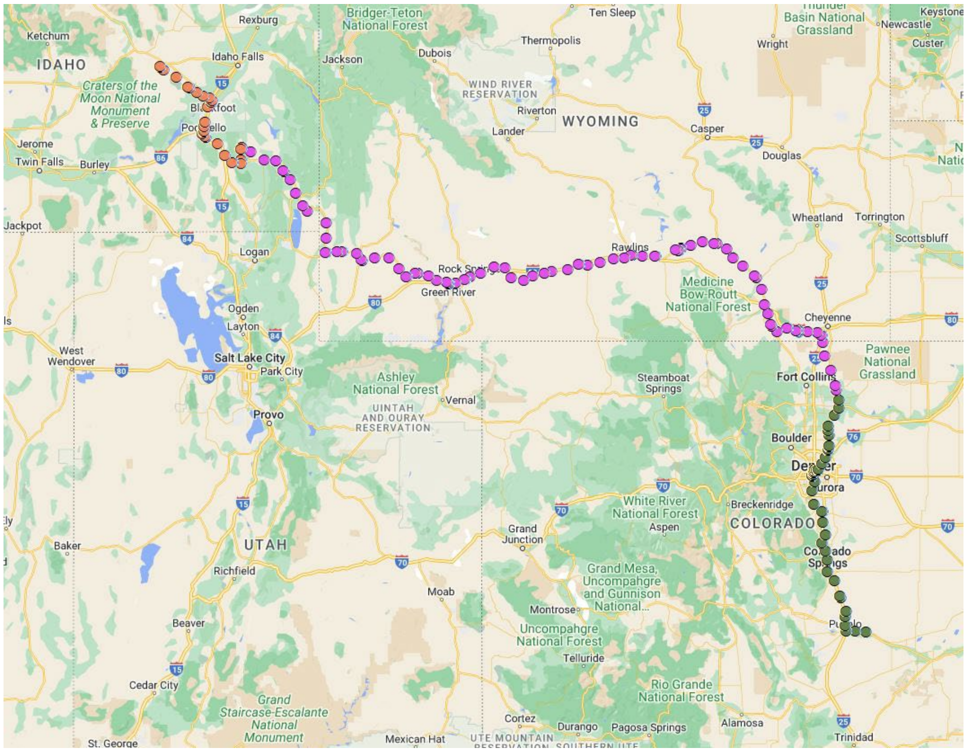

Figure 13. Return route of DTR as recorded by TRANSCOM system

The test consist was made up of two UP locomotives coupled back-to-back, followed by the HLRM train with the maximum test load (no actual HLRM onboard), with the B-end of each car leading as shown in Figure 14.

Figure 14. Train configuration for DTR (maximum test load condition)

7.0 AS-BUILT DRAWINGS AND OPERATIONS AND MAINTENANCE GUIDELINES

Except for the span bolster to truck centerplate connection design change and the wheel tread profile change, the drawings of the Atlas railcar may be found in Atlas Railcar Phase 3 Final Report Appendix A – Atlas Railcar As-Built Fabrication Drawings.[23] A description of the span bolster to truck centerplate connection design change can be found in Kasgro's M-975 Trispan Static Analysis submitted to EEC in June 2023.

Except for the change to the wheel tread profile, the detailed specifications for the Buffer railcar may be found in the Atlas Railcar Phase 3 Final Report Appendix E – Buffer Railcar As-Built Fabrication Drawings.[24]

Except for the change to the wheel tread profile, the detailed specifications for the REV may be found in Vigor Design Report 2760-DR-001.[25]

An overview of the wheel tread profile change is discussed in Section 4.2 of this report. Specifications for the AAR-2A narrow flange wheel tread profile can be found in AAR MSRP, Section G, Specification M-107/M-208, "Wheels, Carbon Steel," revised 2020, Fig. B.12.[26]

The operations and maintenance guidelines for the Atlas railcar may be found in Atlas Railcar Phase 3 Final Report Appendix D - Final Atlas Railcar Operations and Maintenance Information Manual.[27] The operations and maintenance guidelines for the Buffer railcar may be found in Atlas Railcar Phase 3 Final Report Appendix H - Final Buffer Railcar Operations and Maintenance Information Manual.[28] Operations and maintenance guidelines for the REV may be found in the REV Operations and Maintenance Manual.[19]

8.0 CONCLUSIONS

The S-2043 certification process includes a design phase, single car testing, multiple car testing, and post-test analysis. The Standard S-2043 design process includes:

- Structural analysis
- Nonstructural static analysis
- Dynamic analysis
- Brake system design
- System Safety Monitoring
- Railcar clearance and weight

Kasgro Rail Corporation completed the design of the Atlas and Buffer railcars. The AAR/EEC provided design approval for the Atlas railcar and Buffer railcar in separate letters from Nichole Fimple to Rick Ford, both dated February 2, 2018.

Vigor completed the design of the REV. The AAR/EEC provided design approval for the initial REV design in a letter from Nichole Fimple to Brandon Johnson dated July 21, 2016. Due to issues identified during initial construction, a minor redesign was completed by Vigor and approved by AAR/EEC in a letter from Nichole Fimple to Nichole George dated October 12, 2016.

All three vehicle types that make up the Atlas train met single car test requirements for the following Standard S-2043 paragraphs:

- 5.5.8 Twist and Roll
- 5.5.10 Dynamic Curving
- 5.5.11 Pitch and Bounce (Chapter 11)

- 5.5.12 Pitch and Bounce (Special)
- 5.5.13 Single Bump Test
- 5.5.14 Curve Entry/Exit
- 5.5.17 Special Trackwork

The Atlas railcar and the REV did not meet single car test requirements for Standard S-2043, paragraph 5.5.7 "Hunting" at speeds above 65 mph. After extensive modeling and testing with a stiffer primary pad design, MxV Rail found that hunting performance improvements came at the detriment of curving performance. The design was left as it was originally, with a softer primary pad design, thereby preserving better curving performance in lieu of improved hunting performance because, per AAR Operating Transportation (OT) circular OT-55,[20] the car would be limited to less than 50 mph when in high-level radioactive material (HLRM) service, 15 mph below the speed where these vehicles become unstable.

Many of the initial Atlas railcar tests were performed with a stiffer primary pad than the type ultimately selected for use on the car. Some of these tests were not repeated with the final pad design. The Atlas railcar did not meet Standard S-2043, paragraph 5.5.15 "Curving with Single Rail Perturbation" requirements or 5.5.16 "Standard Chapter 11 Constant Curving" requirements with the stiffer pad. Based on the modeling results, improved results would be expected for these regimes with the softer suspension pad ultimately selected.

The REV did not meet the requirements of Standard S-2043, paragraph 5.5.9 "Yaw and Sway" for maximum lateral acceleration or maximum peak to peak lateral acceleration for passenger carrying railcars. The REV did meet the less restrictive criteria for non-passenger-carrying railcars for these metrics.

The EEC approved the Atlas single car test results in a letter from Nichole Fimple to Patrick Schwab dated April 29, 2022. The EEC approved the Buffer car single car test results in a letter from Nichole Fimple to Patrick Schwab dated April 29, 2022. The EEC approved the REV single car test results in a letter from Nichole Fimple to Jeff Cederberg dated June 21, 2022.

The train met multiple car test requirements for the following Standard S-2043 paragraphs:

- 6.1.1.2 Braking in Curves
- 6.1.2 Hand Brake Test
- 6.2 System Monitoring Tests
- 6.3.1.1 Turnouts, Crossovers
- 6.3.1.2 Tight Curves: 12-degree curve at the TTC
- 6.3.1.2 Tight Curves: 10- and 12-degree curves at PCD
- 6.3.2 Class 2 Maintained Track (5 miles no better than FRA class 2)
- 6.3.3 Ride Quality
- 6.3.4 Demonstration Run

The train did not meet multiple car test requirements for the following Standard S-2043 paragraphs:

- 6.1.1.1 Stop Distance Tests
- 6.1.3 Buff and Draft Curving
- 6.3.1.2 Tight Curves: 10-degree curve at Alps, New Mexico
- 6.3.2 Class 2 Maintained: Track (additional revenue service track)

The exceptions to the requirements of Standard S-2043, paragraph 6.1.1.1 “Stop Distance Tests” included an exception to the maximum 15 percent wheel slip on one run. Exceptions to the stop distance requirements also included several exceptions to the maximum jerk rate criterion and the maximum car-to-car variation in jerk rate criterion. The exception to the wheel slip criterion occurred on only one run out of six emergency application test runs with the minimum test load. The exceptions to the car-to-car jerk rate variation criterion appears to have a minimal effect on train operations or safety.

The exceptions to the requirements of Standard S-2043, paragraph 6.1.3 “Buff and Draft Curving” were short duration carbody acceleration events measured on the Buffer cars. These events were not indicative of gross carbody motions and were thought to be due to stick-slip motions of draft gear components.

The exception to the requirements of Standard S-2043, paragraph 6.3.1.2 “Tight Curves: 10-degree curve” at Alps, New Mexico, was a maximum truck side L/V ratio of 0.53 on the Atlas railcar during one of the 32 planned test runs on the Alps curve. At the end of the test series for that day, the test run was repeated without an exception.

The exceptions to the requirements of Standard S-2043, paragraph 6.3.2 “Class 2 Maintained Track” (additional revenue service track) included exceptions in five curves. There was one single wheel L/V ratio exception (0.82, limit = 0.8) in a 6-degree curve. The remaining exceptions were truck side L/V ratio exceptions (worst = 0.57, limit = 0.5). Three 6-degree curves and one 4-degree curve had truck side L/V ratio exceptions. The number of individual truck side L/V ratio exceptions in each curve ranged from two to 45. These exceptions occurred in curves with ground rail profiles. These results were obtained while testing with AAR-2A narrow flange profiles, and they represent significantly fewer exceptions than those measured when using AAR-1B narrow flange wheel profiles in the initial test.

Simulations of the test cars with both AAR-1B narrow flange and AAR-2A narrow flange wheel tread profiles were performed to assess the effect on the test car performance in regimes not tested. The REV and Atlas railcar met Standard S-2043 criteria for simulations of the Alps curve with the AAR-2A profiles but did not meet all criteria with the AAR-1B profiles. With the AAR-2A profile, the simulation predictions were slightly worse than predictions with the AAR-1B profile for the Atlas with minimum test load in No. 7 crossover (wheel L/V ratio = 0.51 compared to 0.49) and for the REV in the Class 4 ride quality simulations (standard deviation of lateral acceleration =0.14 g compared to 0.11 g). In all other regimes, the simulation predictions with both profiles either both met criteria or were the same or better with the AAR-2A wheel profile. The DOE requested exceptions for the multiple car test conditions not met in report P-

23-030 “Certification Testing of United States Department of Energy Atlas Train Multiple Car Test Report.”

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