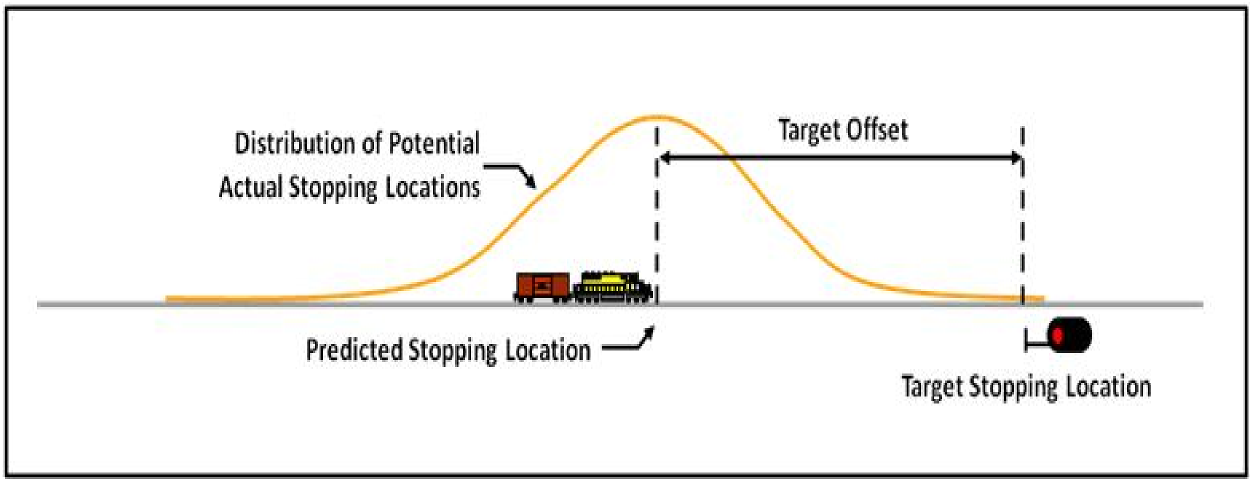
U.S. Department of Transportation

Federal Railroad Administration

Freight Train Positive Train Control Braking Enforcement Algorithm Research and Testing

Office of Research, Development and Technology
Washington, DC 20590



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13. ABSTRACT (Maximum 200 words)

Transportation Technology Center, Inc. (TTCI) researched methods for improving Positive Train Control (PTC) braking algorithm performance and supported industry implementation and evaluation of such improvements. Work completed on the developmental algorithm included: testing additional methods of calculating train brake force; designing and implementing changes for Electronically Controlled Pneumatic (ECP) brake-equipped trains; researching how the PTC braking algorithm handles specialty type equipment; and field testing the PTC braking algorithm on an intermodal train at the Transportation Technology Center (TTC). TTCI provided implementation support to the industry through simulations and field tests of the Interoperable Electronic Train Management System (I-ETMS®) braking enforcement algorithm and supporting troubleshooting of issues within the algorithm as they were identified. The results of the simulations performed by TTCI were also used to support the railroads' PTC safety plans.

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METRIC/ENGLISH CONVERSION FACTORS

ENGLISH TO METRIC

LENGTH (APPROXIMATE)

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

AREA (APPROXIMATE)

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

MASS - WEIGHT (APPROXIMATE)

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

VOLUME (APPROXIMATE)

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

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

AREA (APPROXIMATE)

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

MASS - WEIGHT (APPROXIMATE)

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

VOLUME (APPROXIMATE)

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

TEMPERATURE (EXACT)

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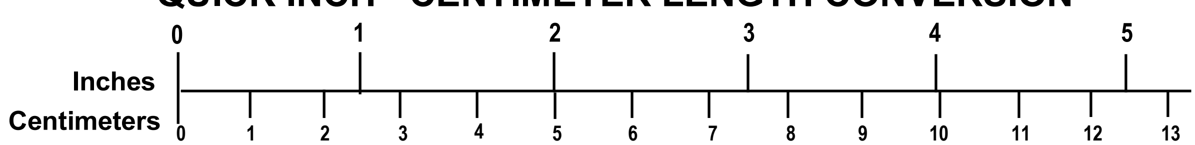

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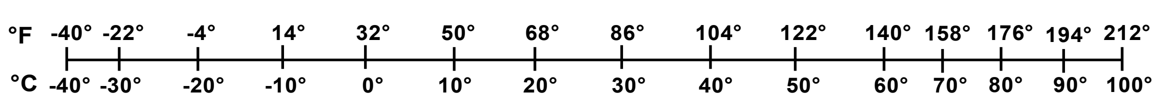

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Executive Summary

The Federal Railroad Administration (FRA) contracted Transportation Technology Center Inc. (TTCI) to improve the safety and operational performance of Positive Train Control (PTC) predictive braking enforcement algorithms and to provide support to the industry in the implementation, simulation, and testing of these algorithms. This work was conducted from May 2012 until April 2014.

TTCI simulated four different methods of supplying a developmental PTC braking enforcement algorithm with the required estimated brake force for the train and compared the results. The most effective and only method that takes environmental variances into consideration is an adaptive brake force calculation performed onboard the locomotive that requires the train crew to manually apply the automatic air brake while the train is moving. This allows the algorithm to adapt to the specific characteristics of the braking system and environment. The other three methods require the brake force to be estimated in the back office server and provided to the PTC onboard system with the consist information. Use of these methods resulted in improvements to the performance of the algorithm to a lesser degree, but may prove to be more practical to implement, than the adaptive brake force calculation. One or more of these methods may be used to help improve the safety and performance of the PTC braking algorithm.

TTCI researched, designed, and implemented changes to the developmental algorithm for operating on trains with Electronically Controlled Pneumatic (ECP) brakes. Monte Carlo simulations using loaded and empty unit trains with ECP brakes were performed to evaluate how the algorithm performed in these scenarios. Results from the simulations show that the ECP brake function works as intended, but would need some adjustments to the safety offset to meet the safety objective of stopping trains short of the target 99.5 percent of the time.

Algorithm performance with two types of specialty vehicles, roadrailers and high capacity flat cars, was researched by TTCI. Roadrailers were modeled in the simulation environment and new scenarios were created in the simulation matrix to include 50-car, 100-car, and 150-car roadrailer trains. Monte Carlo simulations were performed using existing train types within TTCI's developmental braking algorithm. The unit aluminum coal train type was shown to be the best fit and the algorithm met the safety objective in this configuration. High capacity flat cars were only researched, and not simulated, in this project. The research showed that trains with high capacity flat cars should not pose a problem to the enforcement algorithm and that the manifest train type is the likely best fit of the train types existing in the developmental algorithm.

TTCI acquired empty intermodal equipment and tested TTCI's developmental braking algorithm at the Transportation Technology Center (TTC) in Pueblo, CO. Tests conducted showed that the algorithm enforced a train stop short of the target in each test case in which the engineer did not take action to stop the train, and did not enforce a train stop in each test case where the locomotive engineer manually brought the train to a stop before reaching the limits of the authority.

TTCI evaluated the latest Interoperable Electronic Train Management System (I-ETMS®) enforcement algorithm and showed, through the results of Monte Carlo simulations, that it met the safety objective of stopping short of the target 99.5 percent of the time. TTCI also worked with several freight railroads and FRA's Office of Railroad Safety to determine what PTC brake tests would be required from each of the railroads to be used in comparisons with the simulation model to provide sufficient confidence in use of the simulation results in their PTC safety plans. TTCI supported coordination and execution of the field tests. TTCI modeled each of the field tests using the Train Operations and Energy Simulator (TOES^{TM}), when data was available, to further validate the simulation process used for evaluating the I-ETMS enforcement algorithm. Monte Carlo simulations of future releases of the I-ETMS enforcement algorithm are recommended as the simulations cover the practical boundaries of railroad operations in a short period of time and produce the resulting safety and performance metrics.

Finally, TTCI worked with several freight railroads and Wabtec to address issues in specific scenarios that the railroads observed while using the I-ETMS enforcement algorithm in revenue service. These issues included excessive warning and undesired enforcements for non-zero speed restrictions on significant track grades while the crew was handling the train under normal operating conditions, modeling of remote power after a penalty enforcement in distributed power consists, dynamic brake interlocking behavior on short trains, and undesired enforcements at slow speeds while using independent brakes and approaching a stop target. Ongoing efforts between TTCI, the railroads, and Wabtec will help address additional problem areas and improve upon the safety and performance of the algorithm.

1. Introduction

1.1 Background

Positive Train Control (PTC) is an advanced train control technology system designed to enhance the safety of railroad operations. The underlying concept of the technology is that movement authorities and speed restrictions monitored and controlled by dispatchers are transmitted digitally to the controlling locomotive of each train. The locomotive continuously reports back the train location with respect to its authority and speed limits. The suite of integrated technologies comprising PTC also give audible and visual warnings for upcoming violations and will automatically apply the brakes to prevent a violation if the train crew fails to take appropriate action.

The primary objective of the PTC braking enforcement function is to enforce a brake application to stop the train short of a given stop target with a high level of safety. For the system to be effective and practical, however, it is also required that the impact on railroad operations be minimal, which implies that the system will be transparent to a crew operating the train safely and in accordance with applicable operating practices. PTC brake enforcement should be considered an action of last recourse when the crew has failed to take adequate action to stop the train.

Due to the large number and diversity of parameters that can affect freight train stopping distance, and the minimal data available to the PTC system, it is difficult to accurately predict the stopping distance of a specific train in a particular operating scenario or environment. Typically, a PTC brake enforcement algorithm will automatically calculate a nominal minimum stopping distance based on the data available. An offset margin is added to this prediction, based on calculations taking into consideration any uncertainty in the available data, to ensure a high level of safety confidence that the train will stop short of the target.

The problem is that, by adding the necessary target offset in order to meet the safety objective, the system may warn the crew and attempt to enforce the train to a stop considerably earlier than the crew would stop the train under normal circumstances without PTC. Research, test and early operational use of PTC systems to date have indicated that the enforcement logic will have a significant effect on train performance and track capacity.

Prior Federal Railroad Administration (FRA) research [1] has identified, simulated and tested several methods with potential to improve freight train PTC enforcement algorithm safety and performance. Many of these methods have been implemented or are being considered for implementation in the Interoperable Electronic Train Management System (I-ETMS®),[1] the PTC onboard system currently being deployed by Class I freight railroads in the United States. As part of the previous FRA project [1], a comprehensive enforcement algorithm evaluation methodology was developed and used to provide baseline enforcement algorithm performance metrics against which to compare new developments.

The intent of this research project was to continue to support the industry in resolving issues associated with enforcement braking in PTC systems, including research, implementation

[1] I-ETMS® is a registered trademark of Wabtec Corporation

support, testing, and working with the FRA Office of Railroad Safety for support and approval of the concepts and test results.

1.2 Objectives

The primary objectives of this project were to:

- Continue research and development for improving PTC braking enforcement algorithm safety and performance for freight trains,
- Support the implementation of the methods developed in a functional PTC system, and
- Evaluate the safety and performance of the enforcement algorithm, as implemented in a functional PTC system.

1.3 Overall Approach

The project included two primary components: research and development, and implementation and testing support.

The research and development component expanded on the methods developed during previous research projects to include a wider variety of operating scenarios and vehicle types, as well as performing comparisons of various alternatives for improving aspects of the algorithm performance to provide an indication of which may provide the most benefit. The methods developed as part of this component were implemented in test software and evaluated using simulation methods and field testing, where appropriate and practical.

The implementation and testing component of the project focused on supporting the railroads and their suppliers in implementing and verifying new methods and improvements to the I-ETMS enforcement function. This included simulation testing, field testing at the Transportation Technology Center (TTC) and the railroads, modeling of the field testing, and analysis of the data to support the safety case for using the PTC enforcement algorithm.

1.4 Scope

The research and developmental task in this project covered changes and testing of the Phase 3 developmental algorithm [1]. These tasks were not tested with the I-ETMS algorithm.

Implementation support included that provided to Class I freight railroads and their suppliers to test the I-ETMS braking algorithm through simulations and field testing. This included test planning support, test execution, and/or test modeling.

1.5 Organization of the Report

This report is organized into four major sections. Section 1 is the introduction, which includes background information and discusses the project's objectives, scope, and overall approach. Section 2 is a detailed description of the research and development efforts on freight braking enforcement algorithms completed in this project. Section 3 is a detailed description of TTCI's support to the railroads and their suppliers for implementation and testing support with the freight braking enforcement algorithm. Section 4 provides a summary and conclusions. Appendix A provides test comparison charts.

2. Research and Development for Freight Braking Enforcement Algorithms

The braking enforcement function of PTC systems is critical for ensuring that trains comply with movement authorities, speed limits, and train movement through switches. There are a number of parameters that can affect the braking distance of a freight train and it is not practical, or even possible, to provide the onboard system with all the information required to predict the stopping distance with absolute certainty. Currently, the braking algorithm calculates a brake force for the train using consist information that is provided by the back office during initialization. Consist information typically includes trailing tonnage, number of loaded and empty cars, number of locomotives and position of each locomotive within the consist, train length, and number of axles.

This research expands upon the previous work completed [1], by using the developmental algorithm and the enforcement algorithm evaluation methodology that were developed under previous work [1] to research and evaluate additional potential changes to improve braking algorithm performance. The tasks performed under this research included:

- Researching potential modifications to the algorithm to account for cars equipped with empty load devices,
- Comparing alternative methods for providing the enforcement algorithm with brake force information to improve the stopping distance calculations,
- Modifying the enforcement algorithm and simulation environment to include evaluation of trains equipped with Electronically Controlled Pneumatic (ECP) brakes,
- Adding trains with specialty car types to the simulation environment and researching how they can be handled by the enforcement algorithm, and
- Conducting field testing at the TTC with intermodal equipment to evaluate the implementation of the algorithm developed when operating on intermodal trains [1].

2.1 Research and Implementation of Changes for Empty Load Devices

Empty load devices are used to provide wheel slide protection on cars with a high loaded to empty weight ratio. The empty load device senses whether the car is loaded or empty and adjusts brake cylinder pressure (BCP) accordingly, with full BCP buildup for loaded cars and 40, 50, or 60 percent of full BCP buildup for empty cars, depending on the empty load device specifications. Cars equipped with empty load devices can have a higher loaded brake force value than cars without, because they do not have to worry about the brake force causing wheel slip when in the empty position. Table 1 gives an example of loaded and empty brake ratios for cars equipped with empty load devices and cars not equipped with empty load devices. The loaded brake ratio is the ratio of the brake force to the gross weight when the car is loaded and the empty brake ratio is the ratio of the brake force to the tare weight when the car is empty.

Table 1. Example Brake Force Differences – Empty Load-Equipped & Non-equipped Cars

Empty Load Equipped	Gross Rail Load (lbs.)	Tare Weight (lbs.)	Loaded Brake Force (lbs.)	Empty Brake Force (lbs.)	Loaded Brake Ratio (%)	Empty Brake Ratio (%)
Yes	286,000	60,000	31,460	15,730*	11.0	26.2*
No	286,000	60,000	22,800	22,800	8.0	38.0
Yes	220,000	45,000	24,200	12,100*	11.0	26.9*
No	220,000	45,000	17,100	17,100	7.8	38.0

*Assumes 50 percent empty load device

Currently, the enforcement algorithm does not receive information on whether a car is equipped with an empty load device or not. It is only given information on the number of loads and empties. Table 1 shows that the most conservative brake force assumption for a loaded car is the force that corresponds with a car that is not empty load equipped and the most conservative brake force assumption for an empty car is the force that corresponds with a car that is equipped with an empty load device. Since the algorithm does not have information on whether cars are empty load-equipped, it has to assume a brake force towards the lower end of the potential loaded and empty brake forces. If the algorithm were provided information on whether cars were empty load-equipped, more accurate brake force assumptions could be made.

Consist data is provided to the PTC onboard system via a message from the back office. This message currently does not support sending detailed information on each car such as whether it is empty or loaded, whether or not it is equipped with an empty load device, or the gross rail load (GRL). However, the current consist message from the back office does contain a field used for supplying the onboard system with a calculated brake force for the entire consist. With this field, it is possible to calculate the brake force, considering whether each car is empty load equipped, and supply the calculated brake force to the onboard system.

In this task, two different methods of calculating brake force using empty load equipment information were developed and evaluated. The first method used the empty load equipped data along with a train type of either unit, unit aluminum, manifest, or intermodal to calculate a brake force for the consist. The brake force calculations using this method are shown in Table 2. Where W_{GRL_CAR} is equal to the GRL of the car in pounds.

Table 2. Car Brake Force Calculation using Empty Load Information and Train Type

Train Type	Empty Load Equipped Loaded Brake Force Calculation	Empty Load Equipped Empty Brake Force Calculation[1]	Not Empty Load Equipped Brake Force Calculation
Unit	$0.1129*W_{GLR\_CAR}$	$0.0565*W_{GLR\_CAR}$	$0.0822*W_{GLR\_CAR}$
Unit Aluminum	$0.1103*W_{GRL\_CAR}$	$0.0552*W_{GLR\_CAR}$	N/A[2]
Manifest	$0.1128*W_{GLR\_CAR}$	$0.0564*W_{GLR\_CAR}$	$0.0868*W_{GRL\_CAR}$
Intermodal	$0.1141*W_{GLR\_CAR}$	$0.057*W_{GLR\_CAR}$	$0.0987*W_{GLR\_CAR}$

[1]Assumes 50 percent empty load device

[2]Assumes all unit aluminum cars are empty load equipped

The second method used empty load equipped data and car type information to calculate a brake force for the consist. The brake force calculations using this method are shown in Table 3.

Table 3. Car Brake Force Calculation using Empty Load Information and Car Type

Car Type	Empty Load Equipped Loaded Brake Force Calculation	Empty Load Equipped Empty Brake Force Calculation[1]	Not Empty Load Equipped Brake Force Calculation
Steel Hopper	$0.1103*W_{GLR\ CAR}$	$0.0552*W_{GLR\ CAR}$	$0.0788*W_{GLR\ CAR}$
Aluminum Hopper	$0.1103*W_{GLR\ CAR}$	$0.0552*W_{GLR\ CAR}$	N/A[2]
Tank	$0.1182*W_{GLR\ CAR}$	$0.0591*W_{GLR\ CAR}$	$0.0830*W_{GLR\ CAR}$
Refrigerated Box	$0.1174*W_{GLR\ CAR}$	$0.0587*W_{GLR\ CAR}$	$0.1023*W_{GLR\ CAR}$
Multi-Level	$0.1196*W_{GLR\ CAR}$	$0.0598*W_{GLR\ CAR}$	$0.1023*W_{GLR\ CAR}$
Equipped Box	$0.1128*W_{GLR\ CAR}$	$0.0564*W_{GLR\ CAR}$	$0.0990*W_{GLR\ CAR}$
Unequipped Box	$0.1187*W_{GLR\ CAR}$	$0.0594*W_{GLR\ CAR}$	$0.0899*W_{GLR\ CAR}$
Covered Hopper	$0.1132*W_{GLR\ CAR}$	$0.0566*W_{GLR\ CAR}$	$0.0786*W_{GLR\ CAR}$
Equipped Gondola	$0.1097*W_{GLR\ CAR}$	$0.0548*W_{GLR\ CAR}$	$0.0859*W_{GLR\ CAR}$
Flat	$0.1111*W_{GLR\ CAR}$	$0.0556*W_{GLR\ CAR}$	$0.0830*W_{GLR\ CAR}$
Unequipped Hopper	$0.1114*W_{GLR\ CAR}$	$0.0557*W_{GLR\ CAR}$	$0.0777*W_{GLR\ CAR}$
Gondola	$0.1099*W_{GLR\ CAR}$	$0.0549*W_{GLR\ CAR}$	N/A[2]
Equipped Hopper	$0.1106*W_{GLR\ CAR}$	$0.0553*W_{GLR\ CAR}$	N/A[2]
Conventional Intermodal	$0.1026*W_{GLR\_CAR}$	$0.0513*W_{GLR\_CAR}$	$0.1015*W_{GLR\_CAR}$
Stack Single Well	$0.1141*W_{GLR\ CAR}$	$0.0570*W_{GLR\ CAR}$	$0.0864*W_{GLR\ CAR}$
Stack Three Wells	$0.1141*W_{GLR\ CAR}$	$0.0570*W_{GLR\ CAR}$	$0.1042*W_{GLR\ CAR}$
Stack Five Wells	$0.1141*W_{GLR\ CAR}$	$0.0570*W_{GLR\ CAR}$	$0.1054*W_{GLR\ CAR}$
Other	$0.1097*W_{GLR\ CAR}$	$0.0548*W_{GLR\ CAR}$	$0.0777*W_{GLR\ CAR}$

[1]Assumes 50 percent empty load device

[2]Assumes all unit aluminum cars are empty load equipped

In Table 3 the equipped and unequipped description in the Car Type column is not related to a car being empty load equipped or not. This description is used based on if the railcar is equipped with something non-standard. For example, an equipped boxcar may have dividers installed inside the boxcar or racks mounted to store equipment on them and an unequipped boxcar is a standard boxcar.

The following information is needed, on every car in the consist, for both methods shown in Table 2 and Table 3:

- If the car is empty load-equipped or not
- If the car is empty or loaded
- The GRL of the car

Additionally, for the second method, the car type for every car in the consist must be known, whereas in the first method, only the train type must be known. The values used in Table 2 and Table 3 were derived by querying each train type and car type in Umler®, determining how many cars in each category are empty load equipped or not, and calculating an average brake force for each train type and car type for loaded cars that are empty load-equipped, empty cars that are empty load-equipped, and non-empty load-equipped cars. Monte Carlo simulations were run using brake force calculations from Table 2 and then repeated using brake force calculations from Table 3. The results of these simulations and the comparison to other methods are discussed in Section 2.2.

2.2 Research on Alternative Methods for Estimating Train Brake Force

One of the most significant parameters that affects the performance of the enforcement algorithm, and also one of the most difficult to accurately estimate, is the train brake force. Research conducted previously demonstrated the potential benefits in enforcement algorithm performance using an adaptive brake force calculation routine, in which the estimated brake force is adjusted based on actual train performance [1]. This routine requires a brake set to be made by the crew after the train is initialized for the algorithm to measure the train brake performance. If enough data is gathered during a brake application for the brake force to be measured with sufficient confidence, the algorithm will update the estimated brake force using the measured data.

This research compared alternative methods of estimating train brake force to determine the benefits and identify any disadvantages of each method. The developmental algorithm was used for this comparison, and five different methods of estimating brake force were compared [1]:

- Method 1: Assumed brake force using currently available data
- Method 2: Adaptive brake force calculation
- Method 3: Brake force estimated in back office using train type data (see Table 2)
- Method 4: Brake force estimated in back office using individual car type (see Table 3)
- Method 5: Brake force estimated in back office using a method developed within the industry to calculate brake force for the train

Monte Carlo simulations were run using each of the methods above and the results were compared.

2.2.1 Overview of Simulation Testing Process

The simulation testing process is intended to evaluate the enforcement algorithm over a full range of operating scenarios that the system is expected to encounter and considering the practical variability of the parameters that can have a significant effect on the stopping distance of the train. The simulations are organized into test scenarios, each of which represents a potential operating scenario for the system to encounter. Each test scenario is defined by the nominal train consist, the nominal track profile, the initial speed and location of the train, and the target stopping position. The full Monte Carlo test matrix developed in previous research consists of 4,262 scenarios and a subset of 1,528 scenarios used in this work [1].

Multiple braking enforcement simulations were run for each test scenario. The values of the parameters that can have a significant effect on train stopping distance were randomly selected for each simulation from distributions that represent the practical range of values for the given parameter.

To make the simulation process more efficient, the test scenarios are organized into batches that are executed together. A batch could contain any number of test scenarios, each representing a different nominal operating scenario. For this project, each test scenario contained 100 individual simulations, each representing a potential specific instance of the test scenario.

For each individual simulation test, the brake force was calculated for the train, using one of the methods indicated above, and provided to the algorithm. Then the train was simulated approaching the target at the defined initial speed, the enforcement algorithm triggered a brake application to prevent a violation of the stop target, and the response of the train was simulated. The result of each individual simulation represents a single possible stopping location for the given test scenario with the given enforcement algorithm. The aggregate result of the simulations for the entire test scenario then defines the distribution of possible outcomes. This data was analyzed to determine the safety and performance characteristics of the enforcement algorithm for the given test scenario. These characteristics can then be analyzed together to quantify the overall safety and performance characteristics of the enforcement algorithm.

2.2.2 Simulation Testing Tools

The simulation testing tools used for this project are the same that were developed for the previous project [1]. A description of the tools is provided below as well as illustrated in Figure 1:

- The simulation model, TOES, is a proven, validated train action simulation model that accurately models the response of a given train under given conditions, with the ability to modify train, track, and environmental characteristics that can affect the stopping distance of the train.
- The test controller/logger (TCL) is a software application that can generate the simulation inputs to the model from input provided by the user, run large batches of simulations using Monte Carlo simulation techniques, and log the required output.
- The enforcement algorithm under evaluation is the PTC braking enforcement algorithm, implemented as a standalone software application incorporating a common interface to the simulation test components to receive train status and command brake enforcement applications.

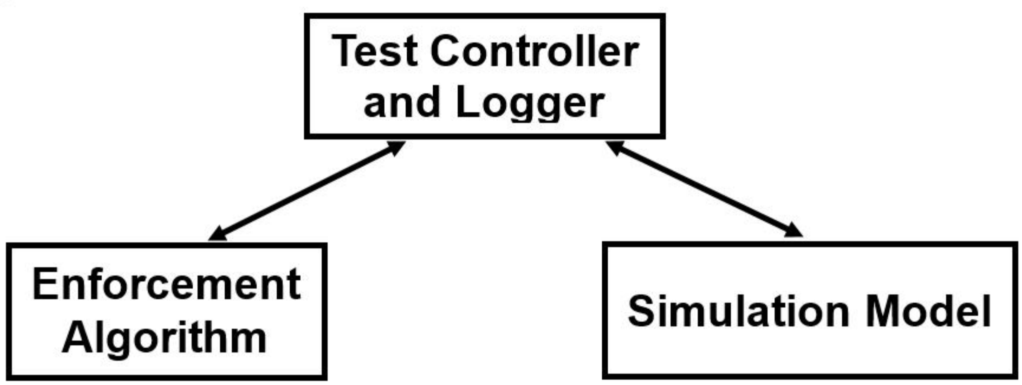


Figure 1. Simulation Software Tools

2.2.3 Test Matrix Used

The test matrix used for this project is a subset of the full test matrix that was defined in previous research [1]. A subset was used to reduce the total number of simulations that needed to be performed for this study, while still maintaining a large enough sample of the different train types to analyze and compare the five different brake force calculations.

The train consists included in the simulation test matrix represent a range of nominal train consists that are regularly and frequently run by the railroads. Each consist is made up of an arrangement of nominal cars, each with a given load. The specific car characteristics that affect braking performance are set to nominal values, which are then varied in the Monte Carlo simulation process. The following three groups of train consists were used in the simulations:

- Unit freight—Trains consisting entirely of a single car type that are typically all loaded to capacity or empty. These are typically bulk commodity trains, such as coal or grain trains
- Manifest freight—Trains consisting of a mix of car types and loads
- Intermodal freight—Trains consisting entirely of intermodal cars that are typically all loaded or empty, although the weight of the loads varies considerably

For each train type, a range of train makeups, train lengths, train loading conditions, and locomotive arrangements were identified. For both the manifest freight and intermodal trains, a pseudo-random process for generating train makeup and car loading was developed. Train make-ups developed from previous work were used for this project [1]. Table 4 summarizes the consists used for each of the three train types.

Table 4. Train Consist Parameters for Simulation Testing

	Unit Freight	Manifest Freight	Intermodal Freight
Train Makeup	Homogenous makeup of: • Aluminum hoppers • Steel hoppers • Covered hoppers • Tank cars • Refrigerated box cars • Multi-levels (vehicular flat cars)	Pseudo-random mix of: • Box cars • Covered hoppers • Gondolas • Flat cars • Open-top hoppers • Aluminum coal gondolas • Tank cars • TOFC/COFC flats • Multi-levels (vehicular flats cars)	Pseudo-random mix of: • Single-platform intermodal well cars • Three-pack intermodal well cars • Five-pack intermodal well cars
Train Length	• 100 cars • 135 cars	• 40 cars • 100 cars • 150 cars • 200 cars	• Short (~ 5,000 ft.) • Medium (~ 7,500 ft.) • Long (~ 10,000 ft.)
Train Loading Condition	• Fully loaded • Fully empty	Pseudo-random loading from historical consist data	• Loaded with pseudo-random loading from historical consist data • Empty with pseudo-random loading from historical consist data
Locomotive Arrangement	• Head end (100-car trains only) • Head and rear (100-car and 135-car trains) • Head, mid, and rear (135-car trains only)	• Head end (40-car and 100-car trains) • Head and rear (100-car, 150-car, and 200-car trains) • Head, mid, and rear (150-car and 200-car trains)	• Head end (short and medium trains) • Head and rear (short, medium, and long trains) • Head, mid, and rear (long trains only)

2.2.4 Simulation Results

The safety objective for PTC brake enforcement algorithms is to stop short of the target 99.5 percent of the time. The performance metric for PTC brake enforcement algorithms is to stop within 500 feet of the target if the train is traveling less than 30 mph and to stop within 1,200 feet of the target if the train is traveling at 30 mph or more. The simulations were analyzed using these metrics. Table 5, Table 6, and Table 7 show a summary of the analysis of the simulations from Unit, Manifest, and Intermodal trains, respectively. The summary tables include the probability of stopping short of the target, the probability of stopping short of the performance metric at speeds less than 30 mph, and the probability of stopping short of the performance metric at speeds of 30 mph and more.

Table 5. Analysis of Unit Train Simulations

Brake Force Calculation	Probability of Stopping short of Target (%)	Probability of Stopping Short of Performance Metric <30 mph (%)	Probability of Stopping Short of Performance Metric >=30mph (%)
Method 1	99.35	4.34	9.00
Method 2	99.80	3.94	7.86
Method 3	98.64	4.23	8.11
Method 4	99.38	2.97	6.55
Method 5	99.30	3.78	7.66

Table 6. Analysis of Manifest Train Simulations

Brake Force Calculation	Probability of Stopping short of Target (%)	Probability of Stopping Short of Performance Limit <30 mph (%)	Probability of Stopping Short of Performance Limit >=30 mph (%)
Method 1	99.85	6.29	14.58
Method 2	99.85	6.24	14.06
Method 3	99.79	5.37	13.29
Method 4	99.74	4.88	12.50
Method 5	99.80	5.60	13.76

Table 7. Analysis of Intermodal Train Simulations

Brake Force Calculation	Probability of Stopping short of Target (%)	Probability of Stopping Short of Performance Limit <30 mph (%)	Probability of Stopping Short of Performance Limit >=30 mph (%)
Method 1	99.52	0.23	5.89
Method 2	99.48	0.26	4.87
Method 3	99.19	0.15	4.19
Method 4	99.28	0.18	4.14
Method 5	99.68	0.27	6.45

Note that the results shown in Table 5, Table 6, and Table 7 are from simulations using the developmental algorithm and do not always meet the 99.5 percent safety objective. If these methods were implemented in an industry enforcement braking algorithm, additional target offset or some other additional safety factor may be needed to satisfy the safety objective.

Method 1 – TTCI's Developmental Algorithm Brake Force Calculation

Table 8 shows the brake force values used in TTCI's developmental braking algorithm.

Some of the advantages of this method are:

- Brake force can be calculated using the consist information that is currently provided to the onboard system

Some of the disadvantages of this method are:

- Unit loaded brake force is based on trailing weight of the train and not GRL weight of the train. This is not an issue for fully loaded unit trains, as the trailing weight of the train and the GRL weight of the train will be equal; therefore, the calculated brake force for the train will be at its maximum possible value. However, for loaded unit trains that are not fully loaded, a smaller brake force will be calculated because the calculation is based on the trailing weight of the train. This results in the algorithm being more conservative for loaded unit trains that are loaded to a value less than the GRL.

- Loaded cars and empty cars will always have a different calculated brake force. This is true for cars equipped with empty load devices, but cars not equipped with an empty load device will have the same brake force whether it is empty or loaded.

Table 8. Brake Force Calculation Using TTCI's Developmental Algorithm

Train Type	**Nominal Loaded Car Brake Shoe Force per Axle** (FB,NOM,AXLE,LOADED)	**Nominal Empty Car Brake Shoe Force per Axle** (FB,NOM,AXLE,EMPTY)
Unit Freight	$\frac{0.093*W_{CARS}}{N_{AXLES}}$	4,962
Unit Aluminum Coal	$\frac{0.11*W_{CARS}}{N_{AXLES}}$	3,975
Manifest Freight	5,870	5,044
Intermodal Freight	6,895	3,746

W_{CARS} = Trailing Weight of Train, N_{AXLES} = Number of Axles in Train (Locomotives Excluded)

The calculated brake force of the train is equal to:

$$Train\ Brake\ Force = N_{AXLES} * \left(F_{B,NOM,AXLE,LOADED} * \frac{N_{LOADED}}{N_{CARS}} + F_{B,NOM,AXLE,EMPTY} * \frac{N_{EMPTY}}{N_{CARS}}\right)$$

N_{LOADED} = Number of loaded cars, N_{EMPTY} = Number of empty cars, N_{CARS} = Number of cars

Below is a comparison of each method with Method 1 and a description of several key advantages and disadvantages of each method.

Method 2 – Adaptive Brake Force Calculation

The adaptive brake force method has a very similar safety performance for manifest and intermodal trains and improved safety performance for unit trains. For all three train types, the performance of the algorithm is improved with this method, as a lower percentage of the trains stopped outside of the performance metric.

Some of the advantages of this method are:

- Calculation of brake force performed onboard and can use consist information currently provided by back office
- Adaptive brake force takes more than brake system performance into account; it also addresses:
  - Brake rigging, cut-out cars, environmental factors, and rail wheel friction

- Brake force is updated throughout train route whenever a brake application is made

A few disadvantages of this method are:

- Additional brake applications may be needed to collect data for the brake force calculation
- Adaptive brake force calculated from the previous brake set may not match current overall consist brake force due to changes in rail lubrication or environmental factors

Overall, the simulations using this method show improvement to both the safety and performance aspects of the algorithm.

Method 3 – Brake Force Estimated in Back Office Using Train Type Data

This method estimates brake force for each simulated consist using empty load-equipped data, GRL data, and train type information. The calculated brake force was provided to the algorithm and used during the enforcement simulations.

Methods 3 and 4 have the benefit of knowing the GRL weight of the train, as well as information if the car is empty load-equipped of which does not address some of the disadvantages described in Method 1.

Some of the advantages of this method are:

- Brake force is calculated based on the GRL of each car as opposed to Method 1, which uses the weight of the car or brake force per axle
- Accounts for empty load equipped cars

Several disadvantages for this method are:

- Brake force needs to be calculated in the back office with additional consist information
  - Empty load data, GRL data, train type
- Does not factor in environmental or rail conditions

Method 4 – Brake Force Estimated in Back Office Using Car Type Data

This method estimates brake force for each simulated consist using empty load-equipped data, GRL data, and car type information. The calculated brake force was provided to the algorithm and used during the enforcement simulations.

This method has a slight improvement in the safety objective for unit trains. The safety objective for manifest trains was better than the 99.5 percent metric, but some additional safety offset would need to be considered for unit and intermodal trains as they were below the 99.5 percent metric. This method did show the most improvement for the performance metric on all three train types.

A few advantages of this method are:

- Brake force is calculated based on GRL of each car as opposed to Method 1, which uses the weight of the car or brake force per axle

- Accounts for empty load-equipped cars

Several disadvantages of this method are:

- Brake force needs to be calculated in the back office with additional consist information
  - Empty load data, GRL data, car type
- Does not factor in environmental or rail conditions

Method 5 – Brake Force Estimated in Back Office Using Method Proposed by BNSF

This method uses a calculation developed within the industry to calculate brake force for the train. The data needed for this method includes car build date, GRL, tare weight, empty load data, and car type.

Using this method, the algorithm met the safety objective for manifest and intermodal trains but was slightly below it for unit trains. This method also showed improvement in the performance metric for unit and manifest trains with a slight decrease in performance for intermodal trains.

A few advantages of this method are:

- Brake force is calculated based on GRL of each car as opposed to Method 1, which uses the weight of the car or brake force per axle
- Accounts for empty load-equipped cars

Several disadvantages of this method are:

- Brake force needs to be calculated in the back office with additional consist information
  - Car build date, GRL, tare weight, empty load data, and car type
- Assumes all non-intermodal, non-empty load-equipped cars built before 2004 have 8.5 percent brake ratio
- Does not factor in environmental or rail conditions

2.3 ECP Brakes

In this task, TTCI researched and implemented changes needed to the developmental enforcement algorithm to handle trains equipped with ECP brakes. With ECP brakes, the BCP on each car is controlled by train brake commands (TBC), which are transmitted electronically from the locomotive head end unit to control devices on each car in the train. Changes to the developmental algorithm for ECP brakes were modeled based on the performance requirements in the AAR Manual of Standards and Recommended Practices (MSRP) Standard S-4200 [2], specifically Sections 4.3.4 through 4.3.11. The Enforcement Algorithm Definition Document was updated to include changes for ECP brakes. The subsections that follow provide a summary of the changes that were implemented in the developmental algorithm to support trains with ECP brakes and the simulations that were run to evaluate those changes.

2.3.1 Consist Information

To handle trains equipped with ECP brakes, the enforcement algorithm needs additional information about the consist. First, an input is needed to indicate if the consist is equipped with

ECP brakes. If the train is equipped with ECP brakes, additional inputs are needed for indicating if the train is empty or loaded and the ECP brake pipe pressure (BPP) setpoint. The empty or loaded information is used by the ECP system to determine the full-service brake cylinder pressure (FSP) for the cars. The ECP brake pipe pressure setpoint is used to determine the maximum FSP, as shown in the equation below.

$$FSP_{Max} = BPP_{Setpoint} * 0.71$$

For this task, a brake pipe pressure setpoint of 90 psi was used for all ECP trains, resulting in a maximum FSP of 63.9 psi.

For fully loaded unit trains, the BCP was modeled to reach 63.9 psi. A value of 20 psi was used for the BCP buildup for empty trains. The minimum BCP allowed per S-4200 is 20 psi [2].

2.3.2 Nominal Brake Force Calculation

In the developmental algorithm, the nominal brake force calculation for an ECP-equipped train is set to the nominal brake force for loaded trains defined in the Phase 3 algorithm of previous research [1], whether the ECP consist is loaded or empty. If the ECP train setting is set to loaded, the calculated nominal brake force is assumed, because the ECP system will allow the car control devices to build BCP to a FSP of 63.9 psi. If the ECP train setting is set to empty, only a proportion of the nominal brake force calculated is assumed, because the ECP system will only allow the car control devices to build BCP to a FSP of 20 psi.

2.3.3 Train Brake Commands

TBCs are commands representing the desired brake application that is commanded by the crew and transmitted to the car control devices installed on each car. These commands are used by the algorithm to determine if a brake set has been made and the magnitude of the brake set commanded. TBCs are represented by a percentage from 0 to 100 or 120. The TBC 100 percent command (representing a full-service brake application) is used to predict the stopping distance of the train to determine if a penalty brake enforcement is needed. After a penalty enforcement has been applied, the TBC 120 percent command (representing an emergency brake application) is used to predict the stopping distance of the train to determine if an emergency brake enforcement is needed. Table 9 gives a description of the different TBC brake states.

Table 9. TBC Brake States

Train Brake Command	Brake State
0%	Brakes Released
0% < TBC <= 10%	Minimum Brake Set
10% < TBC < 100%	Service Brake Set
100%	Full Service Brake Set
120%	Emergency Brake Set

2.3.4 Brake Cylinder Pressure Target and Application Time

The target BCP and BCP rate of change were modeled in the developmental algorithm using the specifications from AAR MSRP S-4200 Sections 4.3.10 and 4.3.11 [2]. Below are the equations for target BCP.

$$BCP_{Target} = \begin{cases} 0 & if\ TBC = 0 \\ MSP & if\ TBC \leq 10 \\ \dfrac{FSP * (TBC - 10) + MSP * (100 - TBC)}{90} & if\ 10 < TBC \leq 100 \\ FSP * 1.2 & if\ TBC = 120 \end{cases}$$

Where FSP is determined by the equation in Section 2.3.1 and whether or not the car is empty or loaded and minimum service pressure (MSP) is set to the default value of 7 psi, as defined in AAR MSRP S-4200 Section 4.3.5 [2].

Below are the equations for BCP rate of change.

$$BCP_{Rate} = \begin{cases} \dfrac{MSP}{2} & if\ BCP_{Target} > BCP\ AND\ BCP \leq MSP \\ \dfrac{FSP - MSP}{8} & if\ BCP_{Target} > BCP\ AND\ BCP > MSP \\ -\dfrac{FSP - 5}{6} & if\ BCP_{Target} < BCP \end{cases}$$

BCP on the cars will increase or decrease based on the above equations, but it must be limited to the target brake cylinder pressure, BCP_{Target}, to ensure it does not rise above the target (when the rate is positive) or sink below the target (when the rate is negative). Figure 2 illustrates the BCP buildup of a TBC 100 percent command from TBC zero percent. The application rate and FSP are calculated using the above equations.

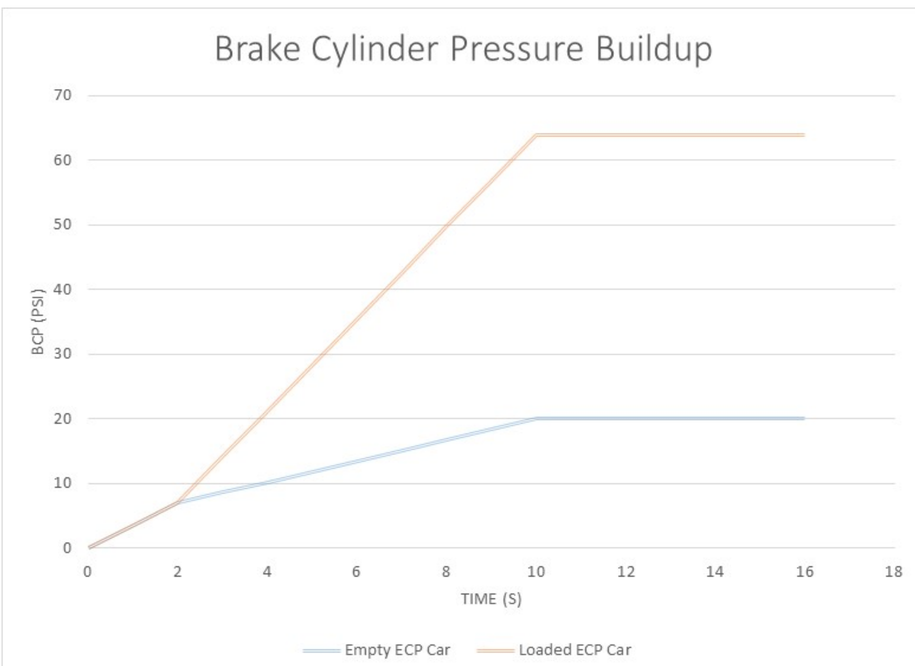


Figure 2. BCP Buildup for ECP Cars from TBC 0 Percent to a TBC 100 percent

The changes outlined in Sections 2.3.1 through 2.3.4 where implemented in the developmental predictive braking enforcement algorithm. Changes were also made to the simulation environment to support the testing of the enforcement algorithm with ECP trains using the Monte Carlo simulation methodology.

2.3.5 Simulations

The test matrix used for the ECP simulations included a subset of the unit train scenarios. The intent was to simulate enough scenarios to provide a reasonable indication of how the algorithm performed with ECP trains. Table 10 describes the consists used in the ECP simulations. The Monte Carlo parameters and distribution of those parameters were used as outlined in previous research [1]. Table 11 shows the results of the ECP simulations. This table includes the probability of stopping short of the target, the probability of stopping short of the performance metric at speeds less than 30 mph, and the probability of stopping short of the performance metric at speeds of 30 mph and more.

Table 10. Consists used in ECP Simulations

ECP Test Matrix Unit Freight	
Train Makeup	Homogenous makeup of: • Aluminum hoppers • Steel hoppers • Covered hoppers • Tank cars • Multi-levels (vehicular flat cars)
Train Length	• 100 cars • 135 cars • 200 cars (Aluminum and steel hoppers only) • 260 cars (Aluminum and steel hoppers only)
Train Loading Condition	• Fully loaded • Fully empty
Locomotive Arrangement	• Head end (100-car trains only) • Head and rear (100-car, 135-car, and 200-car trains) • Head, mid, and rear (135-car, 200-car, and 260-car trains)

Table 11. Results of ECP Simulations

Load Condition	Probability of Stopping short of Target (%)	Probability of Stopping Short of Performance Limit <30 mph (%)	Probability of Stopping Short of Performance Limit >=30 mph (%)
Loaded	96.08	5.94	11.14
Empty	99.94	14.75	68.04
Overall	98.27	10.87	25.21

The results were compiled separately for loaded and empty trains for this analysis, given the differences in how the train and algorithm behave for each loading condition when operating with ECP brakes. An analysis of the simulations showed the ECP function implemented in the enforcement algorithm worked as intended. The analysis also showed that the ECP function used with the existing target offset and onboard estimated brake force, developed for non-ECP trains, was overly aggressive for unit loaded trains and conservative for unit empty trains. Future considerations will need to be considered when implementing ECP brakes into a PTC algorithm to ensure the safety objective of stopping a train short of the target is met for all trains using ECP brakes.

2.4 Specialty Equipment

The final developmental algorithm from the previous effort was developed to handle three different train types: unit trains, manifest trains, and intermodal trains [1]. These train types cover the majority of the equipment that will be used in PTC territory, but there are other specialty types of equipment that the PTC system must handle.

In this task, two types of specialty equipment were investigated to determine if they fit within one of the train types used in the current developmental algorithm or if further modifications will be necessary to handle this equipment.

2.4.1 Roadrailers

Roadrailers are semi-trailers that are built to be interconnected between two railroad trucks to be transported using rail and also connected to semi-trucks for transportation at its initial source and final destination. Once the roadrailers are interconnected together, each roadrailer essentially has two axles, one from the shared truck at one end and one from the shared truck at the other. The only exception is the first and last roadrailer in a consist, which have a truck with two axles on one end and one axle from the shared truck on the other. Roadrailers are also built with a brake pipe running down the length of the trailer to connect the air brake line of the train between each truck and roadrailer. Each roadrailer is equipped with an auxiliary and emergency reservoir and a brake control valve.

Working with a manufacturer of roadrailers, data was gathered to compare roadrailers to other rail cars. This data included tare and GRL weights, truck weights, rail wheel diameter, brake valves used, auxiliary and emergency reservoir information, empty and loaded brake ratios, maximum number of units used within a train, typical number of units used in a train, typical operating speed, brake pipe size and length.

There are many similarities between roadrailers and single platform railcars; each has an auxiliary and emergency reservoir, a single brake control valve per car, similar brake pipe size and length, and they both control the brakes in the same manner. There are also some key differences between roadrailers and single platform rail cars:

- Roadrailers have an auxiliary reservoir volume of 800 cu. in. and an emergency reservoir volume of 950 cu. in. versus a typical freight railcar auxiliary reservoir volume of 2,500 cu. in. and emergency reservoir volume of 3,500 cu. in.
- Roadrailers have a brake control valve for every 2 axles while typical freight railcars have one brake control valve for every 4 axles.
- Roadrailers have a GRL of 76,000 lbs. while most freight railcars typically have a GRL of 220,000–286,000 lbs.
- Roadrailers have a tare weight of 27,300 lbs. while most freight railcars typically have a tare weight of 45,000+ lbs.
- Roadrailers have a 12.6 percent loaded net brake ratio and a 35.3 percent empty net brake ratio, while typical freight railcars have anywhere from a 7 percent to 14 percent loaded net brake ratio and a 20 percent to 38 percent empty net brake ratio.

With these differences, the best way to determine if a roadrailer train would fit within one of the current train types within the enforcement algorithm was to model the roadrailer train in the simulation environment and test it with the algorithm. Using the data gathered, a roadrailer car was added to the simulation model and roadrailer consists were created to use in these simulations. Table 12 gives a description of the roadrailer consists.

Table 12. Description of Roadrailer Consists

	Roadrailer
Train Makeup	Homogenous makeup of: • Roadrailers
Train Length	• 50 cars • 100 cars • 150 cars
Train Loading Condition	• Fully loaded • Fully empty
Locomotive Arrangement	• Head end (50-car and 100-car trains) • Head and rear (100-car and 150-car trains)

Table 13 shows the brake force calculations for the existing train types in the developmental algorithm along with the brake force for the roadrailer, as modeled. From this data, the unit aluminum train type appears to be a good fit. This train type has an estimated brake force that is closest, but not higher than, the actual brake force for the roadrailer train.

Table 13. Brake Force Calculations for a Roadrailer using each Train Type

Train Type	Loaded Brake Force	Empty Brake Force
Unit	7,123	9,924
Unit – Aluminum	8,426	7,950
Manifest	11,740	10,888
Intermodal	13,790	7,492
Roadrailer (as modeled)	9,651	9,651

Simulations using the roadrailer consists in Table 12 were run through the Monte Carlo simulations using the same grade and speed combinations as used with unit, manifest, and intermodal trains. The results of the simulations are shown in Table 14. This table includes the probability of stopping short of the target, the probability of stopping short of the performance metric at speeds less than 30 mph, and the probability of stopping short of the performance metric at speeds of 30 mph and more.

Table 14. Results from Roadrailer Simulations

	Probability of Stopping short of Target	Probability of Stopping Short of Performance Limit <30mph	Probability of Stopping Short of Performance Limit >=30mph
Roadrailers	99.97%	23.54%	27.54%

Simulation results of roadrailers, shown in Table 14, demonstrate that roadrailers can safely be operated within the existing developmental algorithm by using the unit aluminum train type. Simulation results show the algorithm may be on the conservative side for roadrailers, but considering the number of roadrailer trains operated in revenue service and the conditions under which they are operated, this may not be an issue. Revenue service testing of these trains will indicate whether or not the algorithm is too conservative with roadrailer trains.

2.4.2 High Weight Capacity Equipment

The second type of specialty cars researched in this task were high weight capacity vehicles with a GRL greater than 300 tons for a single platform. Using the maximum GRL field in Umler®, high weight capacity vehicles were identified and studied. The cars identified were high capacity flat cars and ranged from a GRL of 302 tons to 500 tons. The flat cars identified had a total number of axles per car ranging from 8 to 20 axles.

TTCI conducted a study to determine how many of the high capacity flat cars are typically placed together within a consist by querying 1 years' worth of *Inte*RRIS® and wheel impact load detector (WILD) data. The data from this study showed that no more than three high capacity flat cars were seen in a consist at the same time and the cars were typically only loaded to approximately half of the maximum GRL, or less. Additionally, the high capacity flat cars make up less than 0.1 percent of the entire fleet. Finally, the specific designs of the high capacity flat cars can vary significantly, and acquiring data for any particular design proved to be difficult. For these reasons, the high capacity flat cars were only researched and were not modeled or tested with the developmental enforcement algorithm.

The methods for calculating empty and loaded brake force, developed in the previous work [1], were used to calculate the loaded and empty brake ratios for the high capacity flat cars identified. Table 15 shows the loaded brake ratios based on the different train type categories and Table 16 shows the empty brake ratios.

Table 15. Loaded Brake Ratios for High Capacity Flat Cars

GRL	Number of Axles	Unit Brake Force (%)	Unit Aluminum Brake Force (%)	Manifest (%)	Intermodal (%)
999,000	16	9.3	11	9.4	11.0
945,000	12	9.3	11	7.5	8.8
858,000	12	9.3	11	8.2	9.6
661,000	12	9.3	11	10.7	12.5
630,000	8	9.3	11	7.5	8.8

Table 16. Empty Brake Ratios for High Capacity Flat Cars

Tare Weight	Number of Axles	Unit Brake Force (%)	Unit Aluminum Brake Force (%)	Manifest (%)	Intermodal (%)
460,000	16	17.3	13.8	18.9	13.0
201,000	12	29.6	23.7	32.5	22.4
250,000	12	23.8	19.1	26.1	18.0
190,000	12	31.3	25.1	34.4	23.7
170,000	8	23.4	18.7	25.6	17.6

Based on the research of the number of high capacity flats within a consist, the best train type for consists containing high capacity flat vehicles would be the manifest freight train type. From Table 15 and Table 16, the range of loaded net brake ratios is 7.5 percent to 10.7 percent and the range for empty net brake ratios is 18.9 percent to 34.4 percent. These ranges fall within the expected net brake ratios, based on the research conducted in previous work [1].

Based on this study, operating with high capacity flat cars within manifest freight trains should not cause any issues for the enforcement algorithm, given the small number of cars within the consists and the fact that their net brake ratios are consistent with other car types within these trains.

2.5 Intermodal Field Test

The objective of this task was to evaluate, through field testing at the TTC, the performance of the Phase 3 developmental algorithm, developed in previous work [1], with intermodal freight equipment. TTCI worked with the TTX Company to acquire a mix of intermodal equipment for this testing. Intermodal cars included a mix of single platform, 2-packs, 3-packs, 4-packs, and 5-packs. The intermodal cars used for this testing were not currently in revenue service, but a checkout of the brake system and an inspection of the cars was performed to make sure everything was in working order.

The field test configuration is shown in Figure 3. The lead locomotive of the test consist contained a Locomotive Control Unit (LCU) and a standard laptop personal computer (PC). The LCU was used to interface the locomotive's brake and computer systems. The laptop PC contained the Phase 3 developmental enforcement algorithm test application.

The enforcement algorithm collected train status data, including train speed, position, head-end brake pipe pressure, tail-end brake pipe pressure as reported by an EOT device, dynamic brake voltage, dynamic brake setup status, and locomotive notch. This train status data was collected by the enforcement algorithm application, in real time as the test was run, and used to enforce penalty and emergency brake applications, as necessary, to avoid a target overrun. The enforcement algorithm test application was also used to record the data throughout each test for use in determining when the brakes were applied, where the train stopped, etc.

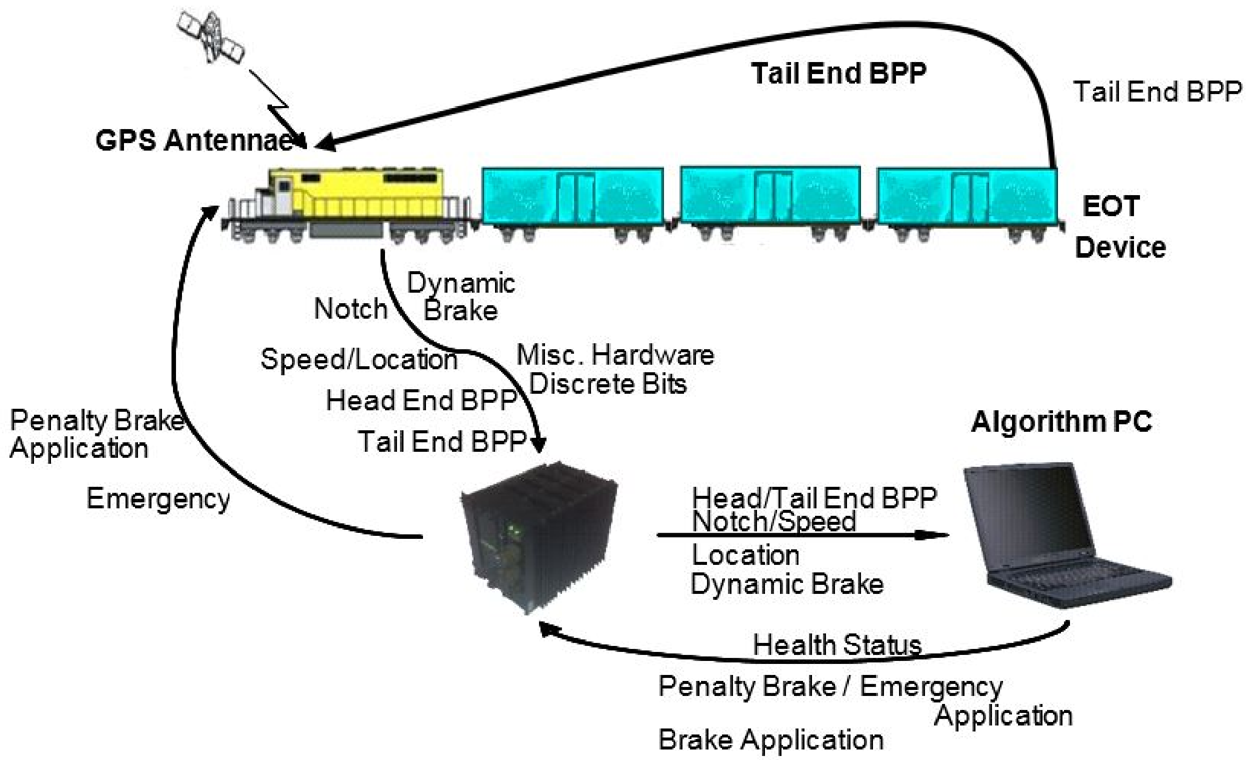


Figure 3. Intermodal Field Test Configuration

The field testing tested the enforcement algorithm over a number of test scenarios, which covered a range of operating conditions. The test scenarios were determined by varying the following independent test variables:

- Consist – The field tests used a test consist made up of a combination of empty intermodal freight cars from TTX. The length of the consist was specified for each test scenario as one of the following:
  - Medium – Approximately 7,500 feet
  - Short – Approximately 5,000 feet
- Track – The approximate track grade over the braking distance:
  - Flat – 0% grade
  - Decline – -1.47% grade
  - Incline – 0.34% – 1.01% grade
  - Crest – 0.79% incline transitioning to a -0.62% grade
- Speed – The target train speed at the time enforcement braking is activated.
- Brake state – The state of the air brake system at the time of enforcement:
  - Fully charged – The brake system is in the fully released/charged state
  - Applied – A service application is made prior to the PTC penalty enforcement

- Type of test – The system objective to be evaluated by the test scenario:
  - Safety – Test to ensure the enforcement algorithm stops the train short of the target or authority limit by running the train at the test speed toward the target until enforcement stops the train.
  - Performance – Test to ensure the algorithm does not interfere with normal train handling by running the train at the test speed toward the target and having the locomotive engineer bring the train to a stop using normal train handling procedures.
  - Safety with brake force – Test to ensure the enforcement algorithm stops the train short of the target or authority limit, using a brake force value that was provided to the algorithm, by running the train at the test speed toward the target until enforcement stops the train.

The specific test cases are listed in Table 17. Tests were run multiple times to evaluate repeatability, up to three tests per test case. Each test case was performed using the developmental algorithm.

Table 17. Planned Intermodal Field Test Cases

Test Case	Consist	Track	Speed	Brake State	Type of Test	Target	Number of Runs
1	Medium	Flat	10	Fully Charged	Safety	R24	2–3
2	Medium	Flat	10	Fully Charged	Performance	R24	2–3
3	Medium	Flat	30	Fully Charged	Safety	R24	2–3
4	Medium	Flat	30	Fully Charged	Safety with BF	R24	2–3
5	Medium	Flat	50	Fully Charged	Safety Safety with BF	R24	2–3
6	Medium	Decline	30	Fully Charged	Safety	R14	2–3
7	Medium	Decline	30	Fully Charged	Safety with BF	R14	2–3
8	Medium	Decline	30	Applied	Safety	R14	2–3
9	Medium	Decline	30	Fully Charged	Performance	R14	2–3
10	Medium	Decline	10	Fully Charged	Safety	R14	2–3
11	Medium	Incline	30	Fully Charged	Safety Safety with BF	R48	2–3
12	Medium	Crest	30	Fully Charged	Safety Safety with BF	R69	2–3
13	Short	Flat	30	Fully Charged	Safety Safety with BF	R24	2–3
14	Short	Flat	30	Fully Charged	Performance	R24	2–3
15	Short	Decline	30	Fully Charged	Safety	R14	2–3
16	Short	Decline	30	Fully Charged	Safety with BF	R14	2–3
17	Short	Decline	50	Fully Charged	Safety Safety with BF	R14	2–3
18	Short	Decline	50	Applied	Safety	R14	2–3
19	Short	Incline	30	Fully Charged	Safety Safety with BF	R48	2–3
20	Short	Crest	30	Fully Charged	Safety Safety with BF	R69	2–3

For each test, the train was moved to the starting position appropriate for the specific test case. The train was then accelerated to the specified test speed and proceeded towards the target stopping location, with the enforcement algorithm monitoring the speed, location, dynamic brake voltage, train acceleration, and brake pipe pressure of the train.

The actual consists used for the field tests are described below.

- Medium consist – 54 empty cars, 6,891 feet, 2,425 trailing tons, and 284 axles
  - 42 single platforms, 7 2-packs, 1 3-pack, 1 4-pack, and 3 5-packs
- Short consist – 34 empty cars, 4,937 feet, 1,726.5 trailing tons, and 204 axles
  - 22 single platforms, 7 2-packs, 1 3-pack, 1 4-pack, and 3 5-packs

Results for the safety and the safety with brake force (BF) cases are shown in Table 18 and Table 19.

Table 18. Results of Safety Test Cases from Intermodal Field Test Using Onboard Calculated Brake Force

Test Case	Predicted Stopping Distance	Actual Stopping Distance
1	406.7	261.5
3	2,074.3	1,410.7
5	4,476.7	3,137.7
6	2,156.5	1,141.13
11	1,586.8	1,213.2
12	1,782.8	1,369.6
13	1,793.3	1,336.7
15	1,949.1	1,091.4
17	4,341.6	2,323.8
19	1,378.1	1,174.4
20	1,559.5	1,333.6

Table 19. Results of Safety Test Cases from Intermodal Field Test Using a Back Office Calculated Brake Force

Test Case	Predicted Stopping Distance	Actual Stopping Distance
4	1,870.3	1,410.7
5	3,655.0	3,137.7
7	1,956.8	1,141.13
11	1,463.5	1,213.2
12	1,717.7	1,369.6
13	1,615.7	1,336.7
16	1,382.4	1,091.4
19	1,286.5	1,174.4
20	1,441.0	1,333.6

Results in Table 18 are from tests where the algorithm calculated an estimated brake force for the train and results in Table 19 are from tests where an estimated brake force for the consist was provided to the algorithm. In all test cases the actual stopping distance was shorter than the predicted stopping distance and the train stopped short of the target every time. Overall the algorithm was on the safe side and not overly conservative, except for some of the higher speed tests. Comparing similar test cases between Table 18 and Table 19, for example test case 5, the predicted stopping distance was closer to the actual stopping distance for the tests ran where an estimated brake force for the consist was provided to the algorithm. These results show that, for the consist tested, the algorithm is less conservative with the brake force provided to the algorithm, while still stopping short of the stop target.

For four of the test cases in Table 17 (2, 8, 9, 14) the locomotive engineer used dynamic braking and/or pneumatic braking to bring the train to a stop before the stop target without a PTC braking enforcement.

3. Implementation Support

The implementation and testing support component of this project focused on supporting the railroads and their suppliers in implementing and verifying new methods and improvements to the I-ETMS enforcement function. This included simulation testing, field testing at the TTC and the railroads, modeling of the field testing, and analysis of the data to support the safety case for the I-ETMS enforcement algorithm.

The following is a timeline of the major implementation support tasks throughout this project.

May 2012

- Emergency brake backup field testing with Wabtec, BNSF, and FRA at the TTC

July 2012

- Emergency brake backup field testing with Wabtec, BNSF, and FRA at the TTC

November 2013

- Dynamic brake field testing with Wabtec, BNSF, and FRA on BNSF Ottumwa subdivision

December 2013

- Dynamic brake field testing with Wabtec and BNSF at the TTC

January 2014

- Meeting with Wabtec, BNSF, and FRA in Washington, DC

February 2014

- Meeting with Class I railroads and FRA in Atlanta

September 2014

- PTC algorithm field test planning with CSX on Wilmington subdivision

October 2014

- PTC algorithm field test planning with NS

November 2014

- PTC algorithm field testing with Wabtec, CP, and FRA on CP Ottumwa subdivision
- PTC algorithm field testing with Wabtec, UP, and FRA on UP Santa Barbara subdivision

May 2015

- PTC algorithm field testing with Wabtec and ARR between Anchorage and Seward

TTCI supported BNSF through December 2013 in testing several new functions implemented by Wabtec in the I-ETMS algorithm. This testing was used, along with the results of the Monte Carlo simulations to demonstrate that the algorithm could be used safely on BNSF PTC trains. The implementation of the new functions, results of the field testing and results of the simulations were presented to FRA's Office of Railroad Safety in the meeting held in Washington, DC, in January 2014. As a result of this meeting, BNSF was approved to operate PTC with the enforcement algorithm in their PTC operations.

TTCI also supported the Class I freight railroads during a meeting with FRA's Office of Railroad Safety in February 2014 where it was discussed how the other railroads could leverage off the work done by Wabtec, BNSF, and TTCI to gain approval for using the I-ETMS algorithm within their PTC operations. It was determined during this meeting that each railroad would conduct additional brake algorithm field testing, with support from TTCI, to expand the number of scenarios tested in the field. Data from these field tests was modeled by TTCI in TOES to help further validate the simulation testing and results. As a result of this meeting, TTCI continued to support the railroads as described above, from September 2014 to May 2015.

3.1 Railroad Field Testing and Results from Modeling Field Tests

Each of the field tests conducted by the railroads were modeled in TOES. The consists and track were modeled to match, as closely as possible, the consist and track information available from the field tests. I-ETMS and/or event recorder logs from the testing were used to determine if there was a brake set and/or dynamic brake set before the penalty application, where the penalty application occurred and at what speed the train was going. After the enforcement, the logs were used to simulate the crew actions (e.g., adjusting dynamic brake, bailing off the locomotive brakes, etc.) throughout the stop. Comparisons between the modeling of the field tests and the results of the field tests show that it was possible to accurately model the field tests performed by the railroads in TOES, with the differences in stopping distance between TOES and the field tests falling well within the distribution of stopping distances in similar Monte Carlo simulation scenarios.

BNSF Railway Company (BNSF)

The objective of the testing in May and July of 2012 was to verify that the emergency brake backup would be initiated if inaccurate data was provided to the onboard system, such that a target overrun would still be predicted after the penalty enforcement is applied. This testing was completed at the TTC on the Railroad Test Track (RTT) with a consist of 4 locomotives and 75 loaded cars, that was 4,368 feet long with 11,812 trailing tons. The test was conducted by BNSF, using a BNSF test plan, with support from TTCI. Figure 4 contains a table of the test results from BNSF's test report. In all cases, the train stopped short of the target with the emergency brake backup function.

Test ID	Date	Time	Speed	Weight	Emergency Brake Forced	Warning Distance	Target Location	Location When Stopped	Distance to Target When Stopped	Predicted Stopping Distance at Penalty	Predicted Stopping Distance at Emergency	Actual Stopping Distance	P/F
5.1	7/19/2012	10:18	60 mph	11,812 tons	No	20,592'	R-24 (MP 7.7)	R-22.1 (MP 7.3)	1889'	14,238'	N/A	12,349'	P
5.2	7/19/2012	20:08	65 mph	11,812 tons	Attempted	19,741'	R-24 (MP 7.7)	R-23.5 (MP 7.6)	510'	12,553'	N/A	12,043'	P
5.3	7/19/2012	13:02	37 mph	11,812 tons	Attempted	7,244'	R-24 (MP 7.7)	R-23.7 (MP 7.6)	339'	3,645'	N/A	3,306'	P
5.4	7/19/2012	12:15	10 mph	11,812 tons	Attempted	1,617'	R-24 (MP 7.7)	R-23.9 (MP 7.7)	58'	487'	N/A	429'	P
5.5	7/20/2012	9:06	49 mph	11,812 tons	Attempted	15,126'	R-14 (MP 5.8)	R-11.9 (MP 5.4)	2131'	8,738'	N/A	6,607'	P
7.1	7/19/2012	12:40	10 mph	11,812 tons	Yes	1,464'	R-24 (MP 7.7)	R-24 (MP 7.7)	48'	478'	111'	429'	P
7.2	7/19/2012	17:20	39 mph	11,812 tons	Yes	10,873'	R-24 (MP 7.7)	R-23.3 (MP 7.5)	654'	4,007'	2513'	3353'	P
7.3	7/20/2012	8:45	68 mph	11,812 tons	Yes	17,660'	R-24 (MP 7.7)	R-23.9 (MP 7.7)	54'	10,116'	699'	10,062'	P
7.4	7/20/2012	9:40	48 mph	11,812 tons	Yes	12,674'	R-14 (MP 5.8)	R-13.7 (MP 5.7)	304'	7,806'	861'	7,502'	P

Figure 4. Results from July 2012 Emergency Brake Backup Testing from BNSF Test Report

The objective of the testing performed in November 2013 was to verify that the dynamic brake function of the algorithm worked as expected under normal circumstances, with and without the presence of an air brake application. The testing was completed on the BNSF Ottumwa subdivision on a 1.3 percent decline. This testing used 50-car and 77-car loaded consists. This field test was led by BNSF, with a BNSF test plan, and was observed by FRA and TTCI. Table 20 shows a description of the test cases run and Table 21 shows the results from the testing. The train was stopped short of the target in all cases, and the dynamic brake function was shown to reduce the conservatism in the algorithm, in terms of stopping the train excessively short of the target.

Table 20. Test Cases for Dynamic Brake Testing in Ottumwa

Test Set	Test IDs	Description	Cars	Grade (%)	Speed (mph)
1	900, 901, 902	Air and DB	50	-1.3	20
2	903, 904, 905	DB only	50	-1.3	20
3	906, 907, 908	DB only	50	-1.3	30
4	909, 910, 911	Air and DB	50	-1.3	40
5	912, 913, 914	Air and DB	77	-1.3	20
6	915, 916, 917	Air and DB	77	-1.3	30
7	918, 919, 920	Air and DB	77	-1.3	40

Table 21. Test Results from Dynamic Brake Testing in Ottumwa

Test Set	Description	Cars	Grade (%)	Test ID	Speed (mph)	Stopping Distance (feet)	Distance to Target at Stop (feet)
1	Air and DB, no actuation	50	-1.3	**900**	20.1	934	**381**
1	Air and DB, no actuation	50	-1.3	**901**	19.5	895	**307**
1	Air and DB, no actuation	50	-1.3	**902**	20.3	938	**373**
2	DB only, no actuation	50	-1.3	**903**	19.5	1,070	**433**
2	DB only, no actuation	50	-1.3	**904**	19.9	1,077	**488**
2	DB only, no actuation	50	-1.3	**905**	20.1	1,153	**546**
3	DB only	50	-1.3	**906**	30.2	1,925	**760**
3	DB only	50	-1.3	**907**	30.0	1,954	**933**
3	DB only	50	-1.3	**908**	30.3	1,858	**857**
4	Air and DB, no actuation	50	-1.3	**909**	39.7	2,794	**1,069**
4	Air and DB, no actuation	50	-1.3	**910**	39.8	2,790	**1,261**
4	Air and DB, no actuation	50	-1.3	**911**	40.1	2,794	**1,320**
5	Air and DB	77	-1.3	**912**	20.3	1,085	**238**
5	Air and DB	77	-1.3	**913**	19.9	1,080	**214**
5	Air and DB	77	-1.3	**914**	20.4	1,114	**257**
6	Air and DB	77	-1.3	**915**	30.1	2,047	**513**
6	Air and DB	77	-1.3	**916**	30.1	1,981	**473**
6	Air and DB	77	-1.3	**917**	30.3	1,943	**538**
7	Air and DB	77	-1.3	**918**	40.1	3,015	**764**
7	Air and DB	77	-1.3	**919**	39.4	2,858	**554**
7	Air and DB	77	-1.3	**920**	40.6	2,890	**862**

The objective of the testing performed in December 2013 was to verify that the dynamic brake function works as expected under normal circumstances and in corner cases, such as dynamic brake failures and dynamic brake transitions. The results from some of these test cases were also compared to Monte Carlo simulations. The testing was performed at the TTC on a 1.47 percent decline and level track. This field test was led by BNSF, with a BNSF test plan, and observed by FRA and TTCI. Table 22 through Table 24 descriptions the test cases run.

Table 22. Dynamic Brake Test Cases that were also Simulated

Test Set	Test IDs	Description	Grade (%)	Speed (mph)
1	921, 922, 923	Enforcement stop on grade with DB only	-1.5	20
2	924, 925, 926	Enforcement stop on grade with DB only	-1.5	30
3	927, 928, 929	Enforcement stop on grade with Air & DB	-1.5	20
4	930, 931, 932	Enforcement stop on grade with Air & DB	-1.5	40
5	933, 934, 935	Enforcement stop on level grade	Level	20
6	936, 937, 938	Enforcement stop on level grade	Level	40
7	939, 940, 941	DB failure at penalty (full consist)	-1.5	20
8	942, 943, 944	DB failure at penalty (full consist)	-1.5	30

Table 23. Dynamic Brake Test Cases with Dynamic Brake Failure

Test Set	Test IDs	Description	Grade (%)	Speed (mph)
7	939, 940, 941	DB failure at penalty (full consist)	-1.5	20
8	942, 943, 944	DB failure at penalty (full consist)	-1.5	30
9	945, 946, 947	DB failure at penalty (1 locomotive)	-1.5	20
10	948, 949, 950	DB failure at penalty (1 locomotive)	-1.5	30
11	951, 952, 953	Pre-penalty DB failure (full consist)	-1.5	30

Table 24. Dynamic Brake Transition Scenarios

Test Set	Test IDs	Description	Grade (%)	Speed (mph)
12	954, 955, 956	Significant reduction in DB as train exits downgrade	-1.5	30
13	957, 958, 959	Decelerate to stop with DB while approaching target	Level	30

Table 25 shows the results of the test cases that were compared to Monte Carlo simulations. The table shows the distance and number of standard deviations the field test data was from the mean of the simulation data, for each field test run. As shown in the table, in all the test cases, the stopping distance fell within two standard deviations from the mean of the simulations of that test case, except for the test case that is highlighted. The event recorder data for that test case showed that the locomotive engineer significantly decreased dynamic brake at the point of enforcement, while the Monte Carlo simulations for this test case were run with constant dynamic brake before and after the enforcement, which explains the difference in the results. Table 25 also shows that all test cases stopped short of the target.

Table 25. Dynamic Brake Field Test Results with Monte Carlo Comparison

Test Set	Description	Grade (%)	Speed (mph)	Monte Carlo Simulations Mean Distance to Target (feet)	Monte Carlo Simulations Standard Deviation (feet)	Field Test ID	Field Test Distance to Target (feet)	Field Test Distance from Mean (feet) [# of σ]
1	Enforcement stop on grade with DB only	-1.5	20	849	106	**921**	**739**	110 [1.0]
1	Enforcement stop on grade with DB only	-1.5	20	849	106	**922**	**866**	17 [0.2]
1	Enforcement stop on grade with DB only	-1.5	20	849	106	**923**	**778**	71 [0.7]
2	Enforcement stop on grade with DB only	-1.5	30	1,310	354	**924**	**1,379**	69 [0.2]
2	Enforcement stop on grade with DB only	-1.5	30	1,310	354	**925**	**1,295**	15 [0.0]
2	Enforcement stop on grade with DB only	-1.5	30	1,310	354	**926**	**1,358**	48 [0.1]
3	Enforcement stop on grade with Air & DB	-1.5	20	883	86	**927**	**917**	34 [0.4]
3	Enforcement stop on grade with Air & DB	-1.5	20	883	86	**928**	**899**	16 [0.2]
3	Enforcement stop on grade with Air & DB	-1.5	20	883	86	**929**	**843**	40 [0.5]
4	Enforcement stop on grade with Air & DB	-1.5	40	1,955	322	**930**	**2,557**	602 [1.9]
4	Enforcement stop on grade with Air & DB	-1.5	40	1,955	322	**931**	**1,707**	248 [0.8]
4	Enforcement stop on grade with Air & DB	-1.5	40	1,955	322	**932**	**1,810**	145 [0.5]
5	Enforcement stop on level grade	Level	20	331	70	**933**	**428**	97 [1.4]
5	Enforcement stop on level grade	Level	20	331	70	**934**	**427**	96 [1.4]
5	Enforcement stop on level grade	Level	20	331	70	**935**	**420**	89 [1.3]
6	Enforcement stop on level grade	Level	40	1,007	195	**936**	**405**	605 [3.1]
6	Enforcement stop on level grade	Level	40	1,007	195	**937**	**1,151**	144 [0.7]
6	Enforcement stop on level grade	Level	40	1,007	195	**938**	**770**	237 [1.2]
7	DB failure at penalty (full consist)	-1.5	20	808	177	**939**	**597**	211 [1.2]
7	DB failure at penalty (full consist)	-1.5	20	808	177	**940**	**784**	24 [0.1]
7	DB failure at penalty (full consist)	-1.5	20	808	177	**941**	**730**	78 [0.4]
8	DB failure at penalty (full consist)	-1.5	30	1,851	436	**942**	**2,175**	324 [0.7]
8	DB failure at penalty (full consist)	-1.5	30	1,851	436	**943**	**2,333**	482 [1.1]
8	DB failure at penalty (full consist)	-1.5	30	1,851	436	**944**	**2,339**	488 [1.1]

The chart in Figure 5 shows the distribution of stopping locations resulting from the Monte Carlo simulations for test set 4, along with the resulting stopping profile from each of the three field test runs for test set 4. Similar charts were developed for each of the test sets in Table 25, these charts are attached as Appendix A. These charts help to visualize where the field test results fell within the distribution of stopping locations from the Monte Carlo simulations. All but one of the field test runs fell within two standard deviations of mean of the stopping distribution from the Monte Carlo simulations, with the majority falling within one standard deviation.

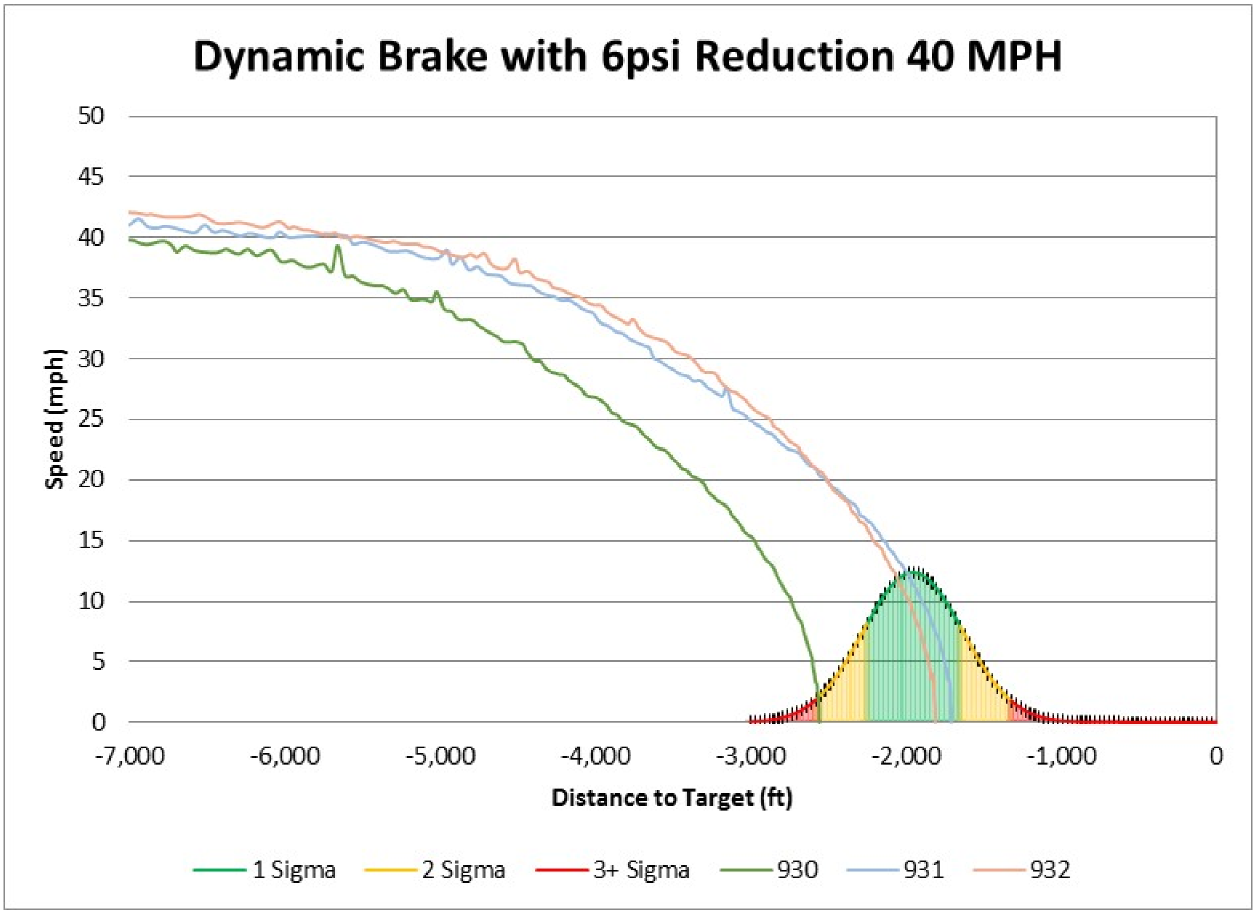


Figure 5. Dynamic Brake Test Set 4 Field Runs Compared to Monte Carlo Simulations

Table 26 shows the results of the test cases that were not simulated. In all the test cases, the train stopped short of the target, even with simulated failures of the dynamic brake system and dramatic changes in the use of dynamic brake. Test case 13 was designed to bring the train to a stop using dynamic brakes before a stop target. With the dynamic brake accounted for in the I-ETMS enforcement algorithm, there was not an enforcement for the three runs in test case 13, which was an issue in previous versions of the algorithm.

Table 26. Dynamic Brake Field Test Results for Cases Not Modeled by Simulations

	Description	Grade (%)	Test ID	Speed (mph)	Stopping Distance (feet)	Distance to Target at Stop (feet)
9	DB failure at penalty (1 locomotive)	-1.5	**945**	20.2	1,744	**664**
9	DB failure at penalty (1 locomotive)	-1.5	**946**	20.3	1,854	**738**
9	DB failure at penalty (1 locomotive)	-1.5	**947**	20.2	1,790	**713**
10	DB failure at penalty (1 locomotive)	-1.5	**948**	30.6	3,329	**1,577**
10	DB failure at penalty (1 locomotive)	-1.5	**949**	30.5	3,412	**1,536**
10	DB failure at penalty (1 locomotive)	-1.5	**950**	30.4	3,144	**1,583**
11	Pre-penalty DB failure (full consist)	-1.5	**951**	31.1	3,931	**1,213**
11	Pre-penalty DB failure (full consist)	-1.5	**952**	30.7	3,614	**1,804**
11	Pre-penalty DB failure (full consist)	-1.5	**953**	31.1	3,526	**1,982**
12	Significant reduction in DB as train exits downgrade	-1.5	**954**	33.5	3,695	**851**
12	Significant reduction in DB as train exits downgrade	-1.5	**955**	32.5	3,498	**1,044**
12	Significant reduction in DB as train exits downgrade	-1.5	**956**	32.2	3,482	**1,018**
13	Decelerate to stop with DB while approaching target	Level	**957**	N/A	N/A	**691**
13	Decelerate to stop with DB while approaching target	Level	**958**	N/A	N/A	**256**
13	Decelerate to stop with DB while approaching target	Level	**959**	N/A	N/A	**323**

CSX Transportation, Inc. (CSX)

TTCI worked with CSX in planning their field tests in order to pick test scenarios that had not previously been field tested. CSX tested a 50-car loaded train that was 2,009 feet long and had 5,337 trailing tons on -0.4 percent and 0.5 percent grades. For the decline tests, CSX tested at a speed of 38 mph and for the incline tests, CSX tested at a speed of 48 mph. This was a CSX led test, with a CSX test plan, and TTCI did not participate in the field testing. Table 27 and Table 28 are tables from the CSX test report with results from this testing. In all the test runs, the train stopped short of the stop target after the penalty enforcement was applied. These tests were not simulated in TOES, because of erroneous event recorder data, but this testing does add scenarios to the matrix of field test scenarios that have been used to evaluate the I-ETMS enforcement algorithm.

Table 27. CSX Incline Field Test Results

Run Number	Grade (%)	Speed per CDU at time of Enforcement (mph)	Distance to Next Target at time of Enforcement (ft.)	Distance to next Target after train has stopped (ft.)	Time (Enforcement Begin/Braking Complete)	Date
1	-.4%	36.9	4,007	**1,272**	13:02:14 13:03:55	09/09/14
2	-.4%	37.7	4,191	**1,442**	13:42:21 13:42:40	09/09/14
3	-.4%	37.6	4,222	**1,456**	14:10:04 14:11:24	09/09/14
4	-.4%	38.0	4,409	**1,576**	14:37:13 14:38:33	09/09/14
5	-.4%	37.5	4,312	**1,513**	11:43:11 11:44:31	09/10/14
6	-.4%	37.8	4,567	**1,542**	12:13:11 12:14:31	09/10/14
7	-.4%	37.7	4,303	**1,504**	12:38:50 12:40:10	09/10/14
8	-.4%	37.8	4,380	**1,541**	13:05:59 13:07:20	09/10/14
9	-.4%	38.1	4,366	**1,523**	13:34:58 13:36:19	09/10/14
10	-.4%	37.6	4,378	**1,510**	13:58:03 13:59:25	09/10/14

Table 28. CSX Decline Field Test Results

Run Number	Grade (%)	Speed per CDU at time of Enforcement (mph)	Distance to Next Target at time of Enforcement (ft.)	Distance to next Target after train has stopped (ft.)	Time (Enforcement Begin/Braking Complete)	Date
11	-.5%	48.1	4,494	**1,289**	12:28:07 12:29:21	09/11/14
12	-.5%	48.5	4,645	**1,340**	12:59:241 13:00:40	09/11/14
13	-.5%	48.1	4,585	**1,315**	13:30:26 13:31:40	09/11/14
14	-.5%	47.8	4,446	**1,230**	14:03:23 14:04:37	09/11/14
15	-.5%	48.1	4,509	**1,235**	14:36:38 14:39:19	09/11/14

Norfolk Southern Corporation (NS)

NS conducted their tests over the Piedmont subdivision from September 25 through October 10, 2014. The test covered both ascending and descending runs, with enforcement occurring at speeds ranging from 31 mph to 48 mph. NS used revenue service manifest freight trains for this brake testing, so each test run had a unique consist. Ten descending runs and 5 ascending runs were modeled using TOES. The event recorder data and consist information for all the test runs were supplied to TTCI for modeling. Based on information provided by NS on the decline simulations, it was assumed that only two locomotives were active and that dynamic braking was present, as the logs indicated.

NS provided consist lists that were used to create the TOES consists. The cars that made up these consists included the following types: Flat Cars, Stack Cars, Covered Hoppers, Equipped Box Cars, Tank Cars, Unequipped Hoppers, Equipped Gondolas, Equipped Hoppers, Gondola Car GT.

Table 29 shows the results of the NS field testing with a comparison to the TOES modeling results for each test run. For all test runs, the train stopped short of the stop target. The modeled stopping distance was within +/- 6 percent for all but three of the test cases and, in those test cases, the modeled stopping distance was within +/- 10 percent. The NS testing was helpful in further verifying the accuracy of the modeling process and was the first-time revenue service manifest freight trains were compared to TOES results for PTC braking enforcements.

Table 29. NS Field Testing and Modeling Results

Description	Consist	Speed at Enforcement (mph)	Stopping Distance (feet)	Distance Short of Target (feet)
Incline Run 1	Field Test	37.7	2,236	**582**
Incline Run 1	TOES	37.7	2,268	**550**
Incline Run 2	Field Test	31.4	1,722	**299**
Incline Run 2	TOES	31.4	1,827	**194**
Incline Run 3	Field Test	47.9	2,727	**978**
Incline Run 3	TOES	47.9	2,775	**930**
Incline Run 4	Field Test	44.6	2,871	**965**
Incline Run 4	TOES	44.6	2,953	**888**
Incline Run 5	Field Test	43.1	2,506	**1,092**
Incline Run 5	TOES	43.1	2,755	**843**
Decline Run 1	Field Test	43.4	3,238	**3,106**
Decline Run 1	TOES	43.4	3,373	**2,971**
Decline Run 2	Field Test	44.7	2,740	**1,428**
Decline Run 2	TOES	44.7	2,738	**1,430**
Decline Run 3	Field Test	43.5	2,792	**1,558**
Decline Run 3	TOES	43.5	2,789	**1,561**
Decline Run 4	Field Test	48.3	3,380	**2,574**
Decline Run 4	TOES	48.3	3,199	**2,755**
Decline Run 5	Field Test	41.5	3,157	**2,895**
Decline Run 5	TOES	41.5	3,282	**2,770**
Decline Run 6	Field Test	40.4	3,881	**2,276**
Decline Run 6	TOES	40.4	3,994	**2,163**
Decline Run 7	Field Test	43.8	3,342	**839**
Decline Run 7	TOES	43.8	3,377	**804**
Decline Run 8	Field Test	45.5	3,326	**2,357**
Decline Run 8	TOES	45.5	3,107	**2,576**
Decline Run 9	Field Test	45.8	2,833	**2,498**
Decline Run 9	TOES	45.8	3,003	**2,328**
Decline Run 10	Field Test	36.2	3,103	**2,750**
Decline Run 10	TOES	36.2	3,349	**2,504**

Canadian Pacific Railway (CP)

CP conducted their tests in Muscatine, IA, over the Ottumwa subdivision during November 2014. The consist was made up of 53 vehicles for each test, which included 50 uniformly loaded aluminum hopper cars, and 3 locomotives: 2 at the head end of the train and 1 at the rear of the train. Each of the aluminum hoppers was loaded to 235,800 pounds. CP worked with TTCI to determine a location on this subdivision that would add a scenario to the list of scenarios field tested with the I-ETMS enforcement algorithm. The chosen location for incline and decline testing was a stretch of 0.77 percent constant grade, run in both directions. CP also performed field tests on level track. Table 30 shows the results of the field testing and the comparison to the TOES simulations. For all test runs, the train stopped short of the stop target. The modeled stopping distance was within +/- 6 percent for all but three of the test cases, and for those three, the stopping distance was within +/- 10 percent.

Table 30. CP Field Testing and Modeling Results

Description	Consist	Speed at Enforcement (mph)	Stopping Distance (feet)	Distance Short of Target (feet)
Level Run 1	Field Test	39.7	2,601	1,459
Level Run 1	TOES	39.7	2,549	1,511
Level Run 2	Field Test	40	2,532	1,506
Level Run 2	TOES	40	2,583	1,455
Level Run 3	Field Test	38.8	2,410	1,476
Level Run 3	TOES	38.8	2,449	1,437
Level Run 4	Field Test	39.5	2,446	1,543
Level Run 4	TOES	39.5	2,526	1,463
Level Run 5	Field Test	38.9	2,445	1,445
Level Run 5	TOES	38.9	2,459	1,431
Decline Run 1	Field Test	36.9	3,117	1,818
Decline Run 1	TOES	36.9	3,028	1,907
Decline Run 2	Field Test	38.4	3,216	1,839
Decline Run 2	TOES	38.4	3,248	1,807
Decline Run 3	Field Test	38.1	3,260	1,894
Decline Run 3	TOES	38.1	3,204	1,950
Decline Run 4	Field Test	40.1	3,575	1,904
Decline Run 4	TOES	40.1	3,508	1,971
Decline Run 5	Field Test	39.9	3,566	1,990
Decline Run 5	TOES	39.9	3,478	2,078
Decline Run 6	Field Test	33.6	3,423	650
Decline Run 6	TOES	33.6	3,213	860
Decline Run 7	Field Test	33.3	3,067	809
Decline Run 7	TOES	33.3	3,243	633
Decline Run 8	Field Test	32.9	2,974	883
Decline Run 8	TOES	32.9	3,062	795
Decline Run 9	Field Test	32.7	3,017	882
Decline Run 9	TOES	32.7	3,276	623
Decline Run 10	Field Test	32.4	3,218	979
Decline Run 10	TOES	32.4	3,472	725
Incline Run 1	Field Test	35.2	1,668	907
Incline Run 1	TOES	35.2	1,622	953
Incline Run 2	Field Test	33.3	1,542	860
Incline Run 2	TOES	33.3	1,467	935
Incline Run 3	Field Test	37.8	1,964	1,099
Incline Run 3	TOES	37.8	1,771	1,292
Incline Run 4	Field Test	37.3	1,915	1,045
Incline Run 4	TOES	37.3	1,799	1,161
Incline Run 5	Field Test	37	1,871	1,084
Incline Run 5	TOES	37	1,773	1,182

Union Pacific Railroad (UP)

UP conducted their testing on the track between Ventura and Las Posas, CA, on their Santa Barbara subdivision in November 2014. The testing used a single consist made up of 5 locomotives and 36 empty cars. The consist used for this testing was an empty intermodal train and the cars that made up the consist included 12 single-platform vehicles, 2 three-platform vehicles and 22 five-platform vehicles. Of the cars used in the consist, eight were not equipped with an Empty/Load device. The cars that were equipped were assumed to be equipped with 60/40 devices, which resulted in 40 percent of the total loaded brake force when the cars were empty. UP worked with TTCI to determine a location on this subdivision that would add a test scenario to the list of scenarios field tested with the I-ETMS enforcement algorithm. The chosen location for incline and decline testing was a stretch of 1.0 percent grade, run in both directions. This was a UP led test, with a UP test plan, and observed by TTCI and FRA. Table 31 shows the results of the field testing and the comparison to the TOES simulations. For all test runs, the train stopped short of the stop target. The modeled stopping distance was within +/- 6 percent for all but one of the test cases, and for that case the stopping distance was within +/- 10 percent. The UP testing was helpful in verifying the modeling process for empty intermodal trains.

Table 31. UP Field Testing and Modeling Results

Description	Consist	Speed at Enforcement (mph)	Stopping Distance (feet)	Distance Short of Target (feet)
Decline Run 2	Field Test	57.6	5,885	2,999
Decline Run 2	TOES	57.6	5,306	3,578
Decline Run 3	Field Test	58.1	5,645	3,109
Decline Run 3	TOES	58.1	5,649	3,105
Decline Run 4	Field Test	58.3	5,599	3,104
Decline Run 4	TOES	58.3	5,661	3,042
Decline Run 5	Field Test	58.6	5,861	2,965
Decline Run 5	TOES	58.6	5,748	3,078
Decline Run 6	Field Test	60.2	6,027	2,832
Decline Run 6	TOES	60.2	5,882	2,977
Decline Run 7	Field Test	57.6	5.784	2,653
Decline Run 7	TOES	57.6	5,774	2,663
Decline Run 8	Field Test	60.4	5,883	3,039
Decline Run 8	TOES	60.4	5,828	3,094
Decline Run 9	Field Test	59.6	6,221	2,513
Decline Run 9	TOES	59.6	5,919	2,815
Decline Run 10	Field Test	58.9	5,641	3,514
Decline Run 10	TOES	58.9	5,765	3,390
Decline Run 11	Field Test	60.6	5,736	2,849
Decline Run 11	TOES	60.6	5,728	2,857
Incline Run 1	Field Test	58.6	3,906	1,949
Incline Run 1	TOES	58.6	3,734	2,121
Incline Run 2	Field Test	58.8	3,892	1,562
Incline Run 2	TOES	58.8	3,744	1,710
Incline Run 3	Field Test	57.0	3,773	777
Incline Run 3	TOES	57.0	3,556	994
Incline Run 4	Field Test	57.4	3,648	879
Incline Run 4	TOES	57.4	3,596	931

Alaska Railroad (ARR)

ARR conducted their tests on track between Anchorage and Seward in May 2015. ARR used a 70-car loaded coal train for this testing with 7 locomotives; 4 on the head end and 3 on the rear. ARR worked with TTCI to determine a location on this subdivision that would add a test scenario to the list of scenarios field tested with the I-ETMS enforcement algorithm. The chosen locations for this testing were a 2.07 percent incline, a 2.15 percent decline, and level track. This was an ARR led test, with an ARR test plan, observed by TTCI. Table 32 shows the results of the field testing and the comparison to the TOES simulations. For all level and decline test runs, the train stopped short of the stop target and the modeled stopping distance was within +/- 5 percent. For the incline test runs, the train stopped short of the target and the modeled stopping distance was within +/- 14 percent, with the largest variance being 72 feet.

Table 32. ARR Field Testing and Modeling Results

Description	Consist	Speed at Enforcement (mph)	Stopping Distance (feet)	Distance Short of Target (feet)
Level Run 1	Field Test	45.3	3,149	**2,407**
Level Run 1	TOES	45.3	3,202	**2,354**
Level Run 2	Field Test	45.2	3,177	**2,559**
Level Run 2	TOES	45.2	3,237	**2,499**
Level Run 3	Field Test	45.4	3,214	**2,451**
Level Run 3	TOES	45.4	3,139	**2,526**
Level Run 4	Field Test	45.3	3,132	**2,381**
Level Run 4	TOES	45.3	3,252	**2,261**
Level Run 5	Field Test	45.5	3,240	**2,360**
Level Run 5	TOES	45.5	3,185	**2,415**
Decline Run 1	Field Test	23.9	1,711	**2,416**
Decline Run 1	TOES	23.9	1,639	**2,344**
Decline Run 2	Field Test	25.8	1,862	**2,644**
Decline Run 2	TOES	25.8	1,897	**2,679**
Decline Run 3	Field Test	26.1	1,938	**2,946**
Decline Run 3	TOES	26.1	2,004	**3,012**
Decline Run 4	Field Test	25.8	1,700	**2,716**
Decline Run 4	TOES	25.8	1,628	**2,644**
Decline Run 5	Field Test	25.6	1,754	**2,724**
Decline Run 5	TOES	25.6	1,757	**2,727**
Decline Run 6	Field Test	24.9	1,799	**2,750**
Decline Run 6	TOES	24.9	1,760	**2,711**
Decline Run 7	Field Test	25.3	1,862	**2,411**
Decline Run 7	TOES	25.3	1,791	**2,340**
Decline Run 8	Field Test	25.4	1,733	**2,781**
Decline Run 8	TOES	25.4	1,797	**2,845**
Decline Run 9	Field Test	25.6	1,786	**2,821**
Decline Run 9	TOES	25.6	1,823	**2,858**
Decline Run 10	Field Test	25.6	1,790	**2,681**
Decline Run 10	TOES	25.6	1,825	**2,716**
Incline Run 1	Field Test	20.5	514	**192**
Incline Run 1	TOES	20.5	451	**255**
Incline Run 2	Field Test	20.5	492	**199**
Incline Run 2	TOES	20.5	451	**240**
Incline Run 3	Field Test	20.4	519	**169**

Description	Consist	Speed at Enforcement (mph)	Stopping Distance (feet)	Distance Short of Target (feet)
Incline Run 3	TOES	20.4	447	**241**
Incline Run 4	Field Test	20.5	447	**260**
Incline Run 4	TOES	20.5	454	**253**
Incline Run 5	Field Test	20.3	508	**199**
Incline Run 5	TOES	20.3	443	**264**

Summary of Field Tests of I-ETMS Algorithm to Date

Figure 6 shows a summary of the scenarios that have been field tested, either at the TTC or by the railroads, including those performed under both this project and previous work [1]. These tests include a mixture of loaded unit, empty unit, empty intermodal, and manifest freight trains. As Figure 6 shows, much of the operational envelope, including many of the corner cases have now been field tested with the I-ETMS enforcement algorithm. The positive results in all these field tests, combined with the accuracy to which the TOES model replicated these results, give confidence in the Monte Carlo simulation process, as well as the safety performance of the algorithm.

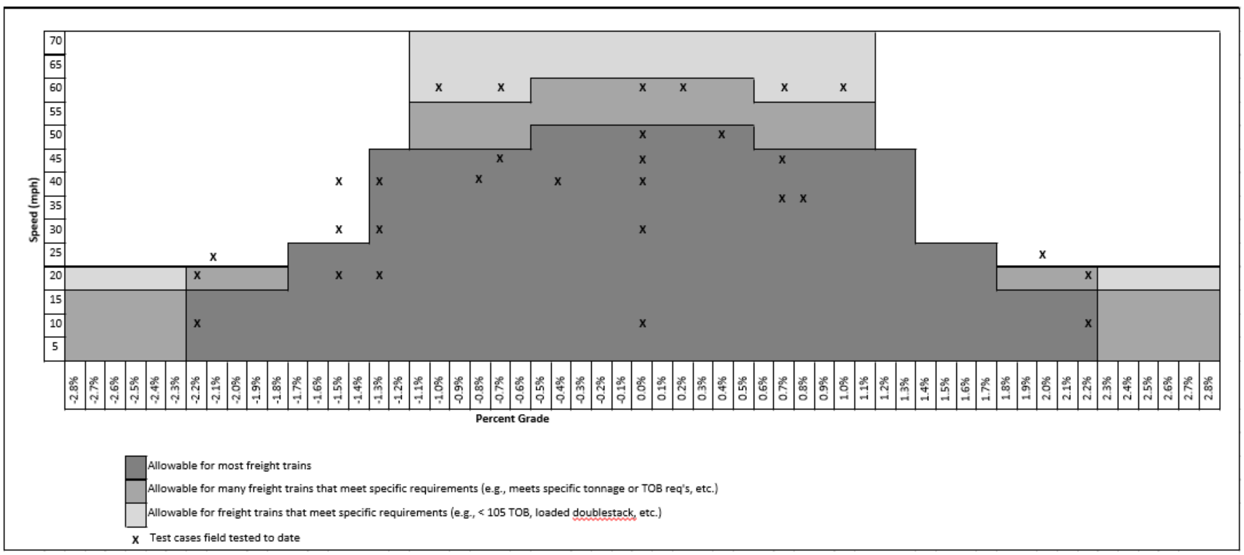


Figure 6. Field Test using I-ETMS Algorithm

3.2 Additional Railroad Support

Throughout this research, TTCI also worked with the railroads and Wabtec to address issues and modifications to the I-ETMS algorithm that were identified by the railroads during testing. Below is a summary of the issues that TTCI supported:

- Excessive warning and undesired enforcements in certain non-zero speed restriction scenarios

The Problem: Crews were seeing warnings and, in some cases, enforcements when heading into speed restrictions while maintaining a speed at or below the upcoming speed restriction.

The I-ETMS algorithm performs calculations to predict the train speed at the location of the speed restriction. If the speed is predicted to be 3 mph over the restriction, it starts warning and if it is predicted to be 6 mph over the restriction, it will enforce.

The Solution: If the train is at or under the speed restriction as it is approaching the speed restriction, any warnings and enforcements associated with that speed restriction will be suppressed.

- Modeling behavior of remote power after an enforcement in distributed power trains

The Problem: For distributed power trains, the I-ETMS algorithm assumed no retarding force for the remote locomotives, causing the algorithm to be more conservative.

The Solution: With help from the railroads, it was determined that remote locomotives, in a distributed power train, are put into idle when a brake application is made and the brake cylinder pressure is allowed to build up to approximately 45 psi. The I-ETMS algorithm was modified by Wabtec to model the brake force from remote locomotives to be used in the prediction calculation.

- Dynamic brake interlock behavior for short trains after an enforcement

The Problem: This problem was identified by a railroad during a demonstration where a consist with just a few cars was used and dynamic braking before an enforcement occurred. For short trains the algorithm assumes the locomotive brakes will be used to help bring the train to a stop and models the predicted stopping profile with full locomotive brakes. This assumption was agreed upon between Wabtec, the railroads, and FRA and is needed to ensure braking distances are reasonable for short consists. The problem that arose during this demonstration is that the dynamic brake interlock (DBI) on the locomotive did not allow the locomotive brakes to build up, because the dynamic brakes were active. This resulted in an overrun, because the force of the dynamic brakes in use was lower than the brake force that would have been produced if the locomotive brakes had been applied.

The Solution: The railroads worked together for a solution and decided that a PTC enforcement will override the DBI and allow locomotive brake forces to apply when an enforcement is issued, even if the locomotive is in dynamic braking. If the locomotive is in dynamic braking, the dynamic braking will remain until the locomotive BCP reaches a certain point, after which the dynamic braking effort will be reduced as the brake force is increased. The locomotive engineer will still have the ability to bail off the locomotive brakes, but they will be trained so they understand that, in scenarios like this, the PTC system is expecting the locomotive brakes to be used to stop the train short in the event of a PTC braking enforcement.

- Undesired enforcements when using independent brake at low speeds while approaching a target

The Problem: Railroads have seen issues when slowly approaching a stop target, while using locomotive independent brakes to pull up as close as possible to the signal. The algorithm currently does not model the locomotive independent brakes and enforces as the crew attempts to pull up close to the target.

The Solution: This problem is actively being investigated at this time. Wabtec and the railroads are working on ways to handle target approach management, for these cases where the crew needs to pull up close to the target. Once this solution is implemented, TTCI will work with Wabtec and the railroads to make sure it is tested in the simulation environment.

3.3 Simulation Testing of I-ETMS Enforcement Algorithm

In this task, simulation testing, using the Monte Carlo process, was conducted on new I-ETMS builds that contained changes to the enforcement algorithm. These simulations ranged from the full Monte Carlo test matrix to small sets of checkout simulations to troubleshoot any issues identified with a new release. TTCI received 13 releases from Wabtec throughout this work, all of which were simulated to some degree. The latest release was version 6.3.11.5.ENG2 and that build was tested against the full Monte Carlo test matrix, both with emergency brake backup enabled and disabled. Table 33 and Table 34 shows the results of the analysis of the simulations on this build with the results when emergency brake backup was disabled in Table 33 and the results when emergency brake backup was enabled in Table 34. The result tables include the probability of stopping short of the target, the probability of stopping short of the performance metric at speeds less than 30 mph, and the probability of stopping short of the performance metric at speeds of 30 mph and more.

Table 33. Monte Carlo Simulation Results for 6.3.11.5.ENG2 Emergency Brake Backup Disabled

Train Type	Probability of Stopping short of Target (%)	Probability of Stopping Short of Performance Limit <30 mph (%)	Probability of Stopping Short of Performance Limit >=30 mph (%)
Unit	99.99	27.63	43.83
Manifest	99.97	32.19	43.75
Intermodal	99.99	28.27	40.27

Table 34. Monte Carlo Simulation Results for 6.3.11.5.ENG2 Emergency Brake Backup Enabled

Train Type	Probability of Stopping short of Target (%)	Probability of Stopping Short of Performance Limit <30 mph (%)	Probability of Stopping Short of Performance Limit >=30 mph (%)
Unit	99.66	14.75	18.39
Manifest	99.90	17.87	19.51
Intermodal	99.95	18.15	14.94

Whether emergency brake backup was enabled or disabled, the safety objective was met, with all train types stopping short of the target greater than 99.5 percent of the time. The tables show that results compared to the performance metric improve when emergency brake backup is enabled. One of the main reasons for this is that all trains are considered to have head-end power only when emergency brake backup is disabled. This results in distributed power trains enforcing earlier, which in turn stops them further from the target.

4. Conclusion

Research on alternative methods of estimating train brake force was conducted on TTCI's developmental freight braking algorithm. The four different methods outlined all showed an improvement in the performance of the braking algorithm, but would need some modifications to the current developmental braking algorithm to ensure the safety objective of stopping the train short of the target 99.5 percent of the time is met. Methods 3, 4, and 5 have the advantage of calculating the brake force of cars in a train using the GRL and tare weights of the cars, which are the values used in the specifications to define the range of brake force the car should have.

Changes were made to the algorithm to support ECP brakes and an analysis of simulations conducted using the ECP function showed that the ECP function works as implemented and as intended. Simulation results also indicated that the current onboard brake force assumptions and the current safety offset, as defined in the developmental algorithm, will likely need to be adjusted when the ECP brake function is implemented within an industry braking algorithm. Using the current assumptions, the algorithm was somewhat conservative for empty trains with ECP brakes and was somewhat aggressive for loaded trains with ECP brakes.

Roadrailers and high weight capacity equipment was also included in the research. Data for roadrailers was collected by a manufacturer of roadrailer equipment and roadrailers were modeled in the Monte Carlo simulation environment. It was determined that roadrailers would best fit within the unit aluminum coal train type. Using this train type and the model of the roadrailers, Monte Carlo simulations were performed and analyzed with the results showing that roadrailers met the safety objective. From an operational performance standpoint, the algorithm performed somewhat conservatively and, if this is unacceptable from the standpoint of implementation in an industry braking algorithm, then further research may be needed. For high weight capacity equipment, a study was conducted to see how many of these cars are found within a train. It was determined that these high weight capacity cars are rarely seen in large numbers within a single consist and were found mainly in manifest train types. Using brake force calculations for manifest trains on the high weight capacity equipment resulted in a reasonable estimated brake force for this equipment. Based on this study, it was determined that the developmental brake algorithm should be able to handle high weight capacity equipment using the manifest freight train type.

A field test of empty intermodal equipment was conducted at TTCI. All the safety test cases stopped short of the target with a penalty brake enforcement and, in all the performance cases, the train was brought to a stop before the target without the braking algorithm enforcing. Tests with the intermodal train were completed with the algorithm calculating an estimated brake force for the train onboard and with an estimated brake force being provided to the algorithm from a back office brake force calculation. The latter resulted in less conservative results while still stopping short of the target in every case.

TTCI provided implementation support to the industry and supplier of the I-ETMS braking algorithm. Through this support, TTCI helped plan railroad field testing of the I-ETMS braking algorithm, witnessed execution of field testing, and/or model and analyzed field testing in TOES for six different railroads. The field tests conducted by the railroads helped further validate the I-ETMS braking algorithm and the modeling of the field tests in TOES helped validate the model used to run Monte Carlo simulations against the I-ETMS braking algorithm.

TTCI also provided other implementation support by working with the railroads and Wabtec to work through operational issues identified by the railroads. The railroads, Wabtec, and TTCI worked through these issues to investigate the issue, identify how it could be solved, and verify the resolution after it was implemented.

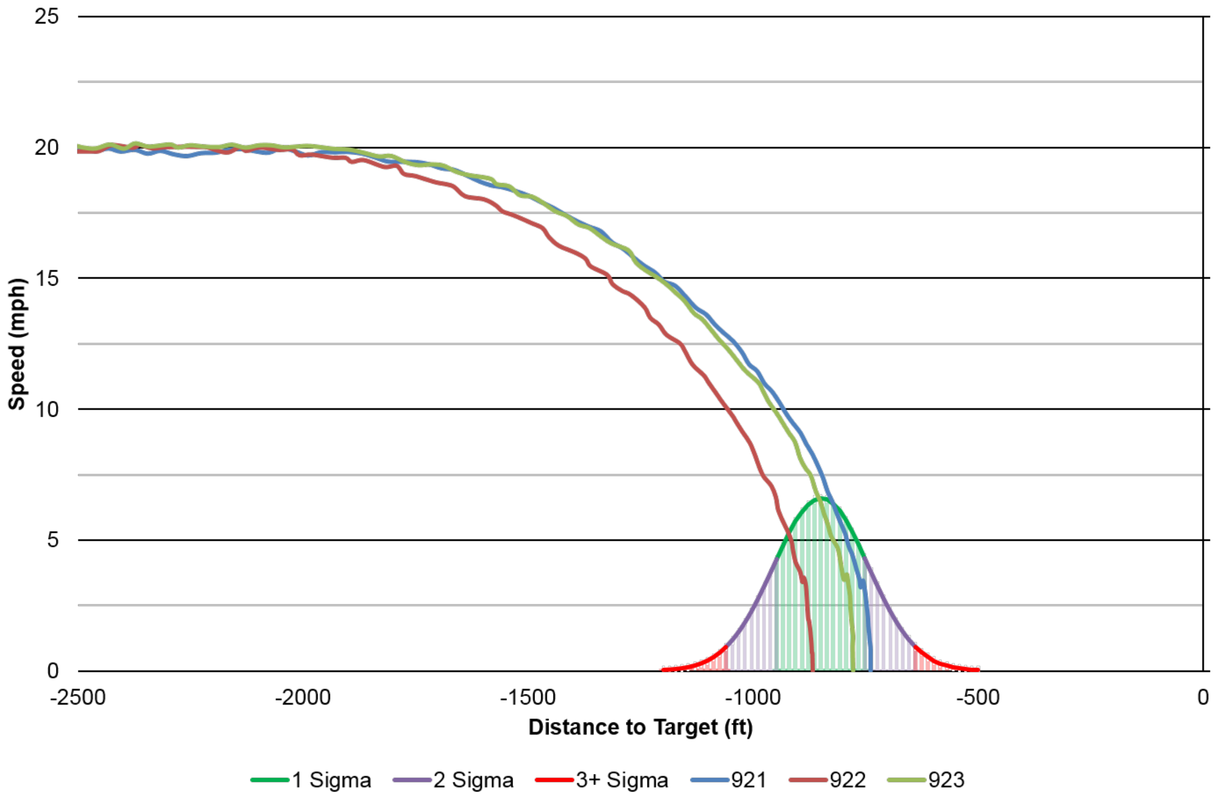
Finally, Monte Carlo simulations were completed and analyzed for version 6.3.11.5.ENG2 of the I-ETMS braking algorithm. Results of these simulations showed that the algorithm met the safety objective of stopping trains short of the target 99.5 percent of the time.

5. References

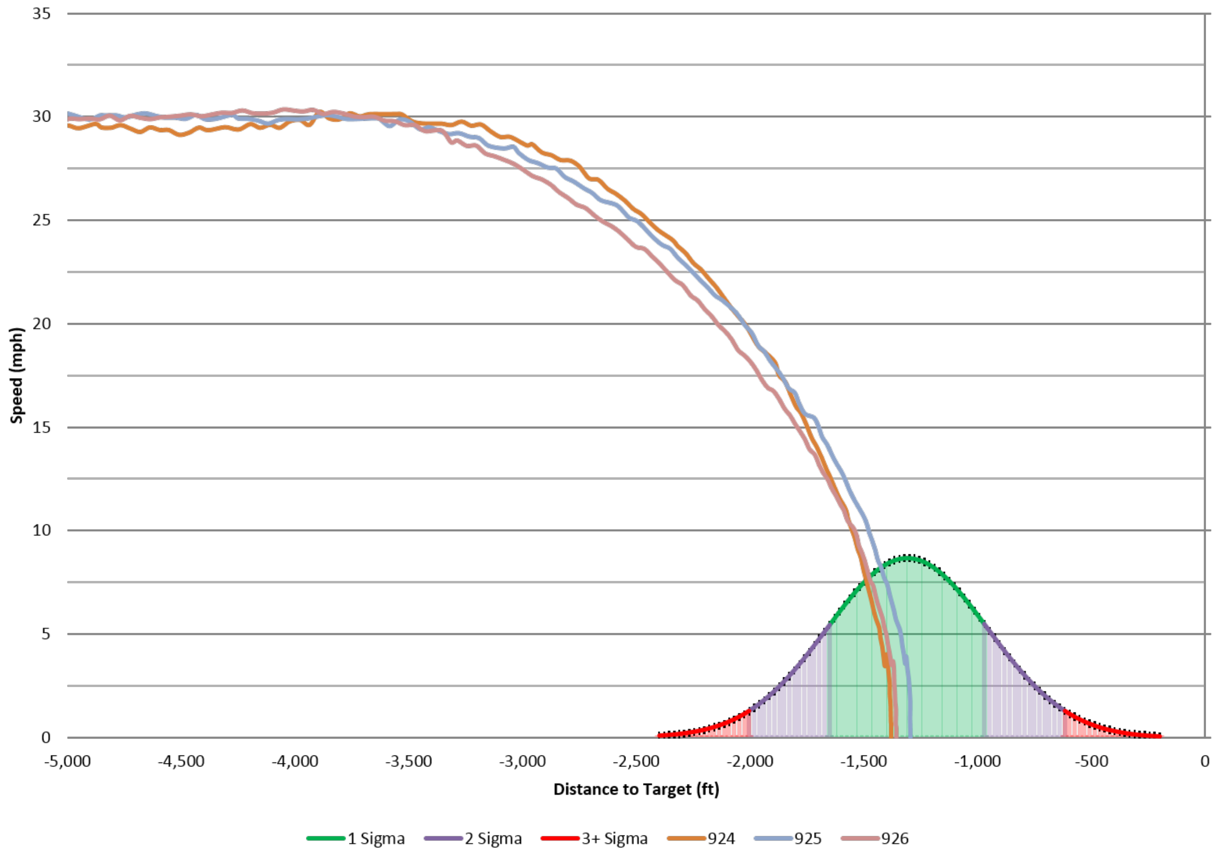
1. Brosseau, J., Moore Ede, B., Pate, S., Wiley, R. B., Drapa, J. (2013) "Development of an Operationally Efficient PTC Braking Enforcement Algorithm for Freight Trains," Technical Report No. DOT/FRA/ORD-13/34, Washington, DC: U.S. Department of Transportation, Federal Railroad Administration.
2. Association of American Railroads. (2014). *AAR Manual of Standards and Recommended Practices* Section E-II Elecronically Controlled Brake Systems, Standard S-4200 "Electronically Controlled Pneumatic (ECP) Cable-Based Brake Systems Performance Requirements."

Appendix A.
Comparison Charts

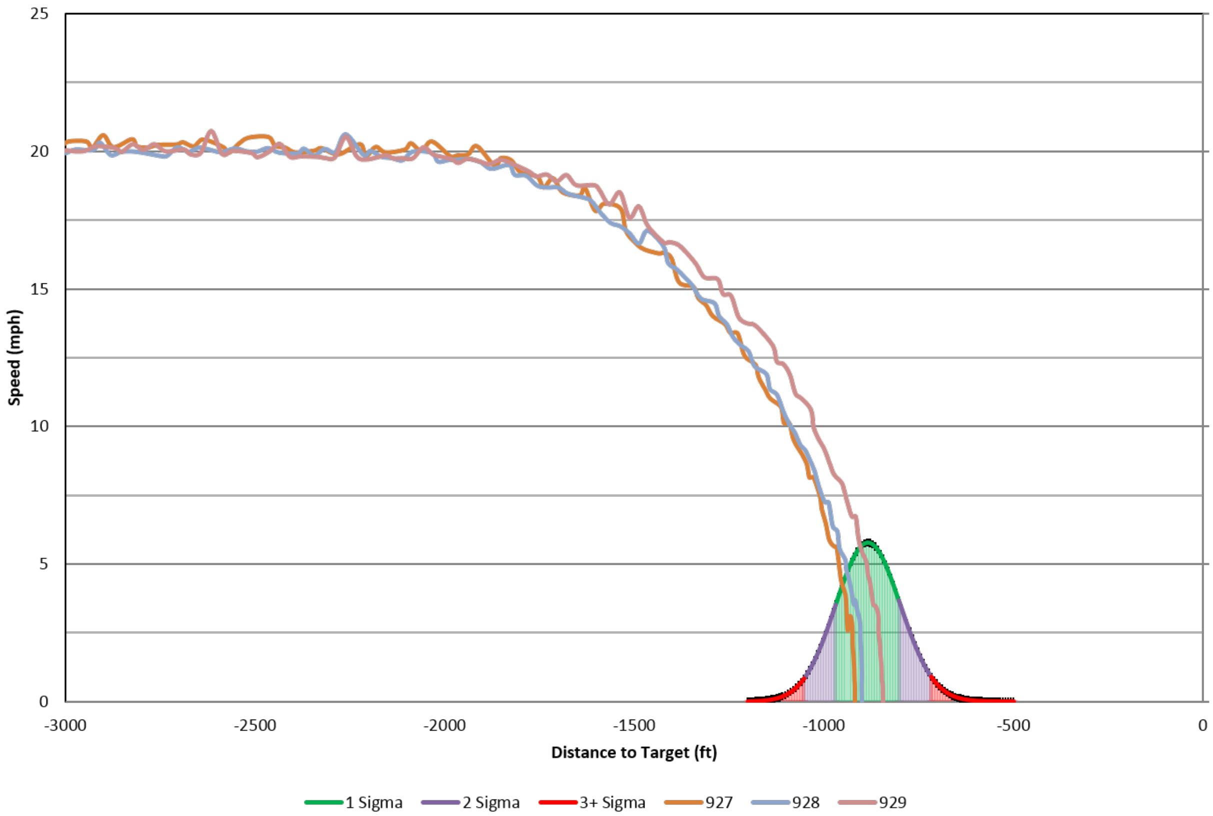
Test Set 1 Comparison



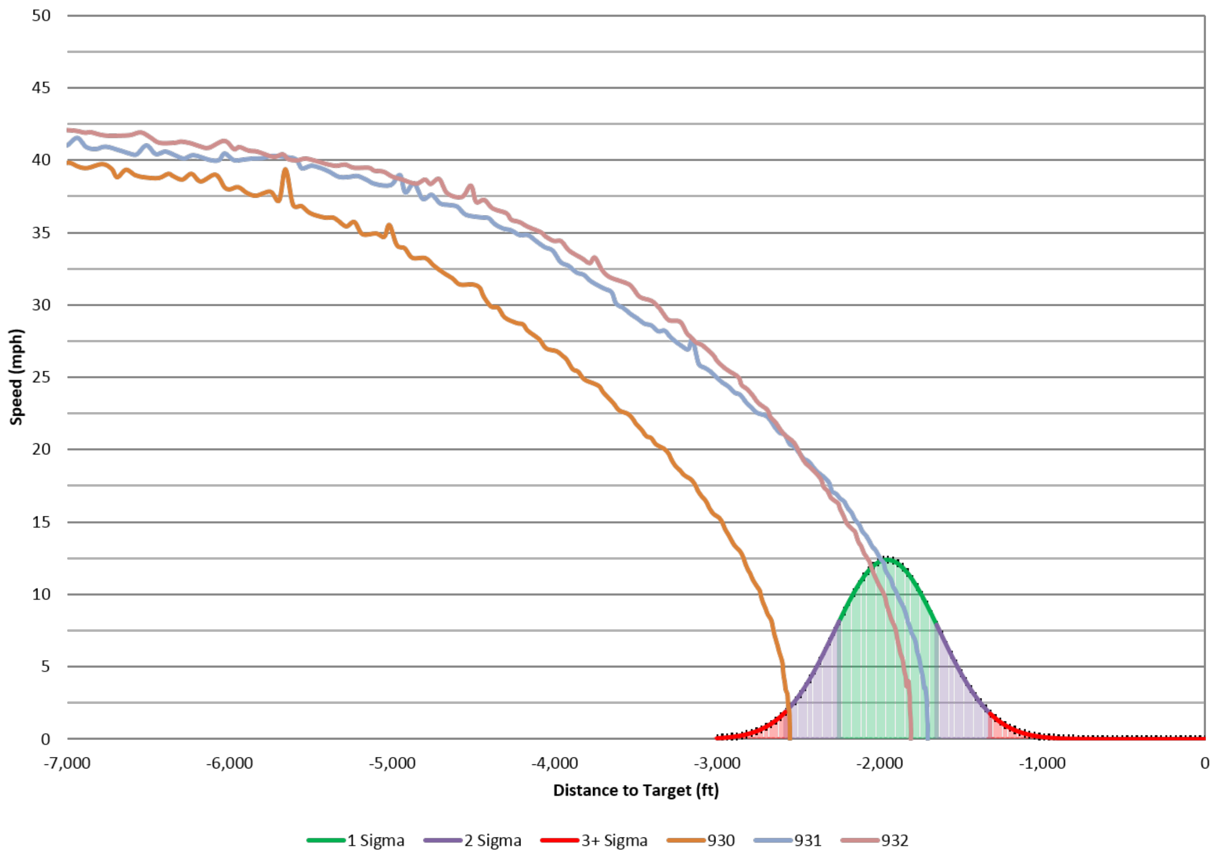
Test Set 2 Comparison



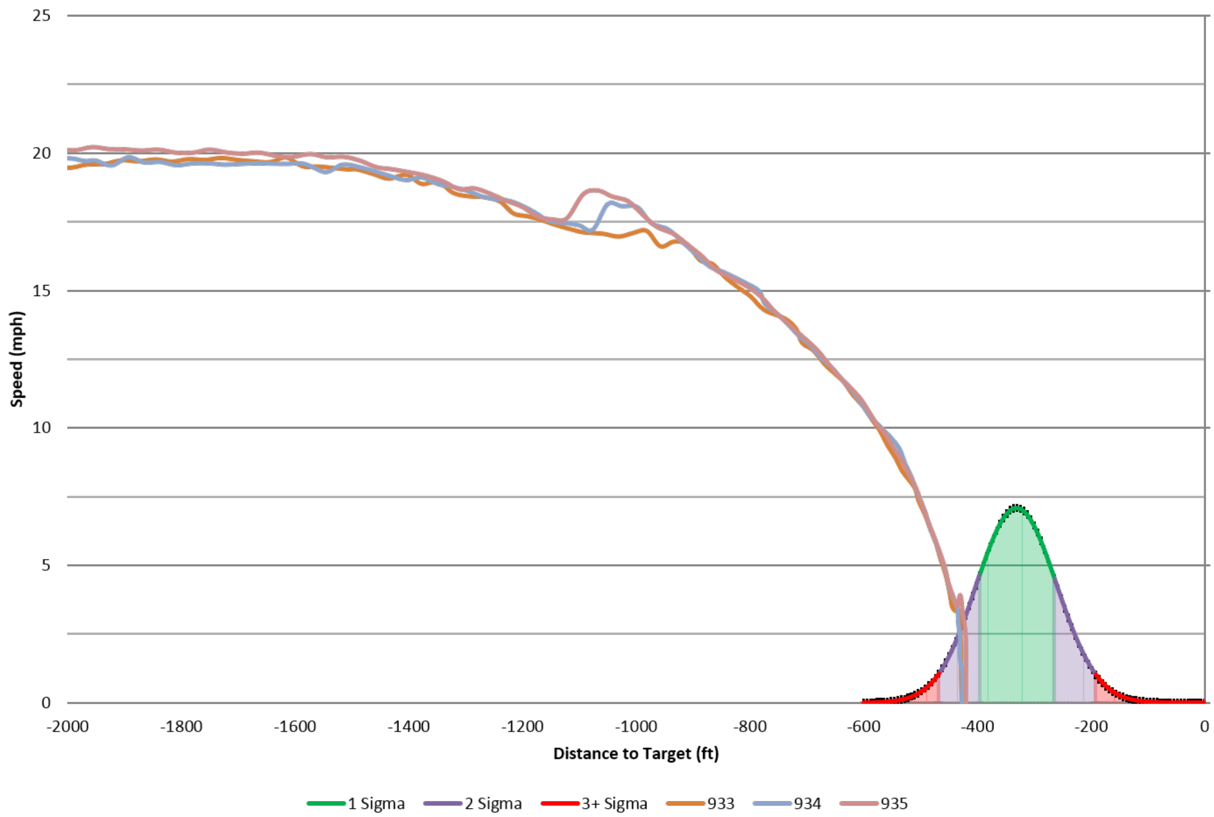
Test Set 3 Comparison



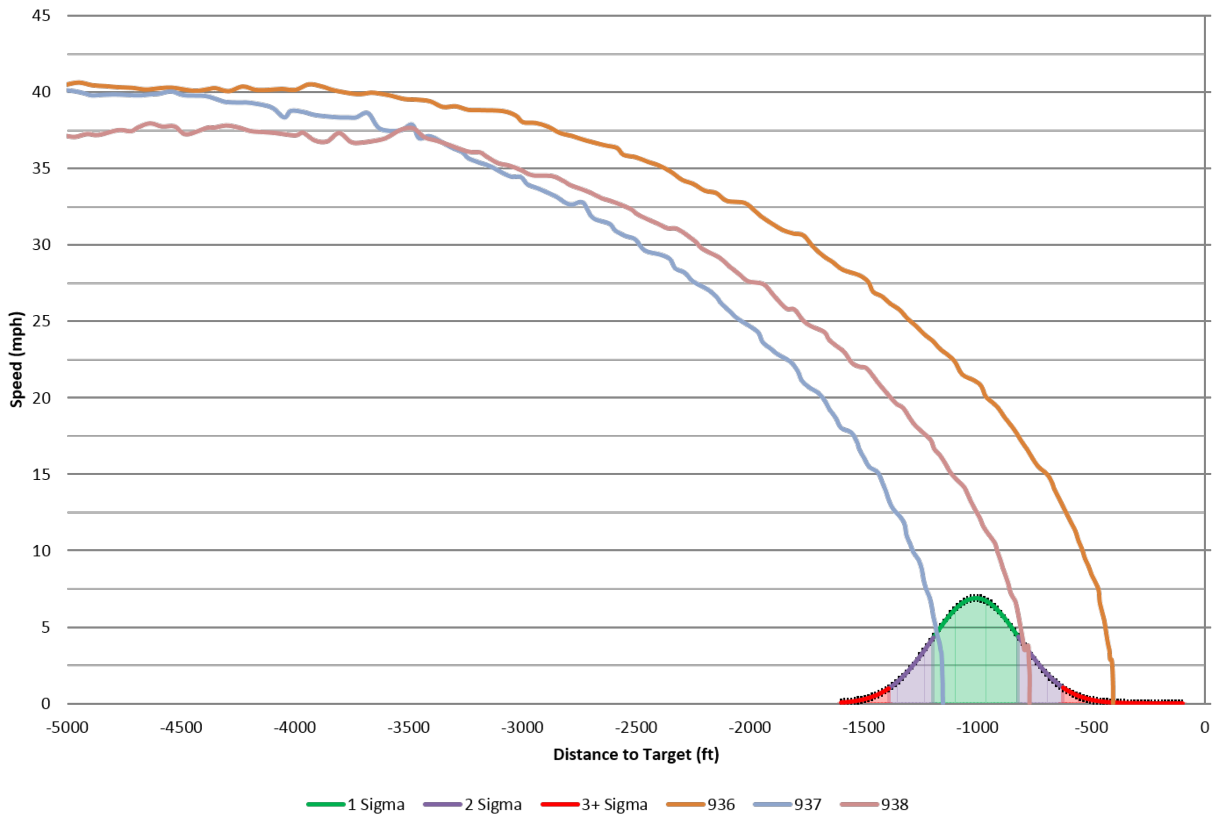
Test Set 4 Comparison



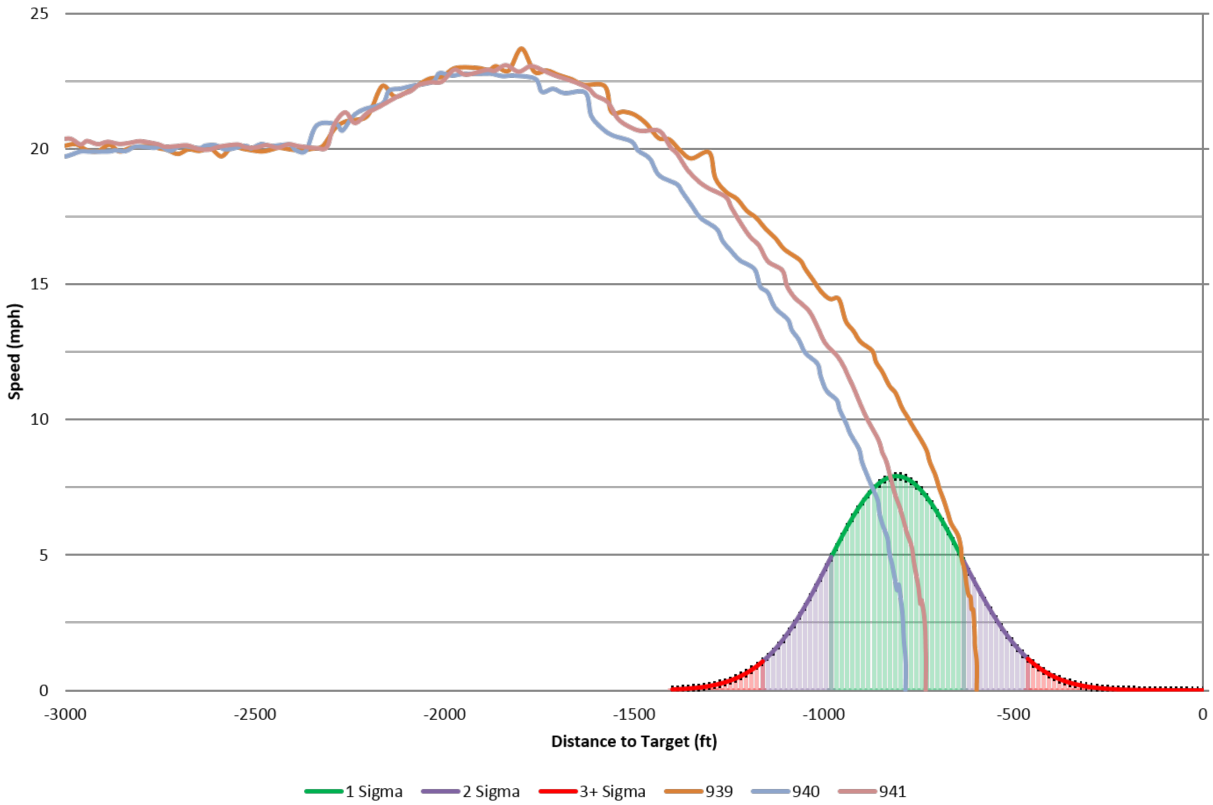
Test Set 5 Comparison



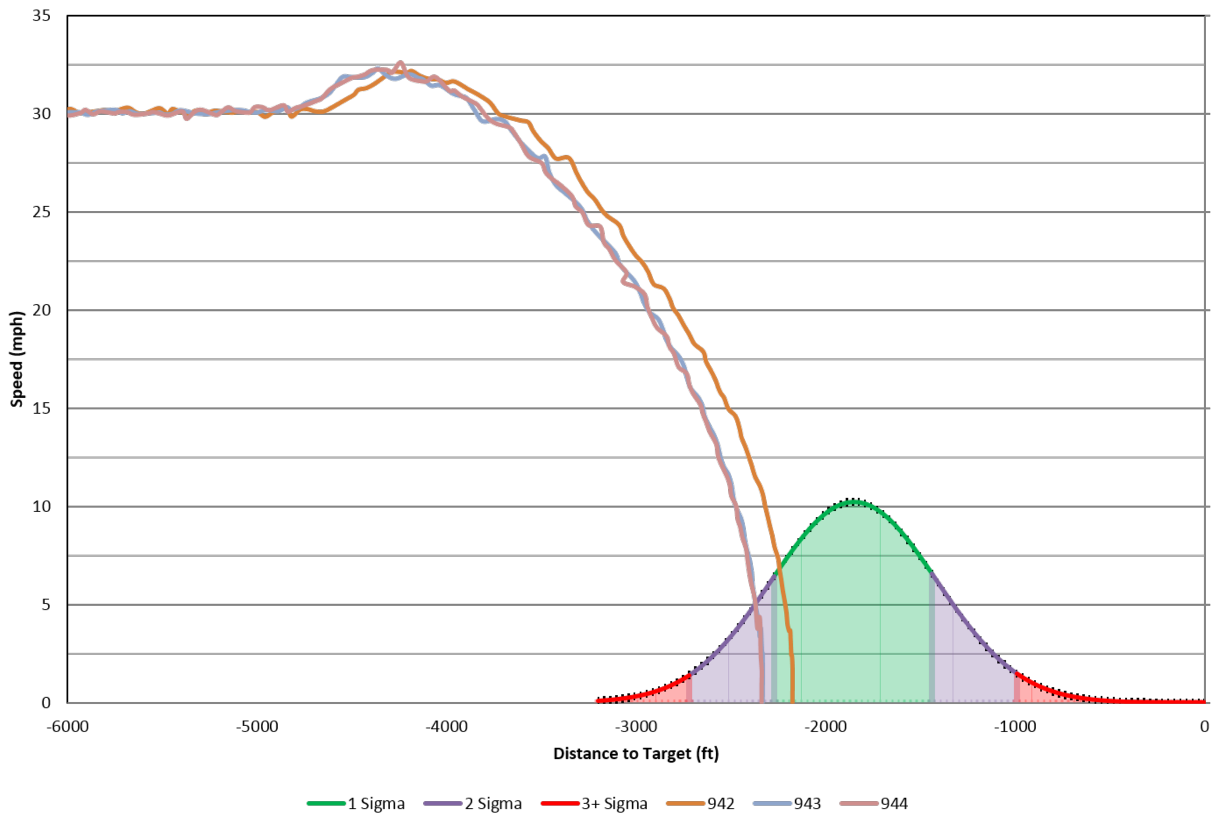
Test Set 6 Comparison



Test Set 7 Comparison



Test Set 8 Comparison



Abbreviations and Acronyms

ACRONYMS	EXPLANATION
ARR	Alaska Railroad Corporation
AAR	Association of American Railroads
BCP	Brake Cylinder Pressure
BF	Brake Force
BPP	Brake Pipe Pressure
BNSF	BNSF Railway Company
CP	Canadian Pacific Railway
CSX	CSX Transportation, Inc.
DB	Dynamic Brake
DBI	Dynamic Brake Interlock
ECP	Electronic Controlled Pneumatic
FRA	Federal Railroad Administration
FSP	Full Service Brake Cylinder Pressure
GRL	Gross Rail Load
I-ETMS®	Interoperable Electronic Train Management System
LCU	Locomotive Control Unit
MSRP	Manual of Standards and Recommended Practices
MSP	Minimum Service Pressure
NS	Norfolk Southern Corporation
PC	Personal Computer
PTC	Positive Train Control
RTT	Railroad Test Track
TBC	Train Brake Command
TCL	Test Controller/Logger
TOES™	Train Operations and Energy Simulator
TTC	Transportation Technology Center
TTCI	Transportation Technology Center, Inc. (the company)

ACRONYMS	EXPLANATION
UP	Union Pacific Railroad
WILD	Wheel Impact Load Detector