NATIONAL TRANSPORTATION SAFETY BOARD

Office of Railroad, Pipeline and Hazardous Materials Investigations
Washington, DC

IIC FACTUAL REPORT FOR TECHNICAL REVIEW

DCA14MR004

Collision and Derailment with Hazardous Materials Release at Casselton, North Dakota

December 30, 2013

Factual Report Prepared by:
R. A. Hipskind,
Investigator-in-Charge

Date: May 17, 2015

Accident

NTSB Accident:	DCA14MR014
Date of Accident:	December 30, 2013
Time of Accident:	2:11 p.m. (CST)
Type of Train:	U FYNHAY4-05 (Petroleum Train) & G RYLRGT9-26 (Grain Train)
Railroad Owner:	BNSF Railroad (BNSF)
Railroad Operator:	BNSF
Crew Members:	Petroleum train—engineer & conductor Grain train—engineer, student engineer & conductor
Location of Accident:	Casselton, ND

Synopsis

On Monday, December 30, 2013, at 2:11 p.m. CST, westbound BNSF Railway grain train G-RYLRGT9-26A, consisting of two head end locomotives, one rear distributive locomotive power unit (DPU) [1]and 112 cars derailed 13 loaded cars (the 43rd through 55th) at milepost (MP) 28.5 of the KO Subdivision, Twin Cities Division in Casselton, North Dakota while traveling on main track 1 . The derailment occurred in the middle of the train resulting in one of the grain cars, the 45th car, obstructing main track 2. Eastbound BNSF petroleum crude oil train U-FYNHAY4-05T consisting of two head end locomotives, one rear DPU and 106 cars, collided with BNSF grain car 486653 and derailed both locomotives and cars 1 through 20 to the south on main track 2. After the collision more than 400,000 gallons of petroleum crude oil was released fueling a fire.

Local emergency officials ordered a voluntary evacuation of the town of Casselton. Approximately 1,400 civilians from the town of Casselton were reported to have evacuated. No civilian injuries were reported. The train crew from U-FYNHAY4-05T, consisting of an engineer and a conductor, escaped from the rear door of the lead locomotive with no physical injuries.[2] The crew from train G-RYLRGT9-26A was not injured.

BNSF damages totaled $13.5 million; this did include lading and environmental remediation. The weather at the time of the accident was cloudy and -1° Fahrenheit, winds north at 7 mph.

The parties to the investigation include the Federal Railroad Administration (FRA), US Department of Transportation Pipeline and Hazardous Materials Safety Administration (PHMSA), BNSF Railway, Brotherhood of Locomotive Engineers and Trainmen (BLET), International Association of Sheet Metal, Air, Rail and Transportation Workers (SMART)[3], TrinityRail and Standard Steel.

1 DPU refers to distributive locomotive power, generally, located as the rear end of a train.

2 Subsequent to the on-scene reporting, both employees lost time and presented BNSF with a medical diagnosis of PTSD due to accident.

3 Formally the United Transportation Union (UTU)

Circumstances Prior to the Accident

On December 30, 2013, at 2:11 p.m. CST, westbound BNSF grain train[4], consisting of two head end locomotives, one rear DPU and 112 cars was operating on main track 1 near Casselton, ND. A signal maintainer was in a vehicle on an access road near the west switch of the crossover located at milepost 28.5 (within the limits of Control Point (CP) Casselton). He had noticed that some of the switch heater covers were damaged and radioed on channel AAR 70 to the grain train and asked if they were aware that their train might be dragging equipment.[5] At the same time, the grain train experienced an undesired emergency brake application (UDE). Immediately a crewmember radioed an emergency announcement on channel AAR 70. Simultaneously, U-FYNHAY4-05T, the eastbound petroleum train[6] was operating on main track 2, but had not passed the head portion of the grain train. The crew of the petroleum train was on another radio channel (AAR channel 39, Jamestown Subdivision) in the process of releasing their track warrant authority from the subdivision that they had recently exited.

Figure 1. This is a global view of derailment area.

4 The westbound grain train with identification symbol G-RYLRGT9-26A, hereafter in this report will simply be referred to as the grain train or G/T.
5 Throughout the report, the radio channels are identified as American Association of Railroads (AAR) assigned channels.
6 The eastbound petroleum train with identification symbol U-FYNHAY4-05T, hereafter in this report will simply be referred to as the petroleum train or P/T.

Accident

While the grain train was traversing CP Casselton, it went into emergency. As the grain train was stopping the crew began to apply the safety procedures required as a result of an emergency brake application. The road foreman of engines attempted to tell the petroleum train of the UDE. The conductor radioed an “emergency” announcement. It was later determined that the grain train had derailed 13 loaded cars (the 44th through 56th) at MP 28.5 with at least one of the cars fouling main track 2. As the eastbound BNSF petroleum oil train proceeded on main track 2, the petroleum train crew observed the car fouling their route, and the engineer made an emergency brake application to take protective measures for their safety. The lead locomotive struck the grain car and the both locomotives and the head 21 cars derailed primarily to the south of main track 2.

Figure 2. This is a photo looking south at the tank cars releasing crude oil and subsequent energetic thermal release. (Photo courtesy of Dawn Faught).

After the collision both crewmembers of the petroleum train exited the locomotive and left the immediate area and walked eastward to the nearest grade crossing, where they met emergency responders. As they placed themselves in a safer position from the train, an undetermined amount of petroleum crude oil was released fueling a pool fire which caused other cars to an energetic thermal release..

Emergency Response

At 2:11 p.m. the local fire department received the first telephone call via the 911 operator advising them that a train derailment occurred west of Casselton, ND. A second telephone call came into the Red River Regional Dispatch Center at 2:12:04 p.m. reporting a train derailment and fire. Shortly thereafter, a Cass County Unified Command Post was established which included the Cass County Sheriff's Department and the Casselton Fire Department. Multiple resources quickly integrated into the Cass County Unified Command Post to include the North Dakota Highway Patrol, Fargo Cass Public Health, and the Fargo Fire Department's Hazardous Material Response Team. At 4:14 p.m., the Cass County Sherriff ordered a ¾ mile isolation perimeter around the accident site. At 4:18 p.m., the Tactical Operations Center (TOC) was established including a telephone number for the public to contact. At 4:33 p.m., the Casselton Fire Department and Cass County Sherriff's Department initially ordered an evacuation for the immediate area. The Unified Command estimated that approximately 1,400 people were evacuated. Responders made the decision to let the tank cars burn, without implementing firefighting measures.

At 4:43 p.m., the command post was moved to the Central Cass School (Casselton High School). At that time, the Sherriff's Department, Fire Department and Red Cross personnel were reported to be canvasing the area to notify residents of the evacuation and provide assistance as needed. At 5:25 p.m., the Command Center Public Information Officer (PIO) issued a public announcement for displaced people to go to the Casselton High School to be transported to Discovery Middle School in Fargo for reunification. Weather information was obtained and distributed hourly. At 5:32 p.m., TOC verified that a voluntary evacuation was expanded to include the city.

The westbound train crew walked to a nearby road crossing where they were met by the Assistant Fire Chief of the Casselton Fire Department who asked them to assist the emergency responders by pulling the non-derailed west portion of tank cars away from the burning derailed cars. The road foreman of engines crew made contact with a BNSF trainmaster and communicated the request. The trainmaster told the crew if the move could be completed safely, then they could proceed. The road foreman of engines consulted with the crew to see if they felt it was safe to move the cars, which they did. The engineer and student engineer went to the DPU on the eastbound train and the conductor and road foreman of engines went to the east to the nearest grade crossing and made a cut of an estimated 50 tank cars, and the engineer and student engineer pulled the cars about a quarter mile west, away from the burning cars.

Figure 3. Photograph of the petroleum train's DPU, locomotive BNSF 6684.

About 30-45 minutes after the crew completed moving the first set of cars, the Assistant Fire Chief of the Casselton Fire Department met the grain train crew at the rear locomotive (the DPU) of the petroleum train and asked if additional tank cars nearer to the derailment area could be moved.

The student engineer left the locomotive with the Assistant Fire Chief heading east to couple the train together and make an additional cut of tank cars. The student engineer borrowed the Assistant Chief's fire protective clothing and walked within 10 cars of the fire and uncoupled the cars to the east. The engineer then pulled approximately 20 additional tank cars a quarter mile west away from the fire.

At 7:11 p.m., a voluntary evacuation order was issued for all of Casselton due to wind shifting to the West and a high pressure system that forced the smoke and combustion products to the ground. Near the end of the evacuation, incident command estimated that about 1,560 Casselton residents voluntarily evacuated. The on scene commander lifted the recommended voluntary evacuation at 3:00 p.m. on December 31, 2013, and the residents returned to their homes.

Emergency Response Activities

During the incident, several of the derailed tank cars experienced thermal tears that resulted in energetic thermal releases. The HAZMAT (hazardous materials) support to the incident was provided by BNSF and Casselton and Fargo Fire Departments.

Several Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) atmospheric air models were developed. The HYSPLIT model is a complete system for computing simple air parcel trajectories to complex dispersion and deposition simulations. Some new features include improved advection algorithms, updated stability and dispersion equations, continued improvements to the graphical user interface, and the option to include modules for chemical transformations. Without the additional dispersion modules, HYSPLIT computes the advection of a single pollutant particle, or simply its trajectory.

On December 31st at 9:00 a.m., the Cass County Sherriff issued a public announcement detailing the number of people and animals that had been provided shelter by the Red Cross at the Discovery Middle School. In addition; he reported that approximately 65% of Casselton had been evacuated; air quality was constantly being monitored. While conditions were improving, air quality concerns continued. It was further reported that the NTSB was on scene and had officially taken over investigation of the accident. The TOC coordinated response personnel and provided current information to the public. At 5:00 p.m., the TOC was formally shut down.

BNSF hired two contractors to move rail cars, three to assist with the incident in terms of hazardous materials and fire-fighting, three for environmental remediation and one for toxicology and air monitoring.

According to the Center for Toxicology and Environmental Health (CTEH), volatile organic compound (VOC) air monitoring conducted at the derailment scene indicated low concentrations of VOCs, likely a result of the effect of the very cold temperatures which reduced volatilization. Only low concentrations of VOCs were detected at the derailment area and occurred only in the immediate location of the spilled oil. The maximum detected concentration of carbon monoxide (CO) in the work area of the Casselton derailment was 2 parts per million (ppm). This concentration is 25 times lower than the Occupational Safety and Health Administration (OSHA) Permissible Exposure Limit (PEL) for an eight-hour exposure period. CTEH sampling results report was provided to the NTSB.

The CTEH developed an air monitoring plan for the incident. The air monitoring plan details the sampled analytes and the detection and action levels. The general description of the CTEH assessment techniques are provided in Table 1.

Table 1: Summary of general assessment techniques used by CTEH.

PROCEDURE	DESCRIPTION
Hand-held Survey	CTEH staff members will utilize handheld instruments (e.g. MultiRAE Plus; UltraRAE, Gastec colorimetric detector tubes, etc.) to measure airborne chemical concentrations outdoors around the incident location as well as inside of the affected residence. CTEH will use these hand-held instruments primarily to measure the breathing zone and locate sources. Additionally, measurements can be made at grade level, as well as in elevated workspaces, as indicated by chemical properties or site conditions
Analytical sampling	Analytical sampling can be used to validate the hand-held data monitoring data, or to provide data beyond the scope of the real-time instruments. Analytical samples will be collected as whole air samples in evacuated canisters or on specific collection media, and sent to an off-site laboratory for further chemical analysis.

The CTEH conducted monitoring in work areas and community/residences.

Table 2. CTEH work areas monitored.

SAMPLING AREA	DESCRIPTION
Work Area	The general area around the incident location where workers are actively or sporadically participating in remediation activities.
Community/Residence	The immediate area in and around the mobile home where individuals not participating in remediation activities could potentially be exposed to the spilled chemicals (i.e. homeowners).
Other	During the course of the remediation, some additional areas may be established which require a unique set of action levels or sampling (e.g. decontamination zones, etc.)

Operations

Train G-RYLRGT9-26A (Grain Train)

The crew of the grain train (outbound crew) involved in the accident consisted of three employees, an engineer, a conductor, a student engineer. A road foreman of engines, who not part of the crew but was performing a qualifying check ride with the student engineer, was also present in the lead locomotive of the grain train. The grain train crew reported for duty at 12:15 p.m. at Dilworth Yard, Dilworth, MN. After collecting the required paperwork, the crew was transported to the train in Fargo, ND for a crew change. Just prior to reaching the lead locomotives, the engineer and student engineer stopped at the DPU at the rear of the grain train to perform a daily inspection of the unit and check fuel levels prior to departure. The crew then continued to the head end of the train where they briefed with the inbound crew (relieved crew) and assumed control of the train. The inbound train crew notified the outbound crew that the lead two locomotives were already inspected and the train had experienced no problems up to that point. The outbound crew contacted the dispatcher for permission to depart and proceeded westward at 1:15 p.m. toward their final destination of Mandan, ND.

The grain train consisted of two head end locomotives, 112 loaded grain covered hopper cars and one rear DPU. The train weighed 14,776 tons and was about 6,840 ft. long. Investigators assessed individual car weights through examination of the train list records. The individual grain cars (as loaded) ranged in weight between 131 and 132 tons.

Train U-FYNHAY4-05T (Crude oil train)

The crew of the petroleum train was called for an on-duty time of 6:10 a.m., in Mandan, ND. The crew arrived at Mandan Yard at 6:10 a.m., and received instructions that they were to take the oil train from Mandan, ND to Dilworth, MN. They reviewed their paperwork, job briefed, safety briefed, verified the air slip and that the air test (Class I brake test) had been completed by the mechanical department, verified the locomotive daily inspection cards were completed and departed at 7:05 a.m. The petroleum train originated and was loaded at the terminal at Fryburg, ND, with a final destination of Hayti, MO.

The petroleum train consisted of two head-end locomotives, 104 loaded tanker cars, two buffer cars filled with sand (located at car positions one and 106) and one rear DPU. The train weighed 13,335 tons and was about 6,536 ft. long. Investigators assessed individual car weights through examination of the train list records. The loaded tanker cars hauling oil cars ranged in weight between 125 and 127 tons. The buffer cars (two cars) weight was listed at 122 tons.

Method of Operations

On the KO Subdivision territory, train movement is governed and authorized by signal indications, a Centralized Traffic Controlled (CTC) system, with the train dispatcher stationed at BNSF's Network Operations Center (NOC), in Fort Worth, Texas.

On the Jamestown Subdivision, the subdivision the petroleum train was travelling on prior to arriving onto the KO Subdivision and CP Casselton; trains are governed by track warrant control/automatic block system (TWC) (ABS). On the Jamestown Subdivision, track authority was granted by the dispatcher at the NOC by mandatory directive, which means authorities are dictated by the dispatcher and copied by the train crew on standard forms. BNSF operating rules state that when a train exits a TWC territory that the crew must release their authority by communicating their location to the dispatcher. In this accident, the petroleum train crew made that communication via the radio channel assigned to the dispatcher for the Jamestown Subdivision. During interviews with investigators, the petroleum train crew said they were coming off the Jamestown subdivision at MP 31.11, controlled by track warrant onto the K.O. Subdivision, which is Centralized Traffic Control territory. According to signal data, at 2:09:50 pm the petroleum train shunted the track east of the controlled signal displaying a flashing yellow over red aspect at CP 30, MP 30.02 on main track 2.

At the accident site, there were two main tracks, each signaled for train movement in both directions and part of a centralized traffic control (CTC) system. The tracks were primarily parallel and oriented in an east and west direction. The north track was designated main track 1 and the south track was designated as main track 2[7].

When a train is passing a signal displaying other than clear in advance of a control point, BNSF operating rules require crews operating in signaled territory to transmit the following by radio[8]:

- Train Identification (Initials Engine Number and Direction);
- Signal Name in advance of control point;
- Location on (Track);
- (Speed) MPH.

When the grain train went into emergency, the crew made an emergency announcement over the radio channel (AAR70) designated for the KO Subdivision. BNSF operating rules that are applicable when a train goes into emergency or, has an undesirable emergency (UDE) brake are described in General Code of Operating Rules (GCOR), Sixth Edition and BNSF Railway Air Brake and train Handling Rules, No. 5. The requirements are specific to the actions required by train crew members such that:

- When an UDE brake application occurs, move the automatic brake valve handle to EMERGENCY and wait until the train stops;
- After stopping, if operating conditions permit, place the automatic brake valve handle in RELEASE to release the brakes and help locate the air hose separation or other problem.

All emergency brake applications that occur while moving, whether undesired or intentionally induced by a crew member, are considered an en route delay and must be reported to the train dispatcher. In addition, all undesired emergency brake applications that occur during normal service braking (commonly referred to as “kickers” or “dynamiters”) are to be reported to the mechanical desk as an air brake defect[9]. However, in this accident, while the grain train was making its emergency announcement on its assigned radio channel, the petroleum train was in the process of releasing its track warrant on a different radio channel (AAR39) assigned to the subdivision it had previously left. Investigators questioned the petroleum train crew regarding the

7 This configuration is often referred to as multiple main.

8 BNSF General Notice #67

9 When a crew reports a UDE brake application, depending upon the details, the dispatcher may refer those details to the mechanical desk for their review.

announcement from the grain train; the petroleum train crew was not able to recall hearing the emergency announcement.

Damage Estimates

The BNSF estimated accident costs are as follows:

- Freight cars/locomotives: $4,453,202 (Both locomotives of the P/T destroyed)
- Clean-up: 1,547,953
- Environmental: 2,650,000
- Track: 1,520,301
- Lading/Other: 3,329,238
- Total damages: $13,500,695

Mechanical

Railroad Equipment Involved in the Derailment:

Petroleum Train

The railroad equipment involved in the collision and derailment of the petroleum train consisted of two leading locomotives and cars 1 through 21 behind the leading units. The two locomotives involved in the derailment were BNSF 4934 (lead unit), BNSF 5958 second unit.

Locomotive BNSF 4934 was a model C44-9W, 4400 HP. Locomotive BNSF 5958 was a model ES-44AC, 4400 HP. Both locomotives were equipped with a network-based, electronic air brake system (CCB2). Both locomotives were equipped with fuel tanks having a capacity of about 5300 gallons of diesel fuel. Fully loaded, the locomotives weighed 420,000 lbs.

The first car in the petroleum train was BNSF 808314 a covered hopper, a buffer car filled with sand. This was an AAR type C113, YHF plate C with 36 inch wheels. The gross vehicle weight (GVW) for this type of covered hopper car is listed on BNSF specification documentation at 143 tons. Train cars 2 through 19 (the position in the train or line number on the train consist) were all AAR type T108, T5I plate C with 36 inch wheels (specific car numbers can be seen in the Hazardous Materials section of this report). These cars are Department of Transportation (DOT) Specification 111-A100W1 (DOT-111) tank cars that measure approximately 59 ft. 5 in. (length), by 10 ft. 8 in. The gross vehicle weight (GVW) for this type of DOT-111 tank car is 131.5 tons. [See Hazardous Materials section for car position and numbers]

Grain Train

The equipment involved in the derailment from the grain train consisted of lines 44 through 56 for a total of 13 cars.[10] Lines 44-47 and 48 are BNSF 486480, 486653, 487137, 481970, 480263, AAR type C114, CXG plate C, with 36 inch wheels. These are covered hopper cars that measure approximately 58 ft. (length), by 10 ft. 8 in. The GVW for this type of covered hopper car is listed on BNSF specification documentation at 143 tons.

Line 49 is the AOK 65732, AAR type C114, CXG plate C, with 36 inch wheels. The covered hopper car measures approximately 58 ft. (length), by 10 ft. 8 in. Lines 50 through 56 are the BNSF 478072, 485951, 486769, 485510, 487701,486563, 475068, AAR type C114, CXG plate C, with 36 inch wheels. These are covered hopper cars that measure approximately 58 ft. (length), by 10 ft. 8 in.

Wreckage Description

Petroleum Train:

The two lead locomotives from the eastbound petroleum train derailed upright to the south of main track 2. The lead unit traveled about 200 feet south of main track 2. The lead locomotive became uncoupled from the second locomotive and the distance between the separated units was about 150 feet. The next 20 cars from this train derailed in a general pile-up. The cars were overturned, smashed and left lying in a zigzag pattern. (See Figure 4) The trailing trucks from the 21st car derailed, the car remained upright and undamaged. The first car that derailed was a buffer car hauling sand. The next 20 cars were tank cars hauling petroleum crude oil. Eighteen of those cars were tank cars that breached as a result of the collision releasing full loads of product resulting in a large fire.

10 Cars are referenced by line number from the listing of the cars in their position in the train as documented on the train consist provided to the crew.

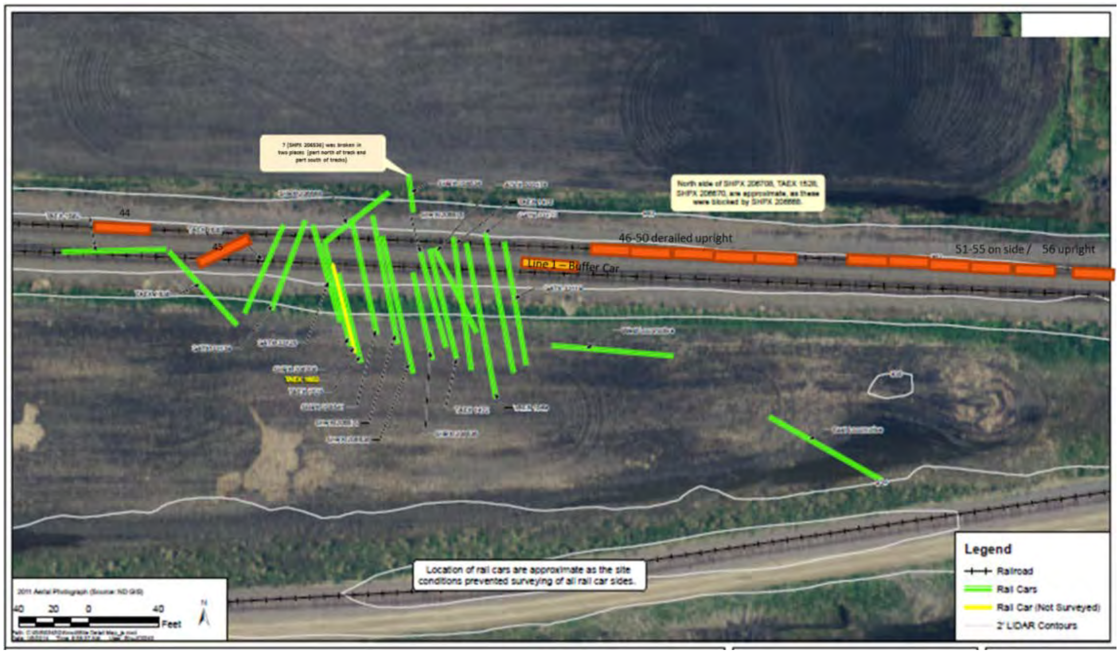


Figure 4. Accident diagram—general car placement.

Grain Train:

The 44th through 56th cars from the grain train derailed. The trailing trucks from the 44th car derailed upright and undamaged. The 45th car was lying over on its side to the south of main track 2. The car was partially blocking the north rail of main track 1.

The 46th through the 51st cars derailed upright to the south of main track 2. The cars remained coupled together nearly straight in a relative linear alignment along the tracks. The 52nd car became uncoupled from the 51st and cars 52 through 56 derailed upright in line.

Equipment Pre-Accident Inspection:

Petroleum Train:

The petroleum train began in Fryburg, ND, where it was given a Class I Air Brake test and car inspection by qualified personnel on December 29, 2013. No defects were noted. The train departed Fryburg at 12:20 p.m. on December 29. 2013.

The petroleum train arrived at Mandan, ND on December 30, 2013, at 4:54 a.m. where a Class I Air Brake test and car inspection was performed by qualified mechanical employees. Mandan mechanical records show the mechanical employees started their inspection on December 30, at 5:13 a.m. and finished at 5:41 a.m. No defects were noted. The train departed Mandan at 7:05 a.m. on December 30, 2013.

Locomotive BNSF 4934, the lead locomotive had its last daily inspection performed on December 30, 2013, at Mandan, ND at 6:54 a.m. by a qualified mechanical employee. No defects noted. A review of inspection records showed all scheduled maintenance activities were up to date.

Locomotive BNSF 5958, the second locomotive had its last daily inspection performed on December 30, 2013, at Mandan, ND at 6:50 a.m. by a qualified mechanical employee. No defects were noted. A review of inspection records showed all scheduled maintenance activities were up to date.

Train G-RYLRGT9-26A (Grain Train):

The grain train originated at Royal, NE. The train consisted of 112 cars. The crew performed a Class I Air Brake test and inspection. No defects were noted.

Equipment Post Accident Inspections:

On January 2, 2014, investigators completed an inspection of the remaining 85 tank cars of petroleum train in Nolan, ND. Investigators performed a Class I Air Brake test and mechanical inspection. No defects were noted. All air brake equipment worked as intended. All equipment was inspected to current FRA standards and no exceptions were taken.

On January 2, 2014, investigators completed an inspection of the remaining 96 grain cars from the grain train in Dilworth, MN. Investigators performed a Class I Air Brake test and mechanical inspection. The inspection identified four freight cars from the westbound train which failed the air brake test. The four defective freight cars are listed below:

- BNSF 483476, air brakes cut-out
- BNSF 481098, no brakes set
- BNSF 481164, no brakes set
- BNSF 483549, no brakes set

No other defects were noted. All air brake equipment on the remaining 92 cars worked as intended. All equipment was inspected to current FRA standards and no exceptions were taken.

On January 3, 2014, investigators inspected the mechanical condition of five grain cars, the 44th through the 48th. The cars were; BNSF 486480, 486653, 487137, 481970 and 480263, respectively.

BNSF 486480, the 44th car of the grain train, derailed the trailing trucks; the car was upright and undamaged. Investigators took no exception with the mechanical condition of this car.

BNSF 486653, the 45th car of the grain train, was inspected after it was removed from the derailment area during emergency response actions. The car was assessed lying on its side.

Investigators noted the damage present on the bottom of the car. All bottom outlet gates appeared to have been damaged. The damage originated at the A-End of the car, or the leading end of the car as it would have been oriented in the westbound train. (See Figure 5).

Figure 5. BNSF 486653, the 45th car with bottom outlet gate damage.

Investigators also identified a circular witness mark about 8-inches in diameter with smaller impressions located within the witness mark, triangularly displaced in an equidistant pattern. This impression was consistent with the broken end of an axle assembly. (see Figure 6).

Figure 6. BNSF 486653, the 45th car, with 8-inch diameter circular witness mark.

Investigators observed damage to the A-End, or leading end of the car structure. The car structure and end sill sustained severe longitudinal load collision damage resulting in tearing and shearing of the structure. The top of the car also exhibited severe collision damage along its entire length. (See Figure 7).

Figure 7. BNSF 486653, the 45th car, showing car damage on the top of the car.

BNSF 487137, the 46th car of the grain train, was inspected after it was removed from the derailment area during emergency response actions. The car was assessed lying on its side. Investigators noted the B-End of the car was relatively undamaged; this was the leading end of the car. Investigators also noted the car's structure did not exhibit collision damage.

Figure 8. BNSF 487137, the 46th car, showing the leading end relatively undamaged.

Investigators also noted two circular witness marks about 8-inches in diameter with smaller impressions located with the witness mark, triangularly displaced in an equidistant pattern. This impression was consistent with the end of a broken axle assembly. (See Figure 9).

Figure 9. BNSF 487137, the 46th car with 8-Inch diameter circular witness mark.

BNSF 481970, the 47th car of the grain train, was inspected and assessed lying on its side. Investigators noted the A-End of the car was relatively undamaged; this was the leading end of the car in the westbound train. Investigators noted the car's structure did not exhibit collision damage. Investigators inspected the underside of this car and noted no remarkable witness marks or damage.

BNSF 480263, the 48th car was inspected and assessed lying on its side. Investigators noted the A-End of the car was relatively undamaged; this was the leading end of the car in the westbound train. Investigators also noted the car structure did not exhibit collision damage.

Investigators observed one circular witness mark about 8-inches in diameter with smaller impressions located within the witness mark, triangularly displaced in an equidistant pattern. This impression was consistent with the end of a broken axle assembly. (See Figure 10).

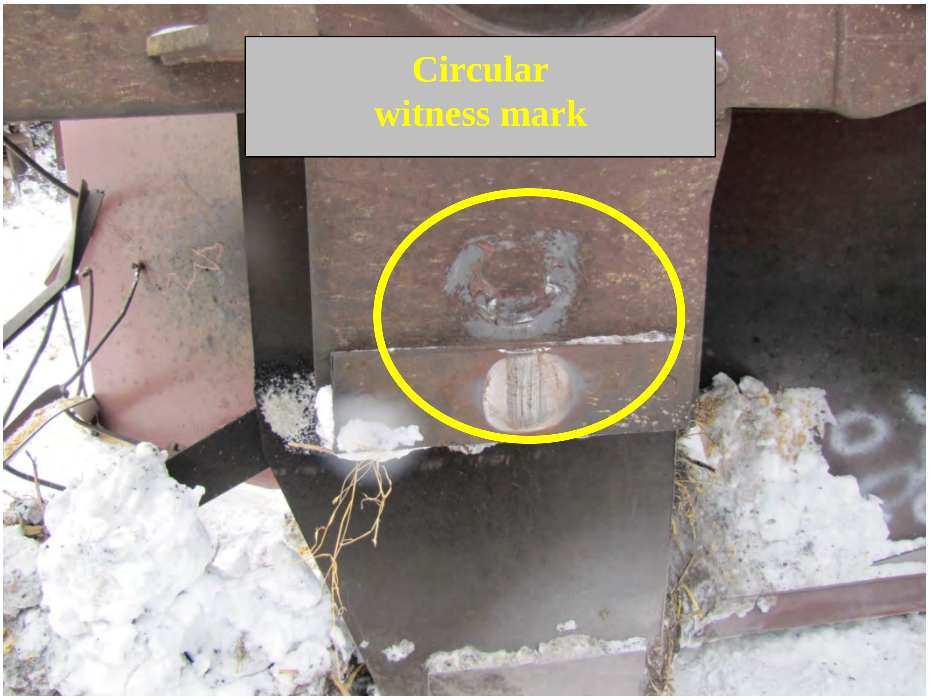


Figure 10. BNSF 480263, the 48th car, with 8-Inch diameter circular witness mark.

During examination of the wreckage, investigators located an axle assembly broken in half. The axle was an AAR Class K (6 ½ X 9) manufactured for freight car service. The wheels mounted to the axle were 36-inch, AAR 1-B, wide flange with a 1:20 taper for freight car service. Each wheel was stamped with a manufacturing date of January 2010. The axle serial number stamped on the end of the broken axle was *SSD 1102 7A1 E 0912 F*[11]. The serial number indicated it was made by Standard Steel, L.L.C., in November 2002.[12]

11AAR serial number designations, specified in AAR Specification M-101, Appendix C (Manual of Standards and Recommended Practices, Wheels and Axles) contain a heat identification number which is stamped on the end of the axle. A heat number is similar to a lot number, which is used to identify production runs of any other product for quality control purposes. This axle's heat number is E0912.
12 Standard Steel, L.L.C, is a manufacturer of rail axles and wheels, located in Burnham, PA. The majority owner of Standard Steel, L.L.C is currently Nippon Steel & Sumitomo Metal Corporation.

Figure 11. Broken axle assembly as found on-scene; serial number *SSD 1102 7A1 E 0912 F*.

The NTSB Materials Laboratory received the broken axle from the Casselton derailment; however, on-scene initial indications were consistent with the axle having fractured from a void[13] along the longitudinal center axis of the axle.

Research of BNSF documentation and maintenance history showed that two derailed cars (the 44th and 45th cars) from the grain train had recent wheel axle assembly change outs in the past four years. Records showed the axle bearings and wheels on the broken axle were installed, or remounted, in April 2010, at the BNSF Havelock Wheel Shop, in Havelock, Nebraska.

Event Recorders—On-scene Review

While on scene, investigators downloaded the event recorder data from the leading locomotives from the grain train and the DPU locomotive from the petroleum train. Investigators collected data from:

- BNSF 6990 leading locomotive from the grain train
- BNSF 6833 second locomotive from the grain train
- BNSF 6745 trailing DPU from the grain train
- BNSF 6684 trailing DPU from the petroleum train

13 A void is a manufacturing defect in an otherwise solid material that can lead to premature failure of a component.

The files were captured using a direct cable interface connection. Time stamps were checked for accuracy against the connected laptop's time. Time event recorder time stamps appeared to have an accuracy of plus or minus one minute. Wheel sizes were collected from each locomotive and documented. [See Event Recorder section of this report]

Signals

Description of Signal System

The BNSF's KO Subdivision consists of main tracks, sidings and yards. The KO Subdivision lies in a geographic east-west direction between Minot, ND (MP 203.2) and East Dilworth, MN (MP 250.3). The maximum authorized speed on the two main tracks in the vicinity of the accident is 70 mph with a permanent head-end speed restriction of 40 mph between MP 27.0 and MP 28.0.

Train movements on the KO Subdivision are governed by the General Code of Operating Rules[14] (GCOR) and the signal indications of a traffic control signal system. The traffic control signal system utilizes four aspect wayside signals. The signal system is arranged for running in both directions on each track.

BNSF's Network Operations Center (NOC) is located in Fort Worth, TX and coordinates train movements. The dispatchers utilize a Train Management and Dispatch System (TMDS) software package to coordinate train movements.

Given the primacy of the BNSF NOC in terms of operational monitoring on the KO Line, the clock time from the NOC was regarded as the standard time. Clock times relevant to this incident are derived from the BNSF's NOC clock[15] and are referenced in this report unless otherwise noted.

Dispatcher Data Logs

Data logs from the TMDS system indicate the eastbound route on main track 2 through CP Casselton (CP30) was requested at 1:52:35 p.m. for petroleum train. The route indicated was lined at 1:52:57 p.m. The westbound route on main track 1 at CP Casselton was requested at 1:56:16 p.m., for the grain train. The route indicated was lined at 1:57:51 p.m.

Signal Equipment Data Logs

Data logs from the signal equipment were downloaded and reviewed. The logs indicate the following:

14 Operating Rules, effective April 7, 2010, as amended September 1, 2013.
15 BNSF's NOC equipment is synchronized to UTC time.

1. At 2:02:30 p.m., the westbound train passes the track side warning device (dragging equipment and hot journal detector) at MP 25.3 on main 1
2. At 2:03:48 p.m., the westbound train passes intermediate signal 25.8, displaying a green aspect, and occupies the track west of the signal on main track 1.
3. At 2:08:02 p.m., the eastbound train passes CP KO Junction at MP 31.11, displaying a flashing yellow over red aspect, occupying the on station (OS) section (east of the controlled signal) of CP KO Junction on main track 2.
4. At 2:08:56 p.m., the westbound train passes the controlled signal displaying a yellow over yellow aspect at CP Casselton, occupying the OS section (west of the controlled signal) of CP Casselton on main track 1.
5. At 2:09:42 p.m., the eastbound train passes the controlled signal displaying a flashing yellow over red aspect at CP 30, MP 30.02, occupying the OS section of CP 30 (east of the controlled signal) on main track 2.
6. At 2:09:26 p.m., the westbound train shunts the track west of CP Casselton at MP 28.45 on main track 1.
7. At 2:09:50 p.m., the eastbound train shunts the track east of CP 30 at MP 30.02 on main track 2.

Signal Maintenance Records

BNSF signal maintenance reports were collected during the on-scene phase on the investigation. Investigators completed their review of the records which included test and inspection records for all systems between approximately MP 31.2 and MP 25.3. Investigators completed a review of the records that indicated all signal tests and inspections were conducted in accordance with FRA requirements. No records exceptions were noted.

Signal System Tests

The switch machine at CP Casselton was damaged as a result of the derailment. It was removed from service for placement in the reverse position, and temporary wiring was installed. The track wires at Casselton were damaged as a result of the derailment and were replaced. The switch was tested in the normal position, the track circuits were shunted and verified, and east and westbound routes were lined over the control point to verify proper aspects prior to continuing operations (train movements through CP Casselton).

Figure 22. Derailment location and the surrounding area of Casselton.

Track

Track Description

The predominant rail section was 132 pound continuous welded rail (CWR). The derailment occurred on the straight line move through a No. 20 turnout within the Casselton interlocking (CP Casselton). The rail was fastened to conventional wooded crossties through double shouldered tie plates with one anchor and one rail spike on each side of the rail. BNSF operated an average of 17 trains within a twenty-four hour period, which amounted to about 66.2 million gross tons (mgt) annually for the line.

Figure 13. This is a view looking west from near the point of derailment.

Inspection and Measurement of Track

Investigators measured the track geometry conditions preceding marks found in the west switch of the crossover located at milepost 28.5 and noted the following:

- The maximum measurement allowed for gage in FRA Class 4 track, a maximum authorized speed of 60 mph (freight) is 57 1/2 inches. Track notes determined that the widest gage prior to the point of derailment (POD) was 56 5/8 inches; or about 7/8 of an inch under the FRA maximum allowable limit.
- The maximum allowed deviation for alignment measured with a 62' chord in FRA Class 4 track is 1 1/2 inches for tangent track. Track notes determined that the greatest alignment deviation prior to the disturbed track was ½ of an inch; or 1 inch under the FRA maximum allowable limit.
- The maximum allowable deviation from zero crosslevel at any point on tangent or reverse crosslevel elevation on curves may not be more than 1 1/4 inches for Class 4 track. Track notes determined that the maximum crosslevel prior to the disturbed track was 1/4 of an inch; or 1 inch under the FRA maximum allowable limit.

This was the last segment of track the grain train traveled over prior to the December 30, 2013, derailment. Investigator's post-accident inspection from mile post 25.2 (east of the accident site) to the beginning of the disturbed track, found there were no visual exceptions.

Point of Derailment[16]

Investigators observed marks at the frog area and on top of the closure rail extending from the switch point area to the frog. The rail exhibited several marks.

Investigators identified the point of derailment (POD) at a location where the outside edge (field side) of the south rail showed an indication of wheel flange trailing off to the field side and continuously marking the field side on track material (OTM) in a westerly direction. The initial mark was located 60 feet 3 inches from the frog point and 96 feet 6 inches from the end of the switch point. On the opposite rail, marks indicated a wheel flange trailing to the inside of the rail head and downward onto the track and OTM marking elastic clips and proceeding in a continuous manner to the heel block location. Investigators observed and documented a deep strike mark at the heel block. The switch crossties supporting the switch point area were damaged and the track west of the switch was destroyed.

Figure 14. View of derailment marks; blue arrow indicates direction of train travel.

16 Point of derailment (POD) GPS coordinates are N46.901067, W97.2278290

Figure 35. Strike mark located at left hand switch point heel block

Track Geometry Test Data

BNSF operated their track geometry measurement vehicle (car 87) over the KO Subdivision, main track 1 on November 13, 2013. The BNSF geometry data generated no exceptions for this area (CP Casselton).

Internal Rail Tests Data

Records Review

On December 10, 2013, an ultrasonic rail test was conducted on BNSF's KO Subdivision. No defects were recorded in the vicinity of the derailment.

Track Inspection Records

The track in the area of the derailment was last inspected on December 29, 2013, by a FRA qualified BNSF track inspector (T/I). The T/I noted no defects in the affected area.

FRA regulations found in 49 CFR 213 require that a rail carrier's track inspection records be prepared and signed on the day of the inspection for frequency of compliance with the Federal Railroad Administration Track Safety Standards (FRA/TSS). FRA track inspection records are required to reflect actual field conditions and deviations from the FRA TSS. BNSF had elected to maintain to FRA Class 4 standards requiring BNSF personnel to inspect the main track at least twice per calendar week. However, BNSF inspected this area of main line tracks a minimum of four times per week.

Track inspection records for the BNSF KO Subdivision were examined from October 22, 2013, through to December 31, 2013. The records showed that the frequency of inspections was in compliance with federal regulations.

Regulatory Track Inspection History

On March 21, 2013, FRA conducted a walking inspection of six switches in the Casselton interlocking area. No defects were noted for the switch where the derailment occurred.

Hazardous Materials

Summary of Transported Hazardous Materials:

BNSF Railway Company train U-FYNHAY4-05T was a unit and "key train"[17] with a total of 104 tank cars containing petroleum crude oil, placarded with United Nations Identification Number (UNID) code 1267, a class 3 flammable liquid (packing group 1). The UNID code 1267 is designated by the U.S. Department of Transportation (DOT) as hazardous for commercial transportation purposes.[18] The loaded tank cars were positioned 2 through 105 in the train.

Commercial transport of petroleum crude oil is subject to the regulatory requirements of the Hazardous Materials Regulations (HMR) in Title 49 of the Code of Federal Regulations (CFR).[19]

A review of the automatic equipment identification (AEI) scan taken of the train at the BNSF Mandan Yard and the BNSF AEI/TSS scan comparison report[20] verified the physical placement of the equipment in the train. The train consist matched the physical placement of the cars in the train with no exceptions taken.

Hazardous Materials Involved in the Derailment:

Twenty (20) hazardous materials tank cars derailed in the accident. These tank cars were in positions 2 through 21 in the train (not including the two locomotives). Table 2 provides a

---

17 Definition of "key train" is provided by Association of American Railroads (AAR) publication OT-55-N, *Recommended Railroad Operating Practices for Transportation of Hazardous Materials*. "Key trains" have speed restrictions and other operating criteria. According to the BNSF Hazardous Materials Instructions for Rail, a key train includes a train with "A. One (1) or more car loads of Spent Nuclear Fuel (SNF) or High Level Radioactive Waste (HLRW) moving under the following Hazardous Material Response Codes (STCCs) - 4929142, 4929143, 4929144, or 4929147, or B. One (1) or more tank car loads of Poison or Toxic Inhalation Hazard (PIH or TIH) (Hazard Zone A, B, C, or D), anhydrous ammonia (UN1005), or ammonia solutions (UN3318), or C. Twenty (20) or more car loads (including intermodal portable tank loads) of any hazardous material."

18 See 49 CFR 172.101, Purpose and Use of Hazardous Materials Table.

19 See 49 CFR 171.1, Applicability of Hazardous Materials Regulations (HMR) to persons and functions.

20 AEI readers detect identification tags on railcars as they pass by the reader. The collected information is automatically relayed to a central computer to update the master train consist.

summary of the current and historical tank car reporting marks, the BNSF field index number, and the car's line number in the train.

All of the 20 derailed tank cars were general service specification DOT-111 tank cars that contained petroleum crude oil from the Bakken region of North Dakota. Eighteen of these tank cars were compromised and released product. Two other tank cars (TAEX 1638 and TAEX 1582) derailed, but they were not breached and did not release their contents.

Figure 46: Fire coming out of thermal tear in top of the tank car GATX 33125.

Table 3: Summary of tank car reporting mark information history and position in train.

Train Position	FIELD INDEX NUMBERS	CURRENT CAR NUMBER	LAST MARK & NUMBER	PREVIOUS MARK & NUMBER
2	17	GATX 33119	N/A	N/A
3	16	GATX 33123	N/A	N/A
4	15	TAEX 1549	ADLX 500237	BNBX 500237
5	14	TAEX 1475	ADLX 500163	BNBX 500163
6	13	ADLX 500176	N/A	N/A
7	12	TAEX 1472	ADLX 500160	BNBX 500160
8	11	SHPX 206675	N/A	N/A
9	10	SHPX 208541	N/A	N/A
10	9	SHPX 208638	N/A	N/A
11	8	SHPX 206670	N/A	N/A
12	7	SHPX 208536	N/A	N/A
13	6	TAEX 1528	ADLX 500216	BNBX 500216
14	Not Tagged (19)	TAEX 1602	ADLX 500102	BNBX 500102
15	5	SHPX 206708	N/A	N/A
16	18	SHPX 206668	N/A	N/A
17	4	GATX 33125	N/A	N/A
18	3	GATX 33139	N/A	N/A
19	2	TAEX 1630	ADLX 500131	BNBX 500131
20	1	TAEX 1638	ADLX 500139	BNBX 500139
21	-	TAEX 1582	-	-

None of the remaining 84 tank cars containing petroleum crude oil were derailed or breached in the accident.

Figure 57. This is an aaerial image of derailment taken from the northwest.[21]

Pre-Accident Events

Hazardous Materials Shipper's Actions - Shipment Preparation

All of the tank cars in petroleum train were offered into rail transportation by Great Northern Gathering and Marketing, the shipper of record. The tank cars originated and loaded at the Great Northern Midstream facility (Fryburg Rail Terminal) in Fryburg, North Dakota. This is a single side loading facility, although double trackage exists at the location. The tank cars were enroute to the consignee, Marquis Energy LLC, in Hayti, Missouri.

On December 29, 2013, Great Northern Midstream conducted quality analysis sampling of the petroleum crude oil that was loaded onto the petroleum train. The tests measured sulfur content, API gravity, bottom sediment and water, and Reid vapor pressure. These results were provided to investigators. Great Northern Gathering and Marketing was unable to produce any classification or characterization documentation to the NTSB. They did not conduct hazardous materials classification sampling for classification and packing group determination prior to shipment.

21 Additional images can be viewed in Hazardous Materials Group Chairman Factual Report.

Figure 68 - Great Northern Midstream Loading Facility in Fryburg, North Dakota.

Tank car loading operations at the Fryburg Rail Terminal are performed by Watco Company. The tank cars were loaded on loaded on December 28 and 29, 2013.[22] Tank car loading and inspection checklist records indicate that pre-loading, in-progress, and post-loading inspections of each tank car were performed. These inspections involved visually checking the tank cars for such things as the following: dents, gouges, cracks, punctures, or signs of leakage; legibility of car stenciling; required outage; currency of tank and safety valve test dates; integrity of valves and fittings; manway gasket condition; securement of the manway; safety valve (pressure relief device) condition; and closure of protective housings. Operators also inspected the bottom outlet fittings of each tank car for valve closure, and condition and securement of the valve cap and gasket. Finally, operators verified the proper placement of hazardous materials placards, placed seals on the manways and bottom unloading fittings, and recorded the seal numbers on the tank car loading and inspection checklist. No exceptions were noted in the loading and inspection records for the three tank cars. After the inspections were completed, a second operator verified the inspections and certified that the loaded railcars were ready for transport.

PHMSA conducted a review of its enforcement history at the Watco Company operations at the Fryburg Terminal over the past 10 years. One defect report was found. The defect (49 CFR 173.31) was a found on May 8, 2013, by FRA inspectors. The defect description states,

22 All of the 20 derailed tank cars were loaded on December 28, 2013.

"Specifications and packaging requirements for this subchapter. Failure to maintain tank car to AAR specifications loaded UN1267 Class 3 tank car removed housing cover seal 1236367 applied seal DOTFRA 8045 vapor line valve safety chain secured to car body with wire."

Tank Car Lading Volumes and Capacity

The waybills indicate that the 20 derailed tank cars contained a total of 553,886 gallons of petroleum crude oil. The load limit weight for the 20 cars ranged from 196,500 to 198,500 pounds; the lading weight ranged from 185,417 to 186,743 pounds. The net barrels of oil ranged from 659 to 664, while the load limit capacity in gallons ranged from 30,060 to 30,140 gallons; the lading volume at loading (in gallons) ranged from 27,674 to 27,872 gallons (See Table 6). The tank cars were examined for excessive weight and minimum outage. None of the tank cars were overloaded by weight. The outage for each tank car was examined to determine if the tank cars met the minimum outage requirement of 1 percent of the total capacity of the tank car at the appropriate reference temperature as required by 49 CFR 173.24b. All tank cars had an outage that was greater than the minimum 1 percent required by 49 CFR 173.24b (a).

Hazardous Materials Description and Information

Petroleum crude oil shipments are the fastest growing of all hazardous materials shipped by rail. The Pipeline and Hazardous Materials Safety Administration's (PHMSA) August 1, 2014, Notice of Proposed Rulemaking (NPRM) titled, *Hazardous Materials: Enhanced Tank Car Standards and Operational Controls for High-Hazard Flammable Trains*,[23] states that the volume of crude oil carried by rail increased 423 percent between 2011 and 2012. According to a July 2014 AAR report titled, *Moving Crude Oil by Rail*,[24] the number of "originated carloads of crude oil on US Class I railroads (including the US Class I subsidiaries of Canadian railroads) rose from 9,500 in 2008 to 233,698 in 2012 to 407,761 in 2013." The report states that this increase in railroad crude oil transportation is largely attributed to increased oil production as a result of "technological advances — especially in hydraulic fracturing ("fracking") and horizontal drilling — along with higher crude oil prices [that] have made recovery of much of this oil and gas economically feasible."

Crude oil is often transported in blocks of crude oil cars within a train and by entire unit trains consisting almost entirely of crude oil tank cars. The crude oil loaded into these tank cars is often a blend of crude from a variety of oil wells which may have varying properties depending on the crude oil components.

According to the PHMSA Central Region, on an average day, BNSF, Canadian National, and Canadian Pacific Railroads move approximately 1,400 to 1,500 railcars loaded with crude oil

23 79 CFR 45015.

24 AAR background paper titled, "Moving Crude Oil by Rail." Published at https://www.aar.org/safety/Pages/crude-by-rail-facts.aspx

from North Dakota to various facilities across the US (East Coast, West Coast, and Gulf Coast). In the Bakken Oil Field Region, the crude oil is gathered from the wells into gathering tanks which, at times may be located at the well. However, generally, the crude oil is moved from the wells using an intra-field gathering line. The crude oil the crude oil goes through a three (3) phase separation process on the well pad. This process separates the water, the gases and the crude oil which are then put in different tanks for storage. The gases are primarily gathered using in field gathering line systems at natural gas processing plants. The water and oil are either transported by truck or pipeline to terminals for further transportation or in the case of water, injection into deep water wells. At that time, depending on the field and the location, the crude oil is then either sent via pipeline or semi-truck cargo tank to one of 13 railroad loading facilities.[25]

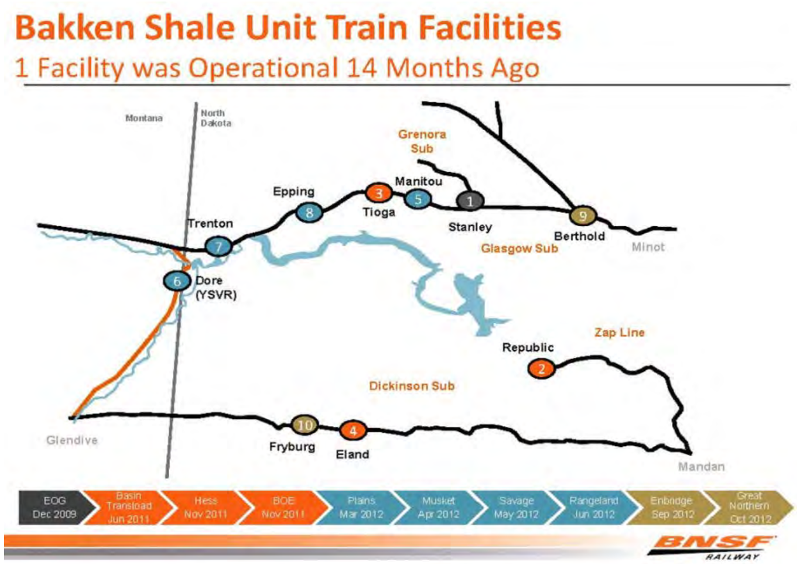


Figure 79 - Map of BNSF-serviced petroleum crude oil terminals in North Dakota, including the Great Northern Midstream Loading Facility in Fryburg.

According to the Pipeline and Hazardous Materials Safety Administration (PHMSA), since February 25, 2014, as a result of the accident in Lac Megantic, Canada, and enforcement efforts by US and Canadian regulatory agencies, the shippers of the facilities now test the product for classification of packing group. Verification of this classification is accomplished by random inspections and sampling conducted by the PHMSA and FRA.

Material Description

Petroleum crude oil is a complex combination of hydrocarbons. It consists predominantly of aliphatic, alicyclic, and aromatic hydrocarbons. It may also contain small amounts of nitrogen, oxygen, and sulfur compounds as well as trace amounts of heavy metals such as nickel, vanadium,

25 In addition to the 10 BNSF-serviced facilities listed in the graphic, there are three other non-BNSF railroad facilities not displayed.

and lead. The volatile organic compounds (VOCs) in crude oil include mono-aromatic compounds such as benzene, toluene, and xylenes as well as aliphatic hydrocarbons such as cyclohexane and hexane. Crude oils are natural products and their chemical and physical properties can vary widely depending on their source and extraction method.

Petroleum crude oil is generally a dark yellow to brown or greenish black liquid with a hydrocarbon odor. If hydrogen sulfide is present, it has a rotten egg odor; however, it should not be used as a warning property of toxic levels because it can overwhelm and deaden the sense of smell.

Petroleum crude oil is a volatile and flammable liquid. Vapors may cause flash fires. It should be kept away from heat, flame, and sources of ignition. According to a 2014 quality assurance study commissioned by the North Dakota Petroleum Council (NDPC), Bakken crude oil is light, sweet crude with an average API gravity of 41° Fahrenheit (F). The study also found that Bakken crude oil has a flash point below 73° F. The report’s other key findings include:

- Bakken crude is a light sweet crude oil with an API gravity generally between 40° F and 43° F and a sulfur content <0.2 wt.%. As such, it is similar to many other light sweet crude oils produced and transported in the United States.
- Bakken crude had an average vapor pressure of 11.5 and 11.8 psi, which is more than 60% below the vapor pressure threshold limit for liquids under the Hazardous Materials Regulations (43.5 psi).
- Bakken crude has a flashpoint of less than 73° F, which is within normal range.
- The Initial Boiling Point (IBP) generally averaged between 95° and 100° F, which are within normal range for a light crude oil (using ASTM D86).
- The light ends concentration of Bakken crude was between three and nine percent, with five percent being the typical concentration.
- The qualities of Bakken were very consistent within the sample population and throughout the supply chain – from wellhead to rail terminal to refining destination. Test results showed no evidence of “spiking” with Natural Gas Liquids (NGLs) before rail shipment.

The American Petroleum Institute (API) analyzed more than 200 samples of Bakken crude oil and sent the data to PHMSA in response to a 2013 DOT letter regarding concerns about Bakken crude oil. The API analysis also concluded that Bakken crude oil is very similar to other light, sweet crude oils. The API gravities for their samples ranged from 38.86° to 47.07° F with the average being 42.66° F. The average sulfur content (wt. %) was 0.1 percent. The average IBP was 91.96° F.

On July 23, 2014, PHMSA released a report titled, Operation Safe Delivery Update , which presents the results of samples collected and analyzed by the agency to determine if shippers were properly classifying Bakken crude oil for transportation. The PHMSA report includes the results of five samples that were collected at the Great Northern Gathering and Marketing Fryburg Terminal. All the samples had flash points under 50°F and IBPs ranging between 86.7 and 91.7° F. All the samples had sulfur content under 1 part per million (ppm). The report concluded:

Based upon the results obtained from sampling and testing of the 135 samples from August 2013 to May 2014, the majority of crude oil analyzed from the Bakken region displayed characteristics consistent with those of a Class 3 flammable liquid, packing group (PG) I or II, with a predominance to PG I, the most dangerous class of Class 3 flammable liquids. Based on our findings, we conclude that while this product does not demonstrate the characteristics for a flammable gas, corrosive liquid or toxic material, it is more volatile than most other types of crude, which correlates to increased ignitability and flammability.

Bakken crude's high volatility level – a relative measure of a specific material's tendency to vaporize – is indicated by tests concluding that it is a "light" crude oil with high gas content, a low flash point, a low boiling point and high vapor pressure. The high volatility of Bakken crude oil, and its identification as a "light" crude oil, is attributable to its higher concentrations of light end hydrocarbons. This distinguishes it from "heavy" crude oil mined in other parts of the United States.

When petroleum crude oil is released to the environment, it undergoes a process known as "weathering" that results in the loss of the more volatile components of oil.

Routes of Exposure and Target Organs[26]

The routes of exposure to petroleum crude oil include inhalation, ingestion, skin, and eye contact. Prolonged direct skin contact with crude oil may cause skin irritation, although short-term skin contact is unlikely to cause adverse effects. Repeated and long term skin exposure contact to components of this product has caused systemic toxicity and cancer in laboratory animals. Inhalation overexposure to the vapors of fresh crude oil may result in headache, dizziness, confusion, nausea, and vomiting. It can contain toxic levels of hydrogen sulfide vapors that accumulate in the vapor spaces of storage and transport compartments. Hydrogen sulfide vapors can cause eye, skin, and respiratory tract irritation and asphyxiation.

When crude oil or other petroleum products burn, they primarily produce particulate matter (PM), carbon monoxide, sulfur dioxide, VOCs including mono-aromatic hydrocarbons and aldehydes, and polynuclear aromatic hydrocarbons (PAHs). Short-term overexposure to PM, VOCs, or sulfur dioxide may result in irritation of the eyes and respiratory tract. Persons with respiratory disease such as asthma may be more sensitive to respiratory irritants produced by burning crude oil. Carbon monoxide primarily affects the central nervous system as a result of its ability to decrease the oxygen-carrying capacity of the blood. Overexposure to carbon monoxide is much less likely to occur in the outdoors due to dilution in the atmosphere.

---

26 Eco-Energy Material Safety Data Sheet and the National Institute of Occupational Safety and Health (NIOSH) Pocket Guide to Chemical Hazards - Ethyl Alcohol and gasoline.

Petroleum crude oil contains carcinogens according to IARC, NTP, ACGIH and OSHA. It contains benzene; a regulated human carcinogen. Benzene is recognized as having the potential to cause anemia and other blood diseases, including leukemia, after repeated and prolonged exposure.

Table 4: Occupational Exposure Limits for Some Typical Components.

INGREDIENT NAME	CAS NUMBER	EXPOSURE LIMIT
Benzene	71-43-2	ACGIH[27] TWA[28]= 0.5 ppm (skin); ACGIH STEL[29]= 2.5 ppm
Toluene	108-88-3	ACGIH TWA= 50 ppm
Ethylbenzene	100-41-4	ACGIH TWA= 100 ppm; ACGIH STEL = 125 ppm
Xylene, mixed isomers	1330-20-7	ACGIH TWA= 100 ppm
Hydrogen Sulfide	7783-06-4	ACGIH TWA= 5 ppm; ACGIH STEL= 10 ppm

Physical Hazards

Tank cars containing petroleum crude oil or other flammable liquids pose a significant hazard when exposed to fire or other conditions that could cause overpressure within the tank.

The 2012 Emergency Response Guidebook (ERG) instructs first responders to establish a half-mile isolation area in all directions around a flammable liquid-filled tank, rail car, or tank truck that is involved in a fire.[30] Responders must always stay away from tanks engulfed in fire. According to a 1970 Cornell Aeronautical Laboratory study for the FRA, "[probably] the single most important element, from a consideration of the possibilities of catastrophic rupture is the presence of a large thermal load due to fire exposure.[31]" Additionally, such incidents can expose responders or bystanders to a high level of thermal radiation heat flux. After conducting a literature study to determine acceptable levels of thermal radiation heat flux for a risk assessment, the FRA concluded that "it is uncertain what level of thermal radiation heat flux can be considered 'safe' for exposing human beings to short duration fires resulting from accidents."[32]

DOT Flammable Liquid Classification Criteria

The Hazardous Materials Regulations (HMR) requires shippers to analyze the hazardous materials to determine the appropriate hazard class and packing group based on the hazard they present. This classification and characterization is a key requirement for the selection of proper packaging. The HMR classifies flammable liquids (Class 3) into three packing groups as follows:[33]

27 American Conference of Government Industrial Hygienists.
28 Time-weighted average.
29 Short term exposure limit.
30 2012 ERG, Guide 128, Flammable Liquids – Non Polar/Water Immiscible.
31 FRA Report Number FRA-RT-71-74, "A Study to Reduce the Hazards of Tank Car Transportation." Final Report, November 1970. Page 5.
32 FRA Report Number FRA/ORD-92/34, "Hazardous Material Transportation in Tank Cars: Analysis of Risks." May 1993. Page Ex-10.
33 49 CFR 173.121(a)(1)

Table 5. Packing Groups

PACKING GROUP	FLASH POINT (CLOSED-CUP)	INITIAL BOILING POINT
I		≤35°C (95° F)
II	<23° C (73° F)	>35°C (95° F)
III	≥23°C,≤60°C (≥73°F, ≤140°F)	>35°C (95° F)

Great Northern Midstream was unable to produce any classification or characterization documentation to the investigation. They did not conduct hazardous materials classification sampling for classification and packing group determination prior to shipment. However, the shipper pack aged and classified the petroleum crude oil as Class 3, PG I, which is the highest risk and most conservative classification of a flammable liquid.

Site Cleanup and Waste Disposal

On December 30, 2013, BNSF activated its Environmental Emergency Response Teams to the site. Response teams met with local officials and emergency responders to develop a safe course of action. Initial actions included removing approximately 70 rail cars that were not derailed from the derailment area to prevent further spread of the fire. Contractors also staged sand near the ditches leading out of the derailment area to prevent possible runoff from leaving the area.

On December 31, 2013, BNSF contractors initiated cleanup operations. Crude oil tanker cars were separated with machinery to isolate the cars that were burning from the remaining cars. Operations to remove the cars were on-going for about 1 ½ days. BNSF representatives met with the North Dakota Department of Health Officials to discuss the cleanup procedure and plans.

On January 1, 2014, the rail cars were removed from the track area into a holding area and environmental cleanup operations began. Crews began the process of removing the contents of the crude oil cars to limit any further environmental impacts. Concurrent with those operations, contractors removed contaminated soil from the right-of-way prior to replacing the railroad tracks. Soil was also excavated on the north side of the rail bed that was contaminated by the crude oil. In addition, grain from the grain cars was separated from the areas impacted by the crude oil with the intentions of keeping the products segregated.

All excavation in the initial emergency response activities focused on removing the gross contamination on the site. Soil excavation depths varied depending on impact depth and site conditions. Several buried fiber optic cables were not damaged between the main line tracks and the Red River Valley and Western tracks.

Figure 20: Image of derailment location and spilt crude oil/debris field.

Contractors metered residual product during the trans-loading from the derailed tank cars. Table 6 provides a summary of the volumes of crude oil lost or recovered. Clean-up activities included documenting, monitoring, and reporting of the locomotive and rail car removal, and impacts to drainage areas, soil, sediment, and surface waters.

Site Cleanup and Waste Disposal

On December 30, 2013, BNSF activated its Environmental Emergency Response Teams to the site. Response teams met with local officials and emergency responders to develop a safe course of action. Initial actions included removing approximately 70 rail cars that were not derailed from the derailment area to prevent further spread of the fire. Contractors also staged sand near the ditches leading out of the derailment area to prevent possible runoff from leaving the area.

On December 31, 2013, BNSF contractors initiated cleanup operations. Crude oil tanker cars were separated with machinery to isolate the cars that were burning from the remaining cars. Operations to remove the cars were on-going for about 1 ½ days. BNSF representatives met with the North Dakota Department of Health Officials to discuss the cleanup procedure and plans.

On January 1, 2014, the rail cars were removed from the track area into a holding area and environmental cleanup operations began. Crews began the process of removing the contents of the crude oil cars to limit any further environmental impacts. Concurrent with those operations, contractors removed contaminated soil from the right-of-way prior to replacing the railroad tracks. Soil was also excavated on the north side of the rail bed that was contaminated by the crude oil. In addition, grain from the grain cars was separated from the areas impacted by the crude oil with the intentions of keeping the products segregated.

All excavation in the initial emergency response activities focused on removing the gross contamination on the site. Soil excavation depths varied depending on impact depth and site conditions. Several buried fiber optic cables were not damaged between the main line tracks and the Red River Valley and Western tracks.

Figure 20: Image of derailment location and spilt crude oil/debris field.

Contractors metered residual product during the trans-loading from the derailed tank cars. Table 6 provides a summary of the volumes of crude oil lost or recovered. Clean-up activities included documenting, monitoring, and reporting of the locomotive and rail car removal, and impacts to drainage areas, soil, sediment, and surface waters.

Table 6: Summary of crude oil lost or recovered.

LINE NUMBER	FIELD NUMBERS	CURRENT CAR NUMBER	LADING VOLUME AT LOADING (GAL)	RECOVERED VOLUME (GAL)	LOSSED VOLUME (GAL)
2	17	GATX 33119	27,678	0	27,678
3	16	GATX 33123	27,674	0	27,674
4	15	TAEX 1549	27,676	0	27,676
5	14	TAEX 1475	27,681	6,000	21,681
6	13	ADLX 500176	27,677	0	27,677
7	12	TAEX 1472	27,676	0	27,676
8	11	SHPX 206675	27,680	0	27,680
9	10	SHPX 208541	27,695	0	27,695
10	9	SHPX 208638	27,683	0	27,683
11	8	SHPX 206670	27,685	50	27,635
12	7	SHPX 208536	27,872	0	27,872
13	6	TAEX 1528	27,677	0	27,677
14	Not Tagged (19)	TAEX 1602	27,678	0	27,678
15	5	SHPX 206708	27,678	0	27,678
16	18	SHPX 206668	27,694	1,000	26,694
17	4	GATX 33125	27,686	0	27,686
18	3	GATX 33139	27,670	3,000	24,670
19	2	TAEX 1630	27,727	12,000	15,727
20	1	TAEX 1638	27,720	No Release	No Release
21	-	TAEX 1582	27681	No Release	No Release
TOTALS			**553,888**	**22,050**	**476,437**

Derailed Tank Cars/Tank Car Descriptions

All of the derailed tank cars were general service specification DOT-111A100W1. They had a maximum gross rail load (GRL) of 263,000 pounds. The Applications for Approval and Certificates of Construction document the tank car Quality Assurance Managers' certification that the constructed tank cars "…conform to…the …[AAR] approved description and to all applicable DOT and AAR requirements, including specifications, rules of interchange, and the DOT Railroad Safety Appliance Standards." (See Table 7 that provides a summary of tank car information retrieved from the certificates of construction and UMLER report.)

The DOT-111 tank car has been the predominant general purpose non-pressure tank car since the 1960's. There are numerous versions of the DOT-111 that have been introduced, with variances in design features such as tank lining, insulation, and materials of construction. General specifications applicable to the DOT-111 tank car are found in 49 CFR 179, Subpart D. The DOT-111A100W1 tank car was the predominant general purpose non-pressure tank car used for the transport of hazardous materials in 2011 and 2012, with about 100,404 used in 2011 (51 percent of tank car fleet used) and 109,342 used in 2012 (52 percent of tank car fleet used).[34]

Due to the large fire after the derailment, several current tank car reporting marks and numbers were burnt off many of the tank cars, revealing previous or historical reporting marks.[35] Table 7 provides a summary of the current and historical tank car reporting marks, the BNSF field wreckage index number, and the car's line number in the train.

Table 7: Summary of tank car reporting mark information history and position in train.

LINE NUMBER [POSITION IN TRAIN]	FIELD WRECKAGE INDEX NUMBERS	CURRENT MARK AND CAR NUMBER	SECOND OWNER - MARK AND NUMBER [HISTORICAL]	FIRST OWNER - MARK AND NUMBER [HISTORICAL]
2	17	GATX 33119	N/A	N/A
3	16	GATX 33123	N/A	N/A
4	15	TAEX 1549	ADLX 500237	BNBX 500237
5	14	TAEX 1475	ADLX 500163	BNBX 500163
6	13	ADLX 500176	N/A	BNBX 500176
7	12	TAEX 1472	ADLX 500160	BNBX 500160
8	11	SHPX 206675	N/A	N/A
9	10	SHPX 208541	N/A	N/A
10	9	SHPX 208638	N/A	N/A
11	8	SHPX 206670	N/A	N/A
12	7	SHPX 208536	N/A	N/A
13	6	TAEX 1528	ADLX 500216	BNBX 500216
14	19	TAEX 1602	ADLX 500102	BNBX 500102
15	5	SHPX 206708	N/A	N/A
16	18	SHPX 206668	N/A	N/A
17	4	GATX 33125	N/A	N/A
18	3	GATX 33139	N/A	N/A
19	2	TAEX 1630	ADLX 500131	BNBX 500131
20	1	TAEX 1638	ADLX 500139	BNBX 500139
21	-	TAEX 1582	ADLX 500080	BNBX 500080

34 *Annual Report of Hazardous Materials Transported by Rail* (Association of American Railroads, Bureau of Explosives, 2011 and 2012).
35 The tank car marks and numbers were changed when ownership of the tank cars changed.

Tank Car Damages

Railroad freight car wrecking contractors removed the tank cars off the track, staged them nearby the derailment site for inspection (north of derailment location). Investigators made observations and recorded measurements of the damages.

The orientation of the tank cars was captured by the AEI in Mandan; however, investigators also determined the orientation of the tank cars based on photographs collected on scene. Table 7A below lists the leading end (either A or B-end) of the tank car as it passed the AEI detector.

Table 7A: Orientation of the tank cars in the train.

LINE NUMBER	REPORTING MARK	LEADING END (A or B)
1	BNSF 808314	B
2	GATX 33119	A
3	GATX 33123	A
4	TAEX 1549	B
5	TAEX 1475	B
6	ADLX 500176	B
7	TAEX 1472	B
8	SHPX 206675	A
9	SHPX 208541	A
10	SHPX 208638	B
11	SHPX 206670	A
12	SHPX 208536	A
13	TAEX 1528	A
14	TAEX 1602	B
15	SHPX 206708	A
16	SHPX 206668	A
17	GATX 33125	A
18	GATX 33139	B
19	TAEX 1630	A
20	TAEX 1638	B
21	TAEX 1582	B

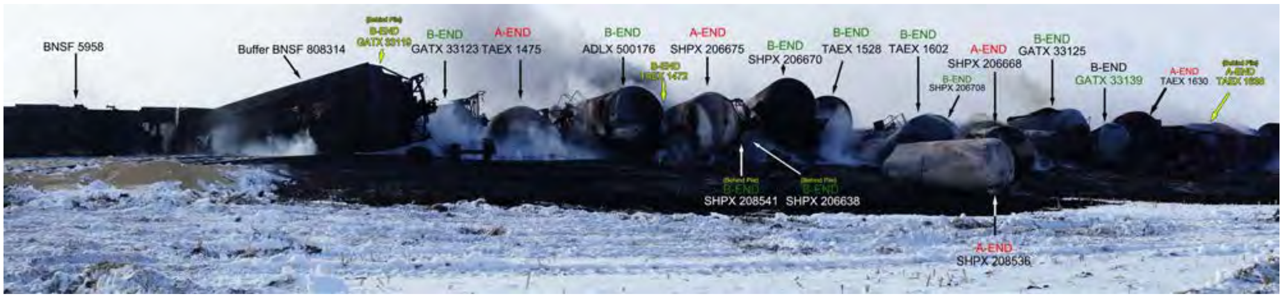


Figure 21. Labeled image of derailment (includes location of unseen tank cars).

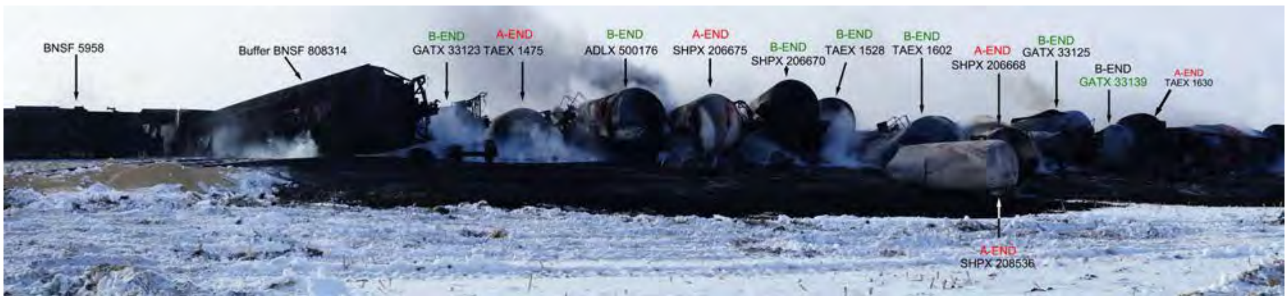


Figure 82. Labeled image of derailment (visible tank cars only).

Figure 93: Tank cars SHPX 206708, left; SHPX 1528, right.

Figure 104: Tank car GATX 33119 (marked #17) on top of tank car GATX 33123 (marked # 16).

Figure 115: Thermal tear in tank car GATX 33119.

Figure 126: Half of tank car SHPX 208536, which was located north of the derailment.

Post-Accident Research

Crude Oil Testing

Three tank cars from the derailment were identified for crude oil sampling. These were tank cars that were not involved in the accident and subsequent fire. These tank cars arrived at the Marquis Energy Terminal in Hayti, Missouri on January 8, 2014. The three tank cars were segregated from the unit train and placed on a siding for sample collection. The sample collection was completed on January 9, 2014.

Samples of crude oil were taken from three tanks on the accident train and were submitted to independent, third-party laboratories for testing. The following tests were performed: 1) ASTM D-5002: *Standard Test Method for Density and Relative Density of Crude Oil by Digital Density Analyzer*; 2) ASTM D-86: *Standard Test Method for Distillation of Petroleum Products at Atmospheric Pressure*; 3) ASTM D-56: *Standard Test Method for Flash Point by Tag Closed Tester* ; 4) ASTM D-7169: *Standard Test Method for Boiling Point Distribution of Samples with Residues Such as Crude Oils and Atmospheric and Vacuum Residues by High Temperature Gas Chromatography* and 5) ASTM D-6730 MOD: *Standard Test Method for Determination of Individual Components in Spark Ignition Engine Fuels by 100–Metre Capillary (with Precolumn) High-Resolution Gas Chromatography (modified)*. The results are listed below. All results were within acceptable specifications ranges (if applicable).

Test Results

		Flash Point (ASTM D56)	First fraction off temp -Light ends report (D7169)	Initial Boiling Point -High temp report (D7169)	API Gravity/ Density/ Relative Density (D5002)	API Gravity/ Density/ Relative Density @ 60F (D5002)	API Gravity/ Density/ Relative Density @ 115 F (extrapolated) (D5002)	API Gravity/ Density/ Relative Density @ 135 F (extrapolated) (D5002)	Initial Boiling Point/ Distillation (D86)	Determination of Light Ends by Crude oil (D6730 MOD)
Tank ID #	SHIPX205162	<10 C / < 50 F	-42.0 C / -43.7 F	14.2 C / 57.5 F	0.8063 g/mL (44 API)	0.8177 g/mL	0.7951 g/mL	0.7868 g/mL	96 F	completed
	TAEX1516	<10 C / < 50 F	-42.0 C / -43.7 F	16.3 C / 61.4 F	0.8067 g/mL (43.9 API)	0.8183 g/mL	0.7958 g/mL	0.7875 g/mL	93 F	completed
	TAEX1634	<10 C / < 50 F	-42.0 C / -43.7 F	14.7 C / 58.5 F	0.8067 g/mL (43.9 API)	0.8130 g/mL	0.7903 g/mL	0.7819 g/mL	86 F	completed
	Packing Group #1	not listed	not listed	≤ 35 C (95 F)	not listed	not listed	not listed	not listed	≤ 35 C / 95 F	not listed
	Packing Group #2	<23 C (73 F)	not listed	>35 C (95 F)	not listed	not listed	not listed	not listed	>35 C / 95 F	not listed
	Packing Group #3	≥23 C, ≤60 C (≥73 F, ≤140 F)	not listed	>35 C (95 F)	not listed	not listed	not listed	not listed	>35 C / 95 F	not listed

Table 8. Results of crude oil testing.

Mobile Phones and Record Description

The Safety Board's Vehicle Recorder Division received mobile phone records from five phones associated with all the five train personnel from the two trains. Mobile phone records were provided to the Safety Board from a mobile phone operator in response to subpoena. Mobile phone records typically provide date, time, duration, direction, and source/destination information for calls, text messages, and data usage.

Mobile Phone Record Timing and Record Investigations

Mobile phone records were provided in CST by the mobile phone operator. Call, text message, and data records from the cell phones were examined for the day of the accident. Two phones showed no call or text activity during the period 12:00 p.m. CST to 2:19 p.m. CST; there was no data activity during the period 12:53 p.m. CST and 3:11 p.m. CST. Three cell phones were examined for the day of the accident. None of the phones showed activity during the period 12:00 p.m. CST to 3:30 p.m. CST.

Event Recorder Data

Investigators on-scene examined the wreckage and shipped the event recorders from the petroleum train to NTSB's Vehicle Recorder Laboratory. The following is a listing of the train identification, locomotive numbers and position in the consist paperwork for both trains:

- Train ID/Locomotive: Grain Train BNSF 6990 (Lead Loco)
- Train ID/Locomotive: Grain Train BNSF 6833 (2nd Loco)
- Train ID/Locomotive: Grain Train BNSF 6745 (Distributed Power Unit (DPU))
- Train ID/Locomotive: Petroleum Train BNSF 4934 (Lead Loco)
- Train ID/Locomotive: Petroleum Train BNSF 5958 (2nd Loco)
- Train ID/Locomotive: Petroleum Train BNSF 6684 (DPU)

Event and On-Board Image Recorder Data Recovery

Three event recorder download files from the grain train were provided to the NTSB's Vehicle Recorder Division for readout and evaluation. These download files were obtained from the lead locomotive, BNSF 6990; the second locomotive, BNSF 6833; and the DPU, BNSF 6745, positioned at the rear of the train. The event recorders from the two locomotives and DPU were undamaged.

One event recorder download file from the petroleum train was provided to the NTSB's Vehicle Recorder Division for readout and evaluation. This download file came from the DPU, BNSF 6684. The remaining two event recorders from the lead locomotive, BNSF 4934 and the second locomotive, BNSF 5958, suffered severe thermal damage and the non-volatile memory was destroyed. Figure 27 shows the BNSF 4934 event recorder download port recovered from the locomotive, along with an exemplar installation; the actual event recorder and non-volatile memory were destroyed in the ensuing fire. Figure 28 shows the BNSF 5958 event recorder recovered from the locomotive, along with an exemplar installation; the non-volatile memory in the recorder was destroyed.

Video was recovered from the on-board image recorders on the grain train (G/T) and petroleum train (P/T). The G/T video was downloaded from the undamaged GE Lococam forward facing on-board image recorder on BNSF 6990 at the NTSB Vehicle Recorder laboratory. The P/T forward facing video file was obtained from data transmitted wirelessly when BNSF 4934 initiated an emergency brake application. BNSF 4934's GE Lococam on-board image recorder was destroyed in the post-impact fire; the non-volatile memory was destroyed.

Figure 27. P/T lead locomotive BNSF 4934 event recorder download port and exemplar installation.

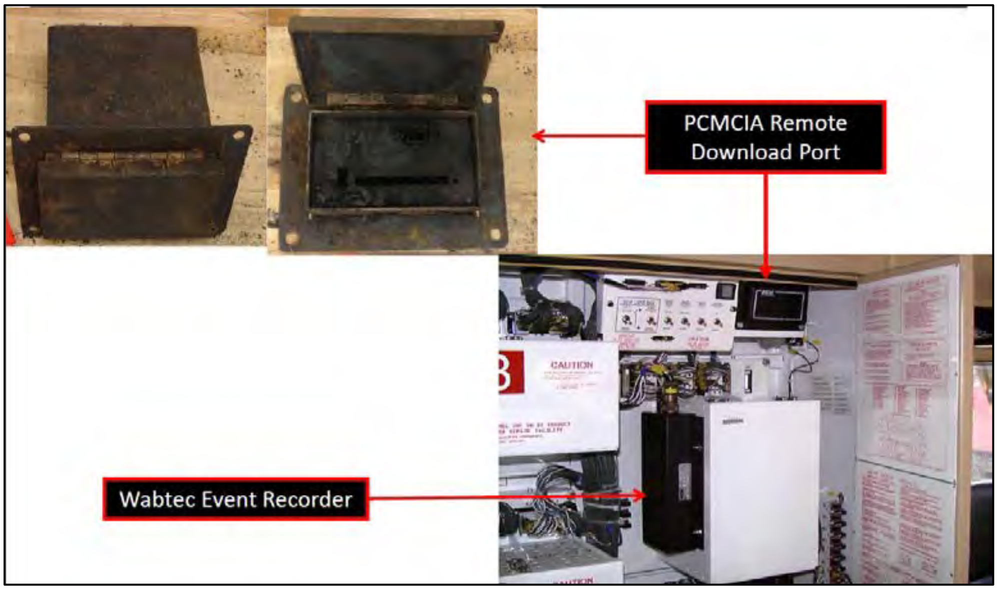


Figure 28. P/T 2nd locomotive BNSF 5958 event recorder and exemplar installation.

Event Recorder Recording Description and Wheel Sizes

For most event recorders, the actual speed and distance values are not recorded but rather the number of drive wheel rotations (or fraction thereof) is stored in memory. At the time the data is extracted, a wheel size is manually entered into the readout station or computer. Wheel size, number of rotations, and time are then used by the program to calculate distance traveled, where the derived distance traveled does not account for any wheel skidding or slipping that could have occurred. Then the calculated distance traveled and time data are used to calculate speed. On-scene investigators provided a wheel size of 41.88 inches for BNSF 6990, 42.38 inches for BNSF 6833, 41.00 inches for BNSF 6745, and 41.0 inches for BNSF 6684.

Using the wheel sizes provided by on-scene investigators, the event recorder data were extracted using the Wabtec Railway Electronics Event Recorder Data Analysis Software. The data exported has a sampling rate of one second.

The event recorder data from the G/T lead locomotive, BNSF 6990 and the P/T DPU, BNSF 6684, were used in this report.

Parameters and Tabular Data

Table A-1 in Appendix B of this report lists the parameters from the event recorders that were verified and provided in this report. Table A-2 contains the unit and discrete state abbreviations for the parameters. Figure 29 contains tabular data of all the parameters listed in table A-1 for G/T BNSF 6990 in comma separated value (CSV) format for the last one hour of BNSF 6990's event recorder data. Figure 30 contains tabular data of all the parameters listed in table A-1 for P/T BNSF 6684 in CSV format for the last one hour of BNSF 6684's event recorder data.

On-Board Image Recorder

The GE Lococam On-Board Image recorder is a forward facing video camera that records to external storage. It records video at a resolution of 720x480 pixels and 15 frames per second (fps) in color with external audio. The system also captures limited parametric data, such as speed.

Recorder Timing

The times used in this report are expressed as local time of the accident (CST). Table 9 summarizes events and times used to convert recorded time to CST.

G/T BNSF 6990 Image Recorder

In agreement with the time synchronization effort, the signal data as recorded at the westbound Home Signal at control point (CP) Casselton was considered the authoritative time for this accident.[36] According to recorded signal data, G/T BNSF 6990 first occupied the westbound Home Signal at CP Casselton 14:08:56 CST. This time was correlated with G/T BNSF 6990's forward-facing image recorder data, which showed the train first occupied the westbound Home Signal at CP Casselton at 14:08:50 image recorder time. Accordingly, six seconds was added to G/T BNSF 6990 image recorder time to convert to authoritative CST.

G/T BNSF 6990 Event Recorder

Horn and Power Cutoff Switch (PCS) video and limited parametric data recorded by G/T BNSF 6990's forward facing image recorder was correlated with the same events recorded by G/T BNSF 6990's event recorder. Specifically, horn activations recorded on the image recorder at 14:10:09 and 14:10:15 and PCS activation at 14:10:23 CST (with the authoritative signal data correction applied) were correlated to the same events on the event recorder at 14:10:04, 14:10:10, and 14:10:18 event recorder time. Accordingly, 5 seconds was added to G/T BNSF 6990's event recorder time to convert to authoritative CST.

P/T BNSF 4934 Image Recorder

Due to the limited data available from the P/T (as described in section on Event and On-Board Image Recorder Data Recovery), recorded video data was supplemented by additional data provided by investigators to correlate P/T BNSF 4934's recorded video data to authoritative CST time: (a) the length of each P/T car was about the same length as each G/T car[37] and (b) the G/T car struck by the P/T lead locomotive was the 45th covered hopper grain car in the G/T consist[38]. According to G/T BNSF 6990's forward facing video, the G/T met the lead P/T locomotive at 14:10:40 CST (with the authoritative signal data correction applied) as the G/T was still moving westbound. At 14:10:57 CST (with the authoritative signal data correction applied), G/T BNSF 6990 came to a stop as the 20th oil carrying car passed[39]. P/T BNSF 4934's video began at 14:09:47 (P/T 4934 image recorder time) as it was passing the 34th grain carrying car of the G/T. Applying the noted assumptions, the start of P/T BNSF 4934's video aligned with G/T BNSF 6990's video recording of the passage of the 35th P/T oil carrying car at 14:11:11 CST (with the authoritative signal data correction

---

36 See the Signal Factual Report in the public docket for this accident.

37 Measured from coupler face to coupler face, a covered hopper grain car is about 58-feet 0-inches and a DOT 111 oil carrying car is about 59-feet 5-inches.

38 According to the IIC, the P/T struck the 45th grain carrying car of the G/T consist. The G/T consist began with the lead locomotive, followed by a 2nd locomotive, and then the 1st covered hopper grain car.

39 The P/T consist began with the lead locomotive, followed by a 2nd locomotive, followed by a buffer car, followed by the 1st oil carrying car.

applied). Accordingly, 84 seconds was added to P/T BNSF 4934's image recorder time to convert to authoritative CST.

P/T BNSF 6684 Event Recorder

Due to the limited data available from the P/T (as described in section Event and On-Board Image Recorder Data Recovery), a further estimate was necessary to correlate P/T BNSF 6684's event recorder to authoritative CST time: the time P/T BNSF 4934's image recorder recorded PCS activation was the same as the time PCS activation was recorded by P/T BNSF 6684's event recorder. P/T BNSF 4934's image recorder recorded PCS at 14:11:13 CST (with the authoritative signal data correction applied) and P/T BNSF 6684's event recorder recorded PCS at 14:11:12 event recorder time. Accordingly, 1 second was added to P/T BNSF 6684's event recorder time to convert to authoritative CST.

Table 9. Summary of timing calculations.

Source	Alignment Event	Recorded Time	Offset (sec.)	CST
Signal Data	Westbound Home Signal CP Casselton	14:08:56	0	14:08:56
G/T 6990 Video Recorder	Westbound Home Signal CP Casselton	14:08:50	+6	14:08:56
G/T 6990 Event Recorder	Horn and PCS	14:10:04 14:10:10 14:10:18	+5	14:10:09 14:10:15 14:10:23
P/T 4934 Video Recorder	Pass 34th G/T grain car	14:09:47	+84	14:11:11
P/T 4934 Event Recorder	PCS	14:11:12	+1	14:11:13

Plots of Event Recorder Data

Figures 29 and 30 contain event recorder data from G/T lead locomotive BNSF 6990 and P/T DPU BNSF 6684, respectively, recorded during the December 30, 2013, event.

Figure 29: Select parameters from G/T BNSF 6990's event recorder data.

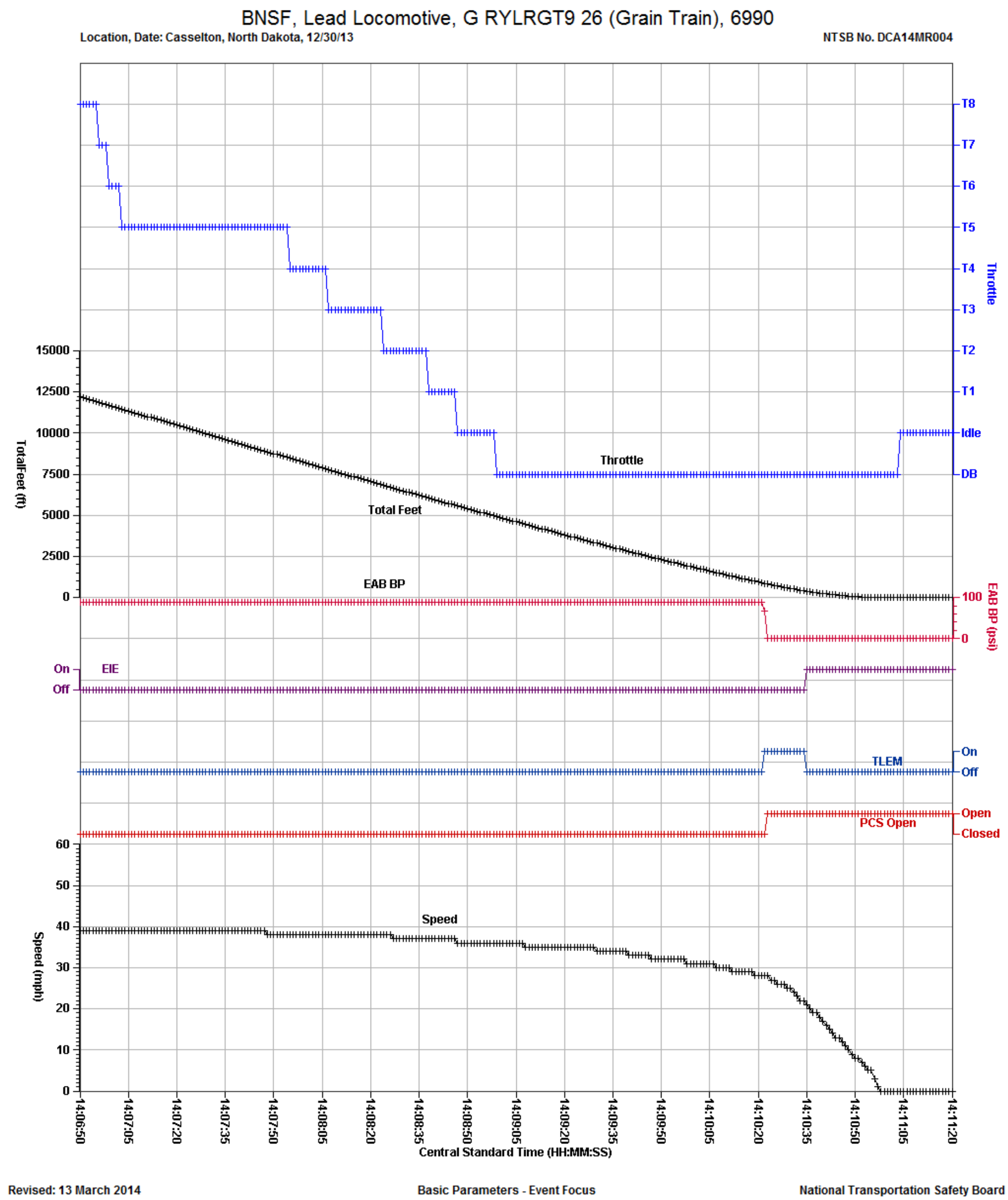
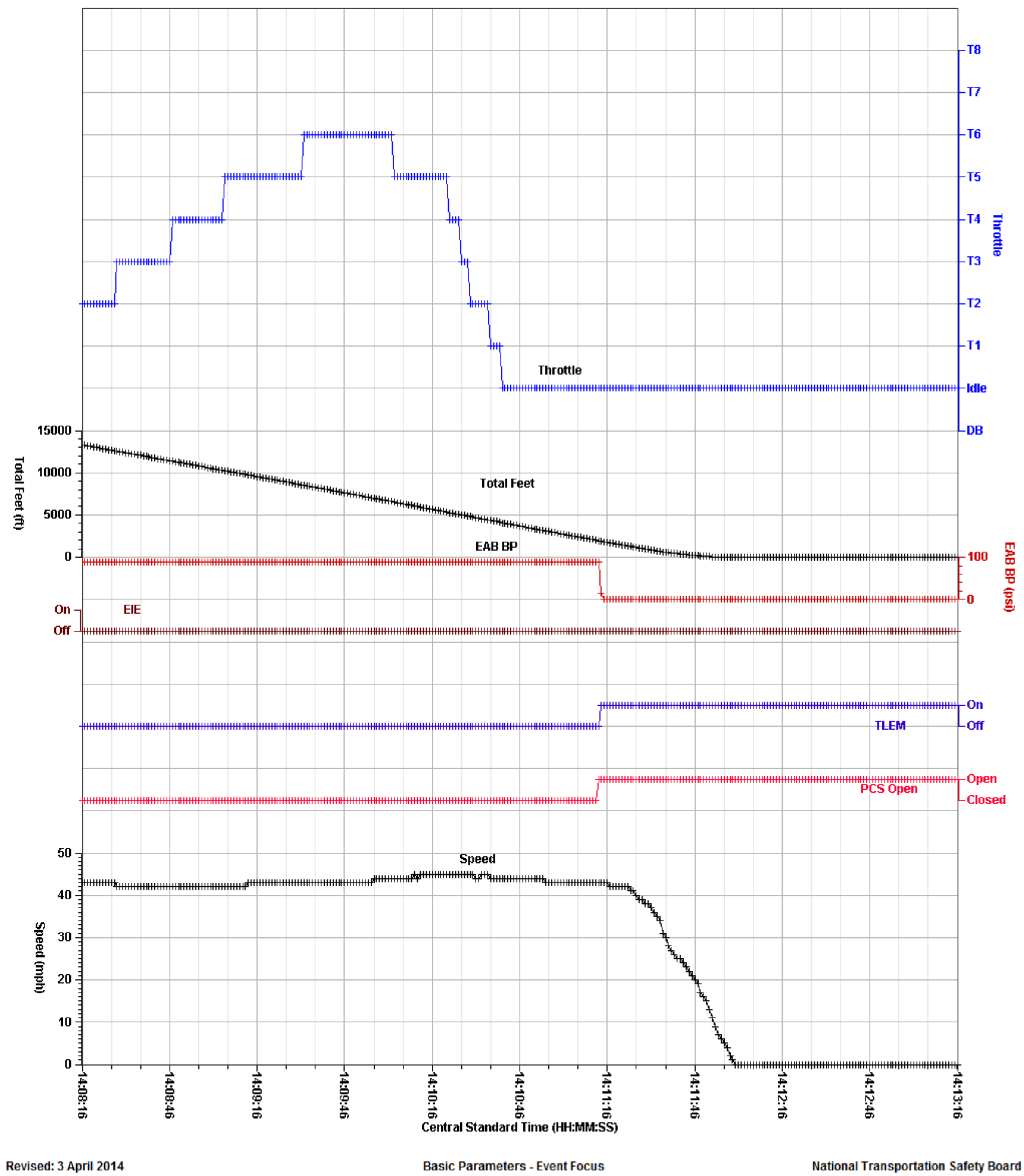


Figure 30: Select parameters from P/T BNSF 6684's event recorder data.



Description of G/T Events

Data from the event and image recorders of the G/T lead locomotive provided investigators with the following chronological order of events:

- The G/T was travelling westbound on the north track; the P/T was travelling eastbound on the south track.

- At about 14:08:56 CST, the G/T was approaching the westbound Home Signal at CP Casselton. At this time the speed was about 36 mph.

- At about 14:09:10 CST, the G/T approached the west switch of the crossover at CP Casselton travelling at about 35 mph. Figure 31 shows the undamaged switch heater covers as the G/T approached.

Figure 31. G/T before heated cover of switch.

- At about 14:10:21 CST, just prior to the train line emergency (TLEM), the G/T was decreasing speed through 28 mph, the throttle was set at Dynamic Brake (DB), Electronic Air Brake (EAB) Brake Pressure (BP) was 89 pounds per square inch (psi), and the G/T was 947 feet prior to a complete stop, according to the event recorder data. At about 14:10:22 CST, the TLEM was activated with an associated decrease in EAB BP to

0 psi. Figure 32 shows the G/T video at the time of the TLEM. The approaching P/T is visible in the distance.

Figure 32. G/T video at time of TLEM.

- At about 14:10:40 CST, the G/T and the P/T met, as shown in figure 33. At the time the G/T and P/T met, the G/T was travelling at about 17 mph and was about 245 feet prior to a complete stop.

Figure 33. G/T video when G/T and P/T met.

At about 14:10:57 CST, the G/T came to a complete stop, as shown in figure 34. When the G/T stopped, the P/T was still moving.

Figure 34. G/T stopped, P/T moving on adjacent track.

The P/T consist west of the G/T did not come to a complete stop until about 14:11:58 CST. Figure 35 shows the P/T stopped; the oil carrying car closest to the G/T was the 65th oil carrying car in the P/T consist.

Figure 35. G/T stopped, P/T as it stops.

Description of P/T Events

Data from the P/T DPU BNSF 6684's event recorder and P/T lead locomotive BNSF 4934's image recorder (a total of 35 seconds of video was available from the P/T's wirelessly transmitted video) provided investigators with the following chronological order of events[40]:

- At about 14:10:40 CST, the P/T met the G/T. According to DPU 6684's event recorder, the P/T was travelling at a steady speed of about 44 mph.

- At about 14:11:11 CST, figure 10 shows the first frame of the P/T video as the P/T is transitioning to a TLEM. Figure 36 also shows an obstruction near or on the south track ahead.

Figure 36. P/T first video frame.

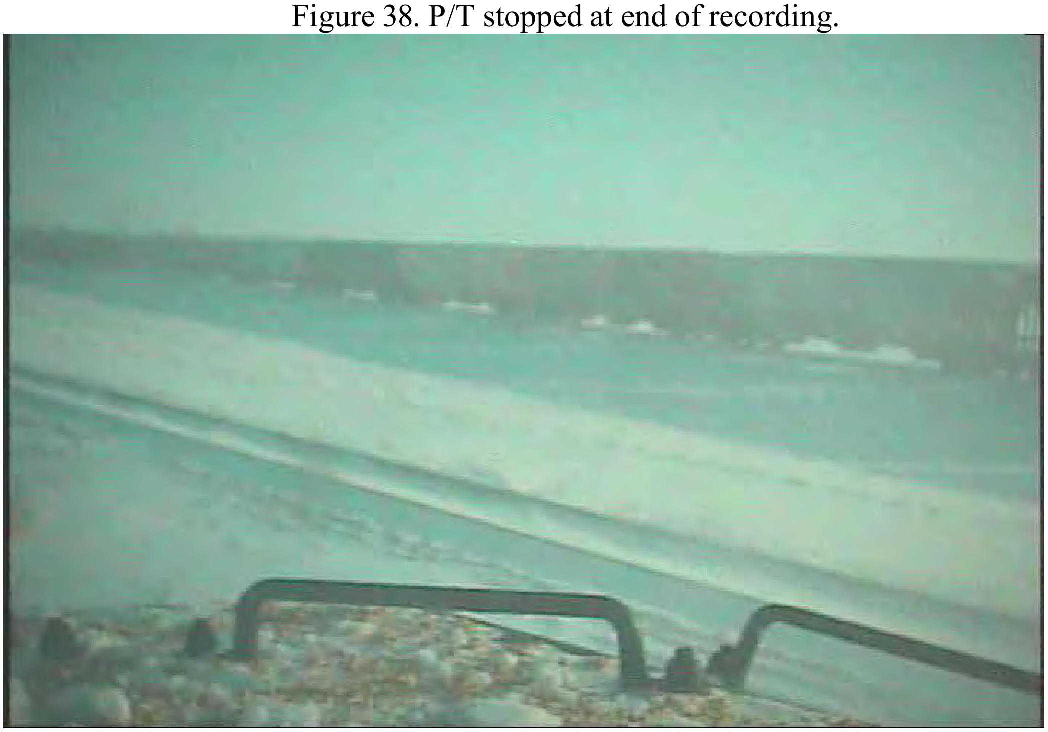
- At about 14:11:21 CST, the P/T struck a derailed G/T car, as shown in figure 37. In the background of the derailed car two features are visible: (1) the derailed G/T car is separated from the rear part of the G/T consist; and (2) there is an obstruction near or on the south track.

40 Since the event and image recorders of the lead P/T were destroyed, precise timing of events was limited.

Figure 37. P/T about to strike derailed G/T car.

At 14:11:46 CST, figure 38 shows the P/T stopped at the end of the 35 second recording.

Figure 38. P/T stopped at end of recording.



Standard Steel

Standard Steel was established in 1795 as Freedom Forge and has been in continuous operation since 1830. While in the past Standard Steel manufactured a variety of alloys and parts for multiple industries, at the time of the visit, the company produced only wheels and axles for the railroad industry.

On January 3, 2014, Standard Steel was notified that one of their axles was involved in a railroad accident. Standard Steel informed the NTSB that the axle had been manufactured in November of 2002 with heat number E0912. On January 14, 2014, Association of American Railroads (AAR) contacted Standard Steel to determine the status of axles produced from heat E0912. Standard Steel notified AAR that the wheels on the broken axle were Standard Steel wheels that have a manufacturing date of January 2010 confirming that the axle in question was a remounted axle. Communications between AAR and Standard Steel resulted in AAR's issuance of a "AAR Maintenance Advisory MA-144" on January 23, 2014, to the railroads and wheel shops to inspect serial numbers to identify and remove from service the remaining axles in that heat.

On January 15, 2014, Standard Steel sent a letter to AAR detailing the number of axles in heat number E0912 (a total of 40 axles) and where those axles were originally shipped and how to identify the axles. On January 17, 2014, AAR requested a list of axle serial numbers to search their Comprehensive Equipment Performance Monitoring (CEPM) system for axles that had been through a wheel shop and remounted. On January 21, 2014, AAR informed Standard Steel that no serial numbers from heat E0912 were in their CEPM system.

On January 30, 2014, the NTSB contacted Standard Steel and offered them Party status. The same day Standard Steel accepted the offer and was granted Party status.

On February 4, 2014, the NTSB held a teleconference call with Standard Steel to discuss the recent invitation for Standard Steel to become a Party to the investigation and to answer any of their questions and that the NTSB wanted to schedule a visit to Standard Steel's facility and to observe the axle and wheel production, inspection and quality control processes.

Beginning on February 14, 2014, Standard Steel reached out to car manufacturers in an ongoing effort requesting a list of railcars where axles from heat E0912 may have been applied. A few days later, Standard Steel received a list of 1,691 potential cars numbers that may have been equipped with one or more of the axles. On February 28, 2014, Standard Steel separated the list by car owner and sent that information to the car manufacturer.

On March 4, 2014, AAR's Wheels, Axles, Bearings and Lubrication (WABL) Committee discussed performing radial ultrasonic testing (UT) on secondhand axles and CEPM reporting of axle serial numbers when remounting secondhand axles. On March 7, 2014, Standard Steel asked AAR at the request of the NTSB axle investigation if it would be possible to check AAR car repair billing records for wheel set removals from the railcars that were built with axles from heat E0912, referring to AAR Maintenance Advisory MA-144, Circular Letter C-12095. In response, on March

14, 2014, AAR notified Standard Steel that according to the Car Repair Billing Records, 233 cars of the 1,691 cars had all four axles replaced since the cars were built. On March 17, 2014, Standard Steel contacted the AAR to provide a list of car owner contacts in order to have the car owners check their billing records on the remaining 1,458 cars. The list was provided the following day.

On March 24, 2014, investigators visited Standard Steel's facility and held a meeting to discuss Standard Steel's and AAR's recent efforts in potentially identifying and locating rail cars with axles from heat E0912. All agreed to continue the collaborative effort in the hopes of locating additional axles.

Throughout February and March, AAR and Standard Steel worked to build a list of potential car owners and cars to be surveyed for the axles from the heat, as well as, to eliminate cars that did not have suspect axles. This effort was to pare down the car count from 1,691 to a more manageable number. Those efforts resulted in identifying 1,160 cars that did not require field testing, which left 531 cars requiring field inspection. AAR drafted Supplement 1 to add to the exiting MA-144 to identify the 531 cars. Supplement 1 for MA-144 was issued on June 16, 2014.[41]

Axles Found—Cars on Watch List

The following is provided as a history of the results for the search efforts thus far:

Chronology of Events – Standard Steel Axle Serial Number SSD 11 02 E0912 7B2

- On April 25, 2014, Standard Steel was notified that axle SSD 11 02 E0912 7B2 was found during inspection at AAR Approved Wheel and Axle Shop. (Result of MA-144 Inspection.)

- On April 26, 2014, Standard Steel notified wheel shop and AAR that Standard Steel authorized return of axle for evaluation.

- On May 5, 2014, a radial ultrasonic test (UT) was performed at Standard Steel. The axle tested clean.

Chronology of Events – Standard Steel Axle Serial Number SSD 11 02 E0912 2B2

- On July 23, 2014, Standard Steel was notified that axle SSD 11 02 E0912 2B2 was found during inspection at AAR Approved Wheel and Axle Shop. (as a result of MA-144 inspection).

41 It is normally 1 year from the date a Maintenance Advisory is issued to close the advisory.

- On July 24, 2014, Standard Steel notified wheel shop that Standard Steel authorized return of the axle for evaluation and the wheel shop was provided with shipping instructions for return of the axle.

- On August 8, 2014, the axle was received at Standard Steel where the axle was UT inspected; a 40 to 60% loss of back reflection was noted at one spot. These results are acceptable to the current standards of AAR M-101. Standard Steel notified both AAR and NTSB of the results of inspection.

As of October 20, 2014, 126 cars remain on MA-144. By November 14, 2014, Standard Steel received three invoices from Mitsui Rail Capital for removal of a total of 232 wheel sets from 140 cars with 241 axles removed. However, none contained an axle from E0912. In early 2015, on February 10th, Standard Steel received one invoice from RAS Data Services for removal of two wheel sets. But again, no axle from E0912 was found.

As of March 3, 2015, 107 cars remain on MA-144 and those were reported to AAR WABL Committee. In response, on March 11, 2015, AAR – WABL Committee Manager sent notification to Standard Steel that Railinc had rechecked CEPM records per Standard Steel request and that no axles were reported with E0912 in the heat field.

Chronology of Events – Standard Steel Axle Serial Number SSD 11 02 E0912 9A1

- 3-25-2015, Standard Steel notified that axle SSD 11 02 E0912 9A1 was found during inspection at AAR Approved Wheel and Axle Shop. (Result of MA-144 inspection.)

- 3-26-2015, Notified wheel shop that Standard Steel authorized return of axle for evaluation and provided shipping instructions for return of axle.

- 5/18/15, Radial UT performed at Standard Steel. One spot on the axle body showed a 15-20% loss of Back reflection, which acceptable to AAR standards.

Chronology of Events – Standard Steel Axle Serial Number SSD 11 02 E0912 8B2

- 5-13-2015, Greenbrier Rail notified Standard Steel that axle SSD 11 02 E0912 8B2 was found during an inspection at their shop. (Result of MA-144 inspection.)

- The axle was found on car AEPX 6925 in position 1.

- On June 26, 2015, a radial ultrasonic test (UT) was performed at Standard Steel. The axle tested clean.

Updated April 24, 2015

Standard Steel learned that on April 25, 2015, Railinc issued a Supplement to Early Warning (EW) notice #5295 “MA-0144 Elevated to EW-5295” and that 104 cars remaining on Early Warning Notice are restricted from interchange.

Materials Laboratory

A broken axle and two wheels were recovered at the accident site and were shipped to the NTSB Materials Laboratory for further evaluation and analysis. Figures 39 and 40 illustrate both sides of the fractured axle, as received.


Figures 39 and 40. Broken axle and wheel assembly as received at Materials Laboratory.

The axle fractured such that one segment was shorter than the other longer segment. The axle had fractured at an internal void located along the axle radial centerline, approximately 15 inches from the wheelseat of the short axle segment. The mating fracture surfaces are shown in Figure 41 and Figure 42. The exposed void halves in the fracture surfaces were filled with debris consistent with post-derailment ground impact. This debris was removed during the examination.

Figures 41 and 42. Mating fracture surfaces of the axle received.

The fracture surface of the long axle segment, located approximately 32 inches from the wheelseat exhibited soot deposits and bluish heat tinting, consistent with exposure to fire. The inboard wheel plate also exhibited indications of fire exposure. Some rusting was observed in sporadic areas on the long axle shaft. The fracture surface exhibited a small outward lip on one side of the fracture surface.

The short axle segment was absent these indications of fire exposure. However, much of the fracture surface had been smeared and scraped consistent with post fracture batter.

Nondestructive Inspection and Group Exam Axle Sectioning

The axle fragments were inspected using ultrasonic testing (UT) by certified operators from Testing Technologies, Inc.[42] The length of the axle body was examined (a radial inspection) after the surfaces had been cleaned and prepared in order to facilitate contact with the UT transducers using a couplant. The UT operators used a 1 inch transducer at 2.25 MHz frequency, with typical amplifications of 55 – 77 dB, depending on the feature being inspected. Both axle segments were inspected by radial UT, and the edges of the drop on the transducer were marked consistent with the edges of the voids during this inspection.

The summary of the results is depicted on the axles in Figure 43. The open centerline void at the fracture surfaces was characterized as asymmetrical in shape based on the UT reflectance data. The larger axle segment contained two indications outboard of the exposed centerline void at the fracture surface. The UT personnel stated that the middle indication was approximately 3 inches long, located approximately midway between the fracture surface and wheel seat. The shorter axle segment contained one indication in addition to the centerline void at the fracture surface. This indication was approximately 1.5 inches in length, but only displayed approximately 10% loss of reflectance off the back wall.

42 Testing Technologies, Inc. is a non-destructive testing (NDT) service provider, located in Woodbridge, VA.

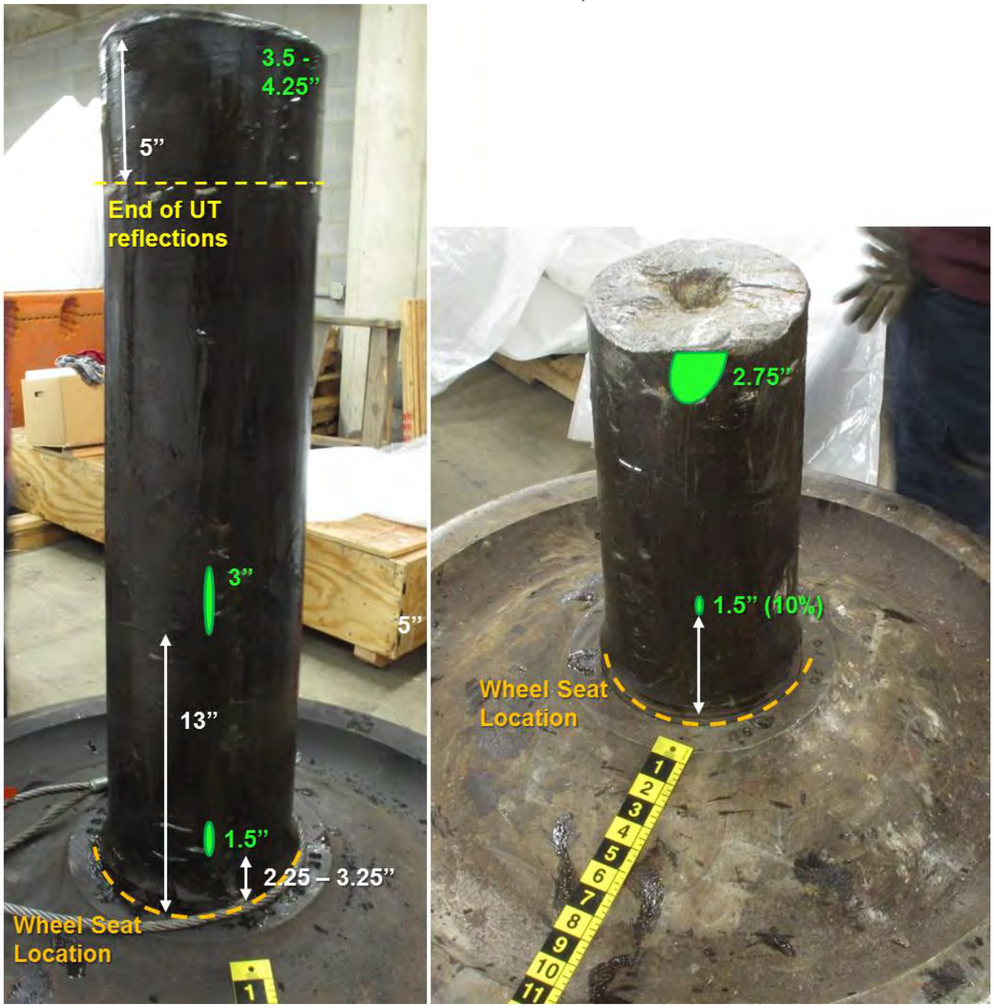


Figure 133 – The axle segments after UT NDT, with the green marks showing the relative locations and distances of the indications, based on the edge of the drop in UT transducer reflectance. The distances were relative to the wheel seat on the axle (dashed orange lines), or fracture surface.

The shorter axle segment was repositioned 90° to facilitate an UT inspection from the free end (an axial inspection). This inspection configuration was similar to the UT inspection prescribed by applicable AAR M-101 specification at the time of the axle manufacture (1998 revision).[43] However, the inspection at manufacture differs, among other issues, in that the three outboard bore holes present in the fracture axle are typically not yet machined before the UT inspection. The results from the axial UT inspection were deemed indeterminate by the inspecting personnel, who stated this was likely due to interference from the drilled cap screw holes (for securing the lock plate) and the rough texture and geometry of the back wall (the fracture surface).

43 The applicable specification for axle ultrasonic inspection, AAR M-101 (1998 revision), prescribed an axial end pulse-echo ultrasonic inspection using a 2.25 MHz frequency with quartz 1” square, quartz 1.125” round, or barium titanate 0.75 - 1.0” round transducers, at the discretion of the operator. Rejectable indications include those with amplitudes less than 40% full-screen height back wall reflection or greater.

After the UT inspections, the longer axle segment was repositioned to allow for sectioning. The axle segment was sectioned below the UT indication for the edge of the transducer drop (dashed yellow line in Figure 43). The fracture surface was then sectioned approximately 1 inch below the lowest surface point. The axle cross-section below the fracture surface is depicted in Figure 44. A portion of the void, approximately 1.25 inches by 0.75 inches, was visible. This axle portion was then cross-sectioned through the void, as depicted by the yellow line in Figure 44. Figure 45 shows the sectioned void from both mating halves of the axle fragment. The void at this cross-section was approximately 1 to 1.25 inches deep.

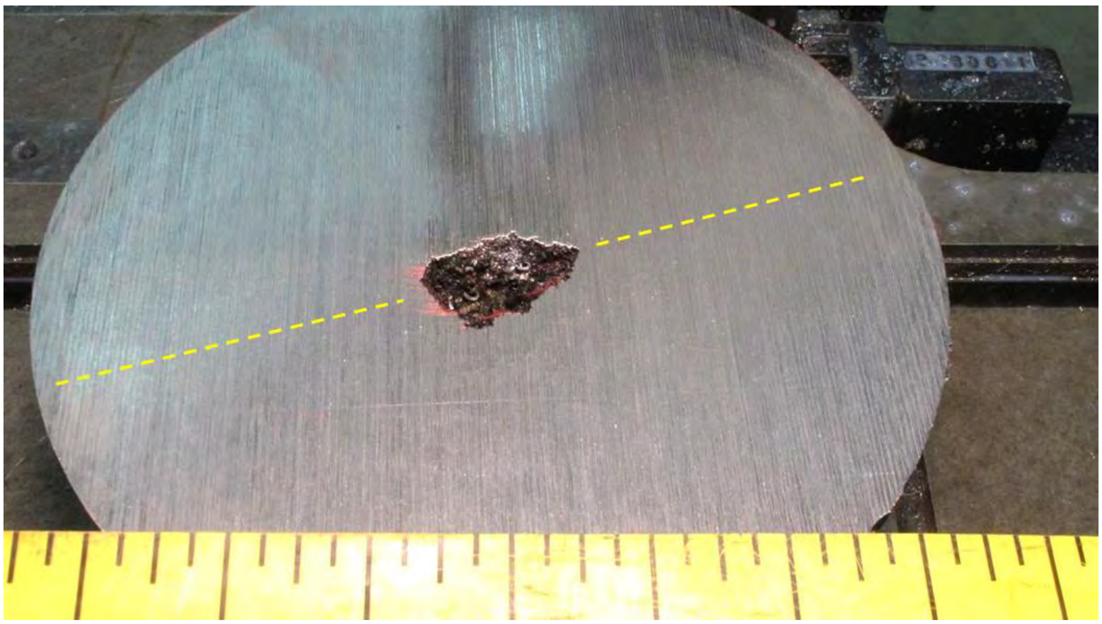


Figure 44 – The internal centerline void on the longer axle segment, after removal of the fracture surface (approximately 1 inch depth). The void measured 1.25” x 0.75”. The dashed line represents the cross-section shown in Figure 45.

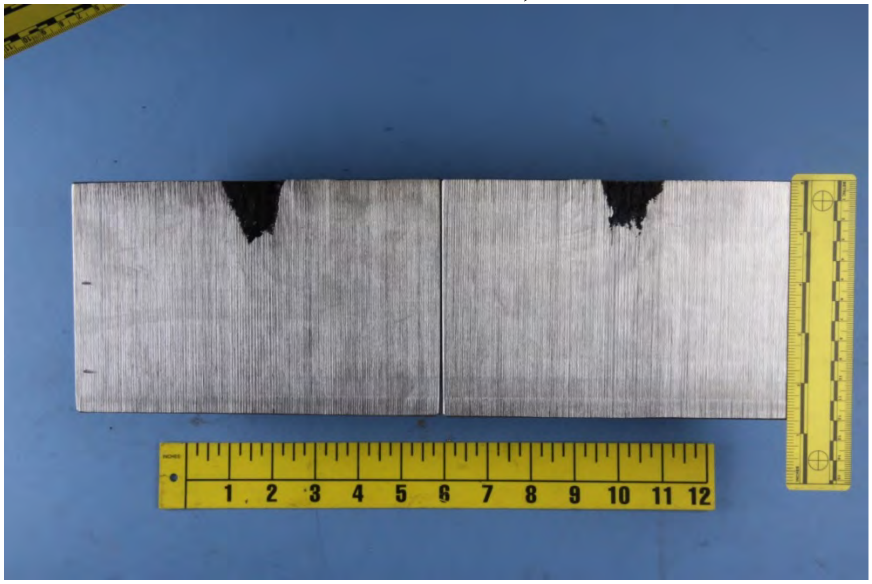


Figure 45 – The internal void from Figure 44 after sectioning down the middle.

The axle fracture surfaces were laser scanned using a FaroArm Quantum portable measurement probe and laser scanner. Using the GeoMagic 12 rendering software on the FaroArm, the surface normals were inverted and merged to reconstruct the centerline void. This void reconstruction is shown in Figure 63 (See Finite Element Modeling Study section of this report), the data from which was used for the Finite Element Modeling Study calculations.[44]

Axle Fracture Surface and Void Examination

The fracture surface of the longer axle segment is shown after sectioning in Figure 46. The fracture surface was cleaned using mild abrasion with soap solution, followed by ultrasonic cleaning in acetone.

44 See *NTSB DCA14MR004 Vehicle Performance Study Report*

Figure 46 – The longer axle segment fracture surface, after removal.

As labeled in Figure 47, approximately half of the fracture surface exhibited features consistent with progressive cracking. The morphology of the progressive region was consistent with cracks that initiated at the internal void and grew outward towards the axle surface. The ratchet marks on the fracture surface were consistent with multiple crack initiation sites and coalescence during crack propagation.

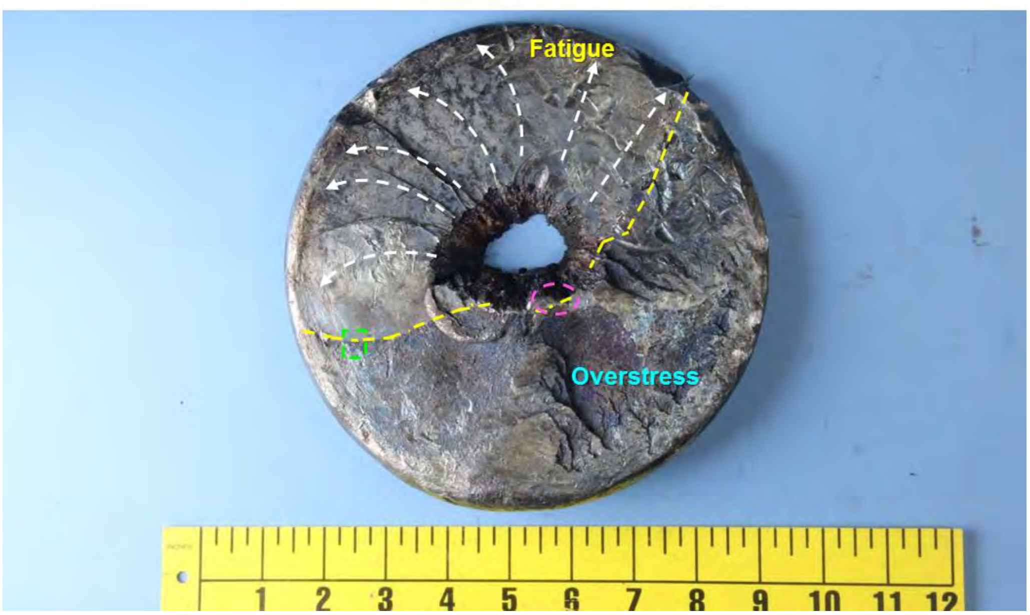


Figure 47 – The fracture surface from Figure 46, after cleaning, with the progressive (latter determined to be fatigue) and overstress areas labeled. The dashed line is the boundary between the progressive and overstress regions. The green dashed box is magnified in Figure 48, and the dashed oval is magnified in Figure 49.

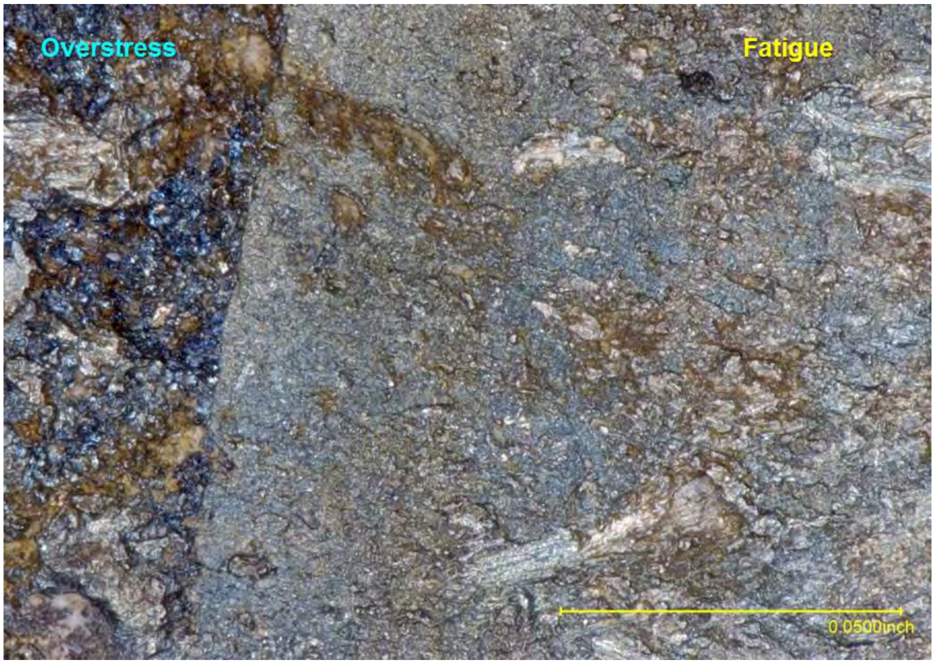


Figure 48 – Edge of the progressive crack on the axle fracture surface.

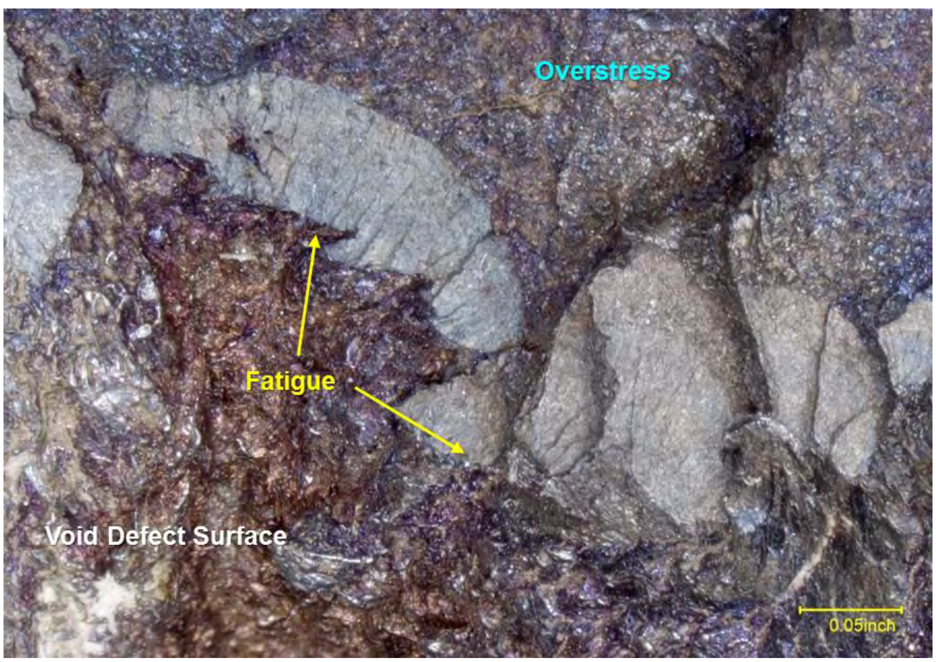


Figure 49 – Small fatigue cracks that had initiated and grew from the internal void in the axle, adjacent the void approximately 180° from the primary progressive fracture in Figure 47.

The remaining half of the fracture surface (from the long axle segment) exhibited an appearance consistent with overstress fracture. Figure 48 shows the edge of the progressive fracture, in contrast with the overstress regions. The progressive region appeared lighter in color and was generally flatter, oriented perpendicular to the axle length direction. Some faint crack arrest marks were visible in the progressive region. The overstress region exhibited rougher, tortuous surface texture. In addition, the heat tint coloring was more pronounced, with darker blues.

Much of the fracture surface had been battered, consistent with post-fracture damage from the derailment. Selected areas of the long axle segment fracture surface were relatively undamaged, such as depicted in Figure 49. This area, opposite the large progressive fracture region, contained small progressive cracks that had initiated at the centerline void. These small thumbnail-shaped cracks exhibited ratchet marks consistent with multiple crack initiation.

Examination in a scanning electron microscope (SEM) revealed fatigue striations present in the progressive fracture areas of the fracture surface (see Figure 50 and Figure 51). The striations emanated outward from the centerline void. No indications of features consistent with other fracture modes were found in the fatigue regions of the fracture surface.

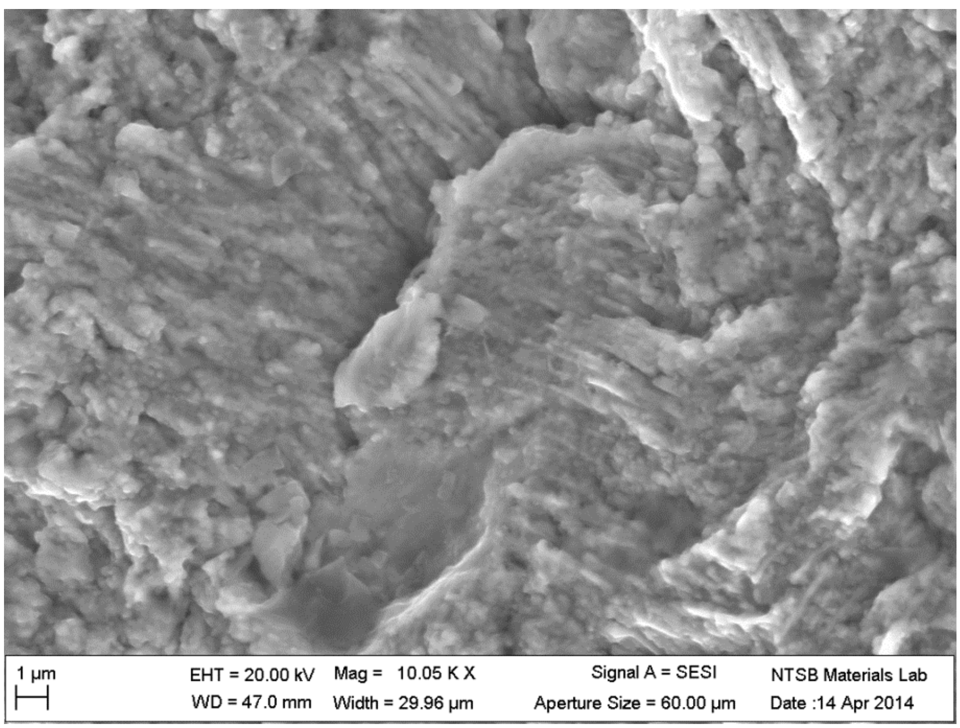


Figure 50 – SE micrograph of oxidized fatigue striations on the long axle fracture surface.

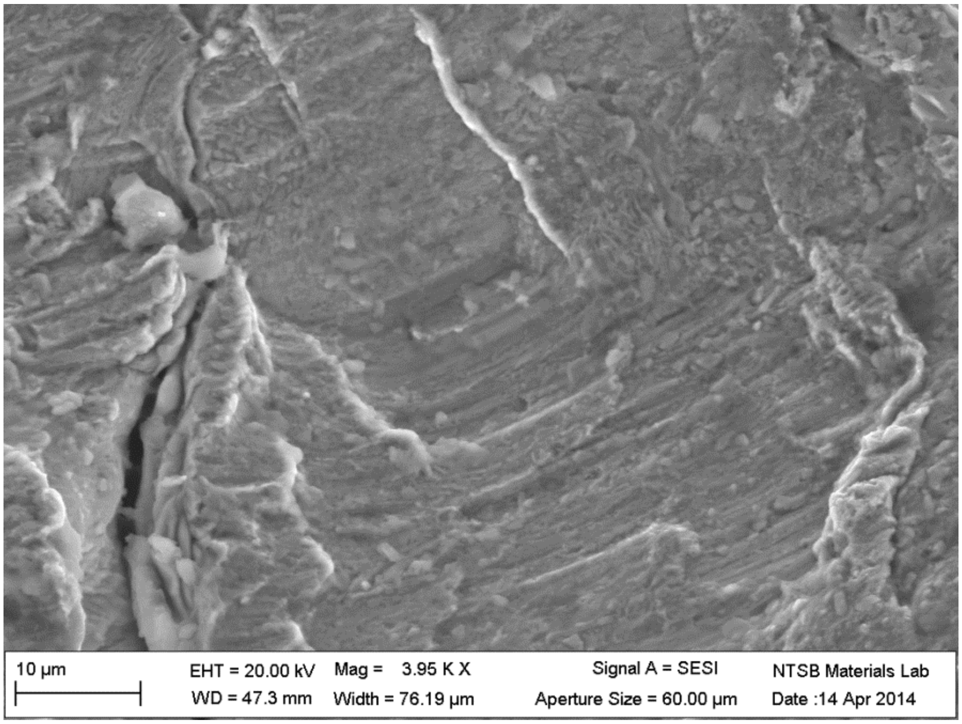


Figure 51 – Secondary electron (SE) micrograph of fatigue striations on the small progressive cracks adjacent to the void, depicted in Figure 49.

The surface of the centerline void was examined in a SEM, as illustrated in Figure 52 and Figure 53. The surfaces of the void consisted of deep valleys protruding into the axle material, with rounded, smoothed peaks. Much of the surface of the void exhibited electron-charging effects in the SEM, consistent with non-conductive material (typically non-metallic). Figure 53 shows a closer view of the void surface, exhibiting blocky non-metallic phases. Inspection of these phases using energy dispersive x-ray spectroscopy (EDS) revealed aluminum and silicon oxides. The other script-shaped surface features exhibited compositions consistent with the remainder of the void surface.

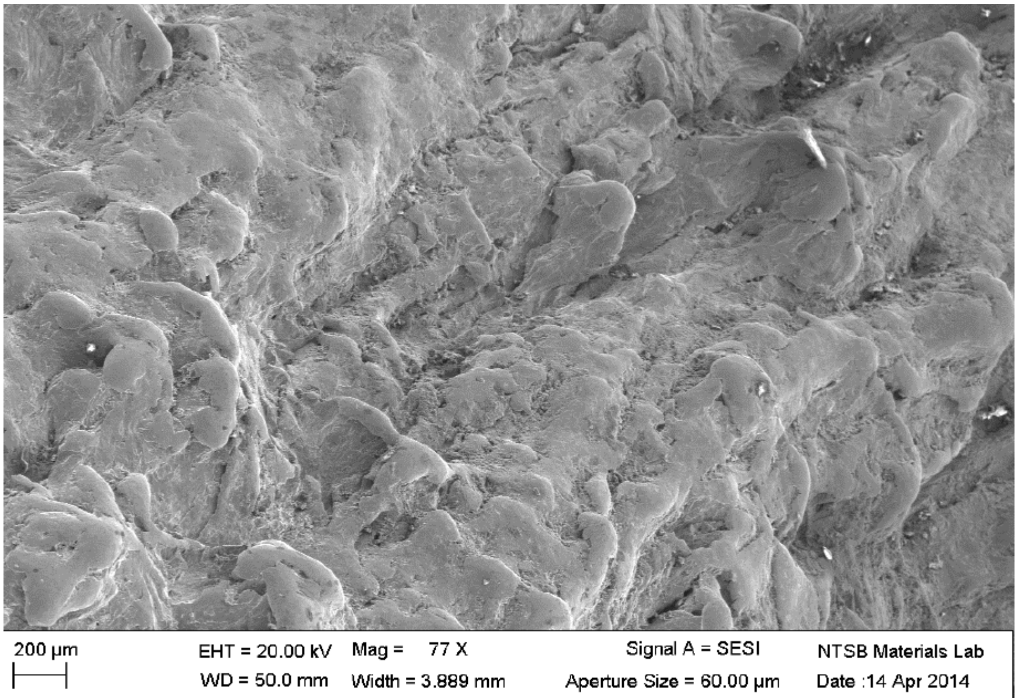


Figure 52 – SE micrograph of the internal void surface, showing rounded, rippled edges.

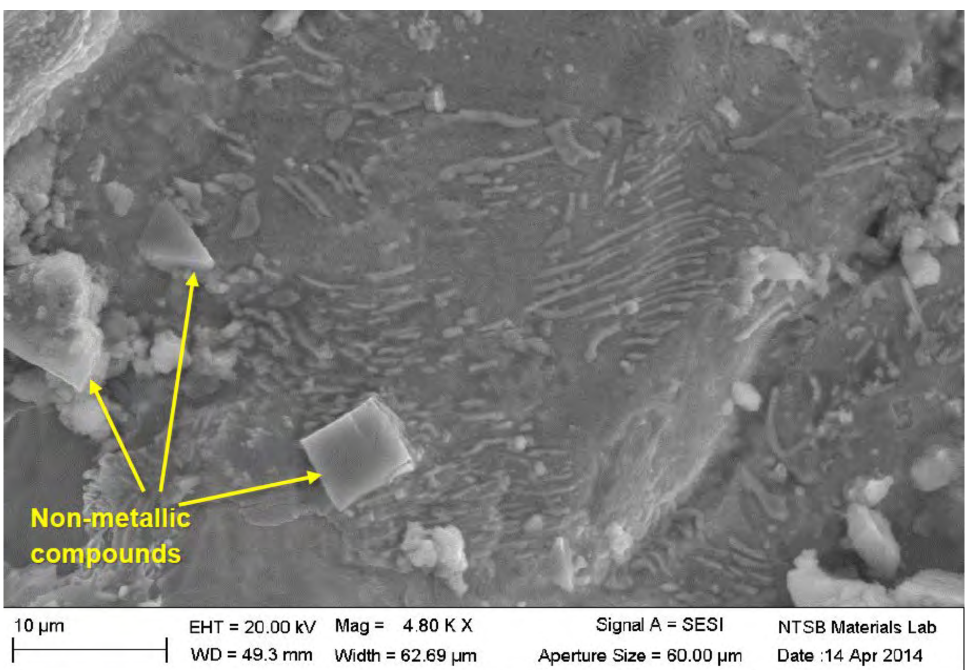


Figure 53 – SE micrograph of a closer view of the internal void surface.

Examination of Additional Internal Indications

On July 28, 2014, the remainder of the axle was sectioned at Standard Steel, LLC in Burnham, PA. The axle fragments had been removed from the wheels, were inspected using a longitudinal ultrasonic inspection, and were sectioned longitudinally along the centerline to determine if other void indications were present inside the axle. Ultrasonic inspection performed at Standard Steel found one indication on the short axle fragment.

Figure 54 and Figure 55 show the voids observed after cross sectioning the axle fragments. The short axle fragment contained three voids, and the long axle fragment exhibited two voids—these voids were observable to the unaided eye. The second void from the wheel seat journal on the short axle segment (Figure 54) was consistent with the location of the observed indication from the ultrasonic inspection.

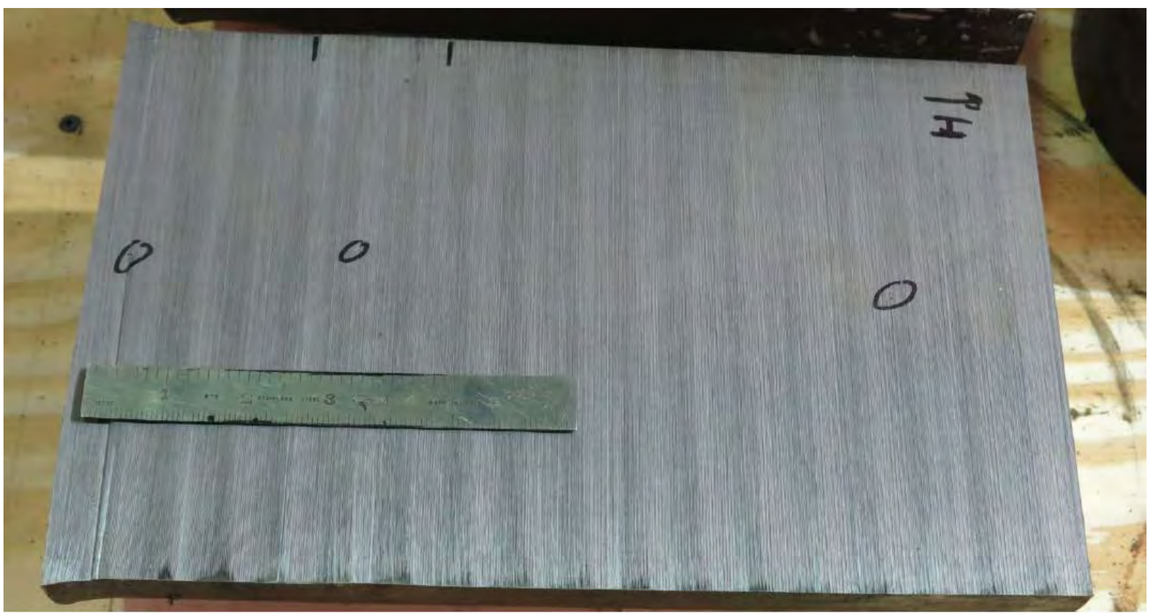


Figure 54 – Cross section of the short side axle fragment, showing three small voids along the centerline.

Figure 55 – Cross section of the long side axle fragment, showing two small voids along the centerline.

All of these voids are shown magnified in Figure 47, ordered from the near the outboard wheel seat journal on the short axle segment (left in Figure 45) to near the wheel seat journal outboard on the long axle segment. All of these voids were generally flattened, oriented along the forging (longitudinal) direction. All of the voids were considerably smaller in volume than the large centerline void at the fracture surface—the largest void was approximately 0.2 inches in the longest direction, located along the centerline location of the axle.

One of the voids (shown in Figure 56c), was sectioned, mounted, polished and etched. This void is shown in Figure 57, with the etchant having revealed the grain flow about the exposed voids. No changes to the microstructure were observed adjacent to the voids (see Figure 58). Figure 59 shows a closer view of the axle microstructure. The microstructure consisted of a fine pearlite structure, with proeutectoid ferrite dispersed between the pearlite colonies. This microstructure morphology was consistent throughout all the areas inspected.

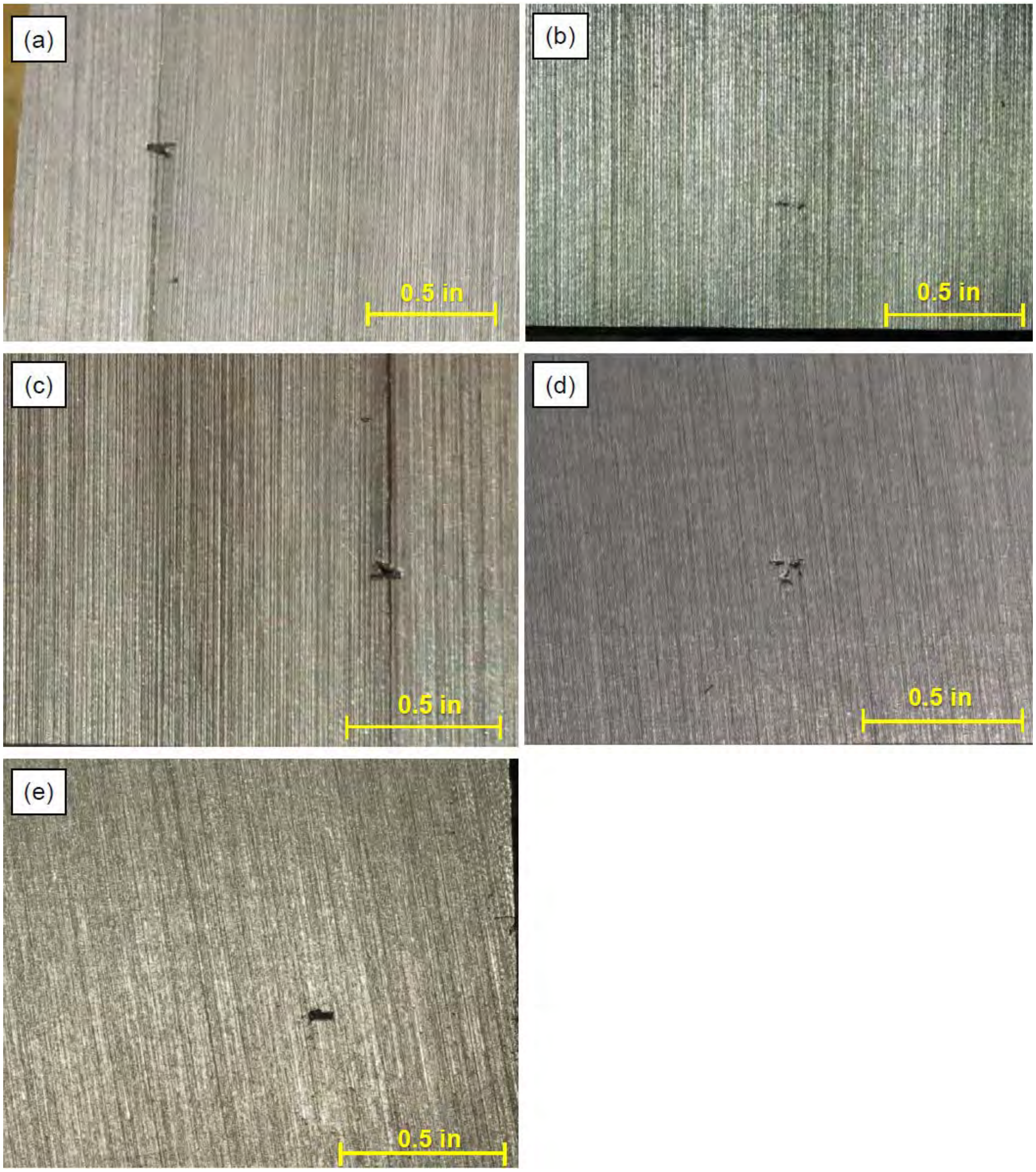


Figure 56 – The five cross-sectioned voids along the axle center lines observed in Figures 54 and 55.

Figure 57 – Optical metallograph of a cross-section through a small void in the centerline of the axle (etched with 2% Nital). The boxed area is shown in Figure 58.

Figure 58 – Optical metallograph showing the microstructure of the axle, showing a small void, the boxed area in Figure 57 (etched with 2% Nital).

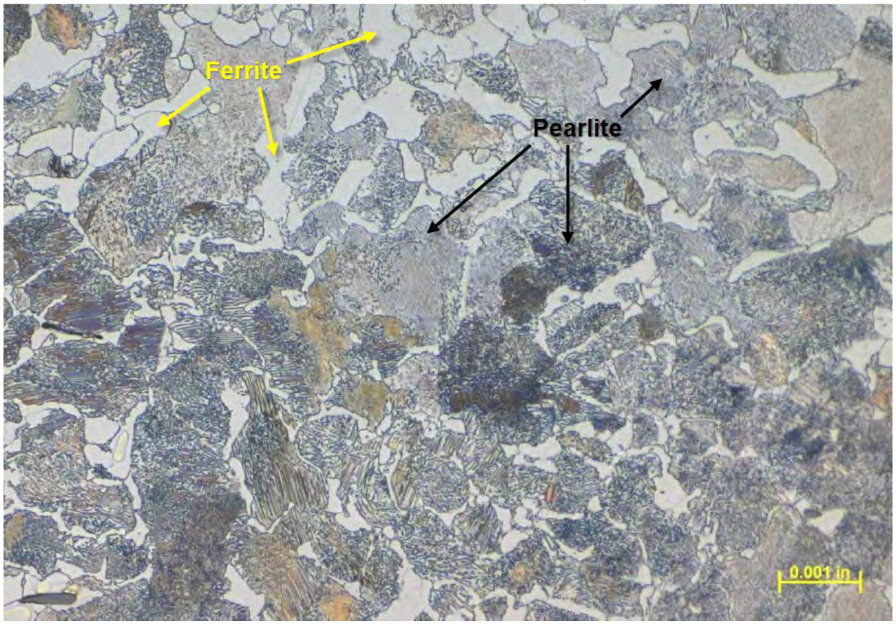


Figure 59 – Optical metallograph showing the microstructure of the axle, with colored pearlite between colorless ferrite (etched with 2% Nital).

When inspected using a SEM, smaller areas of non-metallic material were observed along the periphery of the void surface. One such area is illustrated in Figure 60. This material was found to be consistent with aluminum oxide.

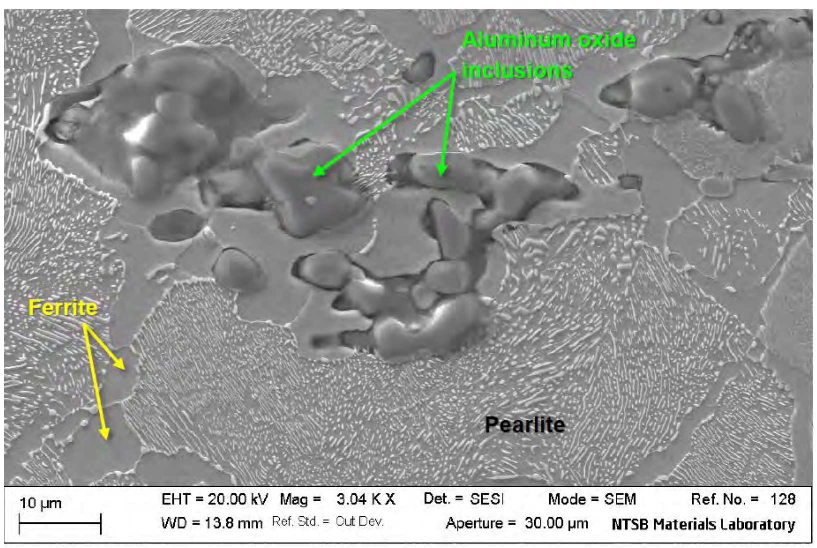


Figure 60– SE micrograph of small inclusions near the void in Figure 58. These inclusions were consistent with aluminum oxide.

Axle Material Properties

The journal from the shorter axle fragment was sectioned and sent to Lehigh Testing Laboratories, Inc. for mechanical and chemical testing.[45] Six specimens were machined from the outer areas of the journal. Each specimen was tensile tested and chemically inspected to determine the material composition. The average chemical composition is shown in Table 10. All specimens were consistent with the prescribed composition from AAR M-101-90 (1998 Rev). All the specimens exhibited compositions consistent with UNS G10500, G10530, and G10550; one of the specimens was also consistent with UNS G10490.

Table 10 – Average chemical composition (in wt. %) of the short axle fragment journal, compared with requirements for AAR M101-90 Grade F (1998 rev), UNS G10500, UNS10530, UNS G10550, and UNS G10490.

Standard	C	Mn	Si	P	S	Cu	Ti	Cr	N
Axle Avg.	0.54	0.79	0.29	0.016	0.032	0.27	0.022	0.12	0.10
AAR M101	0.45-0.59	0.60-0.90	>0.15	<0.045	<0.050				
UNS G10500	0.48-0.55	0.60-0.90		<0.040	<0.050				
UNS G10530	0.48-0.55	0.70-1.00		<0.040	<0.050				
UNS G10550	0.50-0.60	0.60-0.90		<0.040	<0.050				
UNS G10490	0.46-0.53	0.60-0.90		<0.040	<0.050				

The mechanical properties of all the tensile specimens met the tensile requirements of AAR M-101-90, Grade F (1998 Rev). The average mechanical properties are listed in Table 11[46].

Table 11 – Average mechanical properties from tensile testing of the short axle fragment journal, compared with the minimum requirements for AAR M101-90 Grade F (1998 rev).

Standard	Upper Yield Point (ksi)	Lower Yield Point (ksi)	Ultimate Tensile Strength (ksi)	Yield Point Elongation (%)	Elongation in 2 in. (%)	Reduction in Area (%)
Axle Avg.	55.6	52.6	99.7	9.0	25	48
AAR M101		50	88		22	37

45 Lehigh Testing Laboratories, Inc. is a materials testing, inspection, and failure analysis laboratory located in New Castle, DE.
46 Full details of the testing results are shown in the Materials Lab factual Report in NTSB's docket for DCA14MR004.

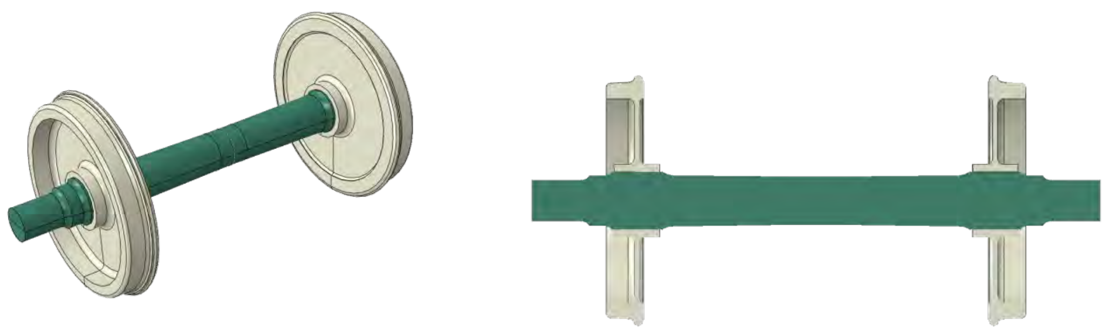
Finite Element Modeling Study[47]

A 3D finite element model of the accident train axle assembly was constructed based on drawings and 3D laser scan data. Loads corresponding to design loads were applied to the structure, as well as boundary conditions simulating wheel-rail interaction. Multiple bending directions were analyzed to identify the worst-case scenario in terms of local stress concentration. Both of the cases with and without the internal void were analyzed, and the results were compared to show the effect of the void on local stress concentration. The finite element modeling was carried out using Abaqus 6.14-1.

Geometry

Wheelset

The finite element model of the wheelset contained the axle and the two mounted wheels. The wheelset in the accident train was identified to have an AAR Class K (6 ½ x 9) axle and 36-inch, AAR 1-B, wide flange wheels.[48] The axle finite element model was created based on the AAR standard dimensions.[49] The wheel model was created based on the AAR standard dimensions with simplified straight flanges. Figures 61 and 62 show the isometric and plan view of the created axle assembly model in Abaqus/CAE.



Figures 61 and 62. The isometric and plan view of the created axle assembly.

Void geometry

Investigation of the fractured axle revealed an internal void. The fractured axle was sectioned and scanned using a FaroArm 3D scanner. The point cloud data from the scan was first converted to smooth 3D surfaces using Geomagic Studio and then imported into Abaqus/CAE to create a 3D model of the axle with the internal void. Figure 63 shows the surfaces composing the internal void, and figure 64 shows the section view of the axle with the internal void visible.

47 Finite Element modeling as a study makes a set of assumptions
48 Mechanical Group Factual Report, Accident DCA14MR004, National Transportation Safety Board, Washington, DC, 2014.
49 Association of American Railroads, Manual of Standard and Recommended Practices, Wheels and Axles Manual, 2011.

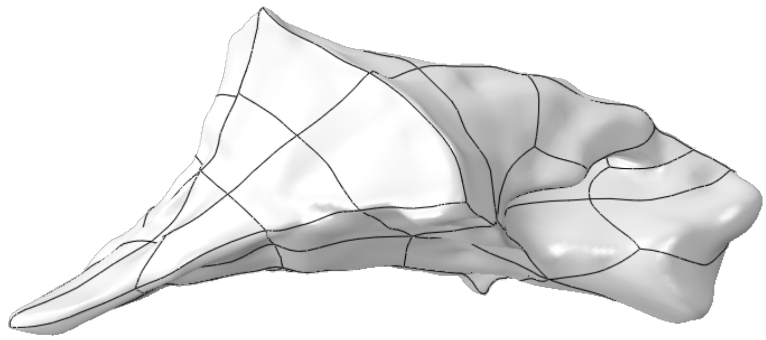


Figure 63 The surfaces composing the internal void.

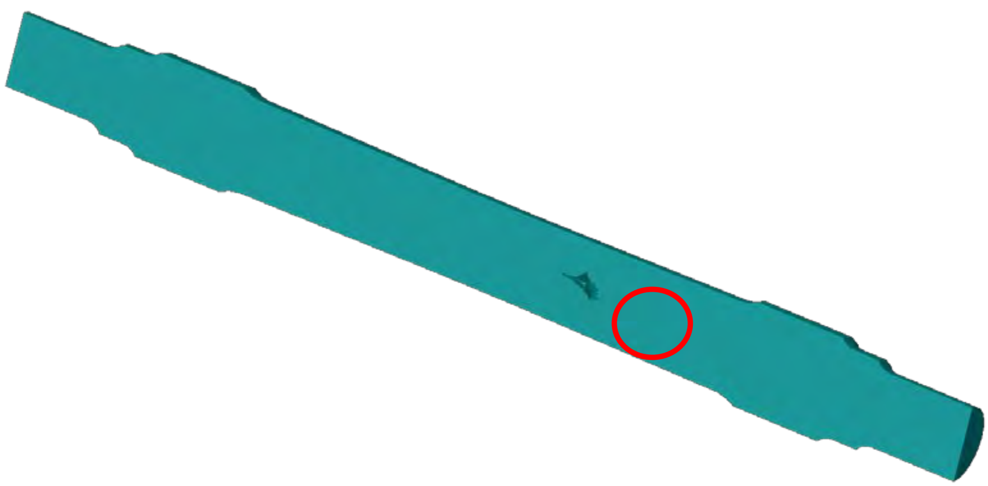


Figure 64. The is a section view of the axle with the internal void visible. The void in its likely orientation and position are circled (red) in the figure.

The relative position of the void in the longitudinal direction was determined based on measurement and is shown in Figure 65.[50] The orientation of the void would rotate with the axle. A view of the void in the cross-section plane is shown in Figure 66. Some characteristic dimensions of the axle and the void are also shown in Figures 65 and 66.

50 Materials Laboratory Factual Report 14-055, Accident DCA14MR004, National Transportation Safety Board, Washington, DC, 2014.

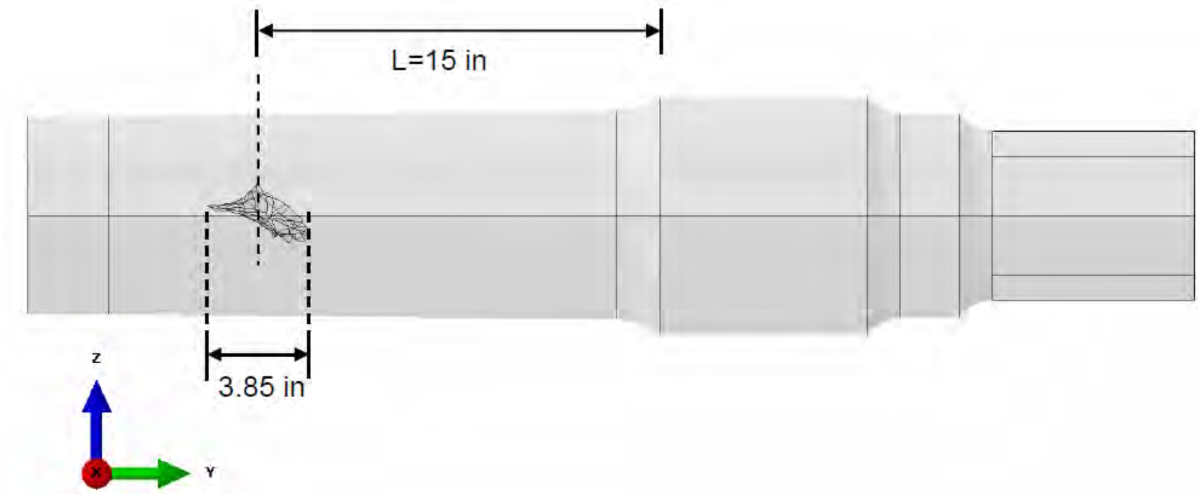


Figure 65. Relative position of the void in the longitudinal direction.

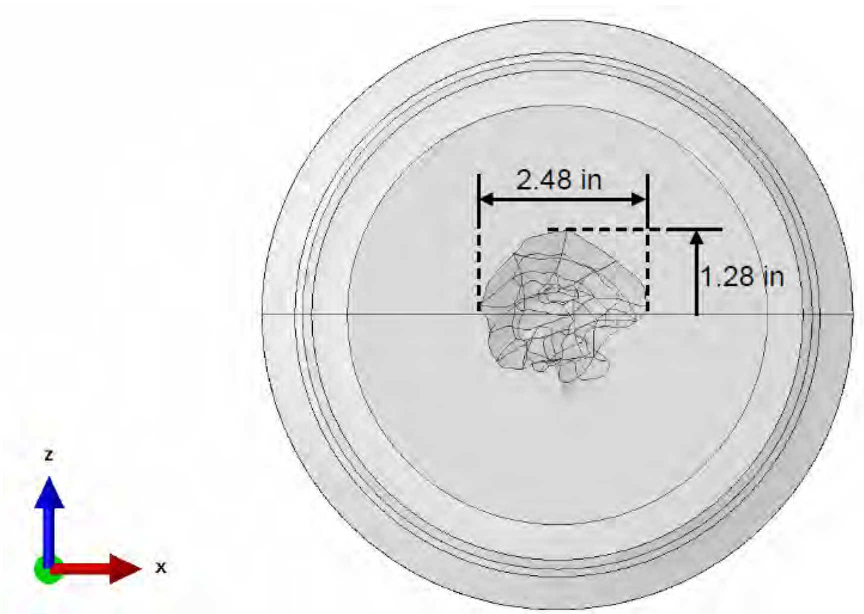


Figure 66 A view of the void in the cross-section plane.

Material properties

Both the axle and the wheels were made of carbon steel. Only elastic properties were needed for the purpose of this study. Specifically, Young's modulus for carbon steel was taken as 29,000 ksi, and Poisson's ratio was taken as 0.3.

Mesh

The axle was meshed with quadratic tetrahedral elements (C3D10 in Abaqus). Tetrahedral elements were necessary for meshing the irregular geometry of the axle with internal void. The wheels were meshed with linear reduced integration brick elements (C3D8R). The wheels only required a coarse mesh as deformation of the wheel was not of interest for this study. Figures 67 and 68 show the finite element mesh on the global structure and in the vicinity

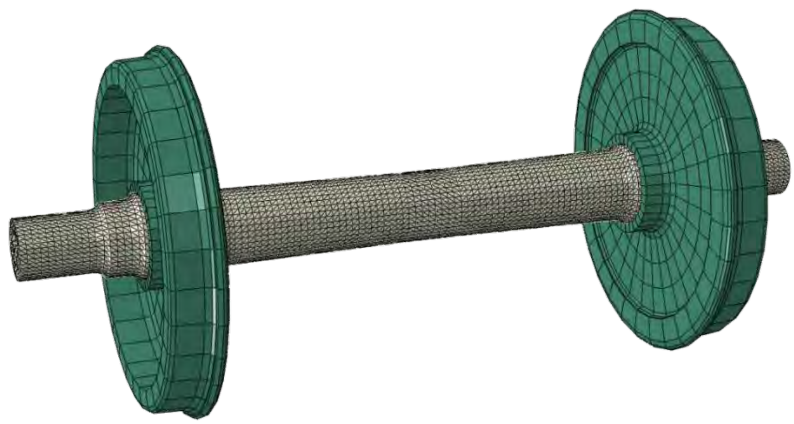


Figure 67. The finite element mesh on the global structure.

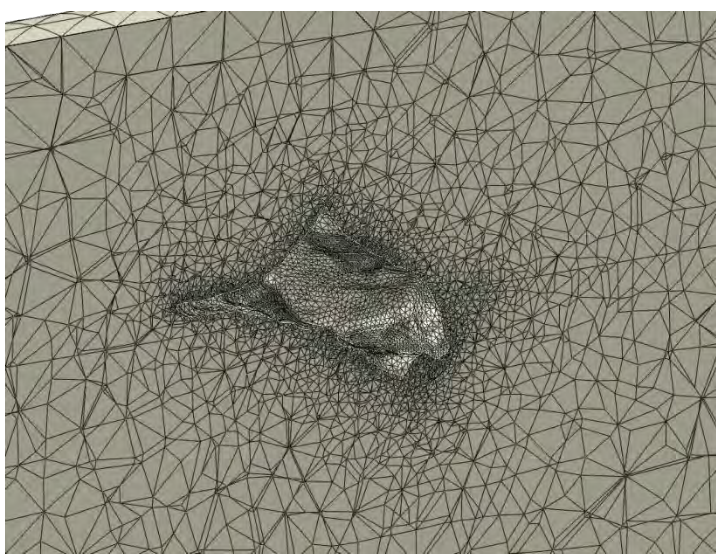


Figure 68. The finite element mesh in the vicinity of the void.

Mesh resolution increased considerably in order to capture the complex geometry associated with the void. The mesh statistics are summarized in Table 12 and show the increased model size with the internal void modeled. Mesh convergence studies were performed for both models, and the mesh size presented was chosen based on both accuracy and efficiency.

Table 12. Mesh statistics			
Model	Total Number of Elements	Typical Mesh Dimension	Smallest Mesh Dimension
Without Void	102,830	0.7 inch	0.7 inch
With Void	252,027	0.7 inch	0.03 inch

Loads and boundary conditions

Two types of loading were considered based on published studies.[51] The first load is a vertical force of 35,750 lbs. evenly distributed on the journal surfaces on both ends of the axle. This load represents the gross rail load (GRL) of 286,000 lbs. The second load is a lateral force of 8,000 lbs. distributed over the axle end face. This load represented curving forces in service.[52] The two loads were applied to the structure in two separate loading steps. The load associated with the wheel press fit on the axle was not included in the analysis since the wheelseat region was not of primary interest of this study. Instead, the wheel was rigidly constrained to the axle at the wheelseat.

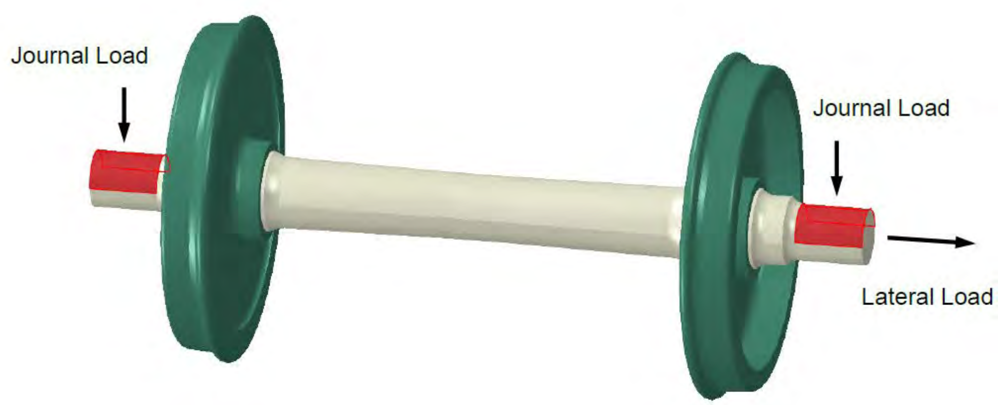


Figure 69. The graphic representation of the applied loads.

The wheels were constrained in a way to simulate wheel-track interaction. Specifically, contact between wheel and track was approximated to a point at the bottom of the wheel, where the structure is constrained for vertical motion. One wheel was also constrained horizontally at the bottom flange to resist the applied lateral force. The wheels were allowed to rotate as a result of the

51 C.P. Lonsdale, G.E. Dahlman, S.L. Dedmon, J.M. Pilch, and J.M. Galbraith, Continuing Efforts to Improve Axle Performance in Heavy haul Service, 15th International Wheelset Congress, Prague, Czech Republic, 2007.

52 C.P. Lonsdale, B.T. Tusa, and S.L. Dedmon, Radial Ultrasonic Testing of Freight Car Axles, ASME/IEEE Joint Rail Conference & Internal Combustion Engine Spring Technical Conference, Pueblo, CO, 2007.

bending of the axle. This approximation did not account for the more complex aspects of wheel-track interaction, such as finite contact area and relative sliding, but was sufficient for the current study focusing on the axle. The structure was also constrained for the rigid body motion of wheel spinning.

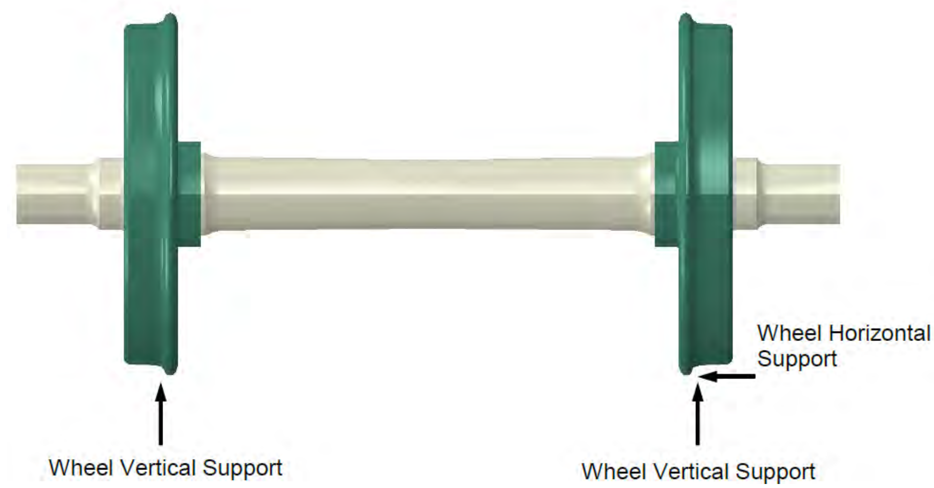
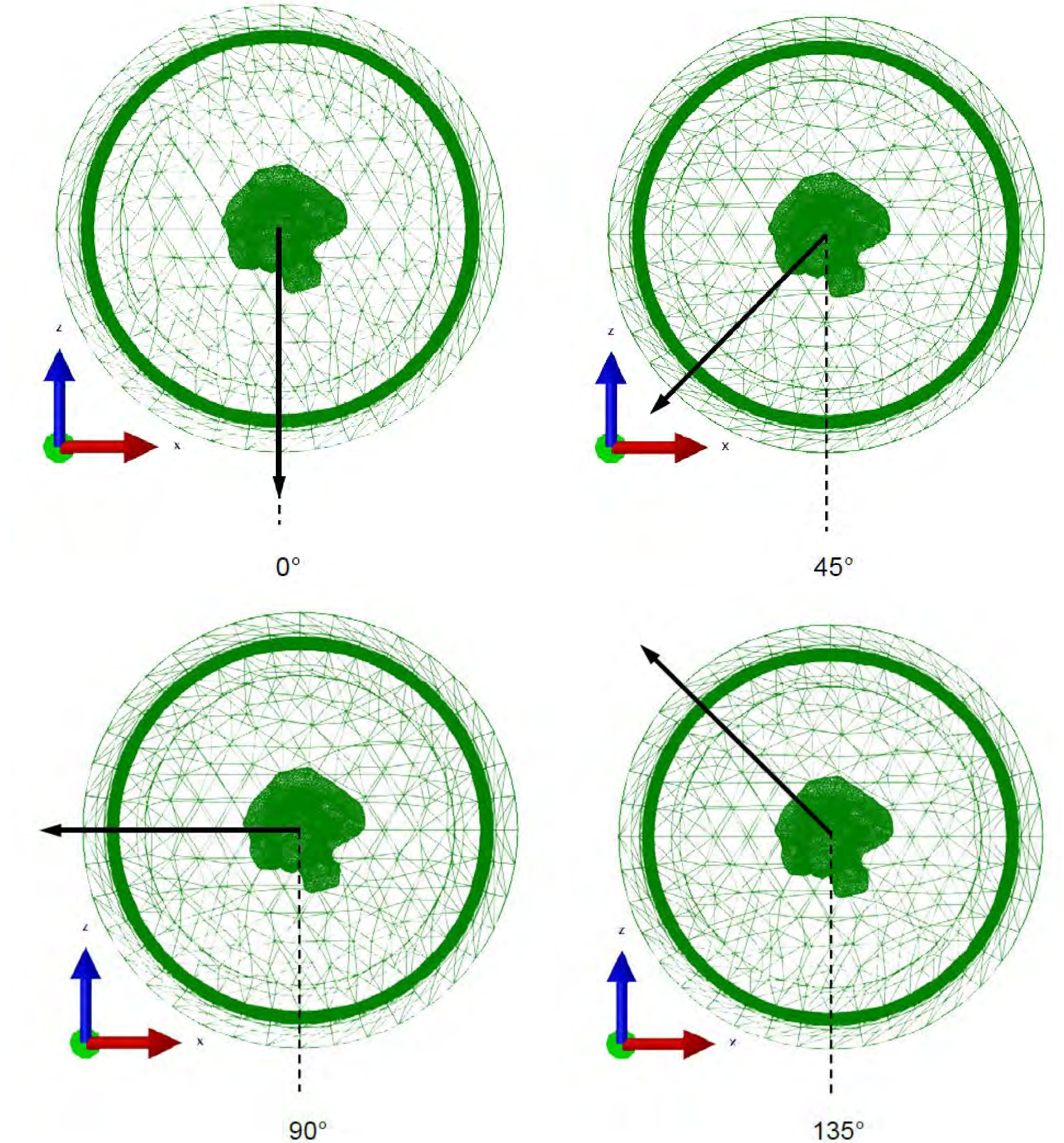


Figure 70. The applied boundary conditions.

For the case without the internal defect, the structure was rotationally symmetric with respect to the longitudinal axis, and hence it was sufficient for this analysis to consider only one bending direction. For the case with the internal defect, the symmetry was lost and different bending directions needed to be analyzed. Eight bending scenarios were analyzed in this study, and the associated bending directions are shown in figure 71. The angle that was used to identify the directions was measured counterclockwise from the negative global z-direction of the model. For each bending scenario the load and support location were rotated about the axle axis accordingly (the next eight images).


z
x
0°
z
x
45°
z
x
90°
z
x
135°

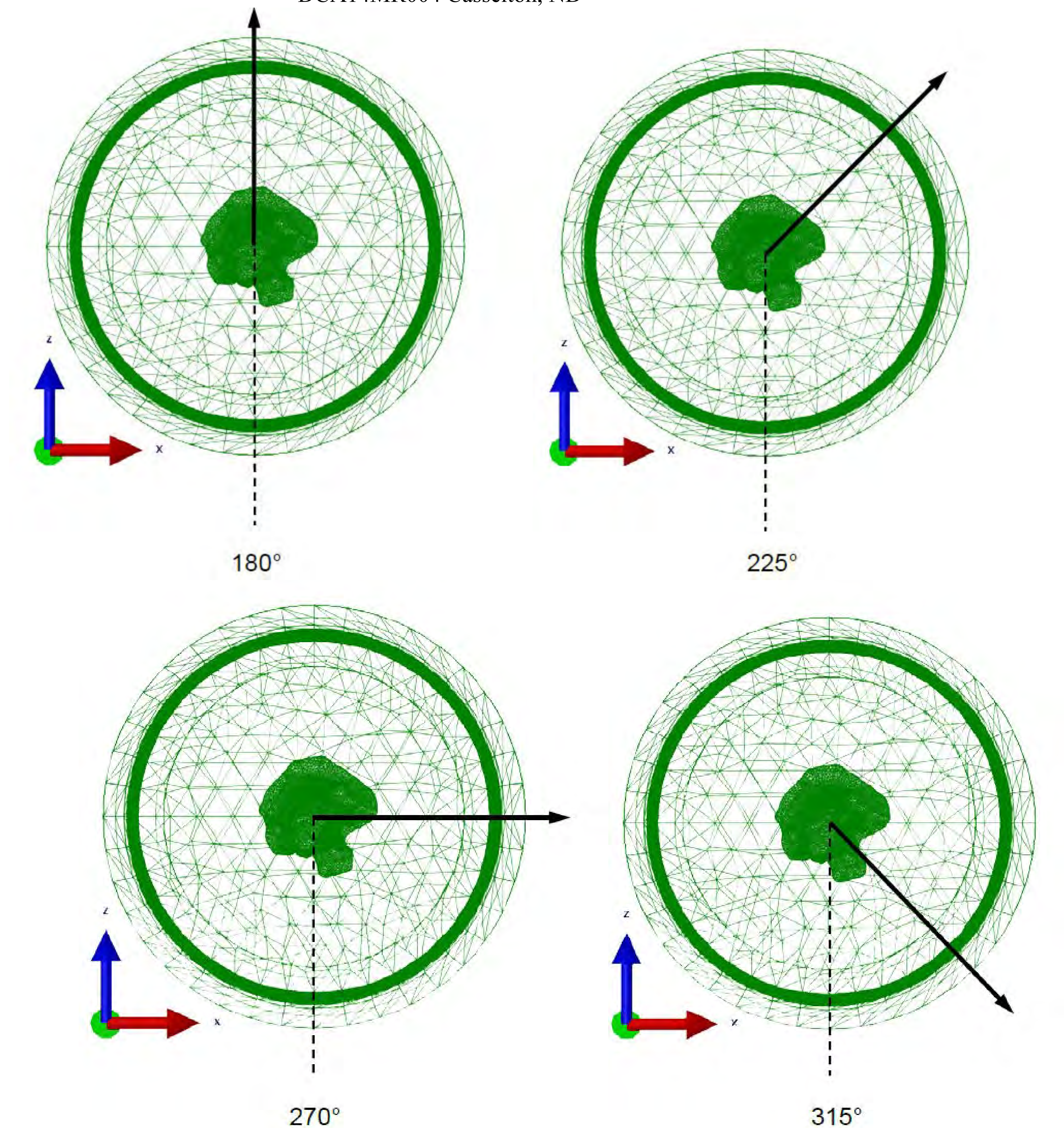


Figure 71. The eight analyzed bending scenarios.

Output

The case without the internal void was analyzed first. Figure 72 shows the deformed axle assembly with deformation magnified 50 times for better visualization.

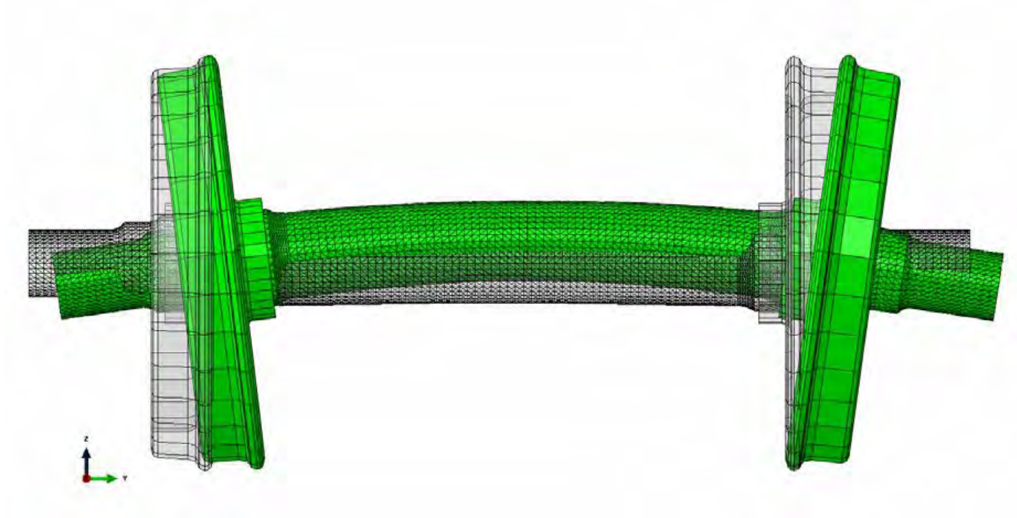


Figure 72. The deformed axle assembly with deformation magnified 50 times.

Figures 73 and 74 show the contours of the Mises stress and the bending stress (σ_{yy} component), respectively. Peak stress was observed at the inboard journal fillet on the side of the lateral load, and the peak tensile stress was about 14.3 ksi[53] in magnitude. Both the deformed shape and the stress distribution were consistent with that of a bent axle with simple supports at wheel locations. The stress distribution and magnitude were also consistent with data previously reported.[54]

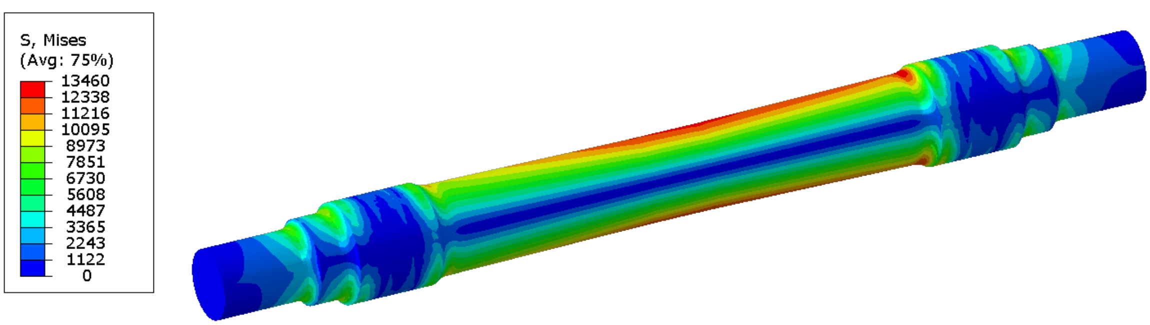


Figure 73. Contours of Mises stress pounds per square inch (:psi) on the axle, for the case without internal void.

53 The term ksi refers to kilo pound per square inch.

54 C.P. Lonsdale, G.E. Dahlman, S.L. Dedmon, J.M. Pilch, and J.M. Galbraith, Continuing Efforts to Improve Axle Performance in Heavy haul Service, 15th International Wheelset Congress, Prague, Czech Republic, 2007.

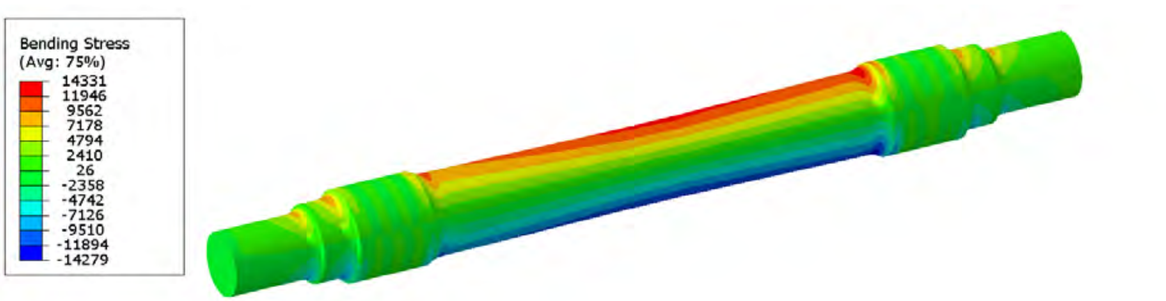


Figure 74. Contours of bending stress (psi) on the axle, for the case without internal void.

The case with the internal void was analyzed next. The previously mentioned 8 bending scenarios were analyzed sequentially. Figures 75 and 76 show the cut view of the Mises stress contour plot of the 0-degree bending case.

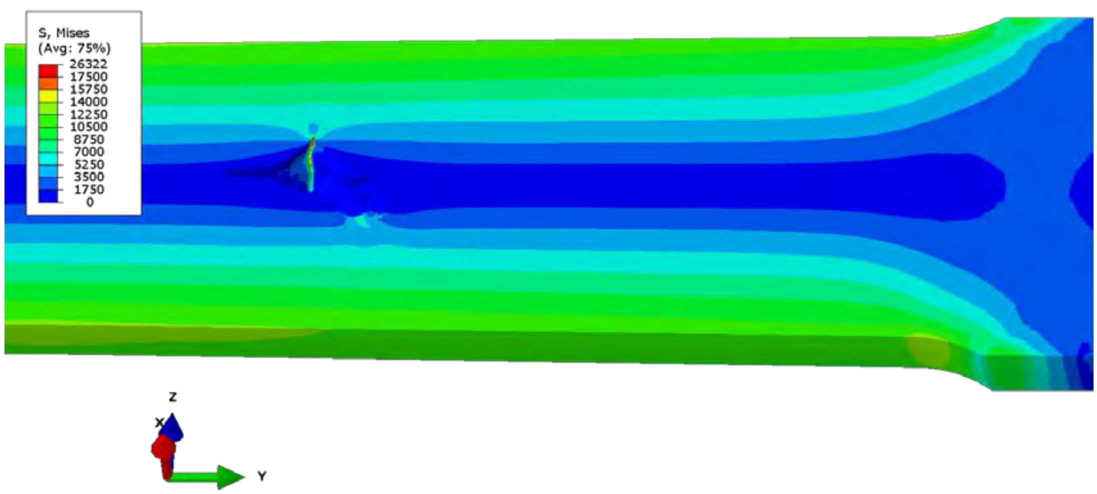


Figure 75. Longitudinal oblique cut view of Mises stress (psi) contour of 0-degree bending case.

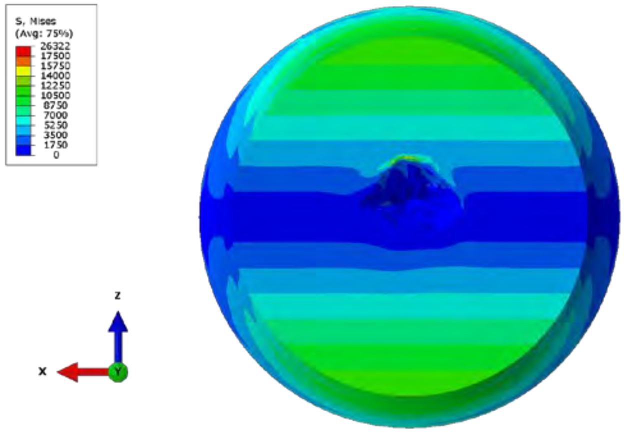


Figure 76. Cross-sectional view of Mises stress (psi) contour of 0-degree bending case.

Figures 77 and 78 plot the same stress of the same case on the void surface.

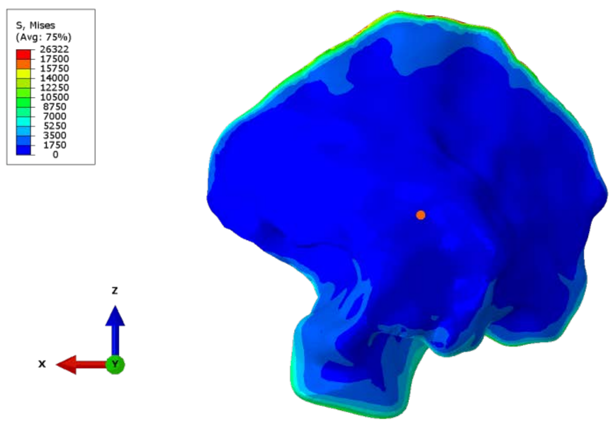
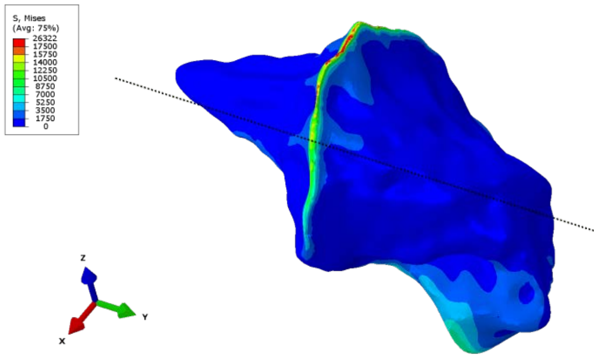


Figure 77. Mises stress (psi) contour on the void surface, 0-degree bending case, end view, with axle centerline location marked.



7

Figure 78. Mises stress (psi) contour on the void surface, 0-degree bending case, isometric view, with axle centerline shown.

Figures 79 through 82 show the corresponding bending stress contours. Local stress exceeding 17.5 ksi, shown in red, can be found on the “ridge” of the surface furthest away from the bending neutral axis, and the peak value for Mises stress was approximately 26.3 ksi, which is nearly twice as large as the peak Mises stress found in the case without the internal void. The 17.5 ksi value was taken from a 1930’s experimental study’ a full scale fatigue test on an axle. That study determined a stress level exceeding 17.5 ksi has a greater probability of fatigue crack initiation in axles[55]. More current full scale axle fatigue test data was not available.

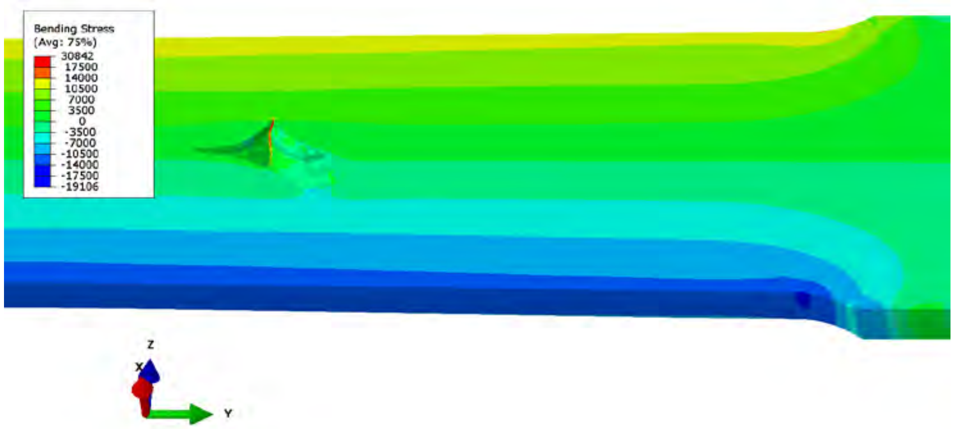


Figure 79. Longitudinal oblique cut view of bending stress (psi) contour of 0-degree bending case.

55 C.P. Lonsdale, G.E. Dahlman, S.L. Dedmon, J.M. Pilch, and J.M. Galbraith, Continuing Efforts to Improve Axle Performance in Heavy haul Service, 15th International Wheelset Congress, Prague, Czech Republic, 2007.

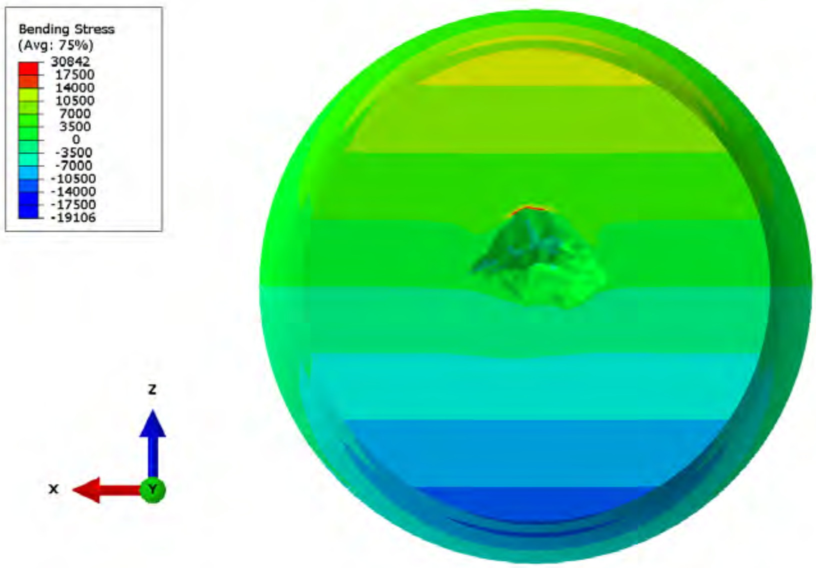


Figure 80. Cross-sectional view of bending stress (psi) contour of 0-degree bending case.

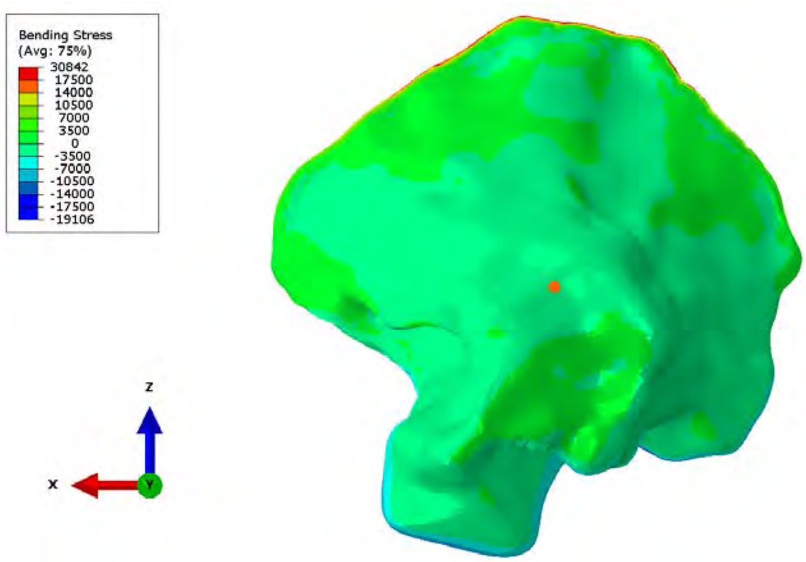


Figure 81. Bending stress (psi) contour on the void surface, 0-degree bending case, end view, with axle centerline location marked.

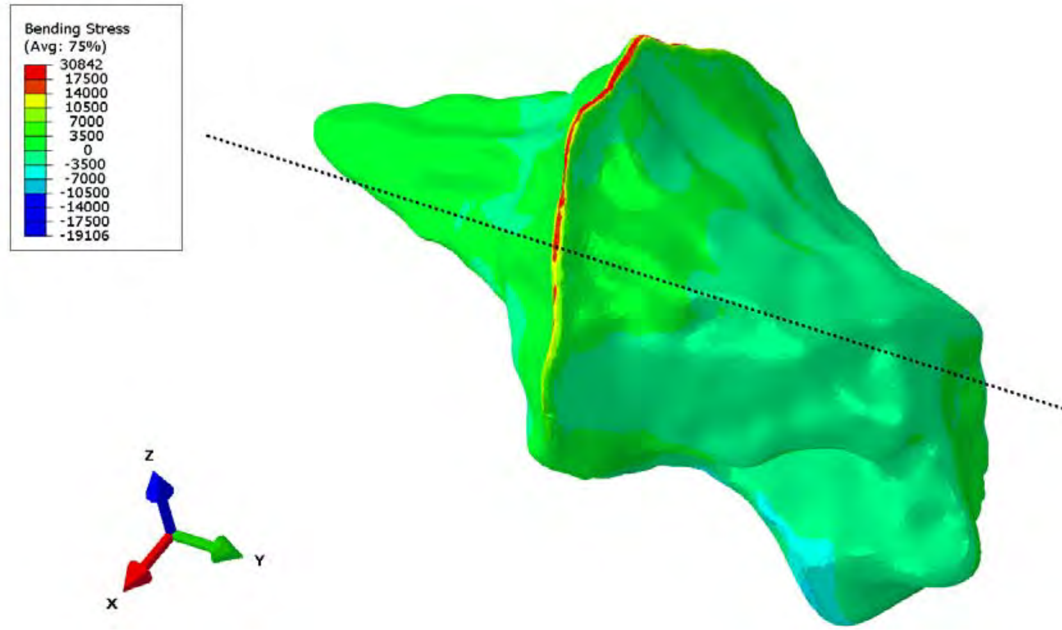


Figure 82. Bending stress (psi) contour on the void surface, 0-degree bending case, isometric view, with axle centerline shown.

Figures 83 and 84 show the Mises stress contour on the void surface overlaid from all 8 bending cases, where maximum stress values from all 8 bending cases are shown in a single plot. The same 17.5 ksi threshold was used for the plot legend.

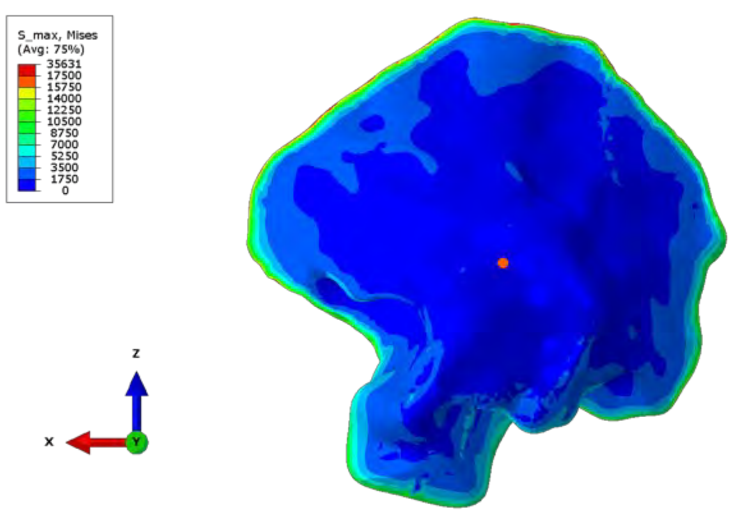


Figure 83. Mises stress (psi) contour on the void surface, overlaid plot from all 8 bending scenarios, end view, with axle centerline location marked.

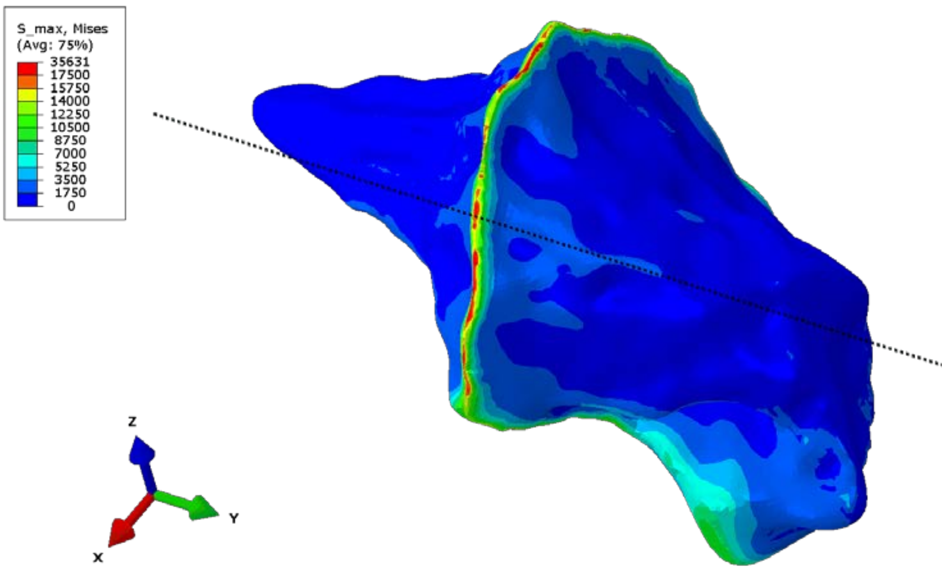


Figure 84. Mises stress (psi) contour on the void surface, overlaid plot from all 8 bending scenarios, isometric view, with axle centerline shown.

Figurs 85 and 86 show the same overlaid plot for the maximum principal stress contour. It can be seen that the region with high stress extends when all 8 bending directions are considered but is still limited to the "ridge" of the void surface.

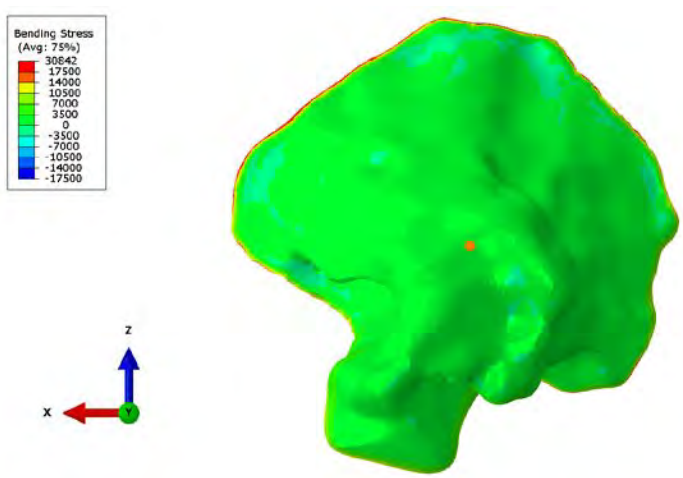


Figure 85. Maximum principal stress (psi) contour on the void surface, overlaid plot from all 8 bending scenarios, end view, with axle centerline location marked.

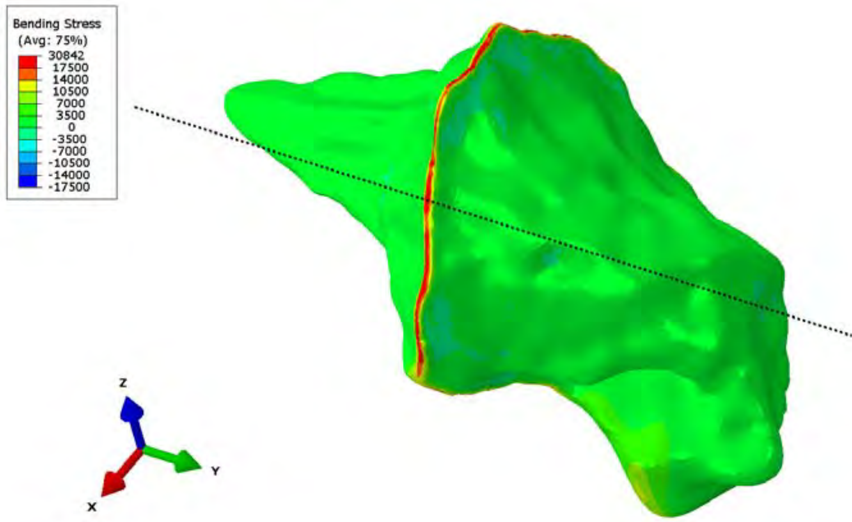


Figure 86. Maximum principal stress (psi) contour on the void surface, overlaid plot from all 8 bending scenarios, isometric view, with axle centerline shown.

The high stress region is highlighted in Figure 87 for better visualization. For comparison, Figure 47 shows fracture surface of the broken axle with fatigue and overstress areas labeled.[56] The area of progressive fatigue cracking was consistent with the high stress region shown in Figure 87.

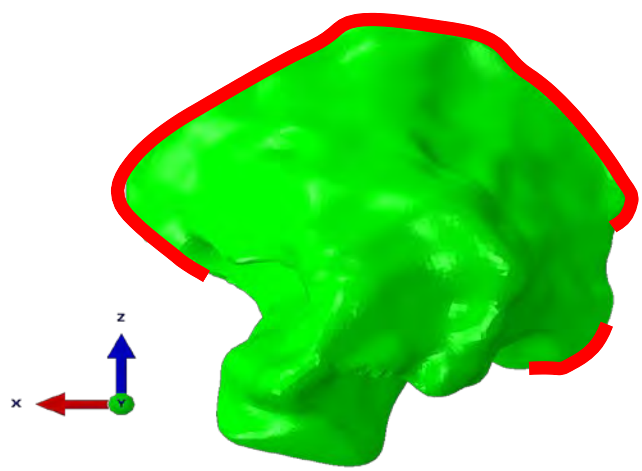


Figure 87. Regions (highlighted in red) on the void surface with high stresses under bending.

56 Materials Laboratory Factual Report 14-055, Accident DCA14MR004, National Transportation Safety Board, Washington, DC, 2014.

Figure 47 (repeated here). Fracture surface of the broken axle with fatigue and overstress areas labeled

Summary

The finite element modeling described in this study shows that the observed internal void could cause a local stress that is significantly higher than the bending stress on the axle surface under the load cases investigated, and the magnitude of that local bending stress can be higher than 17.5 ksi, which according to a previous study can lead to fatigue failure. In addition, the region where high stresses were observed was consistent with where the fatigue cracks originated in the accident axle.

It should be noted that the region of the void surface where high stresses were observed had high curvature and hence required a very dense mesh to accurately capture the local stress field. This was further complicated by the fact that the modeled axle fractured in two halves and the surfaces created from scan data needed to be stitched at the fracture surface, which made the geometry at the jointed interface less precise. For these reasons, the value of the predicted peak stress was only approximate, but the peak stress is still expected to occur in the same place along the void surface, and the stress level would still be expected to exceed the 17.5 ksi threshold.

Train Braking Study[57]

On Monday, December 30, 2013, about 2:11 p.m., Central Standard Time (CST), westbound BNSF Railway Company (BNSF) train G-RYLRGT9-26A (G/T) derailed 13 cars at milepost (MP) 28.5 near Casselton, North Dakota. The grain train consisted of two head-end locomotives, one rear Distributed Power Unit (DPU) locomotive and 112 cars, and was operating on main track 1 at 28 mph prior to the trainline emergency brake application (TLEM). One of the derailed cars, the 45th car from the head end, fouled main track 2.

Oncoming eastbound BNSF petroleum crude oil unit train U-FYNHAY4-05T (P/T), consisting of two head-end locomotives, one rear DPU locomotive and 106 cars, was traveling on main track 2 at 43 mph at the engineer induced emergency (EIE) brake application and collided with the derailed car fouling the track at a speed of about 42 mph (about 10 seconds after the EIE). The head-end locomotives and the first 21 cars of the petroleum crude oil train derailed releasing a substantial amount of crude oil product, fueling a fire. Approximately 1,400 people were evacuated from the town of Casselton. No injuries to the public were reported. The accident occurred on the BNSF KO Subdivision where train movements are governed by signal indications of a traffic control system. The maximum authorized speed for freight trains in the area of the accident is 60 mph.

This accident and other recent North American crude oil and ethanol train derailments resulted in the release of large volumes of flammable liquids. Associated concerns for the safety of persons, property, and the environment led the NTSB to perform a generic train performance study to quantify the expected train stopping distance as a function of train mass, train speed, track grade, train braking configuration [conventional pneumatic (CONV), distributed power pneumatic (DP), or electronically controlled pneumatic (ECP)], emergency or full service brake application, and use of locomotive brakes (bailed off or applied, as applicable) or dynamic brakes. The results of this study are not intended to be used to evaluate the specific stopping performance capability of the BNSF P/T involved in the Casselton, ND accident on December 30, 2013.

Study Overview

The scope of this simulation study is limited to scenarios with train line emergencies initiated at the head-end locomotive on uniform grade, tangent track with clean, dry rail. The trains are assumed to have no inoperative locomotives, no inoperative brakes, no wheel or car derailments, no collisions among cars or with other obstacles, and no loss of communications among applicable electronic devices.

Benefits from the use of advanced train braking systems come from three sources: reduced stopping distances (fewer cars in a potential pileup), reduced vehicle kinetic energy (less energy available to puncture cars in a pileup), and lower and more uniform in-train coupler forces (more

57 Note: References made to “attachments” throughout the Train Braking Study section in this report refer to a table listed in Appendix C.

compatible car-to-car interaction). Many railroads, including BNSF, use locomotive DP to enable longer train operations with added benefits of improved in-train forces and braking performance.

One technique to improve train stopping performance is to increase the nominal car Net Braking Ratio (NBR). This could be accomplished via new car construction or retrofit for a CONV, DP, or ECP train by changing the brake shoe mechanical lever ratio on the foundation brake rigging, adjusting the target brake cylinder pressure, or some combination of the two methods. Increasing the nominal car NBR increases the brake shoe force against the wheel tread during brake application, which in turn increases the energy required to be dissipated as heat. As a result, the brake shoe and wheel tread will be subjected to increased thermal loads and higher wear rates.[58] This study does not evaluate or quantify the consequences of higher thermal loads on in-service wheels.

Technical representatives from BNSF, TrinityRail, Standard Steel, the Brotherhood of Locomotive Engineers and Trainmen (BLET), the Federal Railroad Administration (FRA), and Sharma & Associates, Inc. reviewed draft versions of this study and provided valuable feedback regarding U.S railroad industry operations. Their technical comments were used to revise the study to account for physical constraints (based on locomotive tractive effort and dynamic braking limitations) as well as operational considerations.

Summary of Results

This study documents the calculated stopping performance capability of CONV, DP, and ECP train braking systems for a nominal car NBR of 10% (to compare the effect of different brake signal propagation rates). In addition, the stopping distance benefit due to increasing NBR for exemplar CONV, DP, and ECP trains is illustrated. Finally, this study evaluates the combined brake signal propagation rate and increased brake shoe force benefits of increasing the NBR for an ECP train relative to a CONV train. All simulation scenarios reflect initial conditions with the train in a balanced state (constant initial speed) for level, ascending, and descending track grades.

Different stopping distance performance envelopes were found for emergency and service braking applications with some regions of overlap. For all train braking configurations, the stopping distance benefit relative to the CONV 10% NBR baseline generally increases with increasing train mass, increasing consist length (which affects brake signal propagation time for CONV and DP), and/or descending grades. Exemplar brake signal propagation rate benefits at 10% NBR for emergency and full service braking are shown in Table 13, relative to the CONV 10% NBR baseline. For emergency braking at a constant NBR value of 10%, the ECP brake system provides somewhat better stopping performance than the DP configuration.

58 Higher thermal loads (heat input) from braking may reduce the residual compressive hoop stress in a wheel, increase the risk of wheel defect origination and growth, and increase the risk of brake shoe fade.

Table 13: Percent Stopping Distance Reduction Due to Brake Signal Propagation Rate at 10% NBR (relative to CONV 10% NBR baseline, bailed off).

		Stopping Distance Reduction, Percent	
Braking Configuration	Speed, mph	DP	ECP
Emergency	20	4 to 17	5 to 26
	30	4 to 11	5 to 19
	40	3 to 9	4 to 15
	50	3 to 8	4 to 13
Full Service	20	7 to 46	37 to 75
	30	11 to 39	37 to 68
	40	10 to 39	30 to 64
	50	9 to 37	29 to 60

Smaller percent stopping distance reduction values relative to the CONV 10% NBR baseline generally correspond to these three independent variables: steeper ascending grades (more train kinetic energy is converted to potential energy rather than dissipated by the brake system), shorter consist lengths, and higher train speeds (calculated percent stopping distance benefit decreases even though the absolute stopping distance benefit measured in equivalent car lengths increases).

Calculated CONV, DP, and ECP increased NBR benefits for exemplar emergency and full service braking scenarios are provided in Table 14, relative to the respective brake system 10% NBR baseline. For emergency braking, increasing the NBR for a given brake system and speed yields comparable percent stopping distance reductions among the CONV, DP, and ECP systems.

Table 14: Percent Stopping Distance Reduction Due to Increased NBR, Level Grade (relative to respective CONV 10% NBR, DP 10% NBR, and ECP 10% NBR baseline, bailed off).

		Stopping Distance Reduction, Percent					
		12.8% NBR			14% NBR		
Braking Configuration	Speed, Mph	CONV	DP	ECP	CONV	DP	ECP
Emergency	20	12	14	15	16	18	19
	40	15	17	17	20	22	23
	60	17	18	19	22	24	24
Full Service	20	8	8	16	11	11	21
	40	10	11	18	13	15	24
	60	11	13	19	15	18	25

Combined ECP brake signal propagation rate and increased NBR benefit results for emergency and full service braking are presented in Table 15, relative to the CONV 10% NBR baseline. Increasing the nominal car NBR clearly provides measurable stopping performance benefits. **Note that the summary results in Tables 13–15 are subject to specific train mass (consist length) and track grade conditions** (see details in Attachments 3–6, Appendix C).

Table 15: Percent Stopping Distance Reduction Due to Combined ECP Brake Signal Propagation Rate and Increased NBR (relative to CONV 10% NBR baseline, bailed off).

		Stopping Distance Reduction, Percent		
Braking Configuration	**Speed, mph**	**ECP 10% NBR**	**ECP 12.8% NBR**	**ECP 14% NBR**
Emergency	20	5 to 26	13 to 39	16 to 43
	30	5 to 19	17 to 33	21 to 38
	40	4 to 15	17 to 31	22 to 36
	50	4 to 13	19 to 30	24 to 36
Full Service	20	37 to 75	42 to 80	45 to 82
	30	37 to 68	45 to 74	48 to 76
	40	30 to 64	41 to 71	44 to 73
	50	25 to 60	40 to 68	44 to 71

The in-train force benefits of DP and ECP braking are evidenced by substantially lower car-to-car buff forces (75,000 to 250,000 lb. lower) during emergency brake application. While this generic stopping distance study yields some useful in-train force results and trends, it is not intended to exhaustively compare the in-train force benefits among the train braking configurations evaluated.

Kinetic energy data for an exemplar emergency stop could be used to estimate the energy dissipated (relative to the CONV 10% NBR baseline) over a finite distance window as a function of braking configuration (DP 10% NBR, ECP 10% NBR, ECP 12.8% NBR, or ECP 14% NBR). For example, use of ECP braking at 12.8% NBR to bring the train to a full stop on level grade from an initial speed of 50 mph would decrease the required stopping distance by about 500 to 550 feet (about 8 to 9 tank car lengths) relative to the CONV 10% NBR baseline.

The kinetic energy dissipated over a finite time window could also be compared to estimate the response time margin available (as a function of the brake system configuration) for engineer/conductor corrective or mitigating action via emergency brake application. For the same 50 mph to full stop (zero kinetic energy) example on level grade, use of ECP braking at 12.8% NBR would add about 13 seconds of response time margin relative to the CONV 10% NBR baseline. A hypothetical target vehicle kinetic energy decrease of 50 percent or more (relative to the initial train speed) using ECP braking at 12.8% NBR would equate to a distance reduction of about 850 feet (about 14 tank car lengths) and a time margin benefit of about 27 seconds relative to the CONV 10% NBR baseline.

Simulation Study

The simulation tools, simulation parameters, engineering assumptions, and study scope are described in this section.

Train Energy and Dynamics Simulator (TEDS)

The train braking study was conducted using the TEDS longitudinal train dynamics computer simulation program that was funded by the Federal Railroad Administration (FRA) and developed under contract by Sharma & Associates, Inc. (SA). TEDS was designed to support a range of train simulation applications, including operational, energy consumption, stopping distance, network capacity, safety, risk evaluation, equipment (existing, new, and/or mixed), and incident/accident investigative studies. The FRA and SA provided the NTSB with direct access to the TEDS simulation tools (pre-processor, simulator, and post-processor) as well as timely engineering and information technology technical support. TEDS validation work is discussed in TEDS Stopping Distance Simulation Validation

The current TEDS user base includes the FRA (Office of Research and Development, Office of Safety, and Office of Policy), NTSB, Transport Canada, Transportation Safety Board of Canada (TSB), National Research Council of Canada (NRC), and three FRA contractors. FRA TEDS simulation work has been referenced in Pipeline and Hazardous Materials Safety Administration (PHMSA) rulemaking documents, but PHMSA is not an active user. TEDS is not currently being used by any Class 1 railroads in the United States.[59]

Simulation Parameters

The study input parameters included train mass, initial train speed, track grade, train braking configuration, type of brake application, locomotive independent brake application, locomotive dynamic brake setting, locomotive throttle setting, and initial coupler slack. As train energy increases due to train mass, train speed, descending grade, and/or throttle setting, the required stopping distance and time increase. Note that in emergency and/or penalty brake applications, throttle/tractive effort is cut-out.

Train Consist

The nominal simulation car consist was based on the Casselton, ND petroleum unit train car consist (104 tank cars) and car loading. For CONV train operations, five locomotives were located at the head-end of the train followed by a buffer car, the tank car consist, and a trailing buffer car. For DP and ECP operations, the simulation train makeup included five locomotives (3 head-end, 2 remote rear DPUs), two buffer cars (separating the first and last tank car from the respective

59 The U.S. railroad industry makes use of the AAR Train Operations and Energy Simulator (TOES), which has a detailed air brake model that has been validated and is capable of comparing braking performance for pneumatic and ECP brake systems.

adjacent locomotive), and 104 tank cars. Five locomotives were used for all simulation scenarios to expand the range of train mass, train speeds, and track grades that could be evaluated in the study.

A short simulation consist was defined by reducing the number of tank cars in the nominal train by 25 percent. A 50 percent reduction in the number of tank cars in the nominal train defined a shorter simulation consist. Similarly, a long simulation consist was defined by increasing the number of tank cars in the nominal train by 25 percent. Finally, a longer simulation consist was defined by increasing the number of tank cars in the nominal train by 50 percent. The train consist properties evaluated in the study are summarized in Table 16. Corresponding vehicle length and loading data are provided in Table 17.

Table 16: Train Consist Vehicles (for Length values, TR = train, BP = brake pipe)

Consist	4400 HP Loco.	Buffer Cars	Tank Cars	Total Train		
				Vehicles	Weight, tons	Length, ft.
Shorter	5	2	52	59	7,839.5	3,584.4 (TR) 3,874.3 (BP)
Short	5	2	78	85	11,112.2	5,135.9 (TR) 5,552.7 (BP)
Nominal	5	2	104	111	14,385.0	6,687.3 (TR) 7,231.2 (BP)
Long	5	2	130	137	17,657.8	8,238.7 (TR) 8.909.6 (BP)
Longer[a,b]	5	2	156	163	20,930.5	9,790.1 (TR) 10,588.0 (BP)

[a] The longer train operation trailing tonnage may require distributed power operation to satisfy coupler capacity constraints for certain track grades. Depending on territory, the longer train operation may require DP to be "cut-in" or placed within the train consist. Cut-in DP operation increases brake signal propagation rates relative to rear-end DP. Only rear-end DP configurations are considered here.
[b] If a specific simulation scenario causes coupler force constraints to be violated, conventional braking with head-end only brake signal propagation will not be a valid baseline for stopping distance comparisons.

Table 17: Vehicle Length and Loading

Vehicle Type	Length, ft.		Weight, lb.		
	Vehicle	Brake Pipe[c]	Tare	Reported	Gross Rail Load
Locomotive	73.1	78.1	412,000	420,000	412,000
Buffer Car	58.0	63.5	63,000	244,000	263,000
Tank Car	59.7	64.6	76,800	251,750	263,000

In general, BNSF operates loaded unit trains with a DP configuration when train size exceeds 100–110 cars. The longer train consist in this study exceeds that of BNSF’s current operating environment, where most loaded unit trains operate between 100–135 cars in length. BNSF would not operate loaded unit trains with 158 cars with conventional (head-end only) power. The TEDS conventional braking simulation cases with 158 cars may be interpreted as informational only.

Initial Train Speed

The simulation scenarios included initial train speeds ranging from 20 to 70 mph by 5 mph increments. The speed range modeled for a given train was a function of track grade and train tonnage and generally attempted to reflect real-world, safe, and allowable operating practices. In some cases on steeper descending track grades (e.g., -1.5% and -2.0%), the locomotive maximum dynamic brake performance capability was used, although this dynamic brake effort may exceed recommended operational practice.[60]

All simulation scenarios reflect train movements with balanced (or trimmed) initial speeds. That is, the required tractive effort (for level or ascending grades) or dynamic brake effort (for descending grades) is distributed among the locomotives to ensure that the train will maintain the target initial speed within ±0.1 mph or better for 60 seconds prior to the emergency or full service brake application.

For freight train operations, the 20 to 70 mph speed range covers FRA track classes 1 through 5 as shown in Table 18. The simulation study assumed that train speed was not limited by the train negotiating any track curves, track segments with defective rails, work zones, track frogs with treads worn down, or track frogs with a chipped, broken, or worn down point.

Table 18: FRA Track Classification for Freight Trains

Track Class	Maximum Allowable Speed for Freight Trains, mph
1	10
2	25
3	40
4	60
5	80

Heavy freight trains are not allowed to operate at high speeds down steeper grades due to signal spacing, high track curvature, and/or wheel heating concerns. For the purposes of this study, train simulation scenarios were generally consistent with the FRA railroad industry survey results depicted in Table 19 that quantify the allowable freight train operating envelope as a function of track grade, train speed, and train tonnage. The text content labeled “X” in Table 19 that is identified in the legend as “Planned to be simulated” does not apply to this NTSB study.

60 BNSF limits the total operative dynamic brake retarding force to 28 equivalent dynamic brake axles (to reduce buff forces that might cause a derailment or damage track structure) unless further restricted by another rule or instruction (such as when approaching and operating through turnouts or disturbed track areas). BNSF dynamic brake exceptions include:

1) Trains with remote and/or manned helper locomotive consists entrained or at the rear of the train may have the maximum allowable dynamic brake axles for each locomotive consist, and

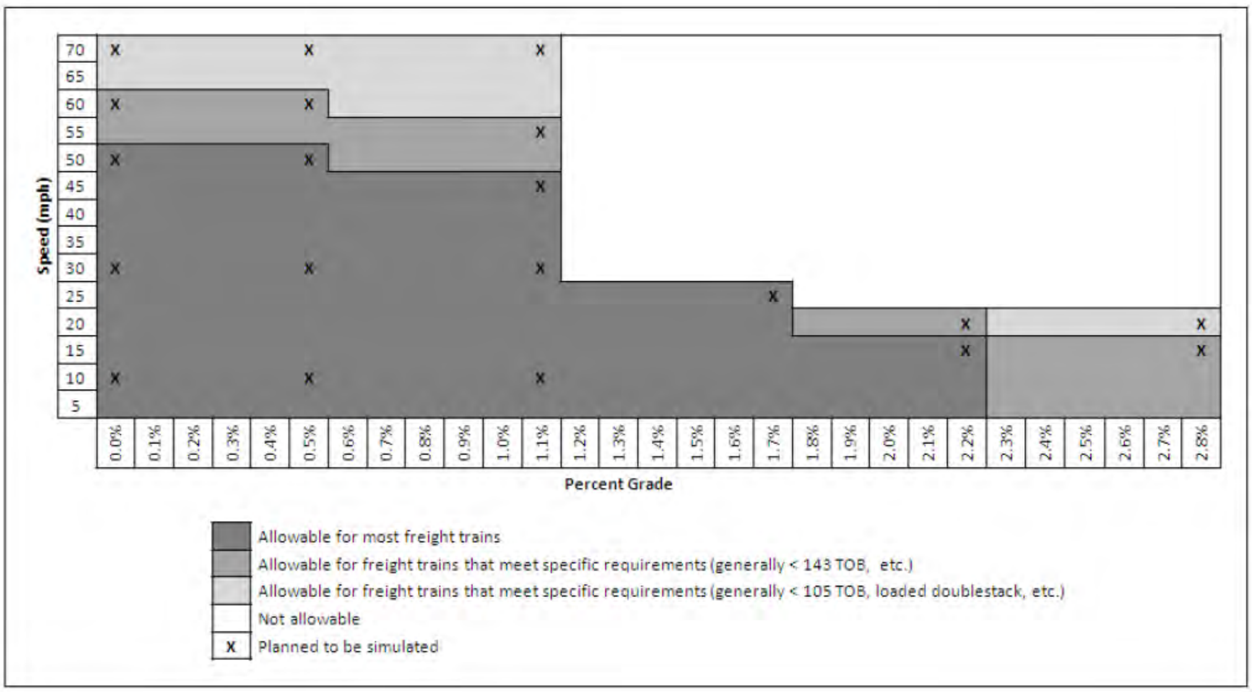
2) Trains may be operated with up to 32 dynamic brake axles in the lead locomotive consist if the first 25 cars are conventional cars weighing at least 100 tons each.

Track Grade

The simulation railroad track geometry was constrained to tangent track with uniform grade values ranging from -2% descending to +2% ascending in 0.5% grade increments.

The conversion of potential energy to kinetic energy (and the converse) is significant for trains on descending (ascending) grades. For example, for the nominal train consist on a uniform descending grade, the incremental energy added to the system per foot of elevation change is (14,385 tons)(2,000 lb./ton)(1 ft.) = 28,770,000 ft-lb. If the train is traveling at an average speed of 20 mph on a uniform 2% descending grade, its elevation change will be about 0.59 feet per second, adding energy at the rate of (0.59 ft./sec)(28,770,000 ft-lb/ft.) = 16,875,025 ft-lb per second, which equates to about 4.4% of the current train kinetic energy added in one second at 20 mph.

Table 19: FRA Summary of Industry Boundary Operating Conditions on Declining Grades



Source: DOT/FRA/ORD-13/34, "Development of an Operationally Efficient PTC Braking Enforcement Algorithm for Freight Trains," Federal Railroad Administration, Office of Research and Development, Final Report, August 2013.

Train Braking Configuration

The train braking configurations considered in this study include conventional pneumatic brakes with a head-end locomotive consist (CONV), conventional pneumatic brakes with distributed power (DP) [a head-end locomotive consist and a remote DP consist at the rear], and electronically controlled pneumatic (ECP) brakes targeting a car net braking ratio (NBR) of 10.0, 12.8, or 14.0 percent. All ECP braking scenarios used a locomotive arrangement similar to the DP train consist [a head-end locomotive consist and a remote DP consist at the rear]. For DP and ECP trains, the head-end locomotive consist was made up of 3 locomotives and the remote DP consist at the rear was made up of 2 locomotives.

Net Braking Ratio

The Association of American Railroads (AAR) defines NBR in the "Manual of Standards and Recommended Practices (MSRP), Section E-II, Electronically Controlled Brake Systems," Appendix A, effective August 2014 as:

> *Net braking ratio; the sum of the actual normal (perpendicular) brake shoe forces on all of the wheels on a car divided by the actual weight of the car on the rail; the term is used specifically in tread braking applications. In this standard, NBR refers to the loaded net brake ratio resulting from a full-service (100%) brake application from a 90-psi brake pipe pressure.*

The ECP 10% NBR scenarios were selected to provide comparable NBR values to nominal freight cars in conventional pneumatic and DP trains.[61] A uniform net braking ratio of 10% was assumed for the CONV and DP car consists. However, actual car-to-car net braking ratios may vary due to brake rigging design or maintenance differences, component wear, and/or built date/re-built date for conventional pneumatic brakes.[62] Car-to-car NBR variation can produce larger intra-train buff (compression) and/or draft (tension) forces.

AAR MSRP S-401 specifies the range of allowable loaded NBR. The NBR for cars built after January 1, 2004 must fall within 11% to 14% (see the last row of Table 20 below). Both conventional pneumatic and ECP braking systems must fall within the same range of loaded NBR. In addition, conventional pneumatic cars can be built or retrofit to the maximum NBR value of 14%. Note that AAR MSRP S-401 is an AAR industry standard, not a PHMSA or FRA regulatory requirement. There are no minimum NBR regulatory requirements for rolling stock equipped with conventional pneumatic brakes. However, there is guidance that specifies a default target NBR value of 12.8% for ECP cars (discussed further below).

---

61 Regarding the use of a nominal tank car net braking ratio of 10%, tank cars ordered before 2004 were recommended by an AAR industry standard to have a loaded NBR between 8.5% and 13%, and an empty NBR of not more than 38%. For the tank car used in this simulation study (76,800 pounds tare) a loaded NBR of 10% corresponds to an empty NBR of 34%, which is comfortably within the recommended limits without the use of an empty/load valve (which would add equipment cost). All cars ordered after 2004 are recommended to have a loaded NBR value between 11% and 14%. Thus, while newer cars are expected to have NBR values of at least 11%, older tank cars, which are a larger portion of the fleet, would likely have NBR values in the range of 9% to 10%.

62 Many of the mechanical wear conditions affecting variability in car-to-car NBR are present in both pneumatic and ECP systems. As a result, car-to-car net braking ratios may also differ for ECP systems. However, the ECP closed-loop brake cylinder pressure control and uniform, train-wide requested NBR features minimize the actual car-to-car NBR variations.

Table 20. Net braking ratios with a 30-psi brake pipe reduction from 90-psi brake pipe pressure.

Car Type		Loaded Net Brake Ratio—Percentage of Gross Rail Load		Empty Brake Ratio—Maximum Percentage of Light Weight		Hand Brake Ratio—Percentage of Gross Rail Load
		Min	Max	Min	Max	
Cars rebuilt or converted	TOFC/COFC	11%	13%	15%	38%	10%[a/]
	All other	8.5%	13%	15%	38%	10%[a/]
All new cars, including TOFC/COFC ordered after January 1, 2004		11%	14%	15%	32%	10%[a/]

Source: AAR MSRP, Section E-I S-401

Differences in the pneumatic or electronic braking signal propagation rates are expected to result in different stopping distances among the CONV, DP, and ECP trains at 10% NBR. Slower car-to-car brake signal propagation and different brake cylinder pressure (BCP) rise rates tend to increase the in-train buff and/or draft forces. ECP braking is designed to provide simultaneous brake signal (full or graduated) application/release commands and target a uniform car NBR, which should yield lower magnitude in-train forces and shorter stopping distances. According to the FRA Final Report, “ECP Brake System for Freight Service,” prepared by Booz-Allen-Hamilton, released August 2006, updated March 10, 2009, ECP braking can also yield operational savings (e.g., fuel and line capacity savings).[63]

Loaded NBR has a significant impact on braking performance. Therefore, when comparing the performance benefits due solely to different brake system signal propagation rates, the NBR should be kept consistent. This study compares the performance benefits of three different brake system configurations at a constant NBR value of 10% as well as three different NBR values for a fixed brake system configuration (using ECP braking). The level grade stopping performance of exemplar 104 tank car consists was also simulated for CONV and DP trains (for 10%, 12.8% and 14% NBR) to demonstrate that stopping distance is heavily dependent on the car NBR.

MSRP Section E-II formalizes the AAR intent that the NBR for a specific ECP train can be varied but that it shall be railroad specific and engineers should not be able to change it. Paragraph 4.2.2.2.5 Train Net Braking Ratio states:

> *The requirements for a specific train net braking ratio (NBR) during ECP braking shall be railroad specific in that railroads do not want the ability for the engineer to make changes. If the optional ability to change the train NBR is provided, then the engineer will not be given the opportunity to change the setting. The change shall be implemented such that it is transparent to the engineer.*

63 BNSF did not find measurable fuel savings or capacity benefits during their 2008 ECP trials.

The ECP 12.8% NBR scenarios were therefore chosen to model the default ECP car control device (CCD) target NBR of 12.8% defined in AAR MSRP Section E-II, paragraph 4.3.6.2, as follows:[64]

> *The CCD shall have a target NBR of 12.8% until a value is received from the HEU* [Head End Unit]. *Due to the variations of the mechanical design of brake systems on different cars, the actual brake ratio may not be 12.8%. The CCD determines the full service brake cylinder pressure as outlined in paragraph 4.3.7, and the actual NBR achieved will correspond to that full-service brake cylinder pressure for the specific brake system configuration of each car.*

The ECP 14.0% NBR scenarios were included to define an upper envelope bound on expected ECP brake performance capability, recognizing that railroads that implement ECP braking can specify train NBR values lower or higher than the AAR MSRP, Section E-II CCD default target NBR of 12.8%. Moreover, per Table 20, 14.0% NBR is the maximum loaded NBR specified for all new cars ordered after January 1, 2004.

Regarding braking ratios in Federal Regulations, 49 CFR 232.103(l) references AAR S-469 for conventional systems while 49 CFR 232.603 references AAR S-4200 for ECP systems. There may have been an FRA waiver that mentioned braking ratios, but that waiver would have preceded the publication of 49 CFR 232 Subpart G – ECP Systems, and therefore, 49 CFR 232 Subpart G now takes precedence.

Operational Differences between ECP and Conventional Braking Systems

Under conventional braking, unplanned service or emergency pneumatic brake signal propagation through the length of the train[65] can result in notable run-in forces on cars at the head-end of the train. Heavy buff and run-in forces may result in 1) derailment of lightly-loaded cars, depending in part on their geometry, track curvature, and local rail conditions or 2) sliding of heavily-braked and/or lightly-loaded wheels (wheel longitudinal motion with low/zero angular velocity), depending in part on actual track contamination and/or environmental conditions.

ECP brake systems can provide the same target NBR on all cars in the train and apply braking force to all cars throughout the train in a near-simultaneous manner. If the ratio of total brake shoe force to gross rail weight is about the same for each car (e.g., a unit train with "near equivalent" car capabilities and equipment), the cars of the train will decelerate at about the same

64 The default ECP CCD target NBR of 12.8% is not necessarily the NBR selected by the car owner or the railroad. The loaded NBR for a sample of BNSF-operated ECP cars ranged from 9.5% to 11.9%. Cars sampled in the 9.5% range were built prior to the 2004 changes to the AAR S-401 minimum loaded net brake ratio specification.

65 AAR performance test procedures to qualify pneumatic control valve operation require a minimum emergency propagation rate of 949 feet per second (calculated by dividing the length of the 7,500-foot brake rack "train" by the maximum emergency brake signal propagation time of 7.9 seconds).

rate (subject to gross weight on rail and brake system design, rigging, and component wear differences) thus minimizing run-in forces.

The near simultaneous brake application under ECP operation results in more uniform braking, minimal run-in forces, and reduced potential of wheel derailment or of sliding braked wheels. DP braking also yields some reduced in-train force benefits. Reduced in-train force benefits may allow a DP- or ECP-braked train to operate with an average NBR closer to the AAR allowable upper NBR limit of 14%. Additional efforts to confirm that increased NBR operations can deliver safe and effective train performance with CONV, DP, and/or ECP braking systems would be prudent. [66]

The increased level of control and 'tunability' offered by the electronic features of ECP brake systems also allows requests, such as changes to net braking ratios, car load states, and isolation of defective equipment to be executed much more easily on ECP systems, compared to the manual or mechanical methods required for conventional pneumatic systems. With this in mind, simulations were run to evaluate the effect that NBR has on stopping distance, specifically with regard to ECP-equipped train consists and for exemplar CONV and DP consists.

Type of Brake Application

Both emergency and full service car brake applications were modeled for each train consist, initial speed condition, track grade, and train braking configuration. For ECP car braking, AAR MSRP, Section E-II, paragraph 4.3.11 Brake Cylinder Pressure Control specifies that:

> *CCDs shall control brake cylinder pressures according to the following performance requirements based on a standard AAR single car test rack with 50 ft. of brake pipe:*
>
> *1. Steady state BCP pressure regulation shall be within ±3 psi of target (final commanded) pressure.*
> *2. The BCP control shall be as follows:*
> *A. Minimum Service Application: BCP shall reach target pressure from a full release, within ±3 psi, in no more than 2.0 seconds.*
> *B. Full-Service Application: BCP shall reach target pressure from a full release, within ±3 psi, in no more than 10.0 seconds nor less than 6.0 seconds.*
> *C. Emergency Application: BCP shall reach target pressure from a full release, within ±3 psi, in no more than 12.0 seconds nor less than 7.0 seconds.*

66 The tank car safety discussion would benefit from efforts to quantify how increased NBR train operations would affect in-train force management requirements for CONV, DP, and ECP brake systems; wheel thermal loading (including wheel defect origination and growth); and the need or incentive to implement tailored NBR schedules to maximize the operational and safety benefits of service and emergency brake applications.

3. Full-Service Release performance, from the time each CCD receives the new brake command, shall be as follows: BCP shall reduce to 5 psi or less in no more than 15.0 seconds nor less than 6.0 seconds.

The results of these simulation studies apply to engineer-initiated brake applications, assuming no in-train hose separation, no train separation, and no wheel or car derailment.

For informational purposes only, if an in-train air hose separation occurs in a DP train, the train behaves in one of two ways, depending on whether or not the train separates and derails.

DP Braking with In-Train Air Hose Separation but No Train Separation or Wheel/Car Derailment:

In this case, an emergency resulting from hose separation at the midpoint of a DP train is identical to a similar in-train emergency in a conventional (head-end only) train. If a hose separation occurred forward of the midpoint on a DP train, the emergency brake signal would simultaneously propagate forward to the head-end locomotive consist and rearward. When the signal reached the head-end, it would be relayed via radio to the trailing locomotive consist where it would then propagate forward. Similarly, if a hose separation occurred aft of the midpoint on a DP train, the emergency brake signal would simultaneously propagate rearward to the trailing locomotive consist and forward. When the signal reached the trailing locomotive consist, it would be relayed via radio to the head-end locomotive consist where it would then propagate rearward.

In this idealized case with no train separation or wheel/car derailment, DP and CONV (no two-way ETD) would have equivalent stopping performance if a in-train emergency originated at mid-train. In every other in-train emergency location (within the first half, or the last half of the train) assuming an idealized case with no train separation or wheel/car derailment, DP would have a stopping performance benefit relative to CONV.

DP Braking with In-Train Air Hose Separation, Train Separation, and Wheel/Car Derailment:

In this case, an emergency resulting from air hose separation and train separation anywhere in the rear half of a DP train is identical to a similar in-train emergency in a conventional (head-end only) train (i.e., there is no benefit to DP if the emergency is initiated in the second half of the train). This DP braking interpretation asserts that when train separation and derailment occurs in the rear half of the train, the head-end train consist will continue forward and stop, but it will not substantively affect the stopping performance of the cars in the trailing consist that are still approaching the point of derailment. In this case, the DP benefits reported in this NTSB study represent the maximum DP benefit that could be achieved with a trailing DP consist and would be overstated for emergency brake applications initiated aft of the train mid-point. For example, the minimum DP stopping performance benefit would be zero relative to the comparable CONV baseline case for train separation anywhere in the rear half of the train. Of the two DP braking scenarios, this scenario is more consistent with recent tank car derailments.

The braking performance of an ECP train, in contrast, is not significantly affected by the location of the emergency initiation (e.g. for either of the DP braking scenarios discussed above), since the car CCD detects the pneumatic in-train emergency and an electronic emergency signal is passed on to all cars.

Locomotive Throttle

Locomotive throttles were set to idle for all descending grade simulation scenarios. For level and ascending grade scenarios, the train was initialized in a balanced condition (to maintain constant train speed) by use of locomotive throttles. If the minimum tractive effort required to maintain constant speed was unavailable for the given consist, speed, and grade, the candidate scenario was not evaluated.

A generic locomotive model was used for this study because the NTSB was not attempting to evaluate the specific BNSF locomotive or car equipment involved in the Casselton, ND accident. The generic notch 8 tractive effort and dynamic brake effort curves for the TEDS 4400 hp locomotive model were derived by SA from the "Car & Locomotive Cyclopedia", dated 1997, published by Simmons Boardman.

The NTSB-estimated locomotive tractive effort performance capability for the TEDS 4400 hp locomotive model on tangent track for level and ascending grades is quantified as a function of train speed, train mass, and track grade in Attachment 1. The notch 8 limiting calculations incorporate a simplistic estimate for rolling friction and bearing losses, no coupler losses, no curving resistance, and a simple air resistance model.

The tables in Attachment 1 illustrate the calculated number of locomotives for balanced speed operations. White and light orange cell backgrounds generally identify practical locomotive power requirements (with two to five locomotives) while light pink and light red cell backgrounds denote more impractical locomotive power operational regions (six locomotives or more).[67]

The baseline number of locomotives for this study was increased from three (from the Casselton, ND P/T initially used as the model for the study) to five to evaluate a wider range of track grade and consist length results without frequently tweaking the number of locomotives.[68]

67 BNSF timetables were used to estimate the P/T ruling grade to be +1.0% between the movement origin at Fryburg, ND and Kansas City, MO. Beyond Kansas City, the BNSF transportation service plan for U FYNHAY trains calls for the addition of a 4th locomotive.
68 The calculation of five to six locomotives is consistent with the Lac Megantic consist, which was traveling on grades on the order of 1 to 1.25 degrees with 5 locomotives, 72 tank cars, 1 buffer car, and 1 other car (special purpose caboose).

Using five locomotives for all simulation scenarios simplified the consist comparisons and maximized the realistic grade/speed/trailing ton envelope.[69]

BNSF reviewed and checked the NTSB locomotive sizing estimates for balanced train operations by estimating the number of 4400 hp locomotives required for each of the following hypothetical conditions:

a) 104 loaded tank cars and 2 buffer cars on 0.5, 1.0, and 2.0 percent ascending grades at 20 mph.
b) 52, 104, and 156 loaded tank cars and 2 buffer cars on level track at 50 mph.
c) 52, 104, and 156 loaded tank cars and 2 buffer cars on a 1.0 percent grade at 40 mph.

BNSF found that the NTSB locomotive sizing estimates in Attachment 1 lined up well with their calculations and assumptions.[70] BNSF did note larger variance with the longer, 156-car train on level track, likely due to differences in the assumed vehicle aerodynamic profile(s).

In response to a related NTSB request, BNSF advised that for normal DP operations, their front-rear DP locomotive arrangement would be as follows: 2 front, 1 rear for three locomotives; 2 front, 2 rear for four locomotives; 3 front, 2 rear for five locomotives; and 3 front, 3 rear for six locomotives.[71]

Locomotive Brake Application

AAR MSRP, Section E-II provides flexibility for railroad-specific ECP locomotive retardation in paragraph 4.3.1.5.1 under Locomotive Retardation during ECP Braking, which states:

> *The requirements for locomotive retardation during ECP braking shall be railroad specific in that not all railroads may want automatic locomotive brake cylinder pressure control or dynamic braking during ECP brake applications (e.g., railroads that always bail off automatic brake applications). The requirement to provide the ability to have locomotive retardation during ECP brake applications shall not preclude manufacturers and railroads from developing other braking systems that meet the intent of providing appropriate locomotive retardation in conjunction with ECP train braking as long as these systems allow for interoperability between locomotives equipped with different manufacturers' ECP equipment.*

69 This number of locomotives may differ from many DP operations where trains have two locomotives at the head-end and one DP locomotive placed at the rear-end or elsewhere. More locomotives would be needed for routes with higher ruling grades.
70 The assumptions for the BNSF locomotive sizing estimates included no track curvature, nominal wheel/rail friction, nominal bearing resistance, a mix of DC and AC 4400 hp locomotives, and vehicle aerodynamic resistance (but the aerodynamics were not specific to tank car geometry).
71 There are DP operational exceptions where BNSF may run with more units on the rear (2 front, 3 rear) or where train size and territory may require DP to be "cut-in" with three distinct locomotive consists (not a common practice at BNSF).

No exemplar ECP locomotive retardation schedules are provided in AAR MSRP, Section E-II. As a consequence of this intended operational flexibility and the limited deployment of ECP locomotives in the U.S. railroad industry to date, ECP locomotive braking for emergency and full service braking simulation scenarios was prescribed to mimic the applicable locomotive retardation schedule for conventional pneumatic brake applications. This simulation model implementation assumes that railroads that would elect to retard ECP locomotives during emergency or full service brake applications would not choose to reduce locomotive braking performance capability relative to existing locomotive retardation options with conventional pneumatic brake equipment.

For level and ascending grade scenarios, the locomotive brakes were assumed to be bailed off (released) for one-half the simulation scenarios and applied (not bailed off) at the emergency or full-service level, as applicable, for the remaining cases. No locomotive dynamic brakes were applied for level or ascending grade scenarios.

A commanded brake pipe pressure reduction did not occur for any scenario until the application of emergency or full service braking.

For descending grade scenarios, the train was initialized in a balanced condition (to maintain constant train speed) by use of locomotive dynamic brakes. If the minimum dynamic brake effort required to maintain constant speed was unavailable for the given consist, speed, and grade, the candidate scenario was not evaluated. Automatic train brakes were not used to maintain the initial speed on descending grades.

The estimated locomotive dynamic brake performance capability on tangent track with descending grades is also quantified as a function of train speed, train mass, and track grade in Attachment 1. Credit for energy dissipated by forces opposing the motion decreases the hypothetical locomotive demand for dynamic braking (or an alternate demand for locomotive independent or car automatic braking) on descending grades.

For one-half the descending grade scenarios, the locomotive dynamic brakes were assumed to be smoothly reduced to zero dynamic brake effort after the emergency or full service brake application within the time period required for the train speed to be reduced by 10% from the initial speed value (i.e., speed decay of 2 mph for a 20 mph initial speed, 5.5 mph for a 55 mph initial speed, etc.). This strategy was used to prevent the train speed from overshooting the initial speed as potential energy from the elevation change was converted to train kinetic energy (before sufficient car brakes were partially or fully applied to prevent an initial speed overshoot). This gradual dynamic brake reduction resulted in the most residual dynamic braking for the CONV 10.0% NBR cases, with progressively less dynamic braking for the DP 10.0% NBR, ECP 10.0% NBR, ECP 12.8 % NBR, and ECP 14.0% NBR cases, respectively. This setup yields conservative results for stopping distance comparisons of the various DP/ECP braking configurations to the CONV baseline. No locomotive independent brakes were applied.

The locomotive dynamic brakes were applied for the balance of descending grade cases, by remaining at the initial notch setting (defined by the dynamic brake effort required to maintain the initial constant speed value) until the train came to a complete stop. Dynamic braking force is dependent on both the handle position and the locomotive speed, and can increase as the speed decreases, to a certain point. Thus, for a specified notch, the net retardation force on the train tended to increase as the speed decreased. No locomotive independent brakes were applied.

The AAR operating practices report (R-185), "Track Train Dynamics - To Improve Freight Train Performance" outlines recommended practice for a planned stop on a downgrade. However, the applicability of the method described to an unexpected emergency or full service stop is debatable.

Initial Coupler Slack

The initial coupler slack was assumed to be neutral throughout the train (as opposed to bunched, stretched, or some combination) for all simulation scenarios. A comparison of calculated stopping distances assuming all coupler slack was initially bunched, stretched, and neutral, respectively, for the nominal consist at near-zero track grade indicated that the initial slack state did not appreciably affect the calculated stopping distance.

For this study, the “balanced” initial train conditions resulted in the coupler slack either bunched or stretched by the time the brake application occurred, even if neutral coupler slack was selected as the initial condition.

Engineering Assumptions

The following assumptions apply to all train stopping distance simulation scenarios:

1. No inoperative locomotives.
2. No inoperative brakes.
3. No wheel or car derailments.
4. Clean, dry rail (no degradation of locomotive tractive effort or braking effort due to environmental precipitation, contamination, oil, grease, or debris that might reduce the available wheel/rail friction coefficient).
5. For a given brake system configuration, car position, and speed, the normal brake shoe force profile is constant, independent of initial train speed, track grade, or brake application time.
6. No braking degradation due to brake shoe fade as the result of friction wheel heating to rolling wheels. Physically, the reduction in brake shoe-to-wheel friction coefficient is due to the change in the shoe material friction properties at elevated temperatures.
7. The brake shoe friction coefficient increases with decreasing speed, consistent with the sanitized, empirically-based profile provided in Attachment 2.

8. Brake pipe leakage is assumed to be 8 Standard Cubic Feet per Minute (SCFM) at 90 psig brake pipe pressure.
9. Due to the locomotive brake pipe pressure (BPP) maintaining feature, negligible loss of BPP prior to the emergency or full service brake application.
10. For ECP braking, no inoperative CCDs.
11. For ECP braking, no loss of communications among any of the devices (the HEU, CCDs, End of Train (EOT) device, or DPUs).
12. The DP radio transmission time delay was assumed to be 0.0 seconds. TEDS requires the user to specify the DP or EOT device radio signal transmission delay.
13. A DP or ECP trainline emergency signal will transmit in less than 1 second.[72]

Simulation Scope

The independent simulation variables described above were multiplied to develop a simulation matrix. For this study, the matrix consists of

1. Five (5) train consists (of 5 locomotives, 2 buffer cars, and 52, 78, 104, 130, or 156 tank cars).
2. Eleven (11) train speeds (20 to 70 mph by 5 mph increments).
3. Nine (9) track grades (-2.0, -1.5, -1.0, -0.5, 0, +0.5, +1.0, +1.5, and +2.0 percent).
4. Five (5) train braking configurations (including conventional pneumatic, conventional pneumatic with rear distributed power, ECP 10% NBR, ECP 12.8% NBR, and ECP 14% NBR).
5. Two (2) types of brake application (emergency or full service).
6. Two (2) locomotive brake settings (bailed off and applied, with different models for level/ ascending grade and descending grade scenarios).
7. One (1) initial coupler slack condition (neutral).

The product of these independent variables is (5)(11)(9)(5)(2)(2)(1) = 9,900 simulation cases. The imposition of representative locomotive tractive and dynamic brake effort constraints to reflect realistic/safe operating conditions for track grade, train speed, and train tonnage combinations reduced the number of candidate simulation cases to 3,790.[73] The number of scenarios evaluated for each train consist is summarized in Table 21.

---

72 There is no industry document specifying the transmission time for a TLEM (trainline emergency) signal. However, technical experts at GE confirmed a TLEM signal will transmit in less than 1 second.

73 An additional 88 cases were later added for the nominal consist to quantify the effect of increased NBR for exemplar CONV and DP trains.

Table 21: TEDS Simulation Cases

Consist	Balanced Cases	Cases Not Evaluated
Shorter	1,190	790
Short	860	1,120
Nominal	640	1,340
Long	580	1,400
Longer	520	1,460
Total Cases	**3,790**	**6,110**

Study Validation

The study validation process included the need to sample and compare TEDS time history parameters from multiple locomotives and multiple cars to the expected throttle, dynamic brake, and automatic brake parameter schedules (timing and magnitude) for five different train braking configurations. Given 3,790 different train configurations yields 378,570 candidate vehicles to sample (70,210 + 73,100 + 71,040 + 79,460 + 84,760 = 378,570). Tools and processes were developed to sample 60 representative trains (1,080 vehicles) which is about 0.3 percent of the vehicle population. Additional trains/vehicles could be similarly validated, as necessary.

TEDS Stopping Distance Simulation Validation

In January 2015, the FRA released a formal TEDS component and system level validation document entitled, "Validation of the Train Energy and Dynamics Simulator (TEDS)," DOT/FRA/ORD-15/01, U.S. Department of Transportation, Federal Railroad Administration, Office of Railroad Policy and Development.[74] The TEDS validation effort compared simulation results to publicly available laboratory, field, or train empirical data for conventional pneumatic and ECP air brake systems (emergency and full service application), coupler force, train speed, and stopping distance cases with favorable results.

Results

The emergency and full service braking stopping distance results are broadly summarized in Tables 22.1 to 25.2. These simplified tables may be used to bound the percent distance required to stop relative to the CONV baseline as a function of train braking configuration, train speed, and track grade. **However, proper interpretation of the calculated stopping distance benefit is also dependent on the consist length (train mass) details provided in** Attachments 3–6.[75] **The reported benefit may be limited to trains with lower trailing tonnage operating on lesser grades, and/or at lower speeds.** Table entries with "---" denote inadequate locomotive tractive

74 The TEDS validation document is publicly available at http://www.fra.dot.gov/eLib/Details/L16212.

75 Train consist quantifying data are provided in Attachments 3–6 as a function of train braking configuration, consist length (train mass), train speed, and track grade.

effort for all consists (in ascending grade columns) or insufficient locomotive dynamic braking effort to prevent an initial speed overshoot for all consists (in descending grade columns).

Braking performance differences are qualified as a function of specific operating conditions. To evaluate brake signal propagation rate effects on stopping distance, the NBR was held constant and the brake system configuration was varied. To exclude brake signal propagation rate effects from stopping distance benefits, the brake system configuration can be held constant while the NBR is varied. For this study, the reported stopping distance benefit was measured relative to the CONV 10% NBR baseline for most cases. However, sufficient supporting data are provided in the attachments to permit the reader to evaluate the stopping distance benefits relative to an alternate baseline case (e.g., DP 10% NBR as opposed to CONV 10% NBR).

The NTSB acknowledges that ECP trains may have a higher NBR than conventional pneumatic trains. However, it is also possible to build and maintain a conventional pneumatic train that has a higher NBR than an ECP train.[76]

Emergency Braking (Brake Signal Propagation Rate Effects)

The emergency braking stopping distance results due to brake signal propagation rate effects (with NBR fixed at 10%) are summarized in Tables 22.1 and 22.2 for scenarios with locomotive brakes applied and bailed off, respectively. These simplified tables can be used to estimate the percent distance required to stop relative to the CONV 10% NBR baseline as a function of train braking configuration, train speed, and track grade. More detailed summary data are provided in Attachment 3 as a function of train braking configuration, consist length (train mass), train speed, and track grade.

At 20 mph with locomotive brakes applied, DP provides 1 to 14 percent shorter stopping distances than the CONV configuration across the track grades and consist tonnage studied. By comparison, the ECP configuration provides 2 to 23 percent shorter stopping distances. At 40 mph, the DP benefit is 3 to 8 percent better than CONV and ECP is 4 to 15 percent better than CONV. Note that the smaller stopping distance improvements are associated with steeper ascending grades or with steeper descending grades where more locomotive dynamic braking was applied for longer periods to prevent initial speed overshoots.

At 20 mph with locomotive brakes bailed off, DP provides 4 to 17 percent shorter stopping distances than the CONV configuration. By comparison, the ECP configuration provides 5 to 26 percent shorter stopping distances. At 40 mph, the DP benefit is 3 to 9 percent better than CONV and ECP is 4 to 15 percent better than CONV.

76 This study does not attempt to evaluate the feasibility or costs of building and maintaining a conventional pneumatic train to have a higher NBR than an ECP train.

Full Service Braking (Brake Signal Propagation Rate Effects)

The corresponding full service braking stopping distance results due to brake signal propagation rate effects (with NBR fixed at 10%) are summarized in Tables 23.1 and 23.2 for scenarios with locomotive brakes applied and bailed off, respectively. These simplified tables can be used to estimate the percent distance required to stop relative to the CONV 10% NBR baseline as a function of train braking configuration, train speed, and track grade. As before, supplemental summary data are available in Attachment 4 as a function of train braking configuration, consist length (train mass), train speed, and track grade.

At 20 mph with locomotive brakes applied, DP provides 6 to 36 percent shorter stopping distances than the CONV configuration across the track grades and consist tonnage studied. By comparison, the ECP configuration provides 43 to 72 percent shorter stopping distances. At 40 mph, the DP benefit is 10 to 36 percent better than CONV and ECP is 40 to 64 percent better than CONV.

At 20 mph with locomotive brakes bailed off, DP provides 7 to 46 percent shorter stopping distances than the CONV configuration. By comparison, the ECP configuration provides 37 to 75 percent shorter stopping distances. At 40 mph, the DP benefit is 10 to 39 percent better than CONV and ECP is 32 to 64 percent better than CONV.

Emergency Braking (Combined Brake Signal Propagation Rate and NBR Effects)

The emergency braking stopping distance results due to the combined brake signal propagation rate and NBR effects are summarized in Tables 24.1 and 24.2 for scenarios with locomotive brakes applied and bailed off, respectively. These simplified tables can be used to estimate the percent distance required to stop relative to the CONV 10% NBR baseline as a function of train braking configuration, train speed, and track grade. Once again, more detailed summary data are provided in Attachment 5 as a function of train braking configuration, consist length (train mass), train speed, and track grade.

Table 22.1: Brake Signal Propagation Effect, Emergency Braking, No Bailoff
Range of Percent Distance Required to Stop Relative to CONV Baseline
(See Attachment 3 for Corresponding Consist Detail)

Train Brake	**Speed**				**Track Grade, Percent**					
Configuration	**Mph**	**+2.0**	**+1.5**	**+1.0**	**+0.5**	**0.0**	**-0.5**	**-1.0**	**-1.5**	**-2.0**
DP 10% NBR	20	-1 to -1	0 to -3	-3 to -3	-4 to -6	-4 to -10	-6 to -12	-6 to -14	-6 to -12	-6 to -9
ECP 10% NBR	20	-2 to -2	-3 to -4	-4 to -8	-5 to -13	-6 to -19	-8 to -22	-8 to -23	-8 to -20	-8 to -12
DP 10% NBR	30	---	---	-3 to -3	-3 to -7	-4 to -10	-5 to -10	-5 to -8	-5 to -6	-5 to -5
ECP 10% NBR	30	---	---	-4 to -4	-5 to -13	-5 to -17	-6 to -18	-6 to -15	-6 to -10	-6 to -6
DP 10% NBR	40	---	---	-3 to -3	-3 to -4	-3 to -8	-4 to -8	-4 to -5	-4 to -4	---
ECP 10% NBR	40	---	---	-4 to -4	-4 to -6	-4 to -14	-5 to -15	-5 to -8	-5 to -5	---
DP 10% NBR	50	---	---	---	-3 to -3	-3 to -7	-3 to -7	-3 to -4	---	---
ECP 10% NBR	50	---	---	---	-3 to -5	-4 to -12	-4 to -13	-4 to -7	---	---

Table 22.2: Brake Signal Propagation Effect, Emergency Braking, Bailed Off
Range of Percent Distance Required to Stop Relative to CONV Baseline
(See Attachment 3 for Corresponding Consist Detail)

Train Brake	**Speed**				**Track Grade, Percent**					
Configuration	**Mph**	**+2.0**	**+1.5**	**+1.0**	**+0.5**	**0.0**	**-0.5**	**-1.0**	**-1.5**	**-2.0**
DP 10% NBR	20	-4 to -4	-5 to -6	-6 to -7	-6 to -9	-6 to -13	-6 to -14	-6 to -17	-6 to -16	-7 to -11
ECP 10% NBR	20	-5 to -5	-6 to -9	-7 to -13	-7 to -19	-8 to -22	-8 to -24	-8 to -26	-9 to -23	-9 to -14
DP 10% NBR	30	---	---	-4 to -4	-4 to -9	-5 to -11	-4 to -11	-5 to -11	-5 to -7	-5 to -5
ECP 10% NBR	30	---	---	-5 to -5	-6 to -15	-6 to -19	-6 to -19	-6 to -16	-7 to -10	-7 to -7
DP 10% NBR	40	---	---	-3 to -3	-3 to -5	-4 to -9	-4 to -9	-4 to -5	-4 to -4	---
ECP 10% NBR	40	---	---	-4 to -4	-5 to -7	-5 to -15	-5 to -15	-5 to -8	-5 to -5	---
DP 10% NBR	50	---	---	---	-3 to -4	-3 to -7	-3 to -8	-3 to -4	-3 to -3	---
ECP 10% NBR	50	---	---	---	-4 to -6	-4 to -13	-4 to -13	-4 to -6	-4 to -4	---

Table 23.1: Brake Signal Propagation Effect, Full Service Braking, No Bailoff
Range of Percent Distance Required to Stop Relative to CONV Baseline
(See Attachment 4 for Corresponding Consist Detail)

Train Brake	Speed				Track Grade, Percent					
Configuration	**Mph**	**+2.0**	**+1.5**	**+1.0**	**+0.5**	**0.0**	**-0.5**	**-1.0**	**-1.5**	**-2.0**
DP 10% NBR	20	-7 to -7	-6 to -9	-8 to -11	-11 to -19	-13 to -28	-16 to -36	-16 to -36	-16 to -33	-16 to -16
ECP 10% NBR	20	-43 to -43	-46 to -47	-49 to -53	-52 to -64	-55 to -70	-50 to -72	-50 to -72	-50 to -69	-50 to -56
DP 10% NBR	30	---	---	-11 to -11	-11 to -22	-13 to -30	-14 to -36	-14 to -32	-14 to -15	-14 to -14
ECP 10% NBR	30	---	---	-44 to -44	-47 to -58	-49 to -66	-42 to -68	-43 to -64	-44 to -50	-44 to -44
DP 10% NBR	40	---	---	-10 to -10	-11 to -11	-11 to -31	-12 to -36	-12 to -13	-12 to -12	---
ECP 10% NBR	40	---	---	-40 to -40	-42 to -45	-43 to -62	-36 to -64	-37 to -44	-38 to -38	---
DP 10% NBR	50	---	---	---	-10 to -10	-10 to -32	-10 to -36	-11 to -12	---	---
ECP 10% NBR	50	---	---	---	-38 to -41	-39 to -59	-31 to -61	-33 to -39	---	---

Table 23.2: Brake Signal Propagation Effect, Full Service Braking, Bailed Off
Range of Percent Distance Required to Stop Relative to CONV Baseline
(See Attachment 4 for Corresponding Consist Detail)

Train Brake	Speed				Track Grade, Percent					
Configuration	**Mph**	**+2.0**	**+1.5**	**+1.0**	**+0.5**	**0.0**	**-0.5**	**-1.0**	**-1.5**	**-2.0**
DP 10% NBR	20	-8 to -8	-7 to -10	-9 to -12	-13 to -22	-16 to -31	-16 to -39	-17 to -46	-17 to -44	-16 to -22
ECP 10% NBR	20	-37 to -37	-40 to -43	-43 to -50	-46 to -62	-49 to -69	-49 to -73	-47 to -75	-45 to -71	-42 to -52
DP 10% NBR	30	---	---	-11 to -11	-12 to -20	-13 to -33	-13 to -39	-13 to -36	-13 to -17	-10 to -10
ECP 10% NBR	30	---	---	-37 to -37	-39 to -54	-40 to -65	-40 to -68	-38 to -63	-35 to -43	-30 to -30
DP 10% NBR	40	---	---	-10 to -10	-11 to -12	-11 to -33	-11 to -39	-11 to -14	-10 to -10	---
ECP 10% NBR	40	---	---	-32 to -32	-33 to -39	-34 to -61	-33 to -64	-30 to -38	-27 to -27	---
DP 10% NBR	50	---	---	---	-9 to -11	-10 to -33	-10 to -37	-9 to -12	-8 to -8	---
ECP 10% NBR	50	---	---	---	-29 to -35	-29 to -58	-28 to -60	-25 to -33	-21 to -21	---

Table 24.1: Combined ECP Brake Signal Propagation and Net Braking Ratio Effect, Emergency Braking, No Bailoff
Range of Percent Distance Required to Stop Relative to CONV Baseline
(See Attachment 5 for Corresponding Consist Detail)

Train Brake Configuration	Speed mph	Track Grade, Percent +2.0	+1.5	+1.0	+0.5	0.0	-0.5	-1.0	-1.5	-2.0
ECP 10% NBR	20	-2 to -2	-3 to -4	-4 to -8	-5 to -13	-6 to -19	-8 to -22	-8 to -23	-8 to -20	-8 to -12
ECP 12.8% NBR	20	-8 to -8	-10 to -11	-12 to -16	-14 to -23	-15 to -29	-22 to -34	-22 to -35	-22 to -32	-22 to -26
ECP 14% NBR	20	-11 to -11	-13 to -13	-15 to -19	-17 to -26	-19 to -32	-26 to -38	-27 to -38	-27 to -36	-27 to -30
ECP 10% NBR	30	---	---	-4 to -4	-5 to -13	-5 to -17	-6 to -18	-6 to -15	-6 to -10	-6 to -6
ECP 12.8% NBR	30	---	---	-13 to -13	-14 to -24	-16 to -29	-22 to -31	-21 to -28	-21 to -24	-20 to -20
ECP 14% NBR	30	---	---	-16 to -16	-18 to -27	-19 to -33	-27 to -36	-26 to -33	-25 to -28	-25 to -25
ECP 10% NBR	40	---	---	-4 to -4	-4 to -6	-4 to -14	-5 to -15	-5 to -8	-5 to -5	---
ECP 12.8% NBR	40	---	---	-13 to -13	-15 to -18	-16 to -27	-22 to -30	-21 to -23	-20 to -20	---
ECP 14% NBR	40	---	---	-17 to -17	-18 to -22	-20 to -32	-27 to -34	-26 to -28	-25 to -25	---
ECP 10% NBR	50	---	---	---	-3 to -5	-4 to -12	-4 to -13	-4 to -7	---	---
ECP 12.8% NBR	50	---	---	---	-15 to -18	-16 to -26	-22 to -28	-21 to -23	---	---
ECP 14% NBR	50	---	---	---	-19 to -22	-20 to -30	-27 to -33	-26 to -28	---	---

Table 24.2: Combined ECP Brake Signal Propagation and Net Braking Ratio Effect, Emergency Braking, Bailed Off
Range of Percent Distance Required to Stop Relative to CONV Baseline (See Attachment 5 for Corresponding Consist Detail)

Train Brake Configuration	Speed mph	Track Grade, Percent +2.0	+1.5	+1.0	+0.5	0.0	-0.5	-1.0	-1.5	-2.0
ECP 10% NBR	20	-5 to -5	-6 to -9	-7 to -13	-7 to -19	-8 to -22	-8 to -24	-8 to -26	-9 to -23	-9 to -14
ECP 12.8% NBR	20	-13 to -13	-16 to -18	-17 to -23	-19 to -29	-21 to -34	-24 to -36	-26 to -39	-29 to -38	-33 to -36
ECP 14% NBR	20	-16 to -16	-19 to -21	-21 to -26	-23 to -32	-26 to -37	-28 to -40	-31 to -43	-35 to -42	-39 to -41
ECP 10% NBR	30	---	---	-5 to -5	-6 to -15	-6 to -19	-6 to -19	-6 to -16	-7 to -10	-7 to -7
ECP 12.8% NBR	30	---	---	-17 to -17	-19 to -27	-22 to -32	-24 to -33	-26 to -33	-30 to -32	-35 to -35
ECP 14% NBR	30	---	---	-21 to -21	-24 to -31	-26 to -36	-29 to -38	-32 to -38	-36 to -38	-42 to -42
ECP 10% NBR	40	---	---	-4 to -4	-5 to -7	-5 to -15	-5 to -15	-5 to -8	-5 to -5	---
ECP 12.8% NBR	40	---	---	-17 to -17	-19 to -22	-22 to -30	-24 to -31	-27 to -28	-31 to -31	---
ECP 14% NBR	40	---	---	-22 to -22	-24 to -26	-27 to -34	-30 to -36	-33 to -34	-37 to -37	---
ECP 10% NBR	50	---	---	---	-4 to -6	-4 to -13	-4 to -13	-4 to -6	-4 to -4	---
ECP 12.8% NBR	50	---	---	---	-19 to -21	-22 to -28	-24 to -30	-27 to -28	-31 to -31	---
ECP 14% NBR	50	---	---	---	-24 to -26	-27 to -33	-30 to -36	-33 to -34	-38 to -38	---

Table 25.1: Combined ECP Brake Signal Propagation and Net Braking Ratio Effect, Full Service Braking, No Bailoff
Range of Percent Distance Required to Stop Relative to CONV Baseline (See Attachment 6 for Corresponding Consist Detail)

Train Brake	Speed	Track Grade, Percent								
Configuration	mph	+2.0	+1.5	+1.0	+0.5	0.0	-0.5	-1.0	-1.5	-2.0
ECP 10% NBR	20	-43 to -43	-46 to -47	-49 to -53	-52 to -64	-55 to -70	-50 to -72	-50 to -72	-50 to -69	-50 to -56
ECP 12.8% NBR	20	-47 to -47	-50 to -52	-53 to -58	-57 to -68	-60 to -74	-58 to -77	-59 to -77	-59 to -74	-59 to -64
ECP 14% NBR	20	-48 to -48	-52 to -53	-55 to -59	-58 to -69	-62 to -75	-61 to -78	-61 to -78	-61 to -76	-61 to -66
ECP 10% NBR	30	---	---	-44 to -44	-47 to -58	-49 to -66	-42 to -68	-43 to -64	-44 to -50	-44 to -44
ECP 12.8% NBR	30	---	---	-50 to -50	-52 to -64	-55 to -71	-52 to -73	-53 to -70	-53 to -58	-53 to -53
ECP 14% NBR	30	---	---	-51 to -51	-54 to -66	-57 to -73	-56 to -75	-56 to -72	-56 to -61	-56 to -56
CP 10% NBR	40	---	---	-40 to -40	-42 to -45	-43 to -62	-36 to -64	-37 to -44	-38 to -38	
ECP 12.8% NBR	40	---	---	-46 to -46	-48 to -51	-50 to -68	-48 to -70	-48 to -54	-48 to -48	---
ECP 14% NBR	40	---	---	-48 to -48	-50 to -54	-53 to -70	-51 to -72	-52 to -57	-52 to -52	---
CP 10% NBR	50	---	---	---	-38 to -41	-39 to -59	-31 to -61	-33 to -39	---	
ECP 12.8% NBR	50	---	---	---	-45 to -48	-47 to -66	-44 to -68	-45 to -50	---	---
ECP 14% NBR	50	---	---	---	-47 to -51	-50 to -68	-48 to -70	-48 to -53	---	---

Table 25.2: Combined ECP Brake Signal Propagation and Net Braking Ratio Effect, Full Service Braking, Bailed Off
Range of Percent Distance Required to Stop Relative to CONV Baseline (See Attachment 6 for Corresponding Consist Detail)

Train Brake	Speed	Track Grade, Percent								
Configuration	mph	+2.0	+1.5	+1.0	+0.5	0.0	-0.5	-1.0	-1.5	-2.0
ECP 10% NBR	20	-37 to -37	-40 to -43	-43 to -50	-46 to -62	-49 to -69	-49 to -73	-47 to -75	-45 to -71	-42 to -52
ECP 12.8% NBR	20	-42 to -42	-46 to -49	-50 to -56	-54 to -68	-57 to -74	-58 to -78	-59 to -80	-60 to -78	-61 to -67
ECP 14% NBR	20	-45 to -45	-49 to -51	-52 to -58	-56 to -69	-60 to -76	-61 to -79	-62 to -82	-63 to -80	-66 to -70
ECP 10% NBR	30	---	---	-37 to -37	-39 to -54	-40 to -65	-40 to -68	-38 to -63	-35 to -43	-30 to -30
ECP 12.8% NBR	30	---	---	-45 to -45	-48 to -61	-51 to -71	-52 to -74	-53 to -71	-54 to -59	-57 to -57
ECP 14% NBR	30	---	---	-48 to -48	-51 to -63	-54 to -73	-56 to -76	-57 to -74	-59 to -64	-62 to -62
ECP 10% NBR	40	---	---	-32 to -32	-33 to -39	-34 to -61	-33 to -64	-30 to -38	-27 to -27	---
ECP 12.8% NBR	40	---	---	-41 to -41	-44 to -49	-46 to -68	-47 to -71	-48 to -54	-50 to -50	---
ECP 14% NBR	40	---	---	-44 to -44	-47 to -52	-50 to -70	-52 to -73	-53 to -58	-55 to -55	---
ECP 10% NBR	50	---	---	---	-29 to -35	-29 to -58	-28 to -60	-25 to -33	-21 to -21	---
ECP 12.8% NBR	50	---	---	---	-40 to -45	-43 to -66	-44 to -68	-45 to -50	-46 to -46	---
ECP 14% NBR	50	---	---	---	-44 to -49	-47 to -68	-49 to -71	-50 to -55	-53 to -53	---

At 20 mph with locomotive brakes applied, the ECP 10% NBR configuration provides 2 to 23 percent shorter stopping distances than the CONV baseline across the track grades and consist tonnage studied. By comparison, the ECP 12.8% NBR and ECP 14% NBR configurations provide 8 to 35 percent and 11 to 38 percent shorter stopping distances, respectively. At 40 mph, the ECP 10% NBR distance is 4 to 15 percent, the ECP 12.8% NBR distance is 13 to 30 percent, and the ECP 14% NBR distance is 17 to 34 percent shorter than the CONV baseline, respectively. As before, the smaller stopping distance improvements are associated with steeper ascending grades or with steeper descending grades where more locomotive dynamic braking was applied for longer periods to prevent initial speed overshoots.

At 20 mph with locomotive brakes bailed off, ECP 10% NBR provides 5 to 26 percent, ECP 12.8% NBR yields 13 to 39 percent, and ECP 14% provides 16 to 43 percent shorter stopping distances than the CONV baseline, respectively. At 40 mph, the ECP 10% NBR benefit is 4 to 15 percent, the ECP 12.8% NBR benefit is 17 to 31 percent, and the ECP 14% NBR benefit is 22 to 36 percent better than the CONV baseline, respectively.

Full Service Braking (Combined Brake Signal Propagation Rate and NBR Effects)

The full service braking stopping distance results due to the combined brake signal propagation rate and NBR effects are summarized in Tables 25.1 and 25.2 for scenarios with locomotive brakes applied and bailed off, respectively. These simplified tables can be used to estimate the percent distance required to stop relative to the CONV 10% NBR baseline as a function of train braking configuration, train speed, and track grade. Again, supplemental summary data are available in Attachment 6 as a function of train braking configuration, consist length (train mass), train speed, and track grade.

At 20 mph with locomotive brakes applied, the ECP 10% NBR configuration provides 43 to 72 percent shorter stopping distances than the CONV baseline. By comparison, the ECP 12.8% NBR and ECP 14% configurations provide 47 to 77 percent and 48 to 78 percent shorter stopping distances, respectively. At 40 mph, the ECP 10% NBR distance is 40 to 64 percent, the ECP 12.8% NBR distance is 46 to 70 percent, and the ECP 14% NBR distance is 48 to 72 percent shorter than the CONV baseline, respectively. As before, the smaller stopping distance improvements are associated with steeper ascending grades or with steeper descending grades where more locomotive dynamic braking was applied for longer periods to prevent initial speed overshoots.

At 20 mph with locomotive brakes bailed off, ECP 10% NBR provides 37 to 75 percent, ECP 12.8% NBR yields 42 to 80 percent, and ECP 14% provides 45 to 82 percent shorter stopping distances than the CONV baseline, respectively. At 40 mph, the ECP 10% NBR benefit is 32 to 64 percent, the ECP 12.8% NBR benefit is 41 to 71 percent, and the ECP 14% NBR benefit is 44 to 73 percent better than the CONV baseline, respectively.

Stopping Distance Performance Observations

For all train braking configurations, the stopping distance benefit relative to the CONV 10% NBR baseline generally increases as consist length (train mass) increases,[77] the track grade decreases, and/or train speed decreases. The following points summarize the relationships that are generally observed along with explanatory notes.

- For a given train (mass, length, NBR) on a given grade, the advantage of ECP over conventional brakes decreases with increasing speed because the portion of the braking time that differs (brake signal propagation) becomes smaller relative to the overall longer braking period required.

- On a given grade from a given initial speed, the ECP advantage increases with increasing train length due to the increasing signal propagation time for longer conventional and DP trains.

- For a given train at a given initial speed, the ECP advantage increases on a decreasing grade (steeper descending) because an increasing portion of the energy is removed by the brakes.

- For a given train at a given initial speed on a given grade, the ECP advantage increases when locomotive brakes are bailed off because a greater portion of the energy is removed by the automatic brakes.

- For a given NBR, the relative benefit of the advanced braking systems tends to reduce with increased speed.

- If ECP braking is artificially constrained to the conventional tank car fleet nominal NBR value (about 10%) and limited to emergency brake application scenarios, then as the required emergency brake application period increases (relative to the "fixed" signal propagation and brake cylinder pressure rise times), there will be a smaller difference in stopping performance when comparing CONV, DP, and ECP braking.

- Improved stopping performance is possible if intended ECP closed-loop control capability is used to target and maintain car NBR values higher than 10%.[78] Additional

77 Train mass has little effect on the stopping distance as long as the effective NBR and train length remain constant. The train mass was modified by changing the number of cars, but the mass of each car remained constant and the train retained the same effective NBR (by design). Train length does affect brake signal propagation time for CONV and DP braking systems.
78 Conventional pneumatic brake equipment could be built and maintained to the same NBR level as ECP equipment.

ECP benefits include ECP graduated full or partial service brake application and release options

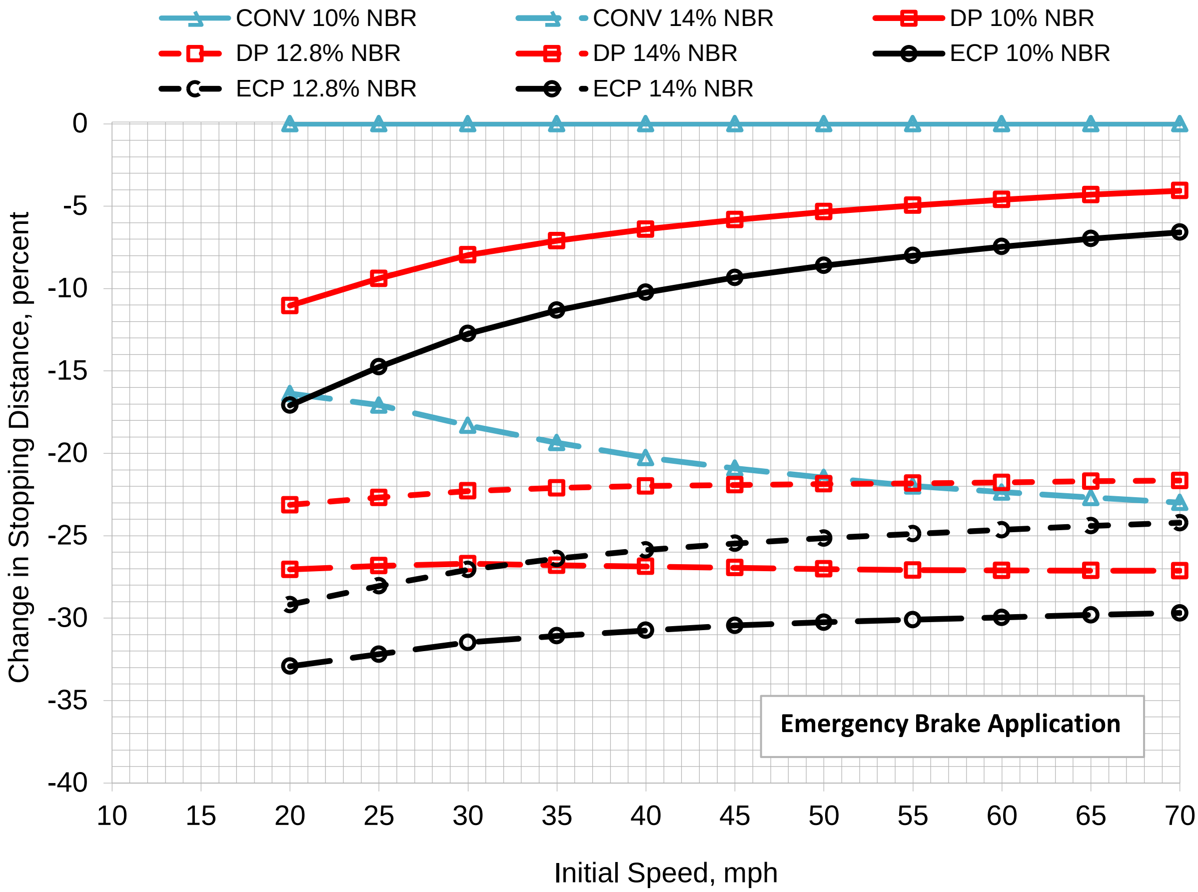
Calculated Emergency Stopping Distance Performance

Detailed summary plots of the TEDS emergency braking simulation results are provided in Attachments 7–16. Plots in the first half of each attachment compare CONV 10% NBR, DP 10% NBR, ECP 10% NBR, ECP 12.8% NBR, and ECP 14% NBR calculated stopping distance (or percent stopping distance reduction relative to the CONV 10% NBR baseline) for a specified track grade as a function of initial train speed. Plots with truncated curves reflect inadequate locomotive tractive effort or dynamic brake effort to balance the trailing tonnage (maintain the desired constant initial target speed for 60 seconds) beyond the range of track grades and speeds depicted (for speeds greater than 20 mph).[79] Plots in the second half of each attachment compare similar stopping distance (or percent stopping distance reduction) results for the applicable range of track grades for the specified train braking configuration (CONV 10% NBR, DP 10% NBR, ECP 10% NBR, ECP 12.8% NBR, or ECP 14% NBR) as a function of initial train speed.

An example plot of the calculated emergency stopping distance benefit for the nominal consist on level track with locomotive brakes bailed off is shown in Figure 88. The incremental emergency braking stopping distance benefit due to increased NBR for a given speed appears to be comparable for the CONV, DP, and ECP braking systems. The emergency braking stopping distance for DP and ECP at 12.8% NBR is reduced by about 22% and 24 to 29%, respectively, relative to the CONV 10% NBR baseline. These data combine emergency braking signal propagation rate and increased NBR effects.

79 Certain plot results for trains with more tank cars on higher ascending and/or steeper descending track grades were omitted because the available locomotive tractive effort (for ascending or level track grades) or dynamic brake effort (for descending grades) was inadequate to reach a balanced speed with the trailing tonnage for the range of track grades and speeds evaluated. That is, no valid data points exist for these scenarios.

Figure 88: Emergency Brake Stopping Performance, 0% Grade, Bailed Off
Benefit Relative to Conventional Pneumatic Brakes, 10% NBR, Head-End Power

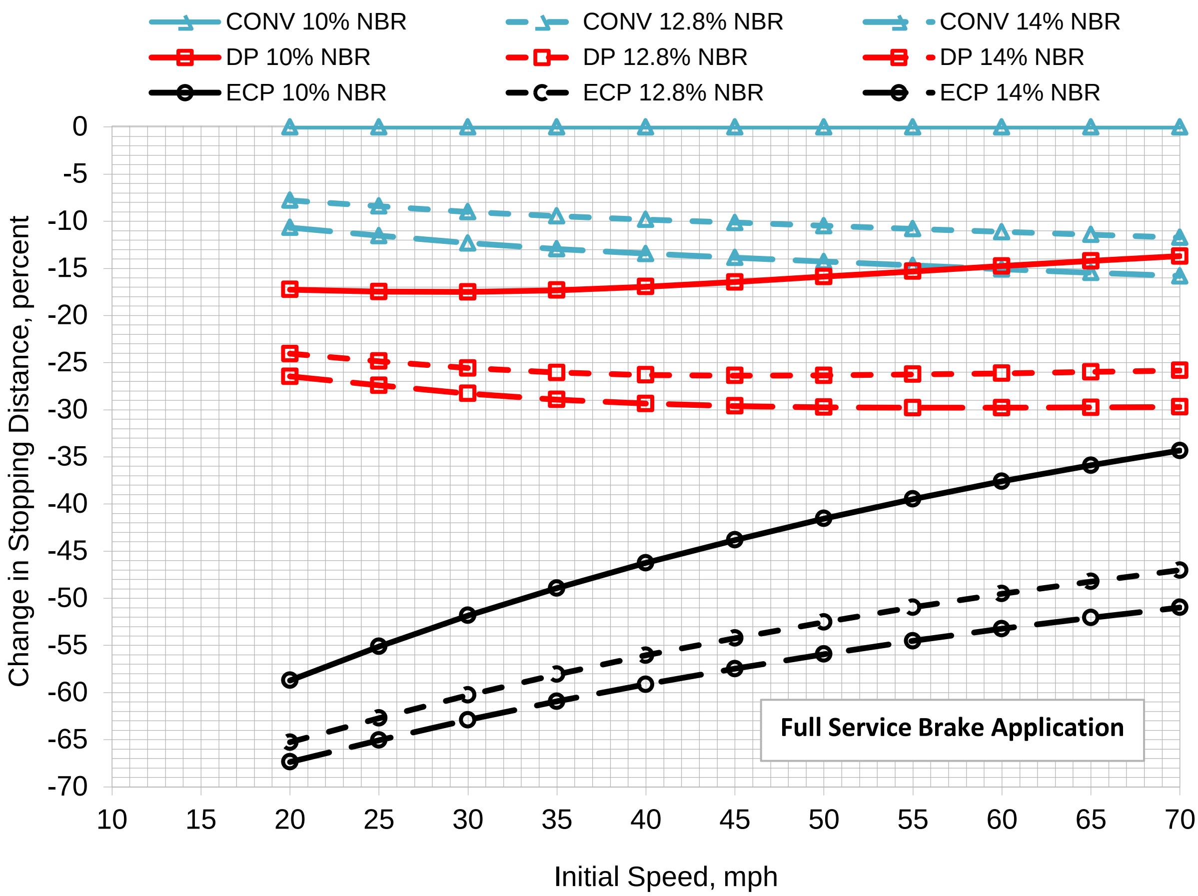


Calculated Full Service Stopping Distance Performance

Similar to the emergency braking results presentation, detailed summary plots of the TEDS full service braking simulation cases are provided in Attachments 17–26. Plots in the first half of each attachment compare CONV 10% NBR, DP 10% NBR, ECP 10% NBR, ECP 12.8% NBR, and ECP 14% NBR calculated stopping distance (or percent stopping distance reduction relative to the CONV 10% NBR baseline) for a specified track grade as a function of initial train speed. As before, plots with truncated curves reflect inadequate locomotive tractive effort or dynamic brake effort to balance the trailing tonnage (maintain the desired constant initial target speed for 60 seconds) beyond the range of track grades and speeds depicted (for speeds greater than 20 mph).[78] Plots in the second half of each attachment compare similar stopping distance (or percent stopping distance reduction) results for the applicable range of track grades for the specified train braking configuration (CONV 10% NBR, DP 10% NBR, ECP 10% NBR, ECP 12.8% NBR, or ECP 14% NBR) as a function of initial train speed.

An example plot of the calculated full service stopping distance benefits for the nominal consist on level track with locomotive brakes bailed off is provided in Figure 89. Once again, the incremental full service braking stopping distance benefit due to increased NBR for a given speed appears to be comparable for the CONV, DP, and ECP braking systems. The full service braking stopping distance for DP and ECP at 12.8% NBR is reduced by about 25% and 47 to 65%, respectively, relative to the CONV 10% NBR baseline. These results combine full service braking signal propagation rate and increased NBR effects.

Figure 89: Full Service Brake Stopping Performance, 0% Grade, Bailed Off
Benefit Relative to Conventional Pneumatic Brakes, 10% NBR, Head-End Power



CONV, DP, and ECP Increased NBR Benefits

The stopping performance benefit due to increased NBR is quantified for the nominal consist on level grade in Attachments 27 and 28. The plots in Attachment 27 compare the calculated CONV, DP, and ECP stopping distance benefit relative to the respective braking system 10% NBR baseline. The emergency braking results indicate comparable stopping distance benefits due to increased NBR for the CONV, DP, and ECP braking systems. The full service braking results also show comparable stopping distance benefits due to increased NBR for the CONV and DP systems but a more significant benefit for ECP braking. These results isolate brake signal propagation rate effects from increased NBR effects.

The plots in Attachment 28 compare the calculated CONV, DP, and ECP stopping distance benefit relative to the CONV 10% NBR baseline. The composite emergency and full service braking results discussed previously (Figures 88 and 89) are presented together with a comparison of CONV, DP, and ECP results for fixed NBR values of 10%, 12.8%, and 14%. These results combine brake signal propagation rate and increased NBR effects.

Calculated Stopping Distance Performance Comparisons and Benefits

To date, the NTSB results have been checked against comparable SA results for 43 mph, ±1 percent grade for both emergency and full service brake applications with favorable results. In addition, technical specialists from the FRA and SA indicated that the NTSB stopping distance results for emergency and full service brake applications were generally consistent with their respective organization's expectations and understanding of conventional pneumatic and ECP brake performance. In addition, the TEDS ECP 10% NBR simulation results appear to be generally consistent with the limited data available in the recent PHMSA NPRM documents.

Benefits from the use of advanced braking systems come from three sources: reduced stopping distances (fewer cars in the potential pileup), reduced kinetic energy (less energy that might be available to puncture cars in the pileup), and lower and more uniform coupler forces (more compatible car-to-car interaction). Note that the relative train braking configuration percentage improvements presented in tables 22.1 to 25.2 (and their supporting tables in Attachments 3-6 and charts in Attachments 7-26) capture only the stopping distance benefit, and that the additional benefits from the other two sources remain to be explored more thoroughly.

Although stopping distance benefits in this study are quantified as a percent relative to a baseline reference case, the equivalent car length benefit varies as a function of the initial speed. For example, a 14% stopping distance reduction at 30 mph (CONV 12.8% NBR relative to CONV 10% NBR baseline) corresponds to about 2.5 car lengths. By comparison, a 17% stopping distance reduction at 60 mph (CONV 12.8% NBR relative to CONV 10% NBR baseline) corresponds to about 11.5 car lengths. Even though the percent stopping distance reduction numbers at higher speeds may be similar to or smaller than those at lower speeds, the absolute stopping distance improvement (how many car lengths shorter the stop would be) may be much more significant toward the safety goal of avoiding a hazard.

FRA ECP Braking Report Excerpts

The FRA Final Report, "ECP Brake System for Freight Service," prepared by Booz-Allen-Hamilton, released August 2006, updated March 10, 2009 describes ECP stopping distance reductions relative to conventional pneumatic brake systems on the order of 30 to 40 percent for lighter or shorter trains and 60 to 70 percent for longer or heavier trains (see Attachment 29).

Unfortunately, the FRA ECP report does not quantify whether these reported stopping distance reductions were accomplished with emergency or full service brake applications.

In this study, the TEDS simulation results for full service brake applications (as opposed to emergency brake applications) are generally consistent with the FRA reported ECP stopping distance reductions.

Technical specialists from SA noted that train stopping distance improvements (resulting from the use of ECP brakes) on the order of 50 to 70 percent may be associated with service brake applications, as opposed to emergency braking applications, which typically have a smaller range of improvement. Brake signal propagation times and brake cylinder pressure rise times for conventional (pneumatic) full service brake applications are much greater than the comparable times for conventional (pneumatic) emergency brake applications. The corresponding brake signal propagation and brake cylinder pressure rise times for ECP full service and emergency brake applications are much closer together. Hence, improvements associated with ECP over conventional braking are much greater for service applications than they are for emergency applications.

NTSB Back-of-the-Envelope Calculations, Emergency Braking

The NTSB also completed independent, back-of-the-envelope emergency stopping distance calculations for ECP and conventional brakes as a function of speed, grade, and ECP NBR. Energy conservation and work principles were used to account for the kinetic energy as a function of speed and mass, potential energy as a function of mass, grade, and distance traveled, wheel bearing resistance, wheel rolling resistance, and brake force as a function of NBR. These validation scenarios assumed emergency braking on tangent track (no curving resistance), no air resistance, and no energy dissipated via friction plate/damper action. A simplified emergency braking model was used to account for pneumatic signal propagation and brake cylinder pressure rise times as a function of car position, as applicable. The resulting calculated stopping distances shown in Attachment 30 are expected to be within ±10 percent (or better) of the required stopping distance.

Calculated Brake System Pressures and In-Train Forces

Time history plots of calculated brake system pressure and brake force parameters are included in Attachment 31 for the nominal consist traveling at an initial speed of 50 mph with initial coupler slack neutral, level track grade, emergency braking, and locomotive brakes applied. The matching in-train coupler buff and draft force time history plots are provided in Attachment 32.

The in-train force benefits of DP and ECP braking are clearly visible for the example case, evidenced by substantially lower car-to-car buff forces (75,000 to 250,000 lb. lower) during emergency brake application.[80] For train operations in general:

80 Note that the DP and ECP braking reduced force magnitudes calculated in the example TEDS simulation cases do not relate directly to the peak forces expected during the Casselton, ND accident.

- A reduction of 75,000 to 250,000 lb. does not imply forces would be that much lower in the event of an incident or accident because most of the energy dissipated in these incidents/accidents is the result of derailing cars running into "the pile."

- Most of these incidents/accidents involve trainline emergencies (derailment occurred under the train, initiating emergency application somewhere between the head- and rear-end.).

While this generic stopping distance study yields some useful in-train force results and trends, it is not intended to exhaustively compare the in-train force benefits among the various train braking configurations evaluated. Grades more representative of actual train operations (i.e., non-uniform, mixed ascending/descending grades, and curves) and more general train handling (i.e., a range of throttle, automatic brake, independent brake, and/or dynamic brake inputs) need to be modeled to better quantify the expected in-train force envelope as a function of CONV, DP, and/or ECP braking.

Kinetic Energy Comparison

The TEDS simulation output data were interpolated to constant distance (10 ft.), time (0.5 sec.), and speed (0.5 mph) increments, respectively, for each vehicle and each braking configuration to enable kinetic energy to be compared for a given vehicle during an example emergency brake application. Exemplar plots for CONV 10% NBR, DP 10% NBR, ECP 10% NBR, ECP 12.8% NBR, and ECP 14% NBR in Attachment 33 (for vehicles 1, 2, 3, 7, and 8 to 108 by an increment of 2) quantify the percent change in individual vehicle kinetic energy relative to the CONV 10% NBR baseline as a function of vehicle distance traveled, elapsed time, and vehicle speed. These emergency braking data correspond to a nominal train configuration (5 locomotives, 2 buffer cars, 104 tank cars) braked to a full stop (with locomotive brakes applied) from an initial speed of 50 mph on a level grade, tangent track segment.

In Attachment 33, the top figure for each vehicle shows the change in kinetic energy as a function of vehicle distance traveled, relative to the CONV 10% NBR baseline. Brakes were applied at the origin of the distance traveled axis, and the data for the CONV 10% NBR baseline (black circles) extends to the point where the vehicle comes to a stop (more than 2,200 feet). The middle figure for each vehicle shows the change in kinetic energy as a function of elapsed time, relative to the CONV 10% NBR baseline. Brakes were applied at time zero, and the data for the CONV 10% NBR baseline (black circles) extends to the time where the vehicle comes to a stop (about 58 seconds). The bottom figure for each vehicle compares the interpolated change in kinetic energy as a function of vehicle speed, to assess the quality of the interpolation. The kinetic energy for each (identical) vehicle is a function only of speed, so the difference should be zero, but small absolute differences from the interpolation process are amplified at low speeds.

Interpolated kinetic energy data for an exemplar emergency stop could be used to estimate the energy dissipated (relative to the CONV 10% NBR baseline) over a finite distance window as a function of braking configuration (DP 10% NBR, ECP 10% NBR, ECP 12.8% NBR, or ECP 14% NBR). For example, use of ECP braking at 12.8% NBR to bring the train to a full stop on level grade from an initial speed of 50 mph would decrease the required stopping distance by about 500 to 550 feet (about 8 to 9 tank car lengths) relative to the CONV 10% NBR baseline.

The kinetic energy dissipated over a finite time window could also be compared to estimate the response time margin available (as a function of the brake system configuration) for engineer/ conductor corrective or mitigating action via emergency brake application. For the same 50 mph to full stop (zero kinetic energy) example on level grade, use of ECP braking at 12.8% NBR would add about 13 seconds of response time margin relative to the CONV 10% NBR baseline. A hypothetical target vehicle kinetic energy decrease of 50 percent or more (relative to the initial train speed) using ECP braking at 12.8% NBR would equate to a distance reduction of about 850 feet (about 14 tank car lengths) and a time margin benefit of about 28 seconds relative to the CONV 10% NBR baseline.

Related plots of the kinetic energy reduction expected due to hypothetical train operating speed reductions of 5 and 10 mph are included in Attachment 34.

Related Industry Simulation Work

The U.S. railroad industry has asserted that the AAR Train Operations and Energy Simulator (TOES) has a detailed air brake model that has been validated and is capable of comparing braking performance for pneumatic and ECP brake systems. Therefore, TOES is a suitable simulation tool for potential railroad industry comparison work to a subset of the simulation scenarios documented in this study. As an example, a recent paper from the industry submitted along with AAR's comments to the PHMSA NPRM ("Analysis and Modeling of the Benefits of Alternative Braking Systems in Tank Car Derailments", R-1007, September 2014, authored by Joseph Brosseau, TTCI) presents simulation data from multiple simulations comparing the kinetic energy benefits resulting from advanced brake systems. A summary table on page 1 of the report (reproduced here as Table 26) includes the calculated ECP brake signal propagation benefits relative to CONV, end-of-train-device (ETD), and several DP configurations. The AAR paper does not attempt to evaluate the stopping distance, in-train force, or kinetic energy benefits related to increased car NBR. Rather, it focuses on the effect of braking system design (CONV, various DP arrangements, ECP) and performance using the same 10% NBR baseline used in this study.

Table 26. Average Percent Reduction in Energy Dissipated in Derailment and Number of Cars Reaching Point of Derailment

Performance of ECP Brake System Compared To:	Average Percent Reduction in Energy Dissipated in Derailment	Average Reduction in Number of Cars Reaching Point of Derailment
Conventional Brakes (Head-end)	13.3%	1.6
Conventional Brakes with ETD	11.6%	1.3
Rear-end DP	12.8%	1.5
Mid-train DP	10.5%	1.2
DP at 2/3	10.8%	1.2

Source: AAR R-1007, "Analysis and Modeling of Benefits of Alternative Braking Systems in Tank Car Derailments", September 2014.

Summary

A generic train stopping distance simulation study was performed to quantify the expected tank car unit train stopping distance as a function of train mass, train speed, track grade, train braking configuration (CONV 10% NBR, DP 10% NBR, ECP 10% NBR, ECP 12.8% NBR, and ECP 14% NBR), type of brake application (emergency or full service), and locomotive brake use. Locomotive brakes were modeled bailed off or applied, as applicable, for both emergency and full service brake application scenarios for all train braking configurations. The results of this study are not intended to be used to evaluate the specific stopping performance capability of the BNSF P/T involved in the Casselton, ND accident on December 30, 2013.

Benefits from the use of advanced train braking systems come from three sources: reduced stopping distances (fewer cars in a potential pileup), reduced vehicle kinetic energy (less energy available to puncture cars in a pileup), and lower and more uniform in-train coupler forces (more compatible car-to-car interaction). Many railroads, including BNSF, use locomotive DP to enable longer train operations with improved in-train forces and braking performance.

This study documents the calculated stopping performance capability of CONV, DP, and ECP train braking systems for a nominal car NBR of 10% (to compare different brake signal propagation rate effects). In addition, the stopping distance benefit due to increasing NBR for exemplar CONV, DP, and ECP trains is illustrated. Finally, this study evaluates the combined brake signal propagation rate and increased brake shoe force benefits of increasing the NBR for an ECP train relative to a CONV train. All simulation scenarios reflect initial conditions with the train in a balanced state (constant initial speed) for level, ascending, and descending track grades.

Different stopping distance performance envelopes were found for emergency and service braking applications with some regions of overlap. For all train braking configurations, the stopping distance benefit relative to the CONV 10% NBR baseline generally increases with increasing train mass, increasing consist length (which affects brake signal propagation time for CONV and DP), and/or steeper descending grades.

Exemplar brake signal propagation rate benefits at 10% NBR for emergency and full service braking are shown in Table 13, relative to the CONV 10% NBR baseline. For emergency braking at a constant NBR value of 10%, the ECP brake system provides somewhat better stopping performance than the DP configuration. Calculated CONV, DP, and ECP increased NBR benefits for emergency and full service braking are shown in Table 14, relative to the respective 10% NBR baseline. For emergency braking, increasing the NBR for a given brake system and speed yields comparable percent stopping distance reductions among the CONV, DP, and ECP systems.

Combined ECP brake signal propagation rate and increased NBR benefit results for emergency and full service braking are presented in Table 15, relative to the CONV 10% NBR baseline. Increasing the nominal car NBR clearly provides measurable stopping performance benefits. **Note that the summary results in Tables 13–15** (Summary of Results section) **are subject to specific train mass (consist length) and track grade conditions** (see details in Attachments 3–6, Appendix C).

The in-train force benefits of DP and ECP braking are clearly visible for the example case, evidenced by substantially lower car-to-car buff forces (75,000 to 250,000 lb. lower) during emergency brake application. While this generic stopping distance study yields some useful in-train force results and trends, it is not intended to exhaustively compare the in-train force benefits among the train braking configurations evaluated.

Interpolated kinetic energy comparison data for an exemplar emergency stop from an initial speed of 50 mph could be used to estimate the energy dissipated (relative to the CONV baseline) over a finite distance window or a finite time window as a function of braking configuration (DP 10% NBR, ECP 10% NBR, ECP 12.8% NBR, or ECP 14% NBR). The time data could also be interpreted to estimate the response time margin available (as a function of the braking configuration) for engineer/conductor corrective or mitigating action via emergency brake application.

For reference, the FRA-commissioned Booz-Allen-Hamilton ECP braking report documents expected or observed ECP braking stopping distance benefits of 40 to 70 percent relative to conventional pneumatic brakes. These benefits are believed to be associated with full service braking. In the absence of contrary factual evidence and/or operator-specific procedures/ training, locomotive brakes should be modeled as not bailed off (applied) for emergency brake application scenarios and bailed off (not applied) for full service brake applications.

Attachments

Supporting data, calculated TEDS simulation stopping distance comparison plots, relevant ECP stopping distance observations documented in a current FRA research report, NTSB back-of-the-envelope ECP calculations, exemplar TEDS simulation time history plots, and exemplar vehicle kinetic energy comparison plots are included in Attachments 1–34. Appendix C provides a description of the content included in each attachment and the starting page number.

Postaccident Actions

BNSF Casselton Pre-Accident Actions:

BNFS provided the following rail industry risk reduction procedures that were in effect prior to Casselton accident:

- 50 MPH Key Train Restrictions
- Dispatcher/Train Crew Securement Briefing to validate unattended train is properly secured.
- Key Train inspection requirements following emergency application of train brakes (i.e., undesired emergency/engineer induced emergency (UDE/EIE)).
- Key train stopped by a hot box detector (HBD) must set-out indicated car (hazmat or not).

Chronology of BNSF Actions post Casselton:

In January 2014 BNSF implemented a specific voluntary action in which they changed the procedures for train inspection following track indication in centralized traffic control (CTC). Stop and inspect requirements for Key Trains due to track indication behind train was reduced from more than one to one. In February 2014 BNSF took a second specific voluntary action when it started radial ultrasonic testing (UT) of all secondhand axles at Havelock wheel shop. This was in advance of NTSB's recommendation issued in April 2014.

In March 2014, BNSF, along with other Class 1 railroads, entered into a voluntary agreement offered by U. S. Secretary of Transportation that included the following:

- Effective July 1, 2014, a speed reduction of 40 mph for hazardous materials carried in DOT 111 tank cars traveling through High Threat Urban Area (HTUA) speed restriction 40 mph (DOT-111)
- Effective July 1, 2014, increased trackside safety technology (Maximum 40 mile spacing)
- Effective July 1, 2014, railroads to implement Risk Based Traffic Routing technology as prescribed in PHMSA Rail Corridor Risk Management System (RCRMS))
- Effective March 25, 2014, increased rail flaw detection frequency.
- Effective May 1, 2014, securement or locking of controlling locomotive cabs
- Additional emergency response for rail industry:

- Five million dollars for crude specific hazmat training
- Develop emergency response resources
- Locations for staging emergency response equipment
- Contacts for community notification

In response to the above voluntary actions adopted from the Secretary's agreement, BNSF developed geographic response plans for certain routes and increased geometry car operations twice the FRA requirements on key train routes.

In July 2014, BNSF entered into an agreement with the Brotherhood of Railway Carmen that included the following:

- Increased the number of Qualified Mechanical Inspectors (QMI)
- Inspections performed at unit crude train originations
- To date, there are approximately 17 mobile inspectors employed for the sole purpose of inspecting, repairing, and maintaining crude equipment at originating crude terminals in the Bakken.
- Expanded this Mobile Inspector Strategy to unit crude train origination points in Wyoming and Colorado

By the end of 2014, BNSF had trained over 8,500 local emergency responders and sponsored 713 firefighters at the Transportation Technology Center, Inc. (TTCI) training program in Pueblo, Colorado. BNSF plans to sponsor 500 firefighters scheduled to attend TTCI in 2015. BNSF in conjunction with its emergency response training/community outreach uses real time GIS tracking application for emergency-response agencies (a.k.a. Secure Trak).

Effective March 25, 2015, BNSF implemented a specific voluntary action to reduce or restrict the authorized operational speed for all key trains through population centers of 100,000 or larger to 35 mph. BNSF intends to conduct remote audits downloads to ensure compliance with these new operational changes.

Effective March 25, 2015, additional changes on BNSF include increased trackside safety technology by adding HBD at ten mile spacing near critical waterways (ongoing).

Where Wheel Impact Load Detectors (WILD) indications rise to a level II read-out of 120-140 kips, those cars will be treated as a level I indication and require immediate set-out.

Effective April 1, 2015, BNSF plans to increase rail detection frequency along critical waterways to 2 ½ times the FRA required frequency.

BNSF has also taken the following action surrounding equipment health:

- All WILD wheels > 90 Kips on KEY trains will be repaired at the next available car repair location
- New Composite Alarm: KEY train with WILD wheels @ 70 Kips plus a single warm bearing outlier (Kvalue > 2.5) will be repaired at next available car repair location
- Hot Wheels: Key train meeting HW1 (stop & inspect), HW2 (running air brake release), HW3 (bad order to destination) criteria will be monitored in real-time & appropriate actions taken based on hot wheel defect criteria
- Wheel Quality: Car Inspection defect criteria based on more restrictive AAR condemnable thresholds for Thin Rims, Thin Flange, Shelled Tread
- Installation of additional Cracked Wheel Detectors (5 more to 10) (CWAD) on Key Routes
- TR&D VSR Research: Destructive testing for 90 KIP and greater wheels off BNSF Key trains to understand correlation between KIP level and propagation of subsurface horizontal wheel cracks.
- TTCI Tank Car/Track Dynamics Research: Incremental funding has been provided for TTCI to model the interaction between loaded tank cars and certain track irregularities that lead into high wheel/rail forces and derailments

PHSMA Post-accident Actions

PHMSA, in coordination with FRA, published a final rule May 8, 2015, (80 FR 26644) adopting safety improvements in tank car design standards, operational requirements, and notification requirements for tank cars used in trains defined as high-hazard flammable trains (HHFTs). The rule also includes new requirements for a sampling and classification program for unrefined petroleum-based products. With respect to tank car and train requirements, the rule specifically provides for:

- Enhanced standards for both new and existing tank cars (e.g., full-height head shields, jackets, etc.);
- Rail routing (risk assessment and notification);
- Reduced operating speeds; and
- Enhanced braking

NTSB Post-accident Action

Urgent Recommendations:

On April 7, 2014, the NTSB issued an urgent recommendation to the Association of American Railroads (AAR) to take action to address the immediate need for more thorough nondestructive testing of secondhand use[81] railroad axles. The recommendation was a result derived from the NTSB's ongoing investigation of a railroad accident near Casselton, North Dakota. Radial Ultrasonic testing of new axles was implemented in 2009, and radial ultrasonic testing of converted axles was implemented in 2011.[82]

81 Secondhand use is a term for an axle that is re-used or re-qualified. This is a common industry practice used when new wheels or bearings are installed on axles that have run in service.
82 A converted axle is a term for an axle which has been machined to a smaller diameter and lower tonnage axle design.

Parties to the Investigation - Acknowledgment Signatures

The undersigned designated *Party to the Investigation* representatives attest that the information contained in this IIC Factual Report for Technical Review is a factually accurate representation of the information collected during the on-scene investigation, to the extent of their best knowledge and contribution in this investigation.

//s// Richard A. Hipskind, NTSB	Date 7/19/15
//s// Matthew Brewer, FRA	Date 7-26-15
//s// Kip Wills, PHMSA	Date 7-21-15
//s// Kevin Wilde, BNSF	Date 7-24-15
//s// D. B. Kenner, BLET	Date 7-23-15
//s// Jerry Gibson, S.M.A.R.T.	Date 7-23-15
//s// Steve Dedmon, Standard Steel	Date 7-27-15
//s// Robert Hulick, TrinityRail Car, Inc.	Date 7-31-15

Appendix A

Mechanical Data for both trains

Grain Train Mechanical Data

Train Position	FIELD INDEX NUMBERS	CURRENT CAR NUMBER	LAST MARK & NUMBER	PREVIOUS MARK & NUMBER
2	17	GATX 33119	N/A	N/A
3	16	GATX 33123	N/A	N/A
4	15	TAEX 1549	ADLX 500237	BNBX 500237
5	14	TAEX 1475	ADLX 500163	BNBX 500163
6	13	ADLX 500176	N/A	N/A
7	12	TAEX 1472	ADLX 500160	BNBX 500160
8	11	SHPX 206675	N/A	N/A
9	10	SHPX 208541	N/A	N/A
10	9	SHPX 208638	N/A	N/A
11	8	SHPX 206670	N/A	N/A
12	7	SHPX 208536	N/A	N/A
13	6	TAEX 1528	ADLX 500216	BNBX 500216
14	Not Tagged (19)	TAEX 1602	ADLX 500102	BNBX 500102
15	5	SHPX 206708	N/A	N/A
16	18	SHPX 206668	N/A	N/A
17	4	GATX 33125	N/A	N/A
18	3	GATX 33139	N/A	N/A
19	2	TAEX 1630	ADLX 500131	BNBX 500131
20	1	TAEX 1638	ADLX 500139	BNBX 500139
21	-	TAEX 1582	-	-

Petroleum Train Mechanical Data

Train Position	CURRENT CAR NUMBER	AAR Type		LAST MARK & NUMBER	PREVIOUS MARK & NUMBER
2	GATX 3119			N/A	N/A
3	GATX 3123			N/A	N/A
4	TAEX 1549			ADLX 500237	BNBX 500237
5	TAEX 1475			ADLX 500163	BNBX 500163
6	ADLX 100176			N/A	N/A
7	TAEX 1472			ADLX 500160	BNBX 500160
8	SHPX 206675			N/A	N/A
9	SHPX 208541			N/A	N/A
10	SHPX 208638			N/A	N/A
11	SHPX 206670			N/A	N/A
12	SHPX 208536			N/A	N/A
13	TAEX 1528			ADLX 500216	BNBX 500216
14	TAEX 1602			ADLX 500102	BNBX 500102
15	SHPX 206708			N/A	N/A
16	SHPX 206668			N/A	N/A
17	GATX 33125			N/A	N/A
18	GATX 33139			N/A	N/A
19	TAEX 1630			ADLX 500131	BNBX 500131
20	TAEX 1638			ADLX 500139	BNBX 500139
21	TAEX 1582			-	-

Appendix B

Event Recorder Parameters & Abbreviations

This appendix describes the parameters provided and verified in this report. Table A-1 lists the parameters from BNSF 6990 and BNSF 6684. Table A-2 describes the unit abbreviations.

Table A-1. BNSF 6990 and BNSF 6684 verified and provided event recorder parameters.

Parameter Name	Parameter Description	6990	6684
1. Air Flow (cfm)	Air Flow	X	X
2. Alerter Alarm (discrete)	Alerter Alarm	X	
3. Auto Brake CO (discrete)	Auto Brake Cutout		X
4. DB Derate (discrete)	Dynamic Brake Derate	X	
5. DB Excit (discrete)	Dynamic Brake Excitation	X	X
6. DB Setup (discrete)	Dynamic Brake Setup	X	X
7. DB Start (discrete)	Dynamic Brake Start	X	X
8. DB Warning (discrete)	Dynamic Brake Warning		X
9. Dir Call (discrete)	Direction of Travel	X	X
10. EAB Bail (discrete)	Electronic Air Brake Bail	X	
11. EAB BC (psi)	Electronic Air Brake Cylinder	X	X
12. EAB BP (psi)	Electronic Air Brake Pressure	X	X
13. EAB Brake Handle (discrete)	Electronic Air Brake Handle	X	X
14. EAB Brake Setup Mode (discrete)	Electronic Air Brake Setup Mode		X
15. EAB ER (psi)	Electronic Air Brake Equalizing Reservoir Pressure		X
16. EIE (discrete)	Engineer Induced Emergency	X	X
17. Emergency Brake (discrete)	Emergency Brake	X	X
18. GPS Latitude (deg)	Latitude	X	
19. GPS Longitude (deg)	Longitude	X	
20. Horn (discrete)	Horn	X	X
21. IBS (discrete)	Independent Brake System	X	
22. PCS Open (discrete)	Pneumatic Control Switch	X	X
23. Speed (mph)	Speed	X	X
24. Throttle (discrete)	Throttle Position	X	X
25. TLEM (discrete)	Train Line Emergency	X	X
26. Total Feet (ft)	Feet Traveled	X	X
27. Total Miles (miles)	Miles Traveled	X	X
28. Trac Effort (klps)	Traction Effort	X	X

Table A-2. Unit and discrete state abbreviations.

Unit and Discrete State Abbreviations	Description
%	percent
DB	Dynamic Brake
Discrete	discrete
For	Forward
Ft	feet
I	Idle
Klps	kilo pounds
Miles	miles
Mph	miles per hour
Psi	pounds per square inch
Rev	Reverse
T1	Throttle 1
T2	Throttle 2
T3	Throttle 3
T4	Throttle 4
T5	Throttle 5
T6	Throttle 6
T7	Throttle 7
T8	Throttle 8
Cfm	cubic feet per minute

NOTE: For parameters with a unit description of discrete, a discrete is typically a 1-bit parameter that is either a 0 state or a 1 state where each state is uniquely defined for each parameter.

Appendix C

Train Braking Study Attachment Table

Attachment	Description	Page
1	Locomotive Sizing (Estimated Tractive Effort and Dynamic Brake Effort)	A1.1
2	Sanitized Model of Brake Shoe Coefficient of Friction (for Type A and B Brake Shoes) Based on Empirical Data from AAR R-469, "Brake Shoe Performance Evaluation," April 1981.	A2.1

3	Brake Signal Propagation Effects, Emergency Braking Percent Distance Required to Stop Relative to CONV 10% NBR Baseline			A3.1
4	Brake Signal Propagation Effects, Full Service Braking Percent Distance Required to Stop Relative to CONV 10% NBR Baseline			A4.1
5	Combined ECP Signal Propagation and NBR Effects, Emergency Braking Percent Distance Required to Stop Relative to CONV 10% NBR Baseline			A5.1
6	Combined ECP Signal Propagation and NBR Effects, Full Service Braking Percent Distance Required to Stop Relative to CONV 10% NBR Baseline			A6.1
7	Emergency Braking Plots; Calculated train stopping distance as a function of speed and grade; Benefit relative to CONV 10% NBR baseline	Locomotive Brakes Bailed Off	52 tank cars	A7.1
8			78 tank cars	A8.1
9			104 tank cars	A9.1
10			130 tank cars	A10.1
11			156 tank cars	A11.1
12		Locomotive Brakes Applied	52 tank cars	A12.1
13			78 tank cars	A13.1
14			104 tank cars	A14.1
15			130 tank cars	A15.1
16			156 tank cars	A16.1
17	Full Service Braking Plots; Calculated train stopping distance as a function of speed and grade; Benefit relative to CONV baseline	Locomotive Brakes Bailed Off	52 tank cars	A17.1
18			78 tank cars	A18.1
19			104 tank cars	A19.1
20			130 tank cars	A20.1
21			156 tank cars	A21.1
22		Locomotive Brakes Applied	52 tank cars	A22.1
23			78 tank cars	A23.1
24			104 tank cars	A24.1
25			130 tank cars	A25.1
26			156 tank cars	A26.1
27	CONV, DP, and ECP Increased NBR Benefit (Relative to Respective 10% NBR Baseline)			A27.1
28	CONV, DP, and ECP Increased NBR Benefit (Relative to CONV 10% NBR Baseline)			A28.1
29	FRA ECP Braking Report Excerpts			A29.1
30	NTSB Back-of-the-Envelope Train Stopping Distance Calculations			A30.1
31	Example Calculated Brake System Pressures; Nominal Consist (Emergency braking; no bail off; initial neutral slack; 0% grade; 50 mph)			A31.1
32	Example Calculated In-Train Forces; Nominal Consist (Emergency braking; no bail off; initial neutral slack; 0% grade; 50 mph)			A32.1
33	Example Kinetic Energy Comparison Plots; Nominal Consist (Emergency braking; no bail off; initial neutral slack; 0% grade; 50 mph)			A33.1
34	Effect of Speed Reduction on Train Kinetic Energy (5 mph and 10 mph Decrements; Constant Mass, V_1, V_2)			A34.1