July 20, 2015

Train Braking Simulation Study

I. ACCIDENT

Description:	Train Derailment, Opposing Train Struck Derailed Car and Derailed, Fire and Evacuation
Location:	Casselton, ND
Date:	December 30, 2013
Time:	Approximately 2:11 p.m. Central Standard Time (CST)
Operator:	BNSF Railway Company (BNSF)
Trains:	Westbound BNSF grain train G-RYLRGT9-26A (G/T) and eastbound BNSF petroleum crude oil unit train U-FYNHAY4-05T (P/T)
NTSB Number:	DCA14MR004

II. VEHICLE PERFORMANCE SPECIALIST

Kevin J. Renze, Ph.D.
Vehicle Performance Division, RE-60
National Transportation Safety Board (NTSB)

1.0 INTRODUCTION

On Monday, December 30, 2013, about 2:11 p.m., Central Standard Time (CST), westbound BNSF Railway Company (BNSF) grain 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. Although several petroleum crude oil unit train consists were modeled in this study, the results 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.

1.1 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 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.[1] This study does not evaluate or quantify the consequences of higher thermal loads on in-service wheels.

Technical representatives from BNSF, Trinity Railcar, 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.

1.2 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

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[1] 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.

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 1, 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.

Table 1: 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	25 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 2, 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 2: 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 3, 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 1–3 are subject to specific train mass (consist length) and track grade conditions** (see details in Attachments 3–6).

Table 3: 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.

2.0 SIMULATION STUDY

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

2.1 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 Section 2.6.

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.[2]

2.2 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 kinetic 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.

2.2.1 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 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 4. Corresponding vehicle length and loading data are provided in Table 5.

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[2] The U.S. railroad industry makes use of the Association of American Railroads (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.

Table 4: 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 5: 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

[c] Brake pipe length is estimated as the length over pulling faces (LOPF) from the UMLER record, plus ~5 feet.

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.

2.2.2 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.[3]

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[3] 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.

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.

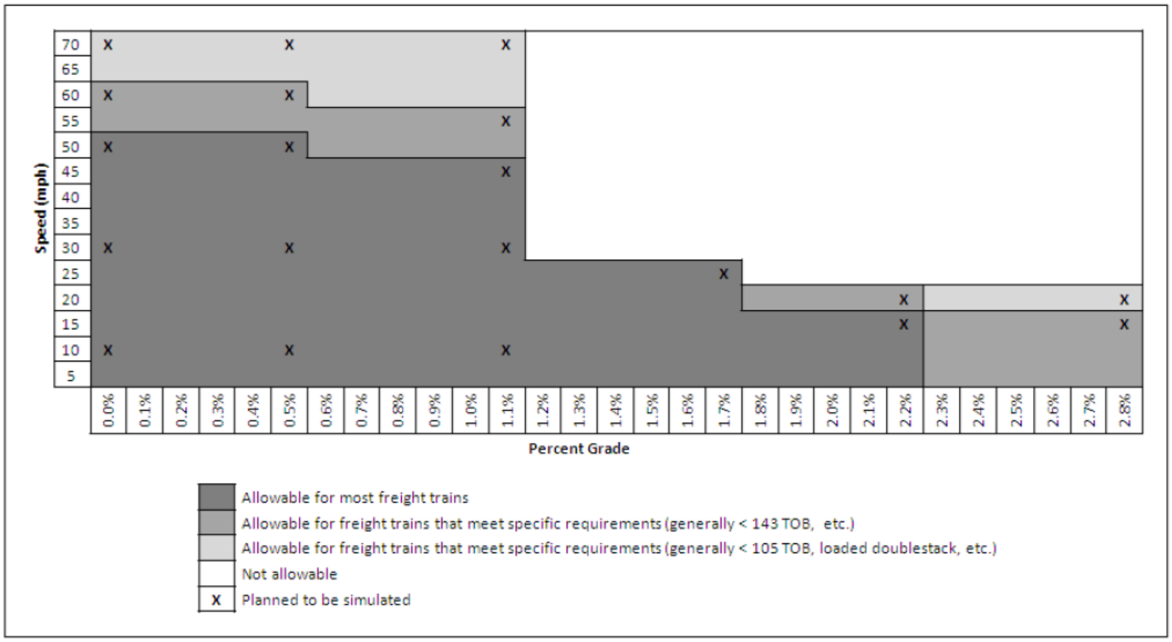
For freight train operations, the 20 to 70 mph speed range covers FRA track classes 1 through 5 as shown in Table 6. The simulation study assumed that train speed was not limited by the train negotiating any track curves, track segments with defective rails, work zones, track frogs with treads worn down, or track frogs with a chipped, broken, or worn down point.

Table 6: 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 7 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 7 that is identified in the legend as “Planned to be simulated” does not apply to this NTSB study.

Table 7: 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.

2.2.3 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. Energy will be added 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.

2.2.4 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.

2.2.4.1 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.*

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 8 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).

The ECP 10% NBR scenarios were selected to provide comparable NBR values to nominal freight cars in conventional pneumatic and DP trains.[4] A uniform net braking ratio of 10% was assumed

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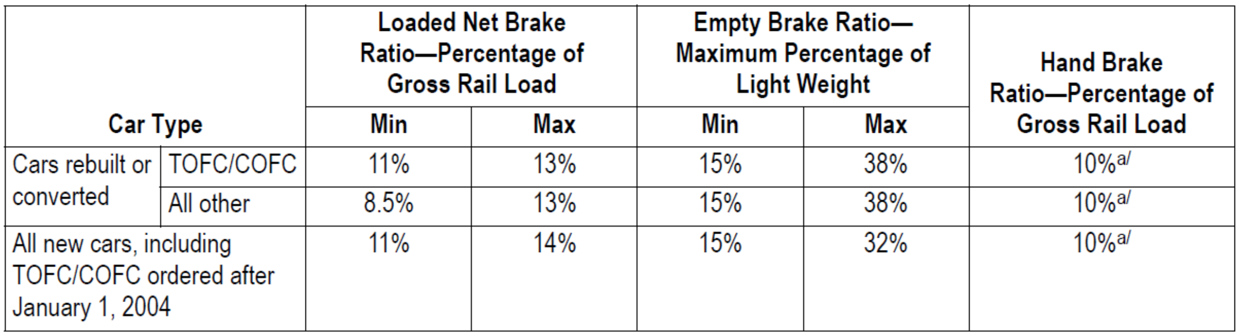
[4] Regarding the use of a nominal tank car net braking ratio of 10%, tank cars ordered before 2004 were recommended by an AAR industry standard to have a loaded NBR between 8.5% and 13%, and an empty NBR of not more than 38%. For the tank car used in this simulation study (76,800 pounds tare) a loaded NBR of 10% corresponds to an empty NBR

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.[5] Car-to-car NBR variation can produce larger in-train buff (compression) and/or draft (tension) forces.

Table 8: 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).[6]

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.*

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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%.

[5] 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.

[6] 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:[7]

> *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 8, 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.

2.2.4.2 Operational Differences between ECP, DP, and Conventional Braking Systems

Under conventional braking, unplanned service or emergency pneumatic brake signal propagation through the length of the train[8] can result in notable run-in forces on cars at the head-end of the train.[9] 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 a 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 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

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[7] 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.

[8] 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).

[9] Not all conventional braking operations result in “notable” slack run-in forces. Planned brake operations typically employ train handling procedures (e.g., dynamic brake or a minimum brake pipe reduction designed to gather slack before making a deeper brake pipe reduction) to minimize severe slack changes and resulting “notable” run-in forces.

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.[10]

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.

2.2.5 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.*
>
> *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.

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[10] 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.

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 an 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 midpoint. 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.

2.2.6 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).[11]

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[11] 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 fourth locomotive.

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, train speed, and consist length results without frequently tweaking the number of locomotives.[12] Using five locomotives for all simulation scenarios simplified the consist comparisons and maximized the realistic grade/speed/trailing ton envelope.[13]

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.[14] 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.[15]

2.2.7 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.*

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

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[12] 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).

[13] 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.

[14] 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).

[15] 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).

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.

2.2.8 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.

2.3 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.[16]

2.4 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).

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[16] 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.

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.[17] The number of scenarios evaluated for each train consist is summarized in Table 9.

Table 9: 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**

2.5 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.

2.6 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.[18] 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.

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

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

3.0 RESULTS

The emergency and full service braking stopping distance results are broadly summarized in Tables 10.1 to 13.2. 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.[19] 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 effort for all consists (in ascending grade columns) or insufficient locomotive dynamic braking effort for all consists to prevent an initial speed overshoot (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.[20]

3.1 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 10.1 and 10.2 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 respective DP and ECP benefits are 3 to 8 percent and 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 respective DP and ECP benefits are 3 to 9 percent and 4 to 15 percent better than CONV.

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[19] 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.

[20] 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.

3.2 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 11.1 and 11.2 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 respective DP and ECP benefits are 10 to 36 percent and 40 to 64 percent better than CONV. 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, 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 respective DP and ECP benefits are 10 to 39 percent and 32 to 64 percent better than CONV.

3.3 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 12.1 and 12.2 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.

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.

Table 10.1: 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 Configuration	Speed mph	Track Grade, Percent								
		+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 10.2: 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 Configuration	Speed mph	Track Grade, Percent								
		+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 11.1: 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 Configuration	Speed mph	Track Grade, Percent								
		+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 11.2: 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 Configuration	Speed mph	Track Grade, Percent								
		+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 12.1: 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 12.2: 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 13.1: 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
ECP 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	---
ECP 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 13.2: 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	---

3.4 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 13.1 and 13.2 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.

3.5 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,[21] 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.

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[21] 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.

- As the required emergency brake application period increases (relative to the “fixed” signal propagation and brake cylinder pressure rise times) for a constant NBR, 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%.[22] Additional ECP benefits include ECP graduated full or partial service brake application and release options.

3.5.1 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).[23] 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 1. 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.

3.5.2 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).[23] 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.

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[22] Conventional pneumatic brake equipment could be built and maintained to the same NBR level as ECP equipment.

[23] 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.

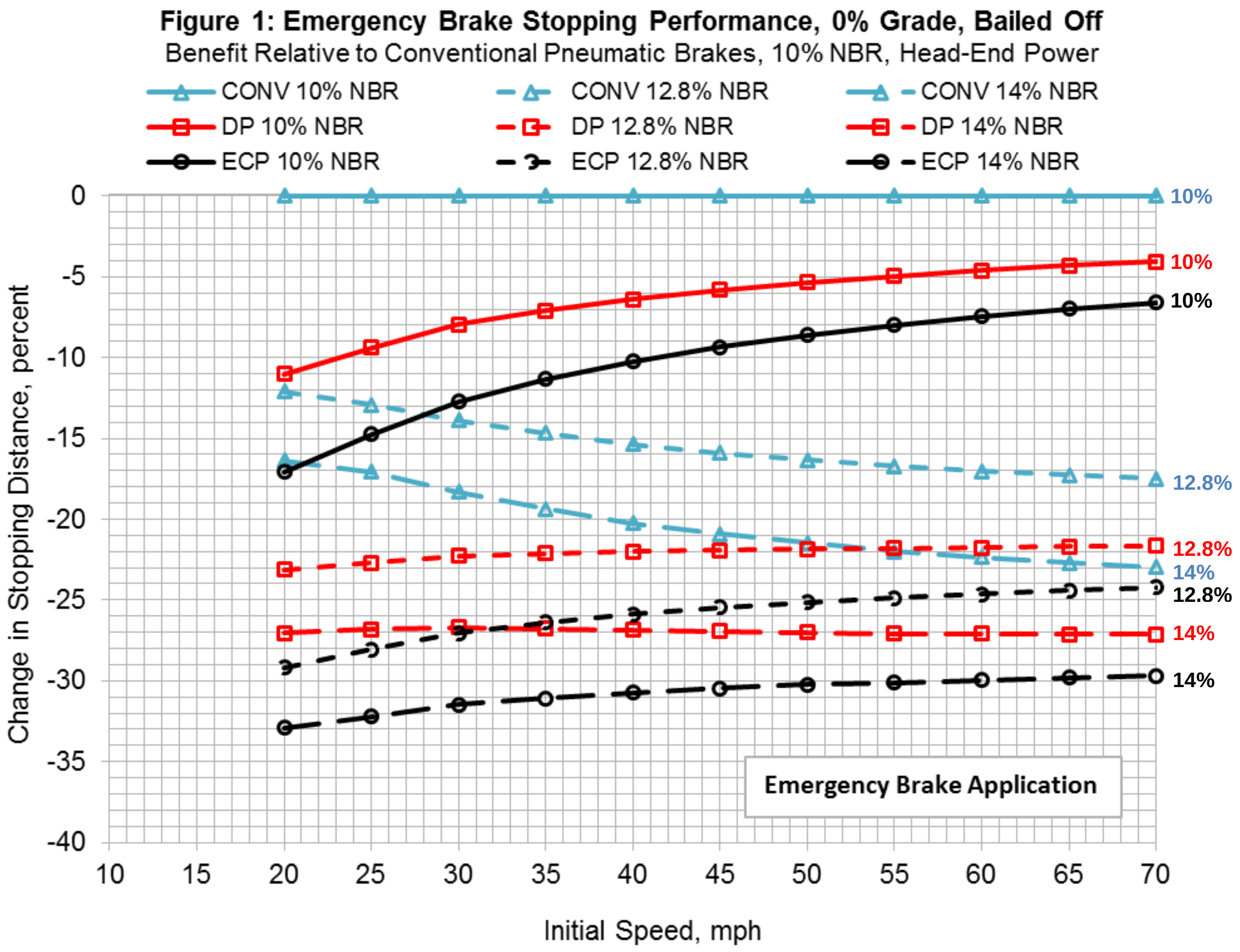


Figure 1: Emergency Brake Stopping Performance, 0% Grade, Bailed Off

Benefit Relative to Conventional Pneumatic Brakes, 10% NBR, Head-End Power

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 2. 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.

3.5.3 CONV, DP, and ECP Increased NBR Benefits

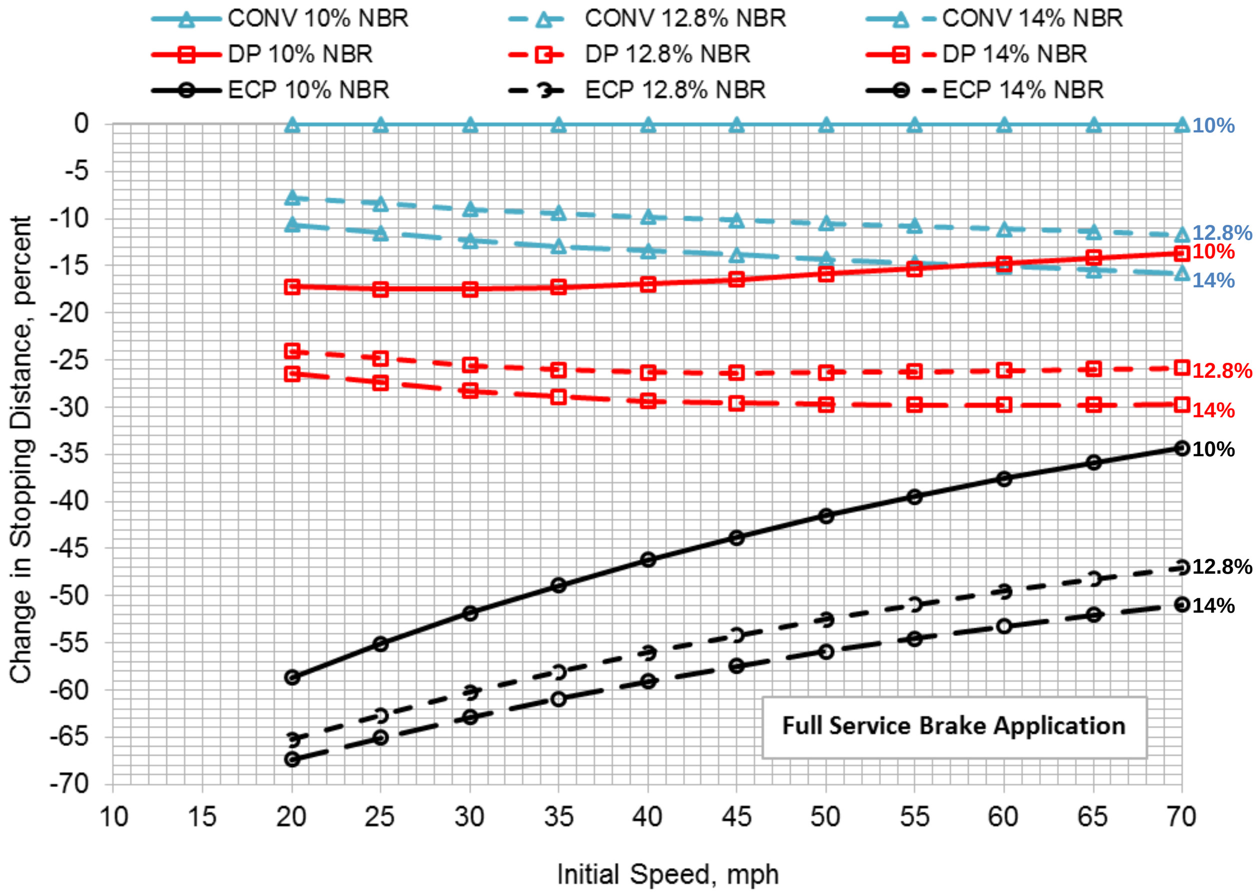
The stopping performance benefit due to increased NBR is quantified for the nominal consist on level grade in Attachments 27 and 28. The plots in Attachment 27 compare the calculated CONV, DP, and ECP stopping distance benefit relative to the respective braking system 10% NBR baseline. The emergency 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 1 and Figure 2) 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.

Figure 2: Full Service Brake Stopping Performance, 0% Grade, Bailed Off

Benefit Relative to Conventional Pneumatic Brakes, 10% NBR, Head-End Power



3.5.4 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 10.1 to 13.2 (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.

3.6 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.

3.7 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.

3.8 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.[24] For train operations in general:

- 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.

3.9 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%

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[24] 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.

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.

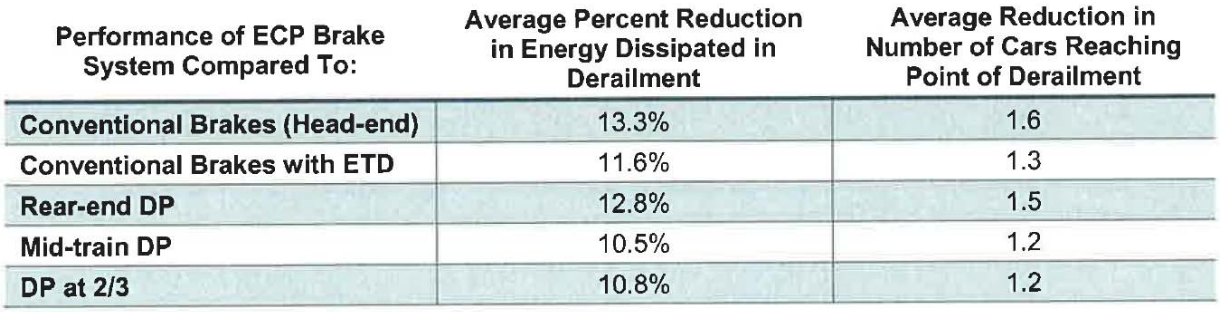
The kinetic energy dissipated over a finite time window could also be compared to estimate the response time margin available (as a function of the brake system configuration) for engineer/conductor corrective or mitigating action via emergency brake application. For the same 50 mph to full stop (zero 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.

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.

3.10 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 J. 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 14) 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 14: 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.

4.0 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 descending grades.

Exemplar brake signal propagation rate benefits at 10% NBR for emergency and full service braking are shown in Table 1, 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 2, 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 3, 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 1–3** (see Section 1.2) **are subject to specific train mass (consist length) and track grade conditions** (see details in Attachments 3–6).

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.

5.0 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. Table 15 provides a description of the content included in each attachment and the starting page number.

Table 15: Summary of Attachments

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 bailoff; initial neutral slack; 0% grade; 50 mph)			A31.1
32	Example Calculated In-Train Forces; Nominal Consist (Emergency braking; no bailoff; initial neutral slack; 0% grade; 50 mph)			A32.1
33	Example Kinetic Energy Comparison Plots; Nominal Consist (Emergency braking; no bailoff; 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