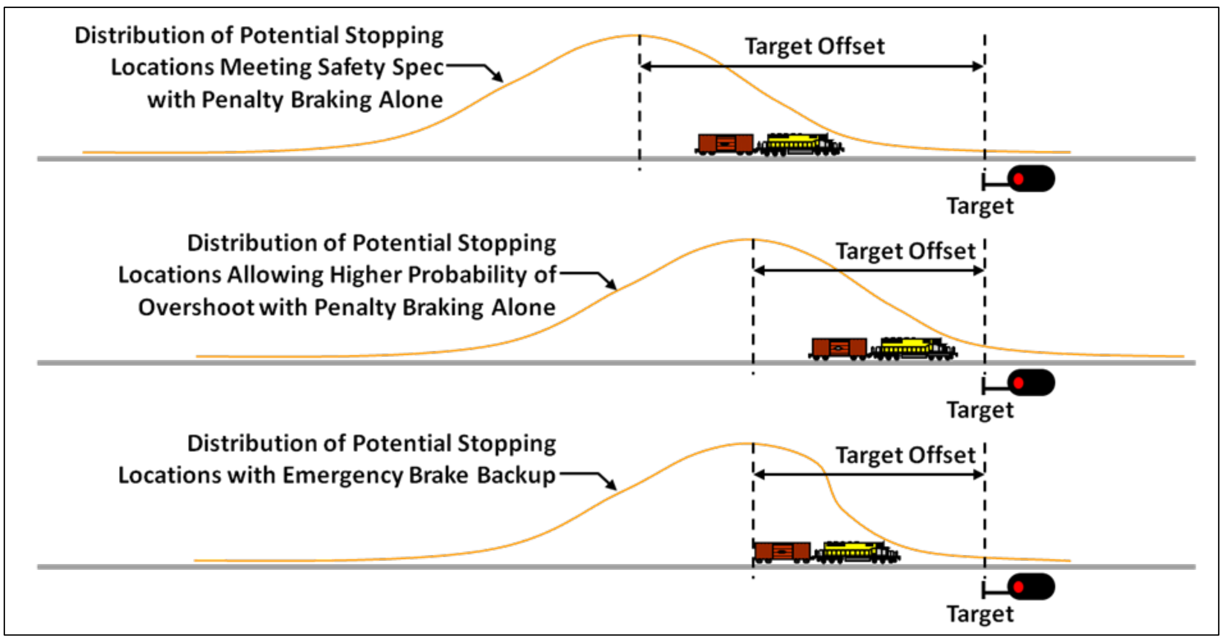
U.S. Department of Transportation

Federal Railroad Administration

Development of an Operationally Efficient PTC Braking Enforcement Algorithm for Freight Trains

Office of Research
and Development
Washington, DC 20590



DOT/FRA/ORD-13/34

Final Report
August 2013

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (Leave blank)	
2. REPORT DATE	August 2013
3. REPORT TYPE AND DATES COVERED	Technical Report
4. TITLE AND SUBTITLE	Development of an Operationally Efficient PTC Braking Enforcement Algorithm for Freight Trains
5. FUNDING NUMBERS	DTFR53-00-C-00012 Task Order 242
6. AUTHOR(S) and FRA COTR	Joe Brosseau, Bill Moore Ede, Shad Pate, RB Wiley, and Joe Drapa
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)	Transportation Technology Center, Inc. P.O. Box 11130 Pueblo, CO 81001
8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	U.S. Department of Transportation Federal Railroad Administration Office of Railroad Policy and Development Washington, DC 20590
10. SPONSORING/MONITORING AGENCY REPORT NUMBER	DOT/FRA/ORD-13/34
11. SUPPLEMENTARY NOTES	COTR: Terry Tse, Jared Withers
12a. DISTRIBUTION/AVAILABILITY STATEMENT	This document is available to the public through the FRA Web site at http://www.fra.dot.gov.
12b. DISTRIBUTION CODE	

13. ABSTRACT (Maximum 200 words)

Software algorithms used in positive train control (PTC) systems designed to predict freight train stopping distance and enforce a penalty brake application have been shown to be overly conservative, which can lead to operational inefficiencies by interfering with normal train operations. Federal Railroad Administration contracted Transportation Technology Center, Inc. to investigate approaches to improve these algorithms and to reduce the associated operational inefficiencies. As part of this program, several new approaches to PTC enforcement were introduced and were shown, through simulations and field testing, to improve the operational efficiency of the algorithm. An appropriate safety objective for these algorithms was established from a fault-tree analysis of the accidents PTC was conceived to prevent. A standard methodology was also established by which any PTC enforcement algorithm can be evaluated against design safety and performance measures. This methodology involves a statistical evaluation of the algorithm by means of a Monte Carlo simulation process, as well as limited, focused field testing, which provides more confidence in the safety and performance of the software at less cost than traditional field testing methods. This methodology was then used to evaluate PTC supplier algorithms that incorporate concepts introduced in this project.

14. SUBJECT TERMS	Braking algorithm, enforcement algorithm, positive train control, PTC, train control, simulation, Monte Carlo simulation, adaptive enforcement algorithm, emergency brake backup
15. NUMBER OF PAGES	314
16. PRICE CODE	

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18
298-102

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)

TEMPERATURE (EXACT)

[(x-32)(5/9)] °F = y °C

METRIC TO ENGLISH

LENGTH (APPROXIMATE)

1 millimeter (mm)	=	0.04 inch (in)
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

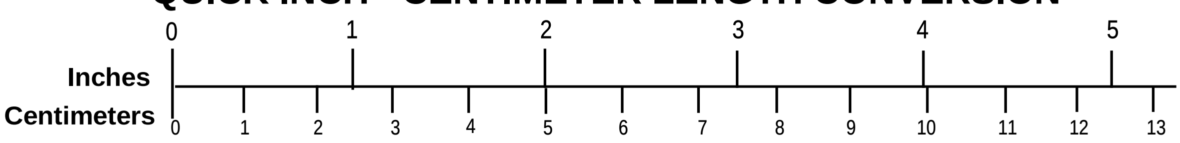
VOLUME (APPROXIMATE)

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)

[(9/5) y + 32] °C = x °F

QUICK INCH - CENTIMETER LENGTH CONVERSION



QUICK FAHRENHEIT - CELSIUS TEMPERATURE CONVERSIC

°F	-40°	-22°	-4°	14°	32°	50°	68°	86°	104°	122°	140°	158°	176°	194°	212°
°C	-40°	-30°	-20°	-10°	0°	10°	20°	30°	40°	50°	60°	70°	80°	90°	100°

For more exact and or other conversion factors, see NIST Miscellaneous Publication 286, Units of Weights and Measures. Price $2.50 SD Catalog No. C13 10286

Updated 6/17/98

Contents

Illustrations

Tables

Executive Summary

Predictive enforcement of authority limits and other stop targets by means of a penalty air brake application is the means by which Positive Train Control (PTC) systems achieve enhanced safety of the railroad operation. Predictive penalty brake enforcement is conceived as the final opportunity to stop the train safely in situations where the train crew has failed to act to do so. Software algorithms designed to predict the stopping distance of freight trains and enforce a penalty application have been tested in freight service in early pilot and production PTC systems and shown to be overly conservative to ensure the train will stop short of the given target; however, they have led to operational inefficiencies by enforcing trains to a stop unnecessarily interfering with the normal operation of the train, which can lead to reduced line capacity. To investigate approaches to improve PTC enforcement algorithms and to reduce the associated operational inefficiencies, the Federal Railroad Administration (FRA) contracted Transportation Technology Center, Inc. (TTCI) to identify, develop, simulate, and test concepts and methods for improving the accuracy of the stopping distance prediction and improving the operational performance of the system.

Through this program, several significant accomplishments have been achieved. First, several new approaches to PTC penalty enforcement have been demonstrated to be useful in improving the operational efficiency of the enforcement algorithm. These concepts are already beginning to be employed by railroads and suppliers in PTC system designs and implementations, proving their worth in a very short time.

Second, a standard methodology was established by which any PTC enforcement algorithm can be evaluated to demonstrate that it meets certain design objectives, such as safety and performance measures. This methodology makes use of Monte Carlo simulation techniques to statistically evaluate the performance characteristics of the enforcement algorithm coupled with small samples of field testing used to validate the results achieved from the simulation modeling process. This methodology is now being used to verify the performance of production-level enforcement algorithms within the industry, to provide better safety and performance data for the system with reduced time and costs associated with the lengthy field testing processes that have traditionally been required.

The methodology developed under this program makes use of the Train Operations and Energy Simulator (TOES™), originally developed by the Association of American Railroads (AAR). The TOES model is a validated industry-standard software application used for performing a wide range of modeling exercises associated with train-level dynamics. The detailed fluid-dynamics model of the brake system and the flexibility for modeling any train and car type over any track profile make it an ideal tool for evaluating predictive braking routines. In the simulation test methodology, the model is used to perform PTC brake enforcement tests on a large scale for a broad range of operating scenarios. Each operating scenario is simulated multiple times, whereas parameters that affect the train stopping distance are varied according to distributions representing their actual, real-world variability in a Monte Carlo method. This allows for evaluation of the full range of potential outcomes from a PTC penalty enforcement in each of the operating scenarios tested, providing a complete statistical view of the safety and performance characteristics of the algorithm.

The research and development of improved techniques for PTC enforcement algorithms was divided into three phases of development, as guided by an industry advisory group made up of representatives from four U.S. Class I railroads: Burlington Northern and Santa Fe Railway Company (BNSF), CSX, Norfolk Southern Corporation (NS), and Union Pacific Railroad (UPRR). The intent of the phased approach was to release the concepts and methods to the industry in a more timely fashion, as opposed to waiting until all of the research was complete. In the first phase, the highest priority concepts were addressed, including an evaluation of the safety objective of the PTC enforcement function, investigating the issues with legacy enforcement algorithms, and developing the functions with the most potential for improvement of algorithm performance.

The primary purpose of reviewing the safety requirement of the PTC enforcement function was to analyze its impacts on the overall safety and performance of the operation and to recommend a revised requirement that meets the need of the safety requirement while, at the same time, not adversely affecting operational performance unduly. The research used data available from the railroads and FRA to perform a fault tree analysis relating to PTC-preventable authority violations and the mechanisms in place to protect against them. It was shown, through this analysis, that a safety objective of stopping a given train short of a given stop target 99.5 percent of the time would result in a significant improvement over the train control system in place today, and provide a substantial level of safety in terms of years between PTC-preventable accidents.

Through investigation of a legacy enforcement algorithm, specifically the algorithm used in the North American Joint Positive Train Control (NAJPTC) project, a number of improvements were identified. These included modifications to the logic within the enforcement algorithm, changes to some of the assumptions, and mostly notably, the development of an improved target offset function. The target offset function is used to provide a cushion to ensure the appropriate level of confidence in the stopping distance prediction. Thus, the stopping prediction is offset from the target by a distance calculated from the characteristics of the situation. In the case of the improved target offset function developed under this program, these characteristics include train makeup, track grade, and train speed. A multiple-variable regression analysis was performed using the results of hundreds of thousands of stopping distance simulations to develop functions for computing the target offset necessary for any operating scenario. The techniques established in this project made it possible to generate a target offset function that is no more conservative than the stated safety objectives, which can, and was shown to, have a significant impact on the operational performance of the enforcement algorithm.

The functions identified by the industry advisory group to include in the first phase of algorithm development were adaptive, emergency brake backup, and distributed power functions. In the case of the adaptive functions, a previous project, undertaken by TTCI for the FRA, had investigated and proved the concept. In this project, further refinement to improve the accuracy, as well as modifications needed to cover the full range of operating conditions were incorporated to complete the functions [1]. Two primary adaptive functions were developed and incorporated into a base algorithm in this project. In the first, the propagation time of the train is measured and the algorithm adapted accordingly. In the second, the braking efficiency of the train is measured and used in the stopping distance prediction within the algorithm. These two functions reduced the uncertainty of some variables affecting braking distance. Thus, the use of the adaptive functions provides a more accurate stopping distance prediction, which reduces the potential variability in stopping distance, allowing for a less conservative algorithm. This ability was demonstrated through field testing of the algorithm with the adaptive functions incorporated and compared against the base enforcement algorithm.

The emergency brake backup function concept is to monitor the stopping of the train following the initial PTC penalty application and apply the emergency brake if the initial PTC penalty is not sufficient for stopping the train short of the target. This improves the safety of the system by providing an additional means for providing more brake force if there is any fault in the initial penalty stopping distance prediction. It also allows for the algorithm to be less conservative, because the worst-case trains will be handled by the emergency brake backup function. This concept was developed and tested to demonstrate that it can be implemented in such a way that the emergency is only utilized when it is necessary to do so, without applying the emergency when it is not. Analysis of the in-train forces associated with using the emergency as a backup to the primary penalty enforcement showed no increased risk or safety concerns with use of emergency braking. A discussion on potential implementation concerns is also included in the main body of the report.

The distributed power function is designed to make use of the improved brake pipe propagation time that comes with operating a train with distributed power. Previous algorithms did not consider this reduced propagation time, resulting in overly conservative stopping distance predictions for these train types. This function was shown through field testing to result in far better stopping distance predictions for these trains, resulting in better performance. The key to implementing this function is in providing a safe way to handle the potential, albeit rare, situation where the communications link to the remote locomotives fails at the time of the PTC penalty enforcement. The analysis presented in this report shows that the emergency brake backup function can be used to mitigate this risk, because the emergency applied from the head end only will stop the train faster than the penalty applied from both ends, in all cases.

In the second phase of development, two additional functions were investigated. The first is a function to use the effect of locomotive engineer applied dynamic braking during PTC penalty enforcement to predict the stopping point. Since dynamic braking is used in many cases to control the speed of the train and will continue to be applied following a PTC penalty application, not including the effects of dynamic braking in the stopping distance prediction can result in excessively long stopping distance predictions, forcing the train crew to apply the air brakes in scenarios they may otherwise not, and potentially resulting in unnecessary service interruptions. The risk of the dynamic brake failing, or being disengaged by the train crew, can be handled effectively by the emergency brake backup function. Field testing of this function showed considerable improvement over the base algorithm for cases where dynamic brakes are exclusively used to control the speed of the train on down grades.

The second function developed and tested in the second phase of development relates to the use of locomotive air brakes during PTC enforcement. Traditionally, enforcement algorithms have assumed that the automatic application of the locomotive brakes during a PTC penalty enforcement will be bailed off by the train crew, in accordance with typical operating procedures. In the case of very short trains and light engines, it is traditionally assumed that the locomotive brakes will not be bailed, to prevent excessive stopping distance predictions in these cases. This presents a potential risk, in the case the locomotive brakes are bailed and the locomotive independent brake is reapplied to a lesser extent to stop the train. Although this is considered to be a low-risk scenario, because the locomotive engineer has the tools to stop these trains very quickly if necessary (independent, dynamic, emergency brake), a method for eliminating this risk was nevertheless considered. The method involves modifying the brake system to prevent a full bail of the automatic application on the locomotives, ensuring some level of braking in these cases. This has the advantage of preventing excessive stopping distance predictions with the assumption of a full bail, but also prevents the train crew from inadvertently causing a target overrun by bailing. Although this function was shown to have potential, the additional costs associated with the modifications to the locomotive combined with the relative low risk of the scenario it is designed to prevent may eliminate it from further consideration.

The third phase of development involved expanding the concepts and functions investigated in the first two phases of development to function on additional train types and locomotives. Specifically, modifications to the algorithm logic, assumptions, and target offset functions were designed and implemented for manifest freight and intermodal freight train types. The functions developed in the previous research phases were tested on these types of equipment to demonstrate their potential to satisfy the safety and performance objectives. An investigation of the data and interfaces available to the enforcement algorithm component of the PTC onboard system were also investigated, and a summary of this analysis is presented within the report.

The final version of the developmental enforcement algorithm produced in this project was evaluated using the established simulation test methodology. Overall, the algorithm was shown to have a probability of stopping short of the target of 98.91 percent, which fell just short of the safety objective of 99.5 percent. TTCI knows where the area of improvements need to be and has fixes for these areas that will be implemented and tested as part of the follow on work. However, the probability of stopping excessively short (> 500 ft for speeds < 30 mph, > 1,200 ft for speeds ≥ 30 mph) was reduced to 8.24 percent from a probability of 75.06 percent demonstrated for the base algorithm. This shows the significant reduction in the impact on the operational performance of the system than can be achieved through the use of the techniques developed in this project.

A final component of the project involved working with the railroads on the advisory group and their PTC onboard system supplier, Wabtec Railway Electronics (Wabtec), to support Wabtec's implementation of some of the concepts developed and evaluate their proprietary enforcement using the methodology developed in this project. In addition to implementing some of the concepts investigated in this project, Wabtec also worked with BNSF Railway to implement a process whereby the braking force assumed by the algorithm is improved through a calculation preformed in the back office server that is provided to the onboard enforcement algorithm software.

The Wabtec algorithm was tested both with the brake force provided through this process, as well as without. With the brake force provided from the back office server process, the Wabtec algorithm was shown to have a probability of stopping short of the target of 99.03 percent and a probability of stopping excessively short (as defined above) of 32.31 percent. Without the brake force provided, the algorithm was shown to have a probability of stopping short of the target of 99.66 percent and a probability of stopping excessively short of 40.27 percent. These numbers show considerable improvement over the base algorithm, clearly demonstrating the effectiveness of the improvements made by Wabtec to the current algorithm. It should be noted that these performance numbers for the Wabtec algorithm do not represent the final state as development will continue to achieve the required 99.5 percent probability of stopping short of the target.

This project effectively showed that it is possible to develop a safe braking enforcement algorithm for PTC systems, without being so conservative as to interfere with the normal operation of the railroad. Although it will take years of operation with these improved algorithms to empirically prove their effectiveness, the simulation and field testing results presented within provide a very strong case that they indeed will. As the industry continues to resolve issues associated with the implementation of PTC on a large scale, and as older cars with poorer braking performance are replaced with newer, it may be relevant to continue to evolve the braking enforcement algorithm over time, to continue to reduce the negative operational impact and realize the full benefits of the PTC system.

1. Introduction

A critical task for the railroad industry in the effort to implement PTC technology on a large scale is the development of a braking enforcement algorithm that enables the system to achieve the stated safety objectives, while maintaining the efficiency of the current freight railroad operation. Research and testing of prototype PTC systems designed for use on North American freight railroads has demonstrated the difficulty these systems face in meeting safety objectives without negatively impacting railroad operation. Additionally, no practical, reliable method has yet been established to demonstrate the safety and performance characteristics of the braking enforcement function of these systems. In order to address these issues, FRA funded a research project aimed at improving PTC braking enforcement algorithm performance and developing a practical methodology to demonstrate it. TTCI was contracted to perform the research and conduct the testing activities associated with the project.

1.1 Background

PTC is a form of communications-based train control (CBTC) intended to improve the safety of the railroad operation through the enforcement of movement authority limits, civil and temporary speed limits, work zone limits, and by preventing train movement through a switch left in the wrong position. In a PTC system, movement authority and speed limit information is transmitted digitally to a locomotive onboard computer. The locomotive onboard computer is capable of accurately determining the speed and location of the train in real time; it also contains a braking enforcement algorithm, which predicts the stopping distance of the train and enforces limits by automatically initiating a penalty brake application to prevent a violation. Braking enforcement is considered the final opportunity to safely prevent a violation when the locomotive crew has failed to do so.

The braking enforcement function of the system is critical to ensuring that trains comply with movement authorities and speed limits. A number of parameters 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. Many of the necessary data elements are not provided to the onboard system, and there is a level of uncertainty in those that are. Thus, there can be a significant difference between the stopping distance predicted by the braking enforcement algorithm and the actual stopping distance of a given train. This difference can be described by a statistical distribution of potential stopping locations about the predicted stopping location, as Figure 1 illustrates.

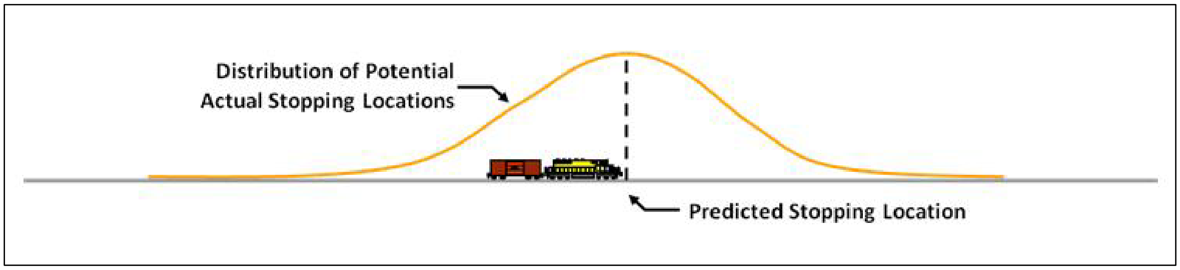


Figure 1. Illustration of Potential Difference between Predicted and Actual Freight Train Stopping Location

The braking enforcement algorithm must compensate for these unknowns and uncertainties so that it can safely stop the train short of a given target location with a specified statistical probability and confidence. Typically, this is achieved by offsetting the predicted stopping distance by some margin, related to the level of uncertainty in the stopping distance prediction. This uncertainty is in turn related to the level of uncertainty in the data provided and the characteristics of the scenario (e.g., train speed at the initiation of enforcement). This offset is typically referred to as the target offset, or safety offset. Figure 2 illustrates the target offset concept.

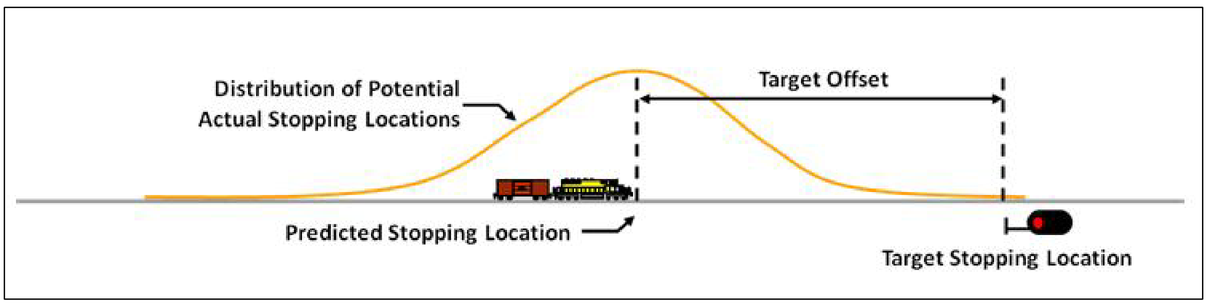


Figure 2. Illustration of the Use of a Target Offset to Compensate for Uncertainty in Stopping Distance Prediction

Braking enforcement algorithms using this target offset concept have been shown to be successful in stopping trains short of the target location as designed, but the conservative nature of these algorithms can, and has been shown to, lead to operational inefficiencies. The target offset for these algorithms can be significant, so much so that the braking enforcement algorithm will issue warnings of impending penalty brake applications in advance of where the locomotive engineer would normally start applying the brakes in accordance with standard operating practices, and in some cases the algorithm forces the train to a stop unnecessarily, Which in turn forces the train crews to operate trains in an operationally inefficient manner.

These large target offsets can be attributed to a variety of factors. First, the width of the distribution of potential stopping locations can be significant, because of the number of parameters affecting the stopping distance and the uncertainty of each. Second, the methods and assumptions typically used for PTC braking enforcement are limited and not typical of normal train crew operating practices. Finally, a statistically significant amount of braking enforcement data is not practically available for the breadth of possible scenarios to precisely meet the safety requirements without significant conservatism.

A previous research effort addressed the first factor by investigating methods to reduce the uncertainty of some of the key parameters in predicting train stopping distance; the methods included measuring brake performance characteristics on the actual train and adapting the algorithm to the specific measured characteristics [1]. This research effort expanded on that concept by addressing all of the factors that contribute to excessive target offsets, as well as other contributors to inefficiencies in the braking enforcement function of the PTC system.

1.2 Objectives

The primary objective of the project was to identify, develop, simulate, and test methods to improve predictive braking enforcement algorithms for freight trains in a PTC system design. Other components of this main objective were to (1) identify and document appropriate safety and performance objectives for the braking enforcement function, (2) develop a practical methodology for statistically demonstrating the safety and performance characteristics of a braking enforcement algorithm, and (3) work with PTC system suppliers to implement the concepts developed and evaluate the performance of the resulting braking enforcement algorithm using the established methodology.

1.3 Overall Approach

The following research focus areas were identified as having the potential to improve both the safety and operational efficiency of the enforcement algorithm:

- A safety objective for the enforcement function of the system that offers a high level of safety, without being unduly restrictive;
- A target offset function related to the statistical variance of freight train stopping distance for the range of potential operational scenarios;
- Adaptive functions that measure the braking performance characteristics of the train and adapt the algorithm to these characteristics to improve the prediction;
- Use of emergency braking as a backup for cases where the penalty brake is insufficient for stopping the train short of a target location;
- Methodology for improving the prediction with trains using distributed power;
- Methodology for including dynamic brakes already in use in the stopping distance prediction; and
- Use of locomotive brakes during PTC braking enforcement to improve safety with short trains and light locomotives.

The project was organized into three research and development phases, with the objective of releasing concepts and methods to the industry in a more timely fashion. Within each project phase, several new methods were researched and incorporated into a developmental braking enforcement algorithm software test application. Each of these methods was then tested, using a combination of simulation and field testing, to demonstrate the potential safety and performance benefits. The complete developmental braking enforcement algorithm logic was then documented and provided to railroads and PTC system suppliers.

The algorithm development was supported by an industry advisory group, which helped to organize the potential new methods into the appropriate phases of development. The major tasks associated with each phase of development are outlined below:

- Phase 1
  - Develop approach/methodology for evaluation of PTC braking enforcement algorithms.
  - Research appropriate safety objective for braking enforcement function.
  - Evaluate base enforcement algorithm.
  - Refine assumptions and logic in base enforcement algorithm, including revised target offset function related to statistical regression of simulation tests.
  - Refine adaptive methods developed in the previous research effort.
  - Develop emergency brake backup functionality and research on safety considerations regarding use of emergency braking.
  - Modify algorithm to handle trains operating with distributed power.
- Phase 2
  - Modify algorithm prediction logic to include estimation of dynamic brake force in use.
  - Research and develop use of locomotive automatic and independent brakes.
- Phase 3
  - Modify algorithm assumptions and target offset function for manifest freight equipment.
  - Modify algorithm assumptions and target offset function for intermodal equipment.
  - Research data and interfaces available on various types of locomotives.

In addition to the research and development tasks listed above, the project also included evaluation of PTC supplier algorithms with the objective of demonstrating the safety and performance characteristics to support necessary additional development and provide data to support documentation of the safety case for the PTC system.

1.4 Scope

This document describes the research, development, and test efforts conducted as part of the subject project. Documentation of the enforcement algorithm evaluation methodology and the enforcement algorithm definition are included in separate documents, attached as appendices to this report.

The project scope includes research, development, and evaluation of improved logic for a predictive braking enforcement algorithm for use in PTC applications for freight trains. Considerations for passenger trains are outside the scope of the project.

Although test software applications implementing the algorithm logic were developed during this project for purposes of test and evaluation, development of source code for use in a safety critical application was outside the scope of work. Some implementation details were considered in certain cases, but were largely not included within the project scope. Documentation of the logic and methods developed was included, but development of software requirements specifications and design documents were not included in the project scope.

1.5 Organization of the Report

The report is organized into sections defined by the various tasks of the project. Section 2 describes the development of a methodology that relies on a combination of simulation and field testing to evaluate PTC braking enforcement algorithms in order to increase confidence in the safety and performance of the algorithm, while reducing the dependency on costly field testing. Section 3 discusses the criteria for a safe braking enforcement algorithm and provides an analysis for developing appropriate criteria. Section 4 describes the algorithm used as the base algorithm for development and provides a summary of the performance characteristics of the base algorithm from both simulation and field tests. Section 5 identifies a number of modifications made to the base algorithm before proceeding with the development of new functions to improve the performance-related issues identified during the evaluation of the base enforcement algorithm.

Sections 6, 7, 8, and 9 describe the first phase of development and testing of new functions to improve the performance of the enforcement algorithm. Section 6 discusses the adaptive functions, originally investigated as part of an FRA-funded proof-of-concept project. Section 7 describes the development and testing of an emergency brake backup function, and Section 8 describes the modifications developed for handling trains operating with distributed power. Section 9 provides a summary of the results of the evaluation of the enforcement algorithm with the new functions developed during Phase 1.

The second phase of development and testing is the subject of Sections 10, 11, and 12. Section 10 discusses considerations for the use of locomotive braking during PTC enforcement and the associated hardware and software modifications required. Section 11 details the development of a function for incorporating the use of dynamic braking into the enforcement algorithm to improve the stopping distance prediction on decline grades and other scenarios where dynamic braking is used to control the speed of the train. Section 12 provides a summary of the results of the evaluation of the enforcement algorithm following the developments from Phase 2.

The third and final phase of development is described in Sections 13, 14, and 15. Section 13 describes modifications necessary to expand the scope of the enforcement algorithm to handle additional train types. Section 14 describes a research task to investigate the data and interfaces available to the PTC enforcement algorithm, with particular focus on those that have not typically been used with previous enforcement algorithms. Section 15 provides a summary of the results of the evaluation of the final developmental algorithm with all functions implemented.

Sections 16 and 17 discuss the evaluation of PTC enforcement algorithms from two different PTC suppliers. Section 16 discusses the development support and testing activities associated with evaluating the enforcement algorithm developed by Wabtec for use in the Interoperable Electronic Train Management System (I-ETMS®) PTC system. Section 17 describes the implementation of the Phase 1 enforcement algorithm by Lockheed Martin Corporation (LMC) for use in the developmental Vital Positive Train Control (V-PTC) system.

2. Development of Enforcement Algorithm Evaluation Tools and Methodology

The braking enforcement function enables the safety benefit of the PTC system by forcing the train to a stop whenever a limit is predicted to otherwise be exceeded. It also has the potential to severely impact the railroad operation by forcing trains to slow or stop in situations where it would not otherwise be necessary. For these reasons, it is essential that the braking enforcement function be rigorously evaluated against a variety of operating scenarios to ensure that it meets the system specifications and expectations of the railroad. To perform such an evaluation, a test methodology must be developed that satisfies the objectives of quantifying the safety and performance of the enforcement algorithm and that is also practical in terms of cost and time.

The primary objective of the enforcement algorithm evaluation methodology is to demonstrate a high degree of confidence that any given train, in any given operational scenario, will stop short of a given target stopping location as a result of PTC brake enforcement. Historically, this objective has been expressed as a probability that a train will stop short of a target stopping location with a given confidence level. This implies that the system specification defines both the probability limit and confidence level for the given probability limit. Section 3 describes the research to identify an appropriate safety objective. For the purposes of the test methodology, it is simply assumed that the safety objective is defined in this manner.

Traditionally, it has been assumed that evaluation of the braking enforcement algorithm would be achieved through a large number of full-scale tests performed on revenue lines with a variety of train configurations and test conditions. This method of evaluation, however, is neither practical, nor does it provide a statistically high level of confidence in the safety and performance of the algorithm. This type of testing is both costly and time consuming, and it also has the potential to affect capacity and cause interference to revenue service traffic. There is limited control over test conditions, in terms of boundary condition (e.g., worst-case) scenarios and, while specific operating conditions such as track grades and train speeds may be possible, it is unlikely that a given test train will exhibit boundary condition characteristics. The potential for repeatability testing is also very limited, and the quantity of field tests practically achievable generally falls short of what is needed for adequate statistical significance.

For these reasons, an enforcement algorithm evaluation methodology that provides a higher level of statistical confidence in a more practical manner was conceived. Appendix A provides documentation of the enforcement algorithm evaluation methodology. The development of the methodology and the tools used are described in this section.

2.1 Overview of Enforcement Algorithm Evaluation Approach

The enforcement algorithm evaluation methodology combines computer simulation testing in a lab environment and field testing in a controlled test environment to achieve the objective of providing a high level of statistical confidence in the result in a more practical and efficient manner. The purpose of the simulation component of the methodology is to statistically quantify the safety and performance of the enforcement algorithm. This is achieved by running large batches of braking enforcement simulations with Monte Carlo variation of train and environmental characteristics that affect train stopping distance over a wide range of operational scenarios. A limited amount of field testing then provides validation of the simulation results using actual hardware inputs to the enforcement algorithm.

This testing methodology provides the capability to test the enforcement algorithm over a wide range of operating scenarios, including boundary conditions, in a safe and efficient manner, through the use of simulations. To rely on simulation data as the primary component of the evaluation process, it is necessary to use a validated mathematical model that accurately represents the response of the train to a wide range of practical inputs and to provide adequate empirical data to demonstrate that the simulation properly represents how the enforcement algorithm will perform in the field.

2.2 Simulation Testing

The simulation testing component of the enforcement algorithm evaluation methodology makes use of a set of computer software tools to employ a Monte Carlo simulation process, which results in a set of output data that can be analyzed to identify the statistical probability and confidence that the algorithm will meet the specified safety and performance criteria. The Monte Carlo method involves running large numbers of simulations with inputs to the simulations randomly assigned on the basis of the practical and physical distributions and limits that define the system. Because of the wide range of parameters that affect the stopping distance of a freight train and the interdependence of these parameters, a deterministic evaluation is not feasible, making the Monte Carlo simulation process the preferred method of evaluating the enforcement algorithm.

2.2.1 Overview of Simulation Testing Process

The simulation testing process is intended to evaluate the enforcement algorithm over the 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. The 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.

Multiple braking enforcement simulations are run for each test scenario. The values of the parameters that can have a significant effect on train stopping distance are randomly selected for each simulation from distributions that represent the practical range of values for the given parameter. In some cases, the distribution of values for a parameter is affected by the value randomly selected for a different, related parameter.

The test scenarios that make up the complete simulation test matrix are intended to include the boundary operating conditions and represent the full range of conditions that can be experienced. 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, and each test scenario could contain any number of individual simulations, each representing a potential specific instance of the test scenario. Figure 3 illustrates the relationship between batches, test scenarios, and simulations.

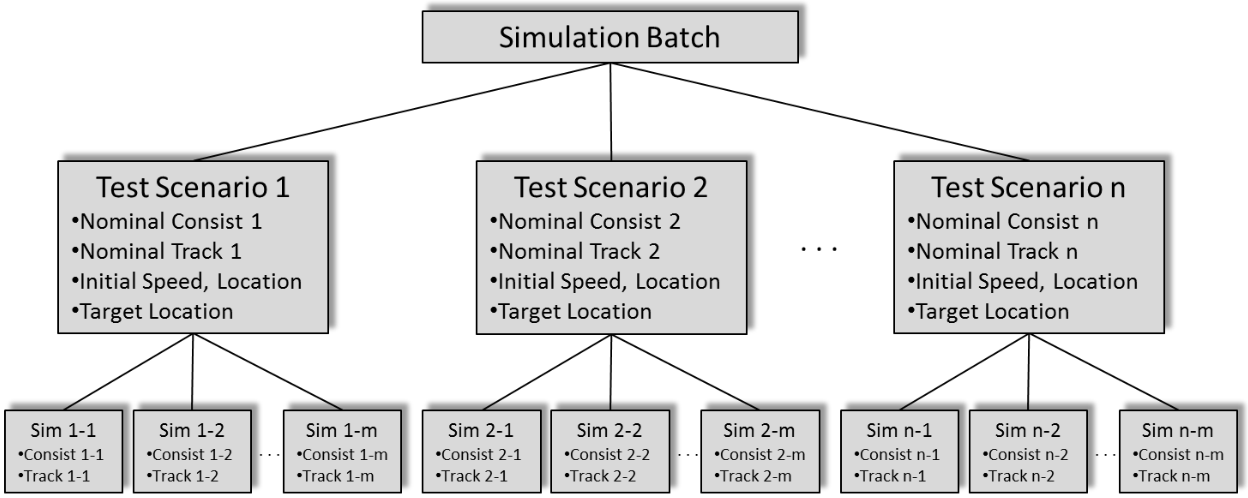


Figure 3. Organization of Simulations

For each individual simulation test, the train is modeled approaching the target at the defined initial speed. The enforcement algorithm triggers a brake application to prevent a violation of the stop target, and the response of the train is modeled. The result of the 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 is 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 portion of the enforcement algorithm evaluation methodology requires the following three components, as Figure 4 illustrates:

- 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;
- A test controller/logger (TCL) 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; and
- The enforcement algorithm under evaluation, implemented as a standalone software application incorporating a common interface to the simulation test components to receive train status and command brake enforcement applications.

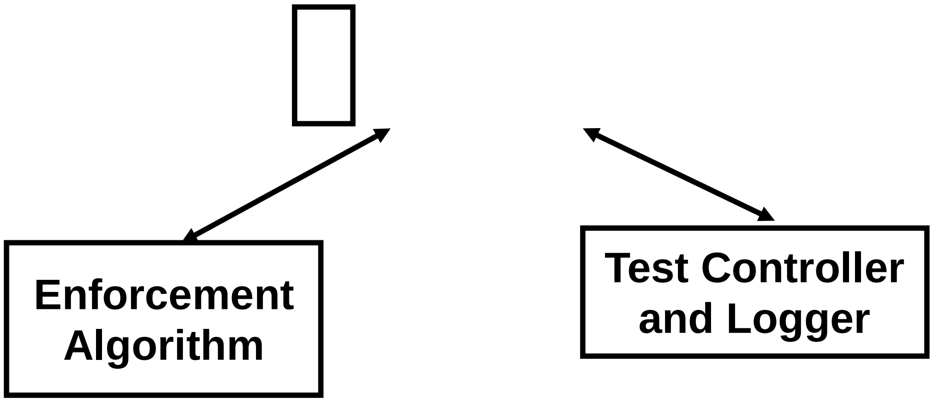


Figure 4. Simulation Testing Components

Simulation Model

To model any given braking enforcement scenario, the chosen simulation model must accurately model the response of the train to given inputs, be capable of modeling the specific characteristics of each component of each car within the train and the specific characteristics of the track, and be capable of reporting train status data at regular, frequent intervals. Therefore, TOES™ was the simulation model selected for enforcement algorithm evaluation. TOES™ is a longitudinal train dynamics model developed by the AAR that models the status of every car in a given train at every time step of the simulation. Car status data includes location, velocity, acceleration, forces acting on the car, and brake system component status.

The model allows the user to enter specific characteristics for each car in the train, including car weights and dimensions, aerodynamic properties, truck characteristics, coupler and draft gear characteristics, and brake system components and characteristics. This flexibility essentially allows the user to model any currently used freight rail cars and arrange them into any train consist desired. The model also allows the user to enter track characteristics (e.g., track grade and curve) that affect the longitudinal motion of the train, allowing any section of track to be modeled. Finally, the model allows the user to enter environmental conditions, such as ambient temperature and the coefficient of friction between the wheels and brake shoes, that can affect the longitudinal motion of the train. The TOES™ model allows the user to enter train handling commands, such as throttle and brake settings, at any time step in the simulation and models how the train reacts to these commands.

The components that make up the TOES™ model include some of the most accurate and proven models currently available to the railroad industry. These include a variety of draft gear models, multiplatform cars, an aerodynamic drag routine, and a variety of user-customizable car components. TOES™ also includes a theoretical fluid dynamics model of the air brake system. This model has been shown to be a significant improvement over similar models empirically derived from test data. The air brake model within TOES™ can simulate the automatic and independent air brakes, a range of brake valve and brake shoe types, any length of brake pipe, brake cylinder dimensions, and reservoir volumes.

Test Controller/Logger Software

In order to manage the vast number of simulations required to generate the necessary statistical significance for the safety and performance of the enforcement algorithm over the entire range of potential operating scenarios, a custom software application was necessary. To support the industry in the development and testing of a safe and operationally efficient braking enforcement algorithm, TTCI developed (using internal research and development funds) a TCL software application with the capability to generate and execute thousands of braking enforcement simulations using a Monte Carlo method that uses operating scenarios and parameter variation distributions entered by the user.

The TCL application performs the following three major functions:

- Generation of random simulation inputs
- Execution of individual simulations
- Logging of output data

To generate simulation input data, the user sets up a batch of test scenarios to be evaluated. The user selects a train consist and track profile and enters the initial train speed and location, as well as the target stopping location for each test scenario in the batch.

The user defines the train consists by selecting the desired cars and arranging them in the desired order. Each car is defined by the nominal components and characteristics of the car and the potential variation of these components and characteristics, also defined by the user. The variation of the car components and characteristics can be represented by a variety of distributions that allow the user to define the variability of a given parameter to match its actual, real-world variation. The user also defines the potential variation of environmental characteristics and the variation because of errors in reported data regarding track characteristics, train speed, and location.

The user selects how many simulations the TCL software will run for each test scenario in the Monte Carlo process. The TCL software then generates the simulation input data for each simulation within each test scenario by randomly selecting values for the variable parameters from the input distributions defined by the user.

Once the simulation input data is generated, the user can run the batch through the TCL software. The TCL application runs each simulation for each test scenario individually in the simulation model by advancing the train toward the target at the given speed. At each second of simulation time, the simulation model reports train status data to the TCL, which then passes the information along to the enforcement algorithm. When the enforcement algorithm predicts an impending target overrun, it sends a command to the TCL application to initiate a penalty brake enforcement, which executes the penalty in the simulation model. The TCL continues to advance the simulation until the train is stopped. The enforcement algorithm can also send a command to initiate an emergency brake enforcement, which TCL then executes in the simulation model.

Once the train has stopped, the simulation is complete, and the TCL software logs the output data in a database for post-process analysis.

Interface to Enforcement Algorithm

The enforcement algorithm evaluation methodology can be applied to evaluate any enforcement algorithm for any North American freight PTC implementation. The methodology treats the software implementation of the enforcement algorithm as a black box that communicates with the simulation testing components over an open communications interface. A document that details the communications process and protocols was prepared for use by developers of enforcement algorithm software to be evaluated using the methodology. This document is attached as Appendix B.

To allow for the most flexibility in the test setup, the interface was designed with communications over transmission control protocol/internet protocol (TCP/IP). This allows for the enforcement algorithm to be implemented as an executable software application running on the same machine as the TCL software, as a virtual machine with a separate IP address, but operating on the same hardware as the TCL software, or as software running on separate hardware that communicates over TCP/IP.

The interface was also designed with flexibility for initializing the simulation test process to allow for more efficient execution of the simulations. The TCL software can execute the enforcement algorithm software directly, if it is run on the same machine as the TCL software. Alternatively, an enforcement algorithm initialization module was developed that sends an initialization message to the enforcement algorithm software, indicating that the previous simulation is complete and the new simulation is beginning. This allows the enforcement algorithm software to re-initialize internal parameters for the new simulation.

To ease the integration of an untested enforcement algorithm with the TCL software setup, a protocol test application was developed. The protocol test application replicates the communications to and from the TCL software with the current protocols, but without all of the other functionality of the TCL software. This allows the developer of the enforcement algorithm software to test its communications interface and debug any issues locally, resulting in reduced time and cost associated with the integration process. The source code for the protocol test application is also available to support the development of the interface on the enforcement algorithm side without releasing the proprietary TCL software source code.

2.2.3 Simulation Test Matrix

To effectively evaluate the safety and performance of the enforcement algorithm for implementation in North American freight service, the test matrix must include an adequate number of simulation test scenarios to provide confidence that the algorithm will perform according to the specifications under virtually any practical conditions that may be encountered. The test matrix was therefore designed to include test scenarios that define the boundaries of practical operating conditions.

Each test scenario is defined by the train, track profile, and operating speed. In order to define the test scenarios to be included in the simulation test matrix, the practical ranges of each of these were researched, using recent consist data, timetables, and operating rules provided by the railroads through the advisory group. This information was used to identify the logical boundaries on operating conditions from which the test matrix was developed. The final version of the simulation test matrix included review and input from the advisory group.

Train Consists

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. From information provided by the railroads, the following three groups of train consists were identified:

- 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.

A number of specialty train types were identified (e.g., RoadRailer™, high and wide load, extra heavy load requiring speed restrictions, and others), but the frequency with which these trains are run is limited. These train types were outside the scope of the enforcement algorithm evaluation methodology.

For each train type, a range of train makeups, train lengths, train loading conditions, and locomotive arrangements were identified. Table 1 summarizes these for each of the three train types. In most cases, 6-axle, high-horsepower locomotives were used in the arrangement indicated. For the shorter manifest freight trains (light locomotives, 3-car, 10-car), where the type of locomotive may have a significant effect on the train stopping distance, both 4-axle and 6-axle locomotives were included. In all cases, the number of locomotives was selected on the basis of the required horsepower, to maintain track speeds on the various track sections selected for the given train type.

For both the manifest freight and intermodal trains, a pseudo-random process for generating train makeup and car loading was developed. Samples of recently run consist lists from each of the railroads represented on the advisory group were used, and the following probabilities were identified:

- Probability that each car type exists in a given randomly generated train;
- Probability that the following car is of the same car type (i.e., a block of cars of similar type within the train); and
- Distribution of nominal load for each car type.

Using these probabilities, a semi-automated process was developed to assign cars to a consist, given the length of the consist, and to assign loads to each car selected.

Table 1. 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 • Multilevels (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 • Multilevel cars (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 • 200 cars • 260 cars (aluminum and steel hopper trains)	• Light locomotives (4-axle and 6-axle) • 3 cars (w/4-axle and 6-axle locomotives) • 10 cars (w/4-axle and 6-axle locomotives) • 40 cars • 100 cars • 150 cars • 200 cars	• Short (~ 5,000 ft) • Medium (~ 7,500 ft) • Long (~ 10,000 ft) • Very long (~ 15,000 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, 135-car, and 200-car trains) • Head, mid, and rear (135-car, 200-car, and 260-car trains)	• Head end (0-car, 3-car, 10-car, 40-car, and 100-car trains) • Head and rear (100-car, 150-car, and 200-car trains) • Head, mid, and rear (150-car, 200-car trains)	• Head end (short and medium trains) • Head and rear (short, medium, and long trains) • Head, mid, and rear (long and very long trains)

The complete matrix of train consists includes a specific combination of train makeup, train length, train loading condition, and locomotive arrangement described in Table 1.

For manifest freight trains, 10 specific consists are included, using the pseudo-random car type selection process for each combination of train length, power arrangement, and locomotive type. Of these, one consist contains all fully loaded cars, one contains all empty cars, and the remaining eight contain cars loaded according to the pseudo-random car load selection process. For the case of light locomotives, train makeup and car loads do not apply, so there are only two consists for each locomotive type—one with a single locomotive and the other with three locomotives.

For intermodal freight trains, five unique consists are included, using the pseudo-random car type selection process for each combination of train length, base loading condition, and power arrangement. For the cases where the base loading condition is met, one of the five consists contains all fully loaded cars, and the remaining four contain cars loaded from the pseudo-random car load selection process for loaded intermodal consists. For the cases where the base loading condition is empty, one of the five consists contains all empty cars, and the remaining four contain cars loaded from the pseudo-random car load selection process for empty intermodal consists (In many cases, trains are designated empty, but actually contain variations in loading because of empty containers, etc.).

Appendix C includes a table with descriptions of the entire list of test consists. Each of these nominal test consists is made up of an arrangement of nominal car types, from the specifics of the consist. The nominal cars that make up each of the test consists were selected from data from Universal Machine Language Equipment Register (UMLER) and from the advisory group to represent a typical instance of each of the given car type. The specific characteristics of each car type that affect braking performance were varied during the Monte Carlo simulation process to represent the range of possible instances of each car type. Appendix C also includes descriptions and references for each of the nominal car types used.

Track Profiles and Operating Speeds

The operating conditions under which the train consists in the test matrix are run are designed to include the boundary of practical conditions for each train type. These boundary conditions were determined from timetables and operating rules provided by the advisory group.

The operating conditions are defined by the track profile (grade and curvature) and the operating speed of the train. The range of track grades was identified first. In most cases, the tests were run on a sustained track grade, with the exception of test cases run over undulating grades (crest or trough). Although there are sections of track with more extreme grades for short sections, the most severe sustained track grade was identified as 2.8 percent.

Data from the advisory group was reviewed to determine the rules governing operation over sustained grades within the identified range. It was observed that, in many cases, characteristics of the train operating over the terrain had an impact on the maximum speed allowed. The consists were therefore divided into the following groups with the following characteristics:

- Loaded intermodal freight trains less than 8,500 ft in length
- Loaded intermodal freight trains greater than 8,500 ft in length
- Empty intermodal freight trains
- Manifest freight trains with less than or equal to 14,000 tons trailing weight
- Manifest freight trains with greater than 14,000 tons trailing weight
- Loaded unit freight trains
- Empty unit freight trains

The data was then analyzed to identify sustained grades and their associated maximum allowable speeds for the various groups of train types. The data was analyzed according to whether a train could be run on a given grade at a given speed, regardless of whether trains of that type were necessarily run on the territory in question. The analysis revealed the maximum percent grade over which a given train type could operate at a given speed. Figure 5 shows a summary of the results of the analysis. The shaded areas of the chart indicate allowable operating speeds for various train types over various grades. Figure 5 is intended to provide a concise summary in a single chart to illustrate the boundary operating conditions; therefore, not all the specific train type groups identified above are displayed. Rather, the train types are sorted into three general groups.

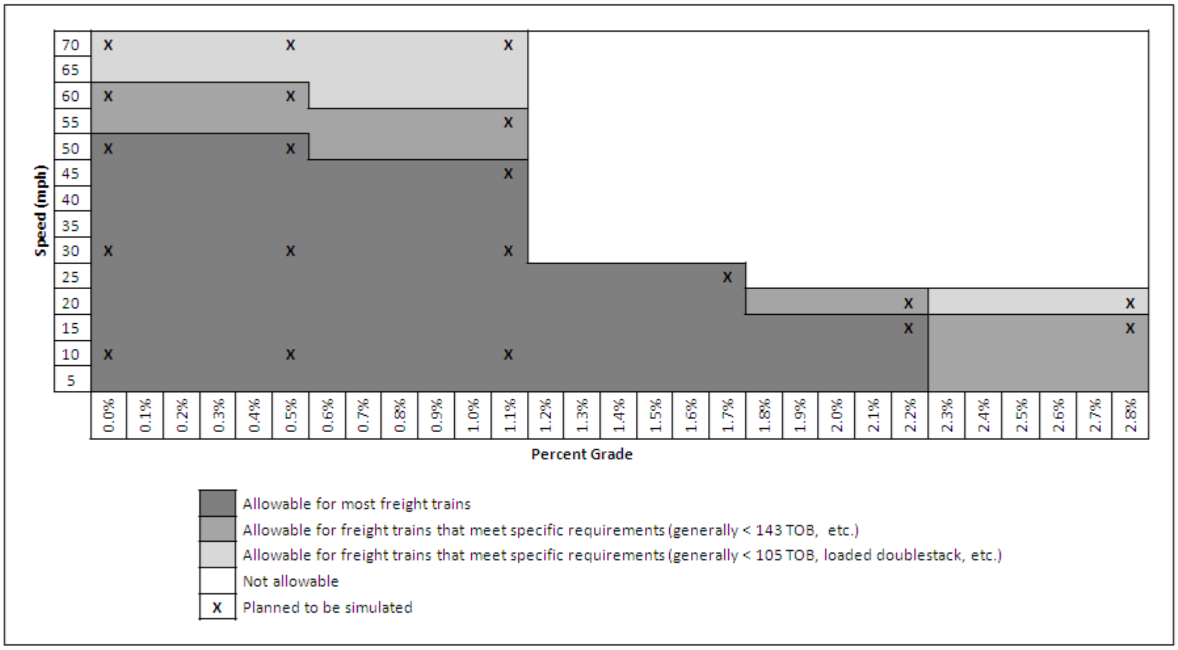


Figure 5. Summary of Boundary Operating Conditions on Declining Grades

As Figure 5 shows, there are natural breaks in the maximum allowable speed as the percent grade increases. These breaks define the boundaries of allowable operating conditions. Although it is conceivable that a certain train type could safely descend a grade at a speed higher than indicated, no such areas were identified in the analysis. The "X" marks in Figure 5 indicate conditions that were selected for simulation on descending grades to cover the boundary operating conditions in terms of maximum allowable speed, medium speed (30 mph), and low speed (10 mph).

In addition to the descending grades, simulations were selected to be run on 0.5 and 1.5 percent ascending grades and 1 percent crest and trough scenarios at the maximum allowable speeds for those grades. In all cases, the maximum allowable speeds were adjusted to the maximum achievable speed for cases where the given train could not maintain the given allowable speed. Table 2 displays a summary of the simulation test speeds for each group of train types on each grade. Appendix C provides a more detailed table with each consist and the allowable speed on each grade in the test matrix.

Table 2. Speed and Grade Configurations for Simulation Testing

	Grade									
	0%	**0.5%**	**1.5%**	**-0.5%**	**-1.1%**	**-1.7%**	**-2.2%**	**-2.8%**	**1% Crest**	**1% Trough**
Loaded Intermodal <= 8500 ft	70, 30, 10	70, 10	25	70, 30, 10	70, 30, 10	25	20	15	70	70
Loaded Intermodal >8500 ft	60, 30, 10	60, 10	25	60, 30, 10	60, 30, 10	25	20	15	60	60
Empty Intermodal	60, 30, 10	60, 10	25	60, 30, 10	60, 30, 10	25	20	20	60	60
Manifest Freight <= 14,000 tons	60, 30, 10	60, 10	25	60, 30, 10	45, 30, 10	25	20	15	45	45
Manifest Freight > 14,000 tons	60, 30, 10	60, 10	25	60, 30, 10	45, 30, 10	25	20	0	45	45
Loaded Unit	50, 30, 10	50, 10	25	50, 30, 10	45, 30, 10	25	0	0	45	45
Empty Unit	60, 30, 10	60, 10	25	60, 30, 10	55, 30, 10	25	20	0	55	55

2.2.4 Identification and Quantification of Variable Parameters

The Monte Carlo simulation technique employed in the simulation testing component of the enforcement algorithm evaluation methodology involves randomly assigning values to the various input parameters to the simulation model, according to the practical variability of each parameter, for each simulation within each test scenario. This is achieved by defining the distribution of possible values for each parameter, including train-level and environmental parameters, for each car type and using the TCL software to randomly assign values from these distributions.

The parameters to include in this process are those that can have a significant effect on the stopping distance of the train and can be practically modeled. Research conducted to identify these parameters included discussion with experts in the air brake field, review of literature on train stopping distance calculations and air brake systems, and review of parameters included in the TOES™ model. In total, 28 parameters were identified as having the potential to significantly affect the stopping distance of a freight train. These parameters are sorted into those that apply to the entire train (train and environmental parameters), listed in Table 3, and those that apply to each car in the train individually (car parameters), listed in Table 4.

Table 3. Train and Environmental Parameters that can Affect Freight Train Stopping Distance

	PARAMETER	UNITS	SOURCE
TRAIN AND EVNIRONMENTAL PARAMETERS	Ambient Pressure	psi	Historical NOAA* weather data for United States
	Ambient Temperature	deg F	Historical NOAA weather data for United States
	Brake Pipe Leakage Rate	psi/min	Expert opinion and limited measured data
	Coefficient of Friction Between Brake Shoe and Wheel	N/A	Expert opinion and data from AAR Reports R-469, “Brake Shoe Performance Evaluation” [2] and R-565A, “Brake Shoe Performance Test II” [3]
	Length of Time of Distributed Power Communications Link Outage	seconds	Expert opinion and information provided by railroads
	Error in End-of-Train Pressure as Reported by End-of-Train Device	psi	Accuracy of +/-3 psig per AAR Standard S-5701 [4]
	Error in Head-of-Train Pressure as Reported by Pressure Sensor	psi	Variability as specified by accuracy of Dynisco Model PT311JA pressure transducer
	Error in Reported Head End Location	ft	V-PTC Build 1A testing results [5]
	Percent Operable Brakes	percent	Expert opinion and information provided by railroads
	Error in Reported Train Speed	mph	V-PTC Build 1A testing results [5]
	Error in Reported Track Grade	percent grade	According to accuracy of grade data in track database
	Error in Reported Degree of Track Curvature	degree curvature	Not varied — Variability not found to significantly affect results
	Nominal Brake Pipe Pressure	psi	Not varied — Slight variation expected and taken care of with other brake pipe pressure parameters (e.g., leakage)
	Wind Speed	mph	Not varied — Variability not found to significantly affect results

*NOAA = National Oceanic Atmospheric Administration

Table 4. Car Parameters that can Affect Freight Train Stopping Distance

	PARAMETER	UNITS	SOURCE
CAR PARAMETERS	Car Tare Weight	lb	Historical consist data provided by railroads and Wheel Impact Load Detector (WILD) data
	Davis resistance equation aerodynamic coefficient (v^2 dependent term)	lb/mph^2	Expert opinion, data from energy testing, and Modified Davis Equation
	Davis resistance equation bearing resistance coefficient (number of axles dependent term)	lb/axle	Expert opinion, data from energy testing, and Modified Davis Equation
	Davis resistance equation rolling resistance coefficient (constant term)	lb/ton	Expert opinion, data from energy testing, and Modified Davis Equation
	Davis resistance equation rolling resistance coefficient (v dependent term)	lb/ton*mph	Expert opinion, data from energy testing, and Modified Davis Equation
	Brake Force Per Brake Shoe with 50 psi Brake Cylinder Pressure, when empty/loaded equipped	lb	UMLER (combination of car build date and whether or not car is empty or load equipped), AAR *Manual of Standards and Recommended Practices* (S-401) [6], and Carlson [7]
	Brake Force Per Brake Shoe with 50 psi Brake Cylinder Pressure, when not empty or load equipped	lb	UMLER (combination of car build date and whether or not car is empty or load equipped), AAR Manual of Standards and Recommended Practices (S-401), and Carlson [7]
	Car Load	percent error	Historical consist data provided by railroads and WILD data
	Brake Cylinder Piston Stroke	inches	Measurements provided by railroads and performed by TTCI
	Control Valve Type	N/A	UMLER (using car build date in relation to year when each model brake valve was introduced), Air Brake Association Proceedings
	Percent empty or load valve equipped	N/A	UMLER
	Brake Rigging Type	N/A	Not varied — Variability not found to significantly affect results and taken care of in other parameters (e.g., Brake Force Per Brake Shoe)
	Brake Pipe Length	ft	Not varied — Variability not found to significantly affect results
	Car Length	ft	Not varied — Variability not found to significantly affect results

Each of the identified parameters was evaluated at a high level to determine if the variability would have a reasonably significant effect on the stopping performance during PTC enforcement. Of the 28 parameters identified, 6 were determined to have such a slight effect that they were not included further in the process:

- Error in reported degree of track curvature — Track curvature is determined by data in the track database, which includes track centerline survey data at intervals of approximately 30 ft. With this level of precision, the error in track curvature is expected to be considerably smaller than the level that would have any appreciable effect on stopping distance prediction.

- Nominal brake pipe pressure — The nominal brake pipe pressure (brake pipe pressure when the brakes are fully released) is set using the feed valve on the locomotive. Although this is adjustable, it is unlikely to vary much from the standard 90 pounds per square inch (psi) pressure. Other brake pipe parameters such as brake pipe pressure leakage will far outweigh the effect of any slight variation in the nominal brake pipe pressure.
- Wind speed and direction — Although wind speed and direction can have a significant effect on energy consumption for freight trains, the effect on stopping distance is minimal because of the large magnitude of the other forces involved (e.g., braking force and grade force).
- Brake rigging type — Differences in brake rigging primarily affect the piston travel of the brake cylinder(s) and the net brake shoe force acting on the wheel. Since each of these parameters is varied independently of brake rigging type, this parameter does not need to be varied.
- Brake pipe length — Although varying the brake pipe length can have a significant effect on the propagation time of the brake signal, and the level of brake pipe length variability between car types can be significant, the variability of brake pipe length for a given specific car type and length is very small, resulting in almost no appreciable added uncertainty in train stopping distance.
- Car length — Total train length is reported to the onboard system using the consist data available. Error in individual car lengths can result in error in this value, which can result in error in calculating grade and curvature forces. However, the magnitude of the potential error is small, and the effect on calculating stopping distance is even smaller.

In order to accurately model the variability in stopping locations using the Monte Carlo process, it was necessary to quantify the variability of each of the remaining 22 parameters according to the actual, real-world variability of the parameter. A variety of sources were used to quantify the variability of the parameters, and these are listed in Tables 3 and 4 for each parameter. The variability of each parameter is described by one of four different types of distributions:

- Continuous uniform (flat or rectangular) distribution, where all values within an interval are equally probable;
- Normal (Gaussian) distribution, where the mean and standard deviation are defined;
- Discrete distribution, where a number of discrete values are possible, each with a defined probability; and
- Discrete continuous uniform distribution, where a discrete number of continuous uniform distributions, each with relatively small defined intervals, are used to describe the probability of each value, to estimate more complex distributions.

The distributions used to describe each parameter and the development of these distributions is described in the following subsections.

Ambient Pressure

Changes in the ambient atmospheric pressure can have an effect on the amount of pressure in the air brake system, leading to an effect on the braking performance of the train. The average sea level pressure of 1013.25 mb[8] was converted to psi, yielding 14.7 psi, which was designated as the mean for the half normal distribution. Adjusting the average sea level pressure value for an altitude of 10,000 ft, representing the highest altitude a train may likely encounter in the United States, yielded a pressure of 10.2 psi. Using 10.2 psi as a point three standard deviations away from the mean gives the standard deviation a value of 1.5 psi. The effect of the half normal distribution is that the probability of any value above the mean is zero, resulting in only half of the distribution being used to describe the variability of this parameter.

Ambient Temperature

The ambient air temperature can significantly affect the flow of air in the air brake system. The NOAA historical weather data [9] was used to quantify the variability in ambient temperature during a PTC enforcement scenario. The variability is defined by a normal distribution with a mean of 54.1 °F and a standard deviation of 10.8 °F.

Brake Pipe Leakage Rate

Brake pipe leakage occurs when air leaks out of the brake pipe at pipe and hose connections, which can result in differences in brake pipe pressure throughout the train and can affect the application and recharge time of the air brake system. The distribution of variability in brake pipe leakage, as well as a limited set of measurements, was developed from discussions with railroad personnel and experts in the field of air brake systems. The variability is defined by a normal distribution with a mean of 2.5 psi/minute and a standard deviation of 0.83 psi/minute.

Coefficient of Friction between Brake Shoe and Wheel

The brake shoe force is applied normally to the wheel tread and relies on the friction between the brake shoe and the steel wheel to retard the rotational motion of the wheel. As the friction between the two changes, so does the ability to slow the car, making this a key parameter in determining train stopping performance. In the TOES™ model, coefficient of friction between the brake shoe and wheel is determined from the type of brake shoe and the speed for each car individually. The coefficient of friction between the brake shoe and wheel can be modified by a percentage to represent variations in the calculated coefficient of friction related to a variety of factors, including weather, wheel temperature, and differences arising from the specific condition and composition of a given brake shoe. Studies conducted by AAR on the variation of the coefficient of friction between the brake shoe and the wheel, [2, 3] along with discussions with experts in the field, were used as a basis for defining the variability of this parameter. From this data, the variability is defined by a normal distribution with a mean of 0 percent and a standard deviation of 6.67 percent, resulting in an equal probability that the coefficient of friction is less than or greater than the nominal calculated coefficient of friction.

Length of Time of Distributed Power Communications Link Outage

The propagation time of the brake signal through the brake pipe is related to the number of locations that the air can exhaust. In a distributed power configuration, air from the brake pipe is exhausted from both the head end and the remote locomotive consist(s). There is some delay from the initiation of the brake application on the head end to the initiation of the brake application on the remote locomotive consist(s) related to the time it takes to transmit the signal via radio. In certain geographical areas (e.g., mountainous areas or tunnels), the communications may be interrupted at the time the brake application is initiated, resulting in further delay to the application on the remote locomotive consist(s). Although there is little data available on the frequency and amount of time these communications outages occur, discussions with appropriate railroad personnel provided a reasonable basis for quantifying this variability. The distribution of delay between application of the brakes on the head end and the remote locomotive consist(s) is defined by a half normal distribution with a mean of 2 seconds and standard deviation of 2 seconds. The effect of the half normal distribution is that any value below the mean has a probability of zero, resulting in only half of the distribution being used to describe the variability of this parameter.

Error in Head-of-Train Pressure as Reported by Pressure Sensor

The braking enforcement algorithm uses pressure data from the brake pipe to determine the state of the brake system at any given time. Error in the pressure reported to the system can vary from one sensor to the next, resulting in potential error in the stopping distance prediction. The head end brake pipe pressure is measured by a pressure transducer inserted into the brake pipe. The potential variability of the pressure reported by this transducer was quantified from the manufacturer specifications for a sample transducer that could be used in a PTC application [10]. The variability is defined by a continuous uniform distribution over a range of +/- 0.5 psi from the actual pressure.

Error in End-of-Train Pressure as Reported by End-of-train Device

In addition to the brake pipe pressure on the head end, the brake pipe pressure on the rear end of the train is also used to determine the state of the brake system at any given time. The rear end brake pipe pressure is measured by an end-of-train device and communicated over a radio frequency link to the system onboard the lead locomotive. AAR specification S-5701 defines the accuracy of the brake pipe pressure reported by the end-of-train device [4]. Therefore, the variability is defined by a continuous uniform distribution over a range of +/- 3 psi from the actual pressure.

Error in Reported Head End Location

Application of the air brake enforcement by the PTC system requires knowing the current location of the train and comparing this against a given stop target. The accuracy with which the system can identify the actual location of the train can therefore have an effect on when the application occurs, which in turn affects the safety and performance of the system. The accuracy of the location is generally determined by the onboard system using a combination of data from the Global Positioning System (GPS), locomotive tachometer, and other sources. Although the specific design could differ from one system to the next, a reasonable quantification of the variability in the error in reported location can be derived from test data reported in the vital positive train control research project [5]. Using this data, the variability in the error in reported location is defined by a normal distribution with a mean of 0 and a standard deviation of 3.6 ft.

Error in Reported Train Speed

The enforcement algorithm depends on knowing the current speed of the train at any given time in predicting the stopping distance of the train. The current speed of the train is generally determined by the onboard system using a combination of data from the GPS, locomotive tachometer, and potentially other sources. Although the specific design could differ from one system to the next, a reasonable quantification of the variability in the error in reported speed can be derived from test data reported in the V-PTC research project [5]. Using this data, the variability in the error in train speed is defined by a normal distribution with a mean of 0 mph and a standard deviation of 0.16 mph.

Percent Operable Brakes

Before a train leaves a terminal, an air brake test is performed to ensure that the brake system on all cars is operational. After the train leaves a terminal, if there are issues with the air brake system on certain cars, the train crew is permitted to cut out the brakes on up to 15 percent of the cars in the train. Although it is conceivable that the system could allow the crew to enter the number of cars with brakes cut out, there is a possibility of error, both in the initial train departure test and the reporting of cars cut out en route. There is limited, if any, data available on the probability that any brakes are cut out on any given train at any given time. However, discussions with railroad personnel indicate that it is rare for brakes to be cut out. Therefore, the percentage of operational brakes at the time enforcement occurs is defined by a normal distribution with a mean of 99 percent and a standard deviation of 0.33 percent.

Error in Reported Track Grade

The system uses a track database to determine the track grade over the section of track the train is occupying during a stopping distance prediction. Error in the reported grade can therefore affect the safety and performance of the system. The track grade data in the track database is generally defined as the percent grade over a given section of track, with a precision of one-tenth of a percent. Therefore, the potential error in track grade over any section of track can be described by a continuous uniform distribution over a range of +/- 0.05 percent.

Car Tare Weight and Car Load

Train weight is provided to the enforcement algorithm from data supplied by the railroad operating the train. In some cases (e.g., unit coal operations), the weight provided is very accurate, although in other cases (e.g., intermodal operations), the error in reported train weight can be significant. The nominal tare weight and load on each car in the test consist represents this reported weight. Variations from the nominal, reported weight can result in inaccuracies in the stopping distance prediction.

The error in reported train weight is applied by randomly varying the tare weight and load of each car from the nominal tare weight and load for the given car. The basis for the distributions used for this variation is an analysis of a sample of train consist lists provided by the railroads compared against wheel impact load detector (WILD) data for those consists, which provide the actual weight of each car. The variation in tare weight and load is defined, using the analysis, by a different distribution for each nominal car type used in the simulation test consists. In many cases, a different distribution is used, depending on whether the car is reported to be loaded or empty. Appendix D provides a table of the distributions used for the error in tare weight and load for each nominal car type.

Percent Empty or Load Valve Equipped

Empty and load valves reduce the amount of brake cylinder pressure that builds on a car when the load on the car is less than a specified level. They are generally used to provide a sufficient level of braking when the car is loaded, without providing excessive braking when the car is empty. Data on whether the cars within a given train consist are empty or load equipped is generally not provided for the enforcement algorithm and this can have a significant effect on the stopping distance prediction.

A discrete uniform distribution was developed to represent the probability that each car type in the simulation test matrix is empty or load equipped, using data in UMLER for the given car type. Appendix D provides a table of the distribution used for each nominal car type.

Net Brake Force per Brake Shoe

The net brake force provided by the brake shoes on a given car is a result of the air pressure in the brake cylinder providing a force on the brake cylinder piston, which drives a system of levers and rods known as the brake rigging to produce a force on the wheels. The net brake shoe force on a given car is required to be within a given range, per AAR specifications for the allowable net brake ratio [6]. Net brake ratio is generally defined as the ratio between the total brake shoe force acting on the wheels of a given car at a given brake cylinder pressure and the total weight of the given car. Net brake ratio is typically broken into loaded net brake ratio (the ratio of the total brake shoe force acting on the wheels when the car is loaded and the maximum gross weight of the car) and empty net brake ratio (the ratio of the total brake shoe force acting on the wheels when the car is empty and the tare weight of the car).

A variety of factors—for example, car design brake ratio, efficiency of the brake rigging, alignment of the brake shoes, and general wear on the brake system components—can affect the net brake shoe force at a given brake cylinder pressure. The potential range in the values for the net brake shoe force on each car within a train can give rise to a great deal of variability in the stopping distance of the train. However, there is very little data available on the measured net brake shoe force on cars, except during initial acceptance tests or when there is an issue with the brake system. Therefore, to quantify the variability in net brake shoe force, a variety of data sources and assumptions was used.

It can be assumed that any given car was designed with a net brake shoe force that provides a net brake ratio within the range of allowable net brake ratios specified in the AAR standard at the time the car was built. Since the AAR specification for net brake ratios has changed over time, data in the UMLER database was used to identify the probability that a car of a given type was built in each of the date ranges when the specification was changed. Research conducted on the reduction in net brake ratio because of wear suggests that a 1 percent reduction in net brake ratio is reasonable over time [7, 11]. Therefore, the range of potential net brake ratios for a given car is defined by the upper limit of the AAR specification at the time the car was built and the lower limit of the AAR specification at the time the car was built minus 1 percent.

Using the above assumption, the distribution of possible net brake shoe forces at a given brake cylinder pressure for a given car type and build date were defined as a continuous uniform distribution, with limits defined as follows:

- For cars that are empty or loaded equipped:
  - The lower limit of the range is defined by the lower limit of the AAR standard for loaded net brake ratio at the time the car was built minus 1 percent.
  - The upper limit of the range is defined by the upper limit of the AAR standard for loaded net brake ratio at the time the car was built.
- For cars not empty or loaded equipped:
  - The lower limit of the range is defined by the lower limit of the AAR standard for loaded net brake ratio at the time the car was built minus 1 percent.
  - The upper limit of the range is defined by the smaller of:
    - The upper limit of the AAR standard for empty net brake ratio at the time the car was built.
    - The upper limit of the AAR standard for loaded net brake ratio at the time the car was built.

Appendix D provides a table of the distribution used for net brake shoe force for each nominal car type.

Train Resistance

In addition to tractive forces, brake forces, and forces arising from the track profile (grade and curvature), there are a number of forces that act to resist the motion of a freight train, including aerodynamic resistance, bearing friction resistance, and rolling resistance at the wheel-rail interface. The magnitude of these resistive forces is generally relatively small in comparison with the other forces present during a penalty braking scenario, but the variability of these forces can have a minimal effect on the stopping distance of the train.

Train resistive forces can be quantified according to a formula known as the Davis resistance formula [12], which estimates the resistive forces acting on a given car at a given speed, according to coefficients that represent the characteristics of the given car:

$$R = Aw + Bn + Cwv + Dv^2 \tag{1}$$

In the above equation, R is the resistance in lb, w is the weight of the car in tons, n is the number of axles on the car, v is the velocity of the car in mph, and A, B, C, and D are the coefficients that define the characteristics of the car. The coefficients for a generic modern freight car are defined by the Modified Davis Equation, as follows:

$$A = 0.6$$
$$B = 20$$
$$C = 0.01$$
$$D = 0.07$$

The variability for these generic coefficients was derived from a combination of results from energy tests and discussions with experts in the area of train energy testing and modeling. Based on these results, the variability of each of the coefficients is represented by a normal distribution, with the mean and standard deviation specific to the car type. Appendix D provides a table of the distributions used for each nominal car type.

Brake Cylinder Piston Stroke

As air pressure builds in the brake cylinder, a piston is extended until the brake shoes contact the wheels. The stroke length of the piston is dependent on wear of the brake shoes and wheels, as well as characteristics of the brake rigging and automatic slack adjuster. As the piston stroke changes, the volume of air in the brake cylinder also changes, which affects the pressure in the brake cylinder. Thus, the brake cylinder piston stroke can affect the level of brake shoe force during penalty brake enforcement and, ultimately, the stopping distance of the train.

To quantify the variability of brake cylinder piston stroke, measurements were taken by both TTCI and several of the railroads on the advisory group on a random sample of cars equipped with standard body-mounted 10-inch by 12-inch brake cylinders. The results of the measurements showed that the variability of brake cylinder piston stroke for these cars followed a normal distribution with a mean of 7.58 inches and a standard deviation of 0.8 inch. According to the AAR Field Manual, the allowable range for these types of brake cylinders is 6 to 9 inches [13]. The center of this range is 7.5 inches, which correlates well with the mean of the measured values. The absolute range of values correlates to approximately two standard deviations from the mean.

Because there are a wide variety of brake cylinder types and sizes, this correlation formed the basis for defining the variability in piston stroke for all brake cylinder types. Using this correlation, the distributions used to model the variability in brake cylinder piston stroke were defined by a normal distribution with a mean at the center of the range of allowable piston stroke for the given brake cylinder type, with a standard deviation of half of the difference between the center and the extreme value of the allowable range. Appendix D provides a table of the piston stroke distributions used for each nominal car type.

Control Valve Type

The control valve is the component of the air brake system on each car that determines whether the brakes are applying, releasing, or lapped, depending on the relative pressures in the brake pipe and auxiliary reservoir(s). Advances in air brake technology over the years have improved the response of the control valves throughout the train, reducing the time it takes for the air brake signal to propagate through the length of the train.

It is recognized that a range of control valves, with varying performance characteristics, are still used in service today. To estimate the probability that a given car is equipped with a given brake valve type, the year in which each type of control valve was introduced was cross-referenced with UMLER build date data for the given car type, with the assumption that the car was equipped with the most technologically advanced control valve at the time it was built. Although control valves can be changed throughout the life of a car, replacing a control valve with a less-capable valve is not allowed, making this a conservative assumption.

The variability in control valve type is therefore represented by a discrete distribution, where each potential control valve is assigned a probability for the given car type. Appendix D provides a table of the probability of each control valve type for each nominal car type.

2.3 Field Testing

The field testing component of the enforcement algorithm evaluation methodology is intended to provide confidence in the results of the simulation testing component by

1. Verifying the accuracy of the model used in the simulation testing;
2. Verifying that the variability in stopping distance is accounted for in the simulation testing; and
3. Verifying that the algorithm responds the same whether tested in the field or simulation environment.

The first two objectives can be satisfied independently of the actual enforcement algorithm, but the third requires testing with the enforcement algorithm under evaluation. The majority of the field testing can be performed in a controlled test environment, which is more practical than testing on revenue service lines. In some cases, testing on revenue service lines may be required for scenarios that cannot be tested in the controlled test environment.

2.3.1 Overview of Field Testing Process

The field testing process is designed to support the simulation testing component of the enforcement algorithm evaluation process by evaluating both the model used for simulation testing and the enforcement algorithm itself, for a limited number of tests, with actual hardware and equipment. The field testing component includes three types of tests.

In the first type of field testing, stopping distance tests are performed with measurements—that can be practically measured—of all parameters that can affect stopping distance. These measurements can then be input to the model, and stopping distance simulations can be run to verify that the modeled results correlate well with the field tests.

In the second type of field testing, stopping distance tests are repeated multiple times without changing any parameters. These results are used to verify that the parameters included in the simulation testing component represent the range of parameters that actually affect stopping distance, or if additional variability can be expected.

Finally, in the third type of field testing, the enforcement algorithm is implemented in field hardware, and enforcement tests are run. In this type of testing, consist data, track data, and a stop target are provided to the enforcement algorithm. The train then approaches the stop target at a given test speed, and the enforcement algorithm is responsible for enforcing a brake application to stop the train short of the given stop target. The results from these tests can be compared with simulation test results to verify that the enforcement algorithm responds and performs the same, regardless of whether it is evaluated in a simulation or field environment.

2.3.2 Field Testing Tools

The field testing component requires test locomotives equipped with onboard hardware to provide the data necessary to the enforcement algorithm and the interface to the brake system to apply the air brakes upon command from the enforcement algorithm. In a complete PTC implementation, the onboard hardware would include the enforcement algorithm software and all necessary interfaces to the locomotive. For development and test purposes, however, the test locomotives were equipped to provide the necessary interfaces to a standalone enforcement application running on a separate laptop computer.

Three test locomotives were set up for enforcement algorithm testing at the Transportation Technology Center (TTC). All three included onboard hardware to interface any developmental enforcement algorithm over TCP/IP, using the same protocol and message structures as specified for simulation testing. In this way, it is possible to evaluate the enforcement algorithm as a black box application in both the simulation and field test environments, without having to make any modifications to the enforcement algorithm software. Appendix B is a document that describes the interface and test setup.

The onboard test hardware includes a location determination system developed by LMC for the V-PTC project, which is used to provide accurate location and speed data to the enforcement algorithm. The onboard hardware also includes a pressure transducer to provide head end brake pipe pressure data and an end-of-train telemetry head end unit to provide tail end brake pipe pressure from an end-of-train device. Finally, the onboard hardware includes interfaces to the locomotive to provide throttle control settings, dynamic brake status data, and to the air brake system to apply penalty and emergency brake applications.

In addition to the onboard hardware designed to evaluate an enforcement algorithm as a standalone software application, two of the three test locomotives were also equipped with Wabtec I-ETMS® hardware. This allows for testing the I-ETMS® enforcement algorithm developed by Wabtec using the complete onboard hardware and software planned for implementation.

Both the V-PTC hardware and the I-ETMS® hardware were installed on the test locomotives with funding from other FRA-sponsored projects.

The field testing performed on this project made use primarily of the test consist used at the Facility for Accelerated Service Testing (FAST) at TTC. At FAST, a heavy-axle load train is run over a 2.7-mile section of track known as the high-tonnage loop (HTL), where a number of experimental track components and wayside systems, as well as certain car and locomotive onboard systems, are evaluated. In service at FAST, the train continually laps the track, testing the components and systems in an accelerated manner. The train itself is made up of aluminum coal gondolas loaded to 315,000-pound gross weight. The availability of this test consist makes it the ideal test train for evaluating enforcement algorithms under this effort.

In addition to the FAST train, which is representative of loaded unit operations, some tasks in this project required testing with manifest freight equipment. In order to accomplish these tasks, a number of empty manifest freight cars were borrowed from the Union Pacific Railroad (UPRR). By combining some of the loaded FAST cars with these empty manifest freight cars, a reasonably representative manifest freight train was assembled.

The field testing also made use of the Railroad Test Track (RTT) at TTC. It is a 13.5-mile track loop with a variety of grades and curves, making it an appropriate test track for enforcement algorithm testing. The maximum grade on the RTT is 1.47 percent. The RTT track profile data was converted into a track database format for use in both the LMC location determination system and the Wabtec I-ETMS® hardware.

2.3.3 Field Testing Comparison to Simulation Testing

Comparison between simulation and field data is intended to verify that the TOES™ model used for simulation testing accurately represents the response of a freight train to a penalty brake application under various operating scenarios. By measuring all of the parameters—that can be practically measured—that affect stopping distance and applying these measurements to the model, it should be possible to replicate the field test results in the model very closely. Demonstrating that the model closely matches the field data when all the inputs are accurately measured supports use of the model to evaluate the enforcement algorithm.

Five test scenarios were identified on which to run these comparisons to demonstrate the accuracy of the model for a variety of train lengths, speeds, and track grades. Measurement of the train consist parameters discussed in Section 2.2.4 was performed to the extent practical. Because the FAST train, which is made up of very similar cars (in effect, a unit train), was used, a number of simplifications were possible. In the case of car weights, the most recent scaled weight of the cars in the train was used. The average weight for all cars was used in the model for simplicity, because these weights were consistent on a per car basis. Brake cylinder piston travel was measured for all brake cylinders in the train, but again, the average was used in the model for simplicity. Measurement of car brake shoe force is a costly and time-consuming process, making it impractical to measure more than a few cars. Therefore, three random cars were measured, and the average of these was assumed for every car in the model.

After the field tests were run, the model of the train consist was simulated for each test scenario using the actual location and speed of the train where the penalty was applied, as well as the actual brake pipe pressures and other test-specific data. The resultant modeled stopping profiles were compared with those from the field data to evaluate the error inherent in the model. Table 5 shows the results of the field and modeled stopping distance tests.

Table 5. Stopping Distance Test Comparison Results

Test Conditions			Measured Stopping Distance (ft)	Modeled Stopping Distance (ft)	Error (ft)	Percent Error
Consist	Speed (mph)	Track Grade				
2 Locomotives, 10 Cars	30	Flat	1,510	1,739	229	15.2
4 Locomotives, 40 Cars	30	Flat	2,015	1,947	-68	-3.4
4 Locomotives, 40 Cars	50	Flat	5,051	5,055	4	0.1
4 Locomotives, 90 Cars	10	Flat	464	461	-3	-0.6
4 Locomotives, 90 Cars	30	Decline	3,690	3,800	110	3.0

Table 5 shows that the model calculated stopping distances that were very close to the stopping distances measured in the field tests, with the exception of the short train test, which was off by 15.2 percent. A number of factors could explain this discrepancy. First, since average numbers were used for a number of the car parameters, it is possible that the short train contained one or two cars that exhibited outlying values for some of these parameters (e.g., a light car or a car with higher than average brake shoe force). These cars have less of an effect in the longer consists where the number of cars is large enough that one or two outliers will not have a significant impact on the overall stopping distance. It is also possible that errors in locomotive characteristics (e.g., weight), which were not measured, had an effect on these cases. Again, the effect of errors in locomotive characteristics is more profound for shorter consists.

With the exception of the short train case, the results showed that the model very closely matched the field test data for a range of speeds and grades. Were it practical to measure every characteristic of the test with even more precision, the results could have been closer still. Given the number of parameters that can affect freight train stopping distance, the range of errors reported here indicate that the model is very accurate in predicting stopping distances.

2.3.4 Field Repeatability Testing

The objective of field repeatability testing is to identify the amount of variability in freight train stopping distance, given identical input conditions. In particular, by fixing all of the parameters that are to be varied in simulation testing, any additional variability because of other factors can be identified and accounted for. Demonstrating that the variation in stopping distance, with all of the parameters fixed, is insignificant can also show that those parameters varied in simulation testing represent the significant contributors to the variability in stopping distance, which supports the findings of the Monte Carlo simulation process.

To assess the repeatability of stopping distances under a variety of fixed combinations of real train operating conditions and configurations, a series of train stopping experiments were run. Six different scenarios were selected to be tested, representing a range of train speeds, train lengths, and track grades, each using the loaded FAST test train described in Section 2.3.2. Table 6 lists the scenarios. The desired sample size is from six to ten stops for each test scenario (sample set). It takes time to test with long trains; therefore, more samples were gathered from the short train tests. However, the minimum desired six tests were achieved for all but one test scenario, as shown in Table 6.

To ensure consistency in stopping location, automatic location detector (ALD) tags were placed on the track at the desired brake locations and an ALD tag reader was installed on the locomotive. The ALD tag reader was wired to the brake system to initiate a penalty brake application when the locomotive crossed the ALD tag on the track. For each test, the locomotive engineer accelerated the train as closely as possible to the desired test speed at the ALD tag, at which point the brakes were applied and the stopping distance was measured.

Table 6. Stopping Distance Repeatability Test Results

Test Conditions			No. of Test Runs	Average Speed (mph)	Standard Deviation of Speed (mph)	Average Stopping Distance (ft)	Standard Deviation of Stopping Distance (ft)
Consist	Speed (mph)	Track Grade					
4 Locomotives, 90 Cars	10	Flat	7	10.2	0.11	559	13
4 Locomotives, 90 Cars	30	Flat	6	29.8	0.24	2,409	10
4 Locomotives, 90 Cars	30	Decline	2	28.7	0.14	3,622	59
2 Locomotives, 10 Cars	10	Flat	10	10.1	0.09	240	6
2 Locomotives, 10 Cars	30	Flat	8	30.0	0.16	1,515	19
2 Locomotives, 10 Cars	30	Decline	8	30.0	0.17	3,322	51

Table 6 shows the average and standard deviation of the speed, as well as the average and standard deviation of the stopping distance for each of the six test scenarios. As the table shows, the tests were highly consistent. The standard deviations were relatively low compared with the stopping distances, and the longer stopping distances generally correlated to the higher speeds, whereas the shorter stopping distances generally correlated to the lower speeds.

The sample sets were evaluated individually for homogeneity of stopping distance variation. The initial comparison tests evaluated the relative variance of each sample's stopping distance from the mean (Levene test) or median (Brown-Forsythe test) for that sample set. Stopping distances by sample set were shown as statistically different, as expected. However, differences from the stopping distance mean, by sample set, were shown not to have statistically significant differences.

Further statistical tests were run that directly compared the mean or median differences. Given the small sample sizes, both parametric (t-test and ANOVA) and nonparametric (K-S, W-W, Man-Whitney) comparison tests were used. All of these tests agree that there are no statistically significant differences between sample sets. The conclusion is that field tests of train stops are highly repeatable with very low variation.

2.3.5 Enforcement Algorithm Field Testing

The purpose of enforcement algorithm field testing is to verify that the enforcement algorithm performs satisfactorily for a sample range of operating conditions and to verify that the enforcement algorithm does not perform differently when implemented in the actual field hardware and when tested in the simulation environment. Statistical justification of the safety and performance of the enforcement algorithm is not a direct objective of the field testing because of the wide range of scenarios and large test sample sizes required. Rather, field testing verifies the statistical justification provided by the simulation testing. In order to provide this verification, a practical range of operating conditions must be evaluated in the field.

Because the test conditions that define the test scenarios are not dependent on specific locations or railroads, but rather on train makeup, track profile, and train speed, it is possible to perform the testing in a controlled test environment, and the results will be equivalent to a test on revenue track, given identical test conditions. This allows for a number of tests to be performed in a controlled test environment to verify the enforcement algorithm performance for those scenarios tested, independent of location or railroad.

There are no criteria for the specific enforcement algorithm field tests that must be run to verify the simulation test process. However, it is important to evaluate a variety of test scenarios that cover a range of practical combinations of train makeup, track profile, and train speed. Although it may be desirable to test boundary conditions such as steep grades, high and low speeds, and long or heavy trains, it is not necessary to test the absolute boundary conditions; test scenarios that are more typical should also be tested.

The enforcement algorithm field testing performed at each stage of development for this project focused on scenarios that exercised each of the new functions developed. These test matrices are described later in this report in the field test sections for each developmental function. A more general field test matrix was developed for evaluating the final developmental algorithm, as well as the algorithm developed by Wabtec. This test matrix was designed to cover a range of operating scenarios that could practically be tested with the equipment and track available at TTC, and it is described in more detail later in this report.

For each of the field tests conducted as part of this project, a test implementation plan (TIP) was developed to describe the test activities, and custom test logs were developed for logging the field test data. Appendix E contains the TIPs for each set of field tests and a sample test log.

2.4 Analysis of Test Results

The final component of the enforcement algorithm evaluation methodology is the analysis of the results of the simulation and field testing to quantify the safety and performance of the enforcement algorithm. In order to provide meaningful results from the evaluation, two key parameters were identified that describe the safety and performance characteristics of the enforcement algorithm:

- Probability of Target Overshoot — The probability that a given train overshoots the target stopping location for a given test scenario, with 99 percent confidence. This is the primary output of the analysis, as it demonstrates whether or not the enforcement algorithm under evaluation meets the safety objective of the system.
- Probability of Excessive Target Undershoot — The probability that a given train undershoots the target stopping location by more than:
  - 500 ft, if the initial train speed at enforcement is < 30 mph
  - 1,200 ft, if the initial train speed at enforcement is ≥ 30 mph

  This probability provides an indication of the operational impact of the enforcement algorithm. Ultimately, the operational impact is defined by whether the enforcement algorithm forces the train crew to slow the train earlier than they would otherwise, and what impact that has on other trains on the network as a whole. However, this is impractical to quantify, given the tools and data available. The probability of excessive target undershoot provides an indication of the operational impact that can be analyzed for each scenario individually and for all of the scenarios combined.

These parameters are determined for each test scenario from the results of the simulation tests. A two-phase analysis method is employed, with the first phase being an exploratory data analysis (EDA) where data augmentation and validation, data consistency checking, and data cleanup is performed, and the second phase being the specific statistical analysis, where the probabilities for the above parameters are estimated.

The EDA phase provides insight into the dataset from common descriptive statistics and graphical analysis outputs. The primary objective is to ensure that the dataset is complete, and that there are no anomalies in the data, which would indicate an error in the simulation test process. For example, deviations in the speed at the point of enforcement are identified, which may indicate that the given train could not maintain the specified speed for the given scenario. Outliers are investigated to determine if they are reliable, or if they are generated from an error in the process. Other statistical anomalies, such as odd shaped distributions (e.g., bimodal), are also investigated. Additional data elements computed from the raw data that are required for subsequent analyses are also computed and validated during the EDA.

A number of techniques are employed during the EDA. Data consistency is evaluated using breakdown tables to isolate the simulations by scenario from the characteristics that make up each scenario (e.g., train type, length, speed, track profile) and observing standard statistical parameters that are generated for each scenario. Graphical outputs such as box plots, histograms, and quantile-quantile (Q-Q) plots are also generated to quickly identify potential data anomalies, and to observe expected trends in the data. The EDA is performed primarily using the data analysis software system Statistica, Version 10 [14].

The specific statistical analysis phase generates the estimated values for the probability of target overshoot and the probability of excessive target undershoot. These are considered specialized statistical parameters because of the uncertainty in their determination. The uncertainty comes from the fact that the estimation of the probability of target overshoot requires parts-per-thousand precision on the basis of a parts-per-hundred data sample, meaning the estimated quantile (e.g., 0.995 probability of target overshoot) is beyond the observed sample data range (100 samples).

For the specific statistical analysis phase, the probabilities are estimated both empirically and via extreme quantile estimation methods [15]. The empirical probability is directly calculated from the sample. A long-term probability is estimated from observations of the distribution tail characteristics using the peaks-over-threshold method as defined by Rychlik and Rydén to be a Generalized Pareto Distribution (GPD). If the right distribution tail is upward-turning, as observed in a Q-Q plot, then the empirical probability will be an underestimate of the true probability [16,17]. For these cases, the extreme quantile estimate is made using a modified peaks-over-threshold method. A more specific and reliable distribution function is substituted following a direct data fitting evaluation. EasyFit Professional, Version 5.5, is used for data fit evaluation and distribution function and parameter generation [18].

A number of additional parameters are computed for each test scenario, in addition to the key parameters identified above. Using the specific simulations run, the following can provide additional insight into the safety and performance of the enforcement algorithm:

- Average and Maximum Target Overshoot — The average and maximum distance beyond the target stopping location for those simulations where the target stopping location was exceeded. These statistics provide an indication of how extreme the observed target overshoots were, which can be useful for additional algorithm development, or to demonstrate how far beyond the target the stopping location can be expected, in the event a target overshoot occurs.
- Average and Earliest Enforcement Location — The average and earliest location, relative to the target, where enforcement occurred for each scenario. This demonstrates how far ahead of the target stopping location the enforcement algorithm will typically enforce for each scenario, which can be compared to where a train crew would initiate braking for the scenario, to identify potential operational performance issues.
- Percent Enforcements Resulting in an Emergency Application — The percentage of the tests where an emergency brake application was used in the enforcement of the target stopping location. For enforcement algorithms that include an emergency brake backup function, this provides an indication of how much the enforcement algorithm relies on the emergency brake, which may be of interest.

In addition to evaluating the probability of target overshoot and the probability of excessive target undershoot for each scenario individually, an estimate of the overall probability of target overshoot and the overall probability of excessive target undershoot are also generated for all scenarios combined. This provides a quick, high-level view of the safety and performance characteristics of the enforcement algorithm without having to dig into the specifics of every test scenario. Additionally, the location relative to the target where the probability of target overshoot is equal to the specified safety requirement is identified. For example, if the enforcement algorithm is determined to have a probability of overshoot that is greater than the specified safety probability limit of 0.005, this would identify the point beyond the target where the probability of overshoot is equal to 0.005. This can be useful for determining how close the enforcement algorithm is to meeting the safety objective or identifying if the enforcement algorithm is too conservative.

The results from the analysis of the simulation test results are confirmed by an analysis comparing these results with the results of the field enforcement tests, for those scenarios where field tests were performed. The approach for this comparison is to support a null hypothesis of no difference, where the field test sample stopping locations cannot be proven to be from a different distribution than that of the sample of simulation stopping locations. This method is well established for cases such as this, where the sample of field test results for each scenario is not large enough to provide statistical significance for comparison with the simulated sample.

The comparison is to hypothesize that the field test result is not different from the distribution of the simulations. This general hypothesis goes for both the single and the small sample case. The approach involves making a statistical test comparison of the single sample value against the mean of the simulation sample (assuming normality). The proof uses a one-sample t-test (or the nonparametric equivalent to compare with the median, if non normal). In general, if the single field test value is within the main body of the distribution of the simulation sample, then the test is satisfied. The closer it is to the mean of the simulation sample, the stronger the significance.

For a small sample of field tests, all of the above discussion holds, except that a two-sample t-test (or nonparametric equivalent) is used. In this case, the means (or medians) of both samples are compared.

The simulation, testing, and analysis described here demonstrate that the model accurately represents the response of a freight train to a penalty brake application for any practical scenario, and that the parameters varied in the Monte Carlo simulation process represent the significant contributors to the variability of the stopping distance. Further, if a given enforcement algorithm can be shown to meet the safety and performance criteria from the simulation testing and analysis, and the field tests of this enforcement algorithm can be shown to correlate to the simulation testing results, it should be considered acceptable for use in PTC systems.

3. Analysis of Enforcement Algorithm Safety Objective

The primary objective of the enforcement algorithm component of the PTC onboard system is to force the train to a stop short of a given stop target. To ensure that modern PTC systems can achieve the expected safety benefits, without presenting any negative operational effects, a safety objective probability limit and confidence level must be determined that provides a high, but realistic, level of safety. The purpose of this component of the research program was to evaluate potential safety objectives and identify an appropriate level of safety for the enforcement function of a PTC system.

3.1 Background and Implications of Enforcement Algorithm Safety Objective

In order for the system to ensure a sufficient level of safety, a probability limit is typically specified to satisfy the safety objective of the system that defines the probability that a given train will stop short of a given target stopping location. For the NAJPTC program, a safety objective probability limit of 0.999995 was specified. This means that the system will enforce a train to stop short of a given target stopping location 99.9995 percent of the time. Little documentation exists on the history of this safety objective probability limit, and no statistical justification could be found for it.

Because the actual probability that any given train will stop short of any given target stopping location cannot be measured or computed deterministically, a confidence level must also be specified. The probability limit is an estimate of the probability that a given train will stop short of a given stopping location on the basis of a sample of tests. The confidence level is from the same sample of tests used to determine the probability limit and represents the probability that the estimated probability limit is the actual probability limit. No documentation of a confidence level could be identified for the NAJPTC program.

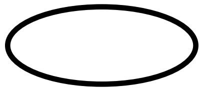
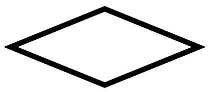
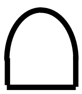
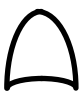
Although the primary purpose for PTC systems is to provide an added level of safety to the railroad operation by enforcing authority and speed limits (among others), it must be understood that authority violations are rare events, and incidents resulting from authority violations are even more so. The PTC system is conceived to force the train to a stop only in these rare cases where an authority violation is imminent (i.e., the crew has not taken proper action to prevent the violation). Therefore, care must be taken in specifying a safety objective probability limit and confidence level such that it prevents the large majority of the potential authority violations without resulting in excessive enforcements for cases where the crew has the opportunity to take proper action to prevent the violation.

3.2 Analysis of Enforcement Algorithm Safety Objective

To illustrate the effect of the safety objective probability limit on incidents resulting from authority violations, a basic fault tree analysis was performed. The objective of the analysis was to demonstrate the effect on safety and operational performance of several potential safety objective probability limits. The result of the analysis could then be used to determine a statistically appropriate safety objective for the PTC enforcement function.

A fault tree is used to identify the probability of an event, using the probability of each individual initiating and contributing event that results in the ultimate fault event. Table 7 describes the symbols used in the fault tree analysis.

Table 7. Symbols used in Fault Tree Analysis

Symbol	Description
	Initiating Event — Event that initiates a leg of the fault tree that leads to the fault event
	Intermediate Event — Event resulting from initiating events below
	Contributing Event — Event that contributes to the ultimate fault event, but is conditional on prior events
	And — All events below must occur to result in the event above (probability of resulting event is the product of the contributing events)
	Or — Any one event below must occur to result in the event above (probability of the resulting event is the sum of the contributing events)

To begin the analysis, a fault tree was constructed to express the probability of an accident resulting from an authority violation in centralized traffic control (CTC) territory. Figure 6 shows this fault tree.

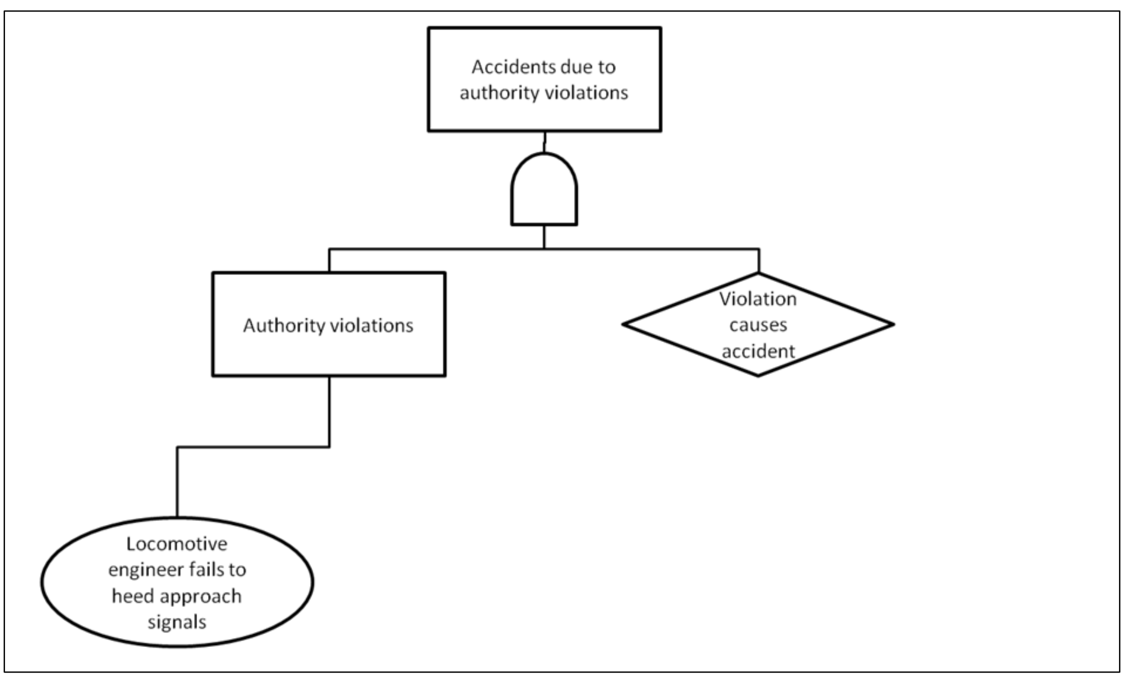


Figure 6. Fault Tree for Accidents Resulting from Authority Violations in CTC

As Figure 6 shows, the initiating event is the locomotive engineer failing to heed the approach signals leading up to the end of the authority, which results in an intermediate event of an authority violation. Every authority violation does not result in an accident, however. The probability of an accident resulting from an authority violation is the probability that there is an authority violation and the probability that the violation causes an accident. The product of these individual probabilities is the probability that an accident results from an authority violation.

For this analysis, the probabilities of each event were identified on a per-train-mile basis. The probability that a locomotive engineer fails to heed the approach signals, leading to an authority violation, was determined from the number of authority violations and the number of train-miles traveled for the four railroads represented on the advisory group over a 2-year period (2007–2008). Data provided by the railroads indicates that in those 2 years, a total of 1,002,737,271 train-miles were traveled, and 820 authority violations were reported. From estimates provided by the railroads, it was assumed that 85 percent of the train-miles were traveled on signaled territory. Using this data, the probability that a locomotive engineer fails to heed the approach signals was determined: 820/(0.85 x 1,002,737,271) = 9.62E-7/train-mile.

The probability that an authority violation results in an accident was determined from the number of authority violations and the number of accidents resulting from authority violations over the same 2 years (2007–2008). Data provided by the railroads indicates that during those 2 years 820 authority violations occurred, and data from the FRA Web site shows that 12 accidents occurred as a result of authority violations. The probability that an authority violation results in an accident was then determined from this data: 12/820 = 1.46E-2.

Finally, the probability of an accident resulting from an authority violation is computed as the product of these two probabilities: 9.62 E-7 x 1.46E-2 = 1.4E-8/train-mile. This can be expressed in terms of the probability of an accident resulting from an authority violation per year by multiplying by the average number of train-miles over the 2-year period: 1.4E-8 x 0.85 x 501,368,635.5 = 6/year. The inverse of this number, 0.167, is the number of years between accidents resulting from authority violations with traditional signaling systems in CTC territory, assuming the yearly average train-miles from 2007–2008.

With PTC, there are a number of functions that contribute to mitigating these faults. First, there is an onboard display, which provides a constant display of the current position of the train and the end of the authority for the train. The onboard display also provides a warning to the locomotive engineer when the train is approaching the end of the authority. Second, the PTC system provides an audible warning inside the locomotive cab when the train is approaching the end of the authority and the locomotive engineer has failed to act to bring the train to a stop. Finally, the PTC system enforces a brake application and brings the train to a stop if the locomotive engineer has failed to respond to either the onboard display or the audible warning. Therefore, in order for an authority violation to occur with PTC, the locomotive engineer must fail to heed the approach signals AND must fail to respond to the onboard display and warning AND must fail to respond to the audible warning AND the enforcement must fail to stop the train short of the authority limit. This scenario is illustrated by the fault tree shown in Figure 7.

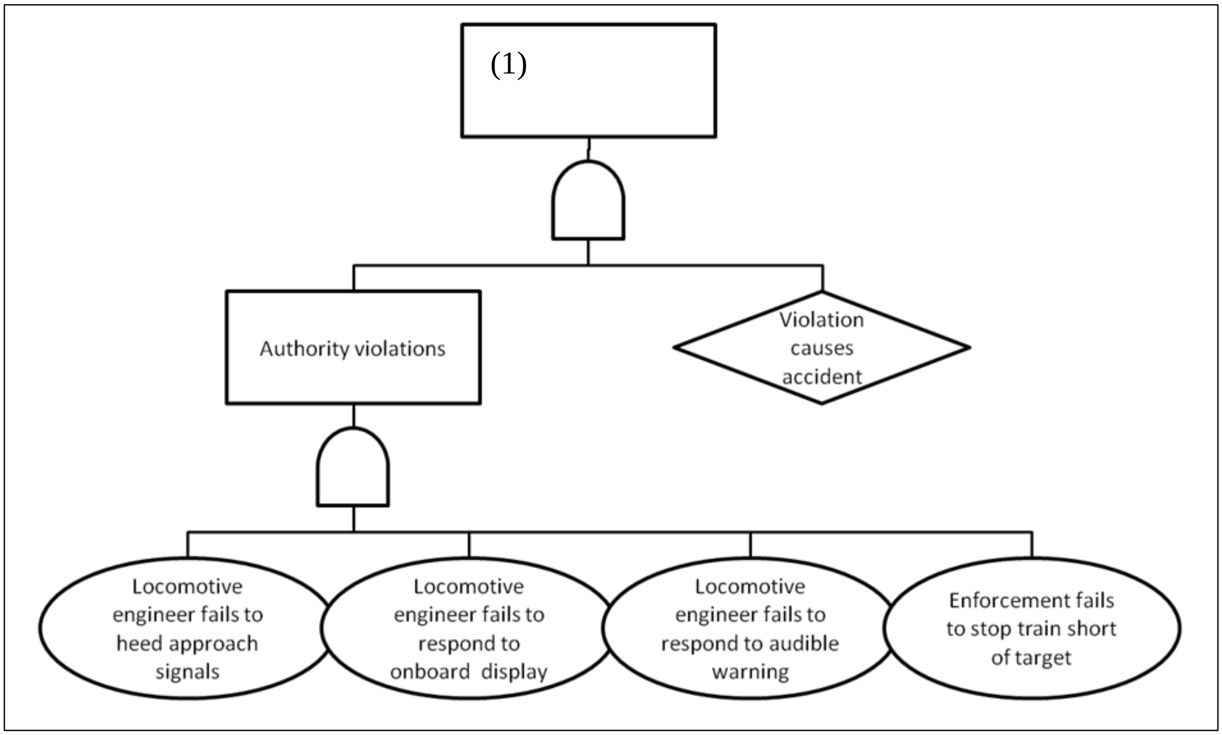


Figure 7. Fault Tree for Accidents Resulting from Authority Violations with PTC

The probability that the locomotive engineer fails to respond to the onboard display and the probability that the locomotive engineer fails to respond to the audible warning are related to human factors that are difficult to estimate precisely. The data available is limited because of the infrequency of these types of events and the difficulty in correlating related events. However, an analysis of the root causes of 27 railroad accidents resulting from human factors errors was performed, using data collected as part of a comparative risk assessment relating to technology driven operations by the AAR [19]. From this data, the probability that the locomotive engineer fails to respond to the onboard display was estimated at 0.4, and the probability that the locomotive engineer also fails to respond to the audible warning was estimated at 0.2. Although these estimates are considered to be conservative, it is recognized that they may be higher.

The probability that the enforcement fails to stop the train short of the target stopping location is equal to 1 minus the specified safety objective probability limit for the PTC enforcement function. For the NAJPTC program, this was specified as 0.999995, meaning the probability that an enforcement would fail to stop the train short of the target stopping location is 0.000005.

Using these numbers, the probability of an authority violation with PTC can be determined: 9.62E-7 x 0.4 x 0.2 x 0.000005 = 3.85E-13. The probability of an accident resulting from an authority violation can then be determined: 3.85E-13 x 1.46E-2 = 5.63E-15/train-mile. Expressed in terms of number of years between accidents resulting from authority violations with PTC, this becomes 416,667 years, assuming annual train-miles from 2007 to 2008. Although the objective of PTC is to improve safety, it is clear that this is an overwhelming reduction in the probability of accidents and is a contributor to the conservative nature of the systems experienced to date.

3.3 Recommendation for Enforcement Algorithm Safety Objective

The fault tree analysis described in the previous subsection was repeated assuming safety objective probability limits of 0.9995, 0.995, and 0.95. Table 8 shows the probability of an accident and the number of years between accidents (assuming yearly train-miles from 2007 to 2008) resulting from an authority violation with each of the probability limits evaluated.

Table 8. Probability and Years between Accidents Resulting from Authority Violations

Enforcement Algorithm Safety Objective Probability Limit	Probability of Accident resulting from Authority Violation per Train-Mile	Number of Years Between Accidents resulting from Authority Violations*
Without PTC	1.4E-8	0.167
0.999995	5.63E-15	416,667
0.9995	5.63E-13	4,167
0.995	5.63E-12	417
0.95	5.63E-11	42

* Assuming annual train-miles from 2007-2008

From Table 8 results, a PTC system with a safety objective probability limit of 0.995 would reduce the probability of an accident resulting from an authority violation by a factor of 2,500 from current train control systems and would result in an estimated 417 years between accidents resulting from authority violations, assuming annual train-miles from 2007 to 2008.

Safety integrity levels (SIL) are used in certain industries to quantify the relative level of risk reduction with a particular function of a system. Systems can be designed to a SIL between 1 and 4, with 4 being the highest level achievable. Table 9 shows the tolerable hazard rate (THR) for the various SILs [20]. Although PTC systems in North America are not designed using this methodology, it can be used to provide context for the level of safety of a system designed to meet a particular probability limit of stopping short of a target.

Table 9. THR for Various SIL

SIL	THR per hour per function
4	1E-9 ≤ THR < 1E-8
3	1E-8 ≤ THR < 1E-7
2	1E-7 ≤ THR < 1E-6
1	1E-6 ≤ THR < 1E-5

In the case of the enforcement function of a PTC system, the probability of a hazardous event is the probability of an authority violation. For a system with a probability limit of 0.995, this is 3.85E-10 per train-mile. Data from the railroads indicates that the average train speed is 21.9 mph, meaning that the probability of a hazardous event is 3.85E-10 x 21.9 = 8.4E-9 per hour, which is decidedly into the SIL 4 level. As mentioned, this does not mean that the system is designed as a SIL 4 system, but it does provide a useful comparison for the level of safety for a system designed with a 0.995 probability of stopping short of a target stopping location.

In addition to specifying the probability that a train stops short of a target, it is necessary to establish a confidence level associated with this probability. Three values are commonly used to measure statistical significance in terms of the confidence level. The confidence level is defined as P(1-a), a defining the critical value or, the probability (P) that the result is false by chance [25]. The commonly used a values are 0.05, 0.01 and 0.001 or confidence levels of 0.95, 0.99 and 0.999. The value 0.95 is considered 'borderline statistically significant', .99 is 'statistically significant' and .999 is 'highly statistically significant' [26]. Thus, 0.95 was considered insufficient with 0.99 an acceptable level of confidence for the PTC braking enforcement function.

Using the analysis performed, it is recommended that the PTC enforcement function be designed to stop a given train short of a given stopping location with a 0.995 probability and a 0.99 confidence. This provides a significant reduction in the probability of a hazardous event from current train control systems and allows for less operational impact resulting from the PTC system. This also provides a quantifiable safety objective that a PTC enforcement algorithm can be evaluated against, using the evaluation methodology presented in Section 2.

4. Base Braking Enforcement Algorithm

A base braking enforcement algorithm is used in two ways in the research and development of methods for improving the safety and performance of PTC braking enforcement algorithms:

1. As a point of reference to measure improvements against
2. As a starting point for development of test software to be used to evaluate the logic for newly developed functions

Once the base enforcement algorithm was selected, the logic was implemented in a test software application that could interface with the test environment. The algorithm was evaluated using the simulation test methodology described in Section 2.2 to develop the reference data for comparison with future developments. The base algorithm logic and assumptions were then reviewed, and issues were identified to be resolved before proceeding with the research and development of new functions. This section details the tasks associated with the base enforcement algorithm and the results of the evaluation of the algorithm.

4.1 Source and Development of Base Braking Enforcement Algorithm

The requirements for selecting a base braking enforcement algorithm were that the enforcement algorithm be nonproprietary so that the logic could be accessed for implementation in the test software and be generally accepted as being representative of the performance available in the industry. Using these requirements, the enforcement algorithm selected as the base enforcement algorithm was one designed by Wabtec and implemented by Wabtec and LMC for the Illinois Department of Transportation (IDOT) PTC project, as part of the NAJPTC program. The algorithm logic is described in the report “Braking and Prediction Algorithm Definition” [21].

The braking enforcement algorithm estimates a conservative stopping distance for the train assuming a penalty brake application is initiated under the conditions at the moment the calculation is made. This estimate is made using a numerical integration method from a force-acceleration model of the train. With this method, the forces acting on the train are estimated at each time step following the penalty brake application; the results are then used to estimate the acceleration of the train. The acceleration is used to predict the velocity and position of the train for the next time step. The process is repeated until the predicted velocity of the train is zero, and then the predicted stopping distance is determined. The stopping distance is then biased using a safety offset determined by the speed of the train at the initial conditions, to ensure an acceptable probability of stopping short of the target. If the stopping location determined from this method is beyond the authority limit of the train, a penalty brake application is enforced.

As part of the proof-of-concept project that preceded this effort [1], this braking enforcement algorithm was implemented in a test software application. The source code from the NAJPTC IDOT project was used to develop this implementation of the algorithm, with some distinct modifications to allow the algorithm to operate as a standalone application and to interface the simulation and field test equipment.

Additional refinement of the base enforcement algorithm test software implementation was performed as part of this research effort. The software was ported from the original C++ code into C# code and many of the initialization and prediction logic routines were broken up and reorganized to prime the code to allow for easier implementation of the functions to be developed as part of this project. Modifications to the interface of the evaluation test environment were also made to allow for more simulations to be run in a shorter period of time than in the previous project.

4.2 Base Enforcement Algorithm Evaluation

Following the additional development of the base enforcement algorithm and the development of the complete enforcement algorithm evaluation methodology and test environment, the base enforcement algorithm was evaluated to provide a baseline level of performance with which to compare new developments, as well as other PTC supplier implementations. The base enforcement algorithm was evaluated with simulations from the enforcement algorithm evaluation methodology described in Section 2.2, as well as a number of field tests, some of which were performed as part of the proof-of-concept project that preceded this effort [1].

4.2.1 Simulation Testing

Simulation testing and analysis was performed on the base enforcement algorithm using the methodology described in Section 2.2. However, the base enforcement algorithm did not include provisions for multiple-platform cars typical of intermodal trains. Therefore, the simulation evaluation was performed using only unit and manifest freight trains. Table 10 shows the overall results of the simulation testing for these train types, in terms of the key parameters, the probability of stopping short of the target, and the probability of stopping short of the performance limit of 500 ft short of the target for speeds < 30 mph and 1,200 ft short of the target for speeds ≥ 30 mph. Appendix G contains the detailed results from simulation testing of the base enforcement algorithm.

Table 10. Base Enforcement Algorithm Simulation Test Results

Train Type	Probability of Stopping Short of Target	Probability of Stopping Short of Performance Limit
Unit Freight	>99.999%	83.57%
Manifest Freight	99.99%	70.89%
Overall	99.994%	75.06%

As the results in Table 10 indicate, the base enforcement algorithm meets the safety objective of stopping the train short of the target with at least a 99.5 percent probability. However, the probability of stopping short of the performance limit is extremely high. This is confirmation of the operational inefficiencies that are inherent in the base enforcement algorithm due to the requirements imposed upon it by the NAJPTC program.

4.2.2 Field Testing

Field testing of the base enforcement algorithm was performed as part of the initial enforcement algorithm development proof-of-concept project that preceded this effort [1]. In this effort, two of the assumptions from the base enforcement algorithm were removed, to provide a better comparison against the proof-of-concept developmental enforcement algorithm. First, the assumption of 85 percent operable brakes was changed to 100 percent. Second, the target offset was removed because the focus of the original project was on improving the prediction with adaptive functions. With these assumptions removed, the results of the base enforcement algorithm field testing do not match the results of the simulation testing because the simulation testing used the base enforcement algorithm without any modifications. Still, these results provide a good indication of how conservative the prediction logic in the base enforcement algorithm is and it provided baseline data that will be used to show improvements with the developmental algorithm.

The base enforcement algorithm was tested during the initial, proof-of-concept effort with the train used at FAST, which, at the time, was made up of primarily steel hopper cars loaded to 315,000 lb gross weight. Table 11 shows the results from the field tests performed. The base enforcement algorithm was tested in seven different scenarios, covering a range of train lengths, speeds, and track grades, as indicated in the table. Each test scenario was run three times, and the average stopping location relative to the target stopping location is reported in Table 11.

Table 11. Base Enforcement Algorithm Field Test Results

Test Conditions			Average Stopping Location Relative to Target (ft)
Consist	**Speed (mph)**	**Track Grade**	
40 Cars – Loaded	40	Flat	-1,294
40 Cars – Loaded	60	Flat	-1,673
40 Cars – Loaded	40	Incline	-479
40 Cars – Loaded	40	Crest	-923
10 Cars – Loaded	40	Flat	-1,397
75 Cars – Loaded	10	Flat	-146
75 Cars – Loaded	40	Decline	-3,895

The results indicate that the base enforcement algorithm, even without the target offset function and the 85 percent operative brake assumption, generally stops the train well short of the target. The results show that algorithm performed more efficiently in the incline and crest grades. This is logical because the effect of gravity helps to slow the train in these cases, making the stopping distance generally more consistent and predictable. The algorithm was also more efficient for the slow speed (10 mph) case, which is also logical. These results provide a good indication of the performance that can be expected for the base algorithm with the single train that was available.

Since the initial proof-of-concept effort, the cars in the FAST train were replaced with newer, aluminum coal gondolas, loaded to 315,000 lb gross weight. Although these cars are newer than those previously used for testing, it was observed anecdotally that the braking capability of the newer cars appeared to be less than that of the older cars. The new train offered an opportunity to test the base enforcement algorithm with a different train of the same type, with presumably different characteristics.

Additionally, one of the functions of the base enforcement algorithm was not evaluated as part of the proof-of-concept effort: the ability to predict the stopping distance in cases where the brake system is in a state other than fully charged (i.e., applying or releasing). To provide test data for this functionality, additional testing of the base enforcement algorithm was performed.

Four brake state conditions were identified for the testing. The first three of these are to verify that the enforcement algorithm will activate the brakes, and the fourth is to verify that it will not activate the brakes if the locomotive engineer has the train under control.

- Fully charged — No brakes applied and brake pipe and reservoirs charged
- Brakes set — Brake application set, but not sufficient to stop the train short of the target
- Brakes set and released — Brake application set and released, but the system is still in the recharging state
- Brakes set to stop — Brake application set sufficient to stop the train short of the target

Although some variations are to be expected, the enforcement algorithm will ideally stop the train at the same location relative to the target, regardless of the state of the brake system, if all else is equal. The only exception is that the enforcement algorithm should not apply a penalty in the last case (brakes set to stop) because it should recognize that the brake application is sufficient to stop the train short of the target without enforcement.

Seven test scenarios were included in the testing, with all four brake states tested under each test scenario. Multiple tests were conducted for each test scenario and brake state. Table 12 shows the test scenarios as well as the average stopping location relative to the target for each of the four brake states in each test scenario.

Table 12. Additional Base Enforcement Algorithm Field Test Results

Test Conditions			Average Stopping Location Relative to Target (ft)			
Consist	**Speed (mph)**	**Track Grade**	**Brakes Fully Charged**	**Brakes Set**	**Brakes Set and Released**	**Brakes Set to Stop**
40 Cars – Loaded	30	Flat	-370	0	-350	-730
40 Cars – Loaded	50	Flat	-850	180	-850	-440
80 Cars – Loaded	30	Decline	-1,930	-410	-1,770	-1,520
80 Cars – Loaded	10	Flat	-140	20	-120	-260
10 Cars – Loaded	30	Flat	-580	-170	-660	-270
28 Cars – Empty	30	Flat	-460	N/A	-420	-440
28 Cars – Empty	30	Decline	-780	N/A	-750	-530

The results in Table 12 indicate that the stopping location for the case where the brakes are set was consistently further down the track than the fully charged case. Post-test analysis of the test results indicates that this is primarily because of a difference in the assumption for brake pipe propagation time between these two cases. This highlights a potential issue with the model of the brake system within the algorithm and is further discussed in Section 4.3.

Table 12 shows that the results for the case where the brakes are set and then released were consistent with the results for the fully charged case. This indicates that the algorithm effectively models the response of the brake system to a brake release and also accurately models the amount of braking capability with a train that has less than a full charge when the brakes are not currently set.

The engineer stopped the train short of the target, closer in some cases than others, for the case where a brake set was made sufficient to stop the train prior to the train reaching the target. However, in all cases, the enforcement algorithm did not apply a penalty brake enforcement, which indicates that the enforcement algorithm properly handled these cases.

4.3 Issues Identified with Base Enforcement Algorithm

In addition to evaluating the base enforcement algorithm with simulation and field testing, a thorough review of the logic contained within the algorithm was completed to identify potential issues and areas of improvement within the original functionality. These issues could then be resolved before proceeding with the development of new functionality throughout the remainder of the project.

One observation from the results of the base enforcement algorithm evaluation is that the results vary dramatically for various types of trains. This is the result of the base enforcement algorithm assuming that the characteristics of the cars are the same for all train types, when they actually can vary significantly from one train type to another, as observed during the development of the enforcement algorithm evaluation methodology discussed in Section 2.2.

The results of the simulation and field testing also illustrate one of the primary issues with the base enforcement algorithm, which is that the algorithm enforces the train far too early in a large number of scenarios, which can lead to operational inefficiencies. One of the primary reasons for this excessive conservatism was identified when reviewing the logic of the base algorithm. The purpose of the target offset function, as discussed in Section 1.1, is to offset the nominal prediction to ensure a sufficient probability of stopping short of the target stopping location. However, in the case of the base enforcement algorithm, many of the assumptions are worst-case assumptions, rather than nominal assumptions. This is the case for the assumption of car brake ratios, brake pipe propagation time, and percent operable brakes. These conservative assumptions, when combined with the target offset, result in an additional layer of conservatism that negatively impacts the operational performance of the enforcement algorithm.

The target offset function in the base enforcement algorithm is a function of train speed, exclusively. Observations from the simulation and field testing indicate that the variability in stopping distance is largely affected by other factors, such as track grade and train consist parameters, in addition to train speed. Additionally, the target offset function computes excessive (greater than 1,000 ft) target offsets for speeds greater than 40 mph, as shown in Figure 8. These observations indicate that the target offset function needs to be improved.

One of the primary components of the enforcement algorithm is the model of the air brake system. The enforcement algorithm uses brake pipe pressure input to determine the state of the air brake system, including the average level of air pressure in the auxiliary reservoirs and brake cylinders in the train, at any given time. This data is then used to determine the amount of air brake force acting on the train at any given time. The air brake model is used to determine the actual state of the air brake system at regular intervals, as well as predict the state of the air brake system throughout the stopping distance prediction loop.

Brake pipe, brake cylinder, and auxiliary reservoir pressures measured during simulation and field testing were compared with the pressures predicted by the base enforcement algorithm, which identified a number of issues with the base enforcement algorithm air brake model. For charging the brake system, the base algorithm brake model predicts very long recharge times that are inconsistent with the test results. The base algorithm brake model also does not incorporate the faster rate of application that occurs with modern control valves at the beginning of a service brake application. There were also a number of scenarios that were modeled where the base algorithm brake model did not react properly; for example, when a service brake application was made, then released, and then another service application was made before the system completed recharging. In addition to these issues, the logic of the base algorithm air brake model was reviewed, and some potential improvements were identified.

5. Revisions to Base Enforcement Algorithm

One of the objectives of this project was to develop PTC enforcement algorithm logic that is ready for implementation by PTC system suppliers. Although the relative safety and performance improvements that can be obtained with the newly developed functions can be demonstrated by comparison with the baseline level of performance, the resulting algorithm logic may still contain deficiencies in the base logic, which could be unacceptable for implementation in a functional PTC system. Therefore, as part of the first phase of development for this project, a number of revisions were made to the base enforcement algorithm logic, using the issues identified with the base enforcement algorithm. The completed revised base enforcement algorithm logic was organized and documented in an algorithm definition document for review by railroads and PTC suppliers. The revisions to the base enforcement algorithm were also implemented in the test software application so that, because the new functions were implemented, the tests would be representative of the revised logic. This section details the revisions to the base enforcement algorithm.

5.1 Addition of Train Types

The results of the simulation testing of the base enforcement algorithm indicated that there is significantly different braking performance among train types. If the enforcement algorithm assumes all trains to behave the same, it must be overly conservative for certain train types in order to maintain the specified level of safety for others. Entering the train type in the enforcement algorithm allows the algorithm to assume the braking performance more appropriately for each train type. This logic can be taken to an extreme level, where the braking performance of every car in every train is specified; but this is not practical, given the availability of the information and the timeliness that is required. The train types were therefore divided into a few broad categories that can be easily determined and supplied to the enforcement algorithm, but that also separate the various trains into groups with similar braking performance.

Using this logic, the following train types were defined for the enforcement algorithm:

- Unit aluminum coal — Unit coal train operations where the trains are made up of exclusively aluminum cars (coal gondolas and/or hopper cars). These cars are becoming increasingly popular for unit coal operations because they have large gross weight to tare weight ratios, meaning they can haul more coal in each car. Because of their high gross weight to tare weight ratios, these cars are all equipped with empty and load devices, making their braking performance significantly different from other train types where the percentage of cars equipped with empty and load devices is much smaller.

- Unit freight — Trains with a homogenous car type throughout that are either all loaded or all empty. This includes unit tank trains, unit grain trains, and unit multilevel trains, as examples. Unit train operations exhibit similar braking performance and can therefore be grouped together under these terms. Since these trains are loaded with the same bulk commodity, the variation in actual train weight from the reported weight is small, making the variability in stopping distance less than that for other train types.

- Manifest freight — Trains with a mix of car types and loads. This type of train includes the largest variety of car types and vintages, and the cars are generally loaded differently, making the variability in braking performance significant. By separating these train types from other more specifically defined train types, it is possible to reduce the conservatism of the braking distance prediction for those train types, while keeping the conservative assumption for the braking performance necessary to maintain the specified level of safety for these trains.

- Intermodal freight — Trains made up of exclusively intermodal cars. The base enforcement algorithm does not have provisions for handling intermodal cars, which can have significantly different braking performance than other types of cars. In many cases, the cars are articulated, meaning the brake force is higher for the overall car, because there are more axles to which to apply brake force. Many of these car types have high gross weight to tare weight ratios, requiring them to be equipped with empty and load devices, and the loading characteristics can vary significantly from car to car, making the variability in braking performance unique compared with the other car types.

Each of the train types was added to the enforcement algorithm, as part of the first phase of algorithm development, to allow for more specific braking performance characteristics and variability to be assumed, as discussed above. However, modifications to the enforcement algorithm for handling manifest and intermodal freight trains were not included until the third phase of algorithm development. Therefore, the other modifications to the base algorithm that are discussed in the following sections apply only to the unit freight train types. The modifications for manifest freight and intermodal freight are discussed in Section 13.

5.2 Assumptions for Unknown Parameters

One of the issues identified with the base enforcement algorithm logic is that some of the key assumptions about parameters that affect the stopping distance of the train use worst-case, rather than nominal, assumptions. This results in a conservative prediction, which is then further offset by the target offset function. By performing a nominal stopping distance prediction, the target offset function can be designed to offset the prediction using the statistical variance in stopping distance for the current conditions, which then results in an enforcement point that is no more conservative than necessary. The three following key assumptions were identified as being worst-case in the base enforcement logic:

- Nominal car brake force
- Brake pipe propagation time
- Percent operable brakes

5.2.1 Nominal Car Brake Force

The nominal car brake force is the amount of force applied by the brake shoes after the brake cylinder pressure has built to its maximum level during a penalty brake application. The enforcement algorithm is provided with the number of loaded and the number of empty cars in the train, which are used to determine the nominal car brake force. The base enforcement algorithm assumes, if not given additional detail on the car types within the train, that all loaded cars in the train are 100-ton cars with a gross rail load (GRL) of 131.5 tons (263,000 lb). The base enforcement algorithm further assumes that the brake force for all loaded cars at 50 psi brake cylinder pressure is 17,548 lb. A brake cylinder pressure of 50 psi is that which would be achieved at equalization (full penalty brake application) if the nominal (released) brake pipe pressure was 70 psi. The AAR specifies loaded net brake ratio as the brake force achieved with a 30 psi brake pipe pressure reduction (to ensure equalization) from a nominal brake pipe pressure of 90 psi divided by the GRL of the car [6]. If the nominal (released) brake pipe pressure was 90 psi, which is typical of North American freight operations and aligns with the AAR definition for loaded net brake ratio, the brake cylinder pressure at equalization would be greater by a factor of 90/70 (approximately 64 psi). At this brake cylinder pressure, the brake force would also be greater by a factor of approximately 90/70 (a brake force of approximately 22,562 lb). For this type of car, the loaded net brake ratio would therefore be 22,562 lb / 263,000 lb x 100 = 8.6 percent, which is slightly more than the minimum allowable net brake ratio of 8.5 percent, according to the AAR standard S-401 [6]. Although it is recognized that older cars, designed to older AAR net brake ratio standards, may have been designed to a lower net brake ratio, and car net brake ratios may fade over time, this assumption is still considered to be worse than nominal for many car types.

For empty cars, the enforcement algorithm must consider that the car may be equipped with an empty and load device. Empty and load devices reduce the amount of brake cylinder pressure to reduce the amount of brake force on the car when the load is below a specified level (typically 20 percent of the GRL when fully loaded). However, because the enforcement algorithm models the air brake system for the train as a whole, it is more appropriate to model empty cars equipped with empty and load devices as having the same brake cylinder pressure, but with reduced nominal brake force. Typically, empty and load devices will reduce the brake cylinder pressure to between 40 and 60 percent of that which would be achieved without the empty and load device. If the empty and load net brake ratio is defined as the ratio of the net brake force when the car is empty to the loaded GRL, it should be approximately 50 percent of the loaded net brake ratio on average for a car equipped with an empty and load device. Since the base enforcement algorithm assumes a loaded net brake ratio of 8.6 percent, it should then assume an empty and load net brake ratio of 4.3 percent for cars equipped with an empty and load device and 8.6 percent for cars not so equipped. The base enforcement algorithm assumes that the brake force for all empty cars at 50 psi brake cylinder pressure is 12,390 lb. This equates to 15,930 lb at a brake cylinder pressure of 64 psi. The empty and load net brake ratio for a 100-ton car with a GRL of 263,000 lb would therefore be 15,930 lb/263,000 lb x 100 = 6.1 percent. This works out to an assumption that 58 percent of the cars are equipped with empty and load devices. For certain train types (e.g., unit aluminum coal trains), where the cars are all equipped with empty and load devices, this is an unsafe assumption, whereas for other train types (e.g., manifest freight), where, on average, very few cars are equipped with empty and load devices, this is an overly conservative assumption. On average, for all cars, this assumption is considered to be conservative and a better approach is needed.

To provide a more nominal assumption for the nominal car brake force, the average car net brake ratio for each train type was used. To determine this, the car type that makes up each of the types of unit trains were each examined individually. For each type of car, bins were defined for the different ranges of brake ratios that a given car of that type could have been designed to. The bins were defined using the range of car build dates that a particular version of the AAR standard for brake ratio was in effect for. For each bin, the mean brake ratio was calculated, using the range of brake ratios for the bin, and the assumption that the brake ratio can fade by 1 percent over time [7, 11]. UMLER data was used to identify the probability that a given car of that type could fit into each bin, both for cars of that type equipped with empty and load devices and for those not equipped with empty and load devices. The average net brake ratio was then calculated by averaging the mean net brake ratios for all of the bins, weighted by the probabilities identified by the UMLER data.

When a unit train is identified as being loaded, the cars within the train are, by the definition of a unit train, all loaded to capacity. Because of this, it is possible to assume the nominal car brake force for loaded unit trains, $F_{B,NOM,LOADED}$, using the average net brake ratio, NBR_{AVG}, the total gross trailing weight, W_{CARS}, and the total number of loaded cars, N_{CARS}, according to the following formula:

$$F_{B,NOM,LOADED} = \frac{NBR_{AVG} * W_{CARS}}{N_{CARS}} \tag{2}$$

For the unit aluminum coal train type, the average net brake ratio is simply the average net brake ratio for aluminum coal cars. For the other unit freight train type, the average net brake ratios for all of the other unit car types, which include steel coal cars, covered hoppers, tank cars, multilevels, and refrigerated box cars, are averaged together to determine the overall unit freight average net brake ratio.

Using the average net brake ratio to determine the nominal car brake force, as opposed to defining the nominal car brake force directly, means that the enforcement algorithm has to assume the GRL of the cars that make up the train. This can only be done on loaded unit trains where the total trailing weight of the train divided by the number of cars in the train is equal to the GRL of each of the cars in the train. For empty unit trains and other train types, this cannot be assumed, so the nominal car brake force must be assumed, rather than using the average net brake ratio.

For empty unit trains, the nominal car brake force was determined by multiplying the average net brake ratio for each car type by the average tare weight for that car type. Since there are two unit train types, unit aluminum coal and unit freight, there are two different empty brake force values. In the case of the unit aluminum coal train type, the nominal car brake force was equal to the average net brake ratio multiplied by the average tare weight for unit aluminum coal cars. In the case of the other unit freight train type, these values were averaged for all of the other unit car types to determine the nominal car brake force. It was observed that the brake force values were exceptionally high for the refrigerated box car and the multilevel car, whereas the average tare weights were much higher than for other cars. So, it was determined that these cars would be left out of the average for the unit freight train type, which results in some additional conservatism for these trains, but maintains the safety required for the other unit freight trains. Table 13 shows the revised assumption for the nominal car brake force for unit trains.

Table 13. Revised Nominal Car Brake Force for Unit Trains

Train Type	Nominal Loaded Car Brake Force	Nominal Empty Car Brake Force
Unit Aluminum Coal	$\frac{0.11 * W_{CARS}}{N_{CARS}}$	15,900 lb
Unit Freight	$\frac{0.093 * W_{CARS}}{N_{CARS}}$	19,850 lb

5.2.2 Brake Pipe Propagation Time

The brake pipe propagation time is the time it takes for the average auxiliary reservoir pressure to reach equalization pressure following a service brake application from a fully charged brake pipe. The brake pipe propagation time is affected primarily by the length of the brake pipe, the location and type of control valves and vent valves along the length of the brake pipe, and the ambient air conditions (temperature and pressure). This data is not provided to the enforcement algorithm, although a reasonable assumption can be made about the relationship between the length of the brake pipe and the length of the train, which is provided to the enforcement algorithm. Therefore, the assumption for the brake pipe propagation time is based exclusively on the train length. For the base enforcement algorithm, the following formula is used:

$$T_{APPLY} = 12.22 + 0.0156 L_{TRAIN} - 0.000000278 L_{TRAIN}^{2}$$ Accide

Using the results of the simulation and field tests, it was determined that this formula produces a brake pipe propagation time that is generally longer than the actual brake pipe propagation time. To develop a formula that produces a more nominal assumption of the brake pipe propagation time, a number of simulations were conducted for each unit train type over a variety of train lengths. For each train type and length, the types of control valves on the cars and the ambient air conditions were randomly varied according to the distributions developed for the enforcement algorithm evaluation methodology. The results of these simulations were analyzed using train length, and a best fit regression line was developed. From this analysis, the formula for estimating brake pipe propagation time was revised from that in the base enforcement algorithm to the following:

$$T_{APPLY} = 13 + 0.01179 L_{TRAIN} + 0.000000256 L_{TRAIN}^{2} \quad (3)$$

5.2.3 Percent Operable Brakes

The assumption for percent operable brakes in the base enforcement algorithm uses the minimum allowable percent operable brakes, 85 percent, per FRA regulation. This is a worst-case assumption because trains with less than 85 percent operable brakes cannot be operated. Before a train leaves its origin, a brake test is performed and if there are any inoperable brakes, they must be repaired, or the offending car must be removed from the consist before it departs. Thus, the minimum allowable percent operable brakes at the time the train departs from its origin is 100 percent. If, along the train route, problems occur with the brakes on certain cars (e.g., stuck brakes, etc.), the crew is permitted to cut the brakes for up to 15 percent of the cars. However, it is rare that any brakes are cut en route, and extremely unlikely that 15 percent of the cars would have their brakes cut. Given this low probability, the assumption for percent operable brakes was revised from 85 to 100 percent, which represents the nominal level. It should also be noted that the adaptive brake efficiency routine, defined in Section 6.3, can compensate for brakes cut in the train.

5.3 Improved Target Offset Function

The target offset function is used to add margin to the nominal stopping distance prediction to ensure that the train will stop short of the target stopping location according to the statistical probability and confidence specified. The amount of margin required to meet the specification is dependent on the amount of variability in stopping distance for the given scenario, which is further dependent on the characteristics of the specific scenario (e.g., train makeup, train speed, etc.) Since these characteristics are constantly changing, it is not practical, nor feasible, to compute the potential variability in stopping distance in real time each time a stopping distance prediction is performed. Therefore, a target offset function is used to estimate the variability, using the known characteristics of the scenario.

The following is the target offset function used in the base enforcement algorithm:

$$Offset = 145 + 0.025V + 0.5188V^2 \tag{4}$$

V is the current velocity of the train in mph. This target offset function has two primary shortcomings. First, it does not take into account several factors, such as train makeup and track grade, that can have a significant effect on the variability of stopping distance. This results in excessive target offsets for scenarios where the variability may be much less, but for which the function does not compensate. The other primary shortcoming is that the function generally computes target offsets that are excessively large. Figure 8 shows a plot of the target offset computed by the base enforcement algorithm target offset function against train speed. As the plot shows, at a speed of 40 mph, the base enforcement algorithm will generate a target offset of approximately 1,000 ft. This means that the algorithm will enforce an air brake application 1,000 ft prior to where it predicts a brake application is necessary to stop the train at the target stopping location. Because the function is quadratic, the target offsets get even more excessive as train speeds increase; at 60 mph, the target offset is approximately 2,000 ft.

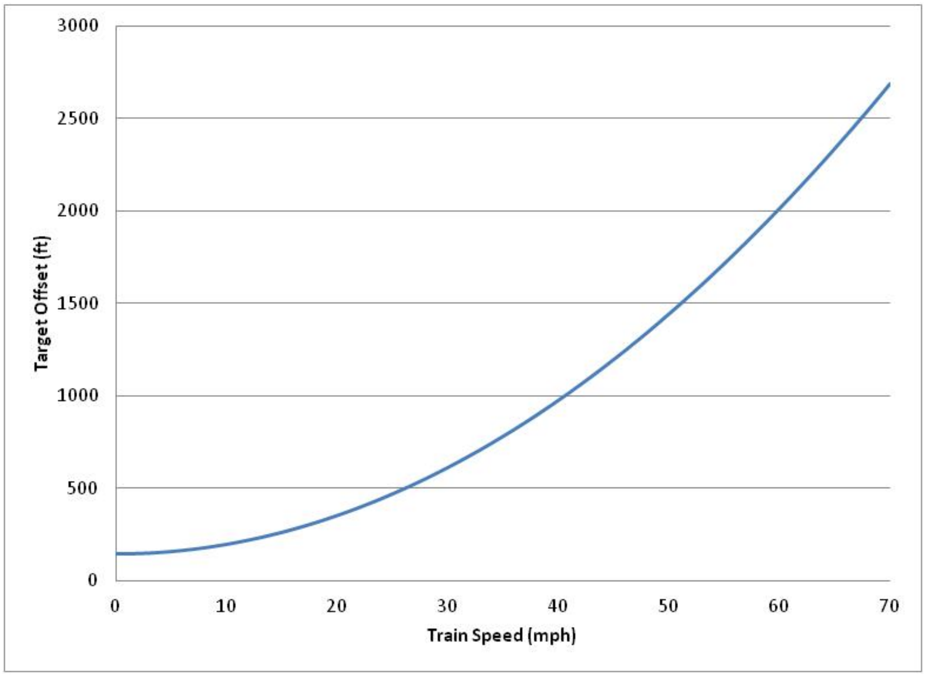


Figure 8. Base Enforcement Algorithm Target Offset Function

To compute the target offset to better represent the variability of the stopping distance for any given scenario, Monte Carlo simulation techniques were used to quantify the variability of stopping distance for a range of specific scenarios. Statistical analysis techniques were then used to determine the target offset necessary to meet the safety objective probability limit of 99.5 percent for each of the specific scenarios, and these results were combined using multivariable regression techniques to generate a function that estimates the required target offset for any scenario.

For this process to be successful, it was necessary for the matrix of test scenarios to cover a range of train types, train lengths, train loading conditions, train speeds, and track grades. The simulation test matrix included 5 different types of trains, both loaded and empty, with head end only and distributed power configurations, 10 different train speeds, and 8 different track grades. The total number of test scenarios was 2,160, and 100 simulations were run for each scenario with Monte Carlo variance of the parameters discussed in Section 2.2.4.

From the stopping distance simulation data, the target offset for each scenario was computed using the mean of the distribution and the 99.5 percent quantile, one of the class of values of a variate that divides the total frequency of the population into a given number of equal proportions, as follows:

$$Target\ Offset = 99.5\%\ Quantile - Mean \tag{5}$$

Direct computation (empirical determination) of the 99.5 percent quantile for each scenario in terms of parts-per-thousand was not possible given that the sample for each scenario was only of 100 data points. When estimating quantiles beyond the limit of the observed dataset, so-called, extreme quantiles are found by use of the peaks-over-threshold method [15]. The tail of the sample distribution is expanded via Monte Carlo simulation after fitting the tail to an appropriate distribution.

To visualize the process of the peaks-over-threshold method, first, a lower limit is applied to the upper tail of the distribution (in this case, the 90 percent quantile). This assigns 10 percent of the data (10 data points of the 100 output per scenario) to the tail as the source of the Monte Carlo expansion. The resultant required large sample size (in this case, 5,000 simulated sample points) provides the statistical granularity that allows the desired extreme quantile to be estimated by direct calculation. In short, the 95 percent quantile of the simulated 5,000 points (the tails' 10 percent over the threshold) is equivalent to the 99.5 percent quantile of the original distribution. This high-level overview of the peaks-over-threshold method gives the main steps of the process, but it should be understood that there are further details to the steps which ensure its effective application.

The Winsorized mean was used to calculate the target offset for each scenario because it reduces the effect of the data in the distribution tail and provides a more accurate estimate of the true mean, using the main body of the distribution [14]. Winsorizing is accomplished by changing the highest and lowest *x* percent to the next smallest or highest value in the distribution, respectively; 5 percent was selected as the "trimming" threshold. In this case, the Winsorized mean with a 5 percent threshold was found by replacing the bottom 5 percent of the ranked values (s_1, s_2, s_3, s_4, and s_5) with the next higher adjacent value in the distribution (s_6). Likewise, the top 5 percent (s_{96}, s_{97}, s_{98}, s_{99}, s_{100}) were replaced with the next lower adjacent value (s_{95}).

After determining the target offset values for each of the simulated scenarios, regression models were built to predict the target offset for any scenario, using those simulated. Regression models are a method of expressing the underlying statistical relationships between two or more independent variables (predictors or contributors) in predicting a dependent (response) variable. Thus, certain aspects of a specific train type and configuration were used as significant contributors for predicting the dependent target offset value. Specifically, multiple linear regression models were determined from the related independent variables (e.g., train speed, track grade, and train weight), which provide for relatively uncomplicated models to predict the target offset by train type, loading condition, locomotive arrangement within the train consist, etc.

Multiple linear regression models reflect the tendency of the dependent variable (target offset) to vary linearly with two or more of the predictor variables in such a way that a scattering of points randomly about a regression curve denotes an inherent relationship between such variables. The optimum model is fit to the data using a least squares method (multiple commercial software packages are available to accomplish this). The process also determines the significant contributor variables, input variable interactions, and their order of importance. This prevents the use of redundant factors that complicate the model without improving prediction accuracy [22]. For example, train length, train weight, and number of axles are generally redundant, particularly for unit train types, where the trains are either fully loaded or empty.

The usual application of regression modeling estimates the mean performance of a stochastic dependent output variable given the input variables. Because the output of interest is the 99.5 percent quantile for target offset, these are the input dependent values for which the regression fit is calculated. The mean prediction for the 99.5 percent quantile of the target offset is the result of applying the model. A 95 percent confidence or prediction interval band was calculated for the regression line, giving quantifiable confidence evaluations for the model.

Using this process, several functions were developed to define the best fit overall target offset function, dependent on loading condition and power configuration. Each is a function of train velocity, v, the equivalent constant grade over the predicted stopping distance, g, the trailing weight in tons, W_{CARS}, and the total length of the train in feet, L_{TRAIN}. The equivalent constant grade over the predicted stopping distance is a computed value to convert undulating grades into an equivalent constant grade, to simplify the target offset function.

For empty unit freight trains, the target offset, TO, is equal to:

$$TO = (0.326v - 1.358g + 0.000573W_{CARS} + 0.000103L_{TRAIN} - 0.891)^2 \tag{6}$$

For loaded unit freight trains, the function used to determine the target offset is dependent on the power configuration. For loaded unit freight trains with distributed power, the target offset, TO, is equal to:

$$TO = (0.465v - 2.071g + 0.0000287W_{CARS} + 0.000145L_{TRAIN} + 0.709)^2 \tag{7}$$

For loaded unit freight trains with head end power, the target offset, TO, is computed from one of three equations, depending on the equivalent constant percent grade over the predicted stopping distance, g:

$$TO = \begin{cases} TO_{DEC},\ if\ g \leq 0 \\ \left(1 - \frac{g}{0.5}\right) * TO_{DEC} + \frac{g}{0.5} * TO_{INC},\ if 0 < g < 0.5 \\ TO_{INC},\ if\ g \geq 0.5 \end{cases} \tag{8}$$

Where the values for incline and decline are determined from the following two equations:

$$\begin{gathered} TO_{DEC} = (0.536v - 2.97g - 0.000147W_{CARS} + 0.0013L_{TRAIN} - 3.698)^2 \\ TO_{INC} = e^{0.0774v - 0.911g + 0.0000104W_{CARS} + 0.0000566L_{TRAIN} + 2.933} \end{gathered} \tag{9}$$

The use of this target offset function results in a target offset that is more closely related to the specific characteristics of the scenario at the time the stopping distance prediction is made. The target offset function is also designed to produce a result that will ensure the 0.995 probability of stopping short of the target, without additional unnecessary conservatism. In many of the cases tested, the resulting target offset is significantly smaller than the target offset produced by the base enforcement algorithm, further indicating the inefficiency of the original target offset function.

5.4 Modeling of the Air Brake System

As identified in Section 4.3, the logic in the air brake model of the base enforcement algorithm produces results that are inconsistent with some of the observed simulation and field testing results. Therefore, a thorough review of all of the logic within the air brake model was performed, and a variety of improvements were made.

The logic in the air brake model seeks to estimate the amount of force applied by the brake shoes in the train at any given time, both in real time and in the stopping distance prediction routine. The logic uses modeling the air brake system as a state machine, where the state of the brake system is determined from the previous state and changes to the inputs and the computed air brake parameters. From the state of the air brake system, the air brake parameters, such as average auxiliary reservoir pressure and average brake cylinder pressure, are computed and used to determine the brake shoe force. In general, this design was kept intact, but many of the methods for computing the air brake parameters using simulation and test results were modified, with the objective of making the logic more accurate, as well as simpler and easier to follow. In certain cases, empirically derived formulas were replaced by more deterministic mathematical models, and unnecessary intermediate parameters were eliminated. The redesigned air brake model can be found in the algorithm definition document (Appendix F).

6. Adaptive Functions

The first of the developmental functions researched in this project were adaptive functions. One of the primary issues with the base enforcement algorithm that contributes to the operational inefficiencies experienced is the reliance on assumed data for items that are not known by the enforcement algorithm. The objectives of the adaptive functions are to improve the stopping distance prediction and reduce the variability of the stopping location from that prediction by measuring key performance characteristics of the train and adapting the algorithm to predict the stopping distance from these characteristics rather than relying on the assumed values.

When train crews slow a train to a stop, they generally will start with a minimum level of braking to get a feel for how the train responds to the brake application and then supplement with additional brakes, as necessary, to bring the train to a safe stop. With PTC brake enforcement, this gradual stop is not an option because the system waits until a full penalty brake application is necessary to stop the train short of the target. The adaptive functions therefore allow the enforcement algorithm to get a "feel" for how the train responds to a brake application before the penalty enforcement occurs.

The concept of using adaptive functions was initially investigated in a previous work effort reported to FRA [1]. At the conclusion of that project, issues with, and potential improvements to, the concepts developed were identified. In this project, the functions developed were enhanced and implemented in the improved base enforcement algorithm and tested to demonstrate the improvement achieved.

6.1 Overview of Adaptive Functions

The adaptive functions are intended to provide more accurate data to the stopping distance prediction than is initially provided for some of the assumptions that can vary the most significantly. From research conducted in the previous proof-of-concept project, the following three areas were identified:

- Brake pipe propagation time — This is defined as the time from when the penalty air brake application is initiated to when all cars in the train have reached equalization pressure, or full penalty brake force. This can vary widely from the assumed value, with varying brake pipe lengths and control valve types.
- Train weight — The weight of the train can be determined in various ways prior to initializing the enforcement algorithm, but rarely is a scaled weight used. This inaccuracy can lead to significant errors in estimating the resistance of the train.
- Brake efficiency — This is defined generally as the ability to stop the train during a penalty brake application, and it is specified in the enforcement algorithm by the nominal brake shoe force at a given brake cylinder pressure. Varying car brake system designs and wear on the brake system components can contribute to significant variations from the assumed values.

Although there are a number of other parameters that can vary from assumed values, as discussed in Section 2.2.4, these three represent the most significant parameters that can be practically measured. These parameters also compensate for a number of the other parameters identified in Section 2.2.4. For example, the brake efficiency adaptive function not only corrects for errors in the nominal brake shoe force, but also compensates for errors in the percentage of operable brakes, among others.

Each of these three train characteristics can be measured using data generally available to the enforcement algorithm. By interpreting the data in certain situations, it is possible for the algorithm to use the response of the train to estimate characteristics used in the stopping distance calculation. The variability of each of these characteristics from the assumed value can be considerable. The variability of each of these characteristics from the value measured by the adaptive functions can be significantly less, because the variability depends on the accuracy of the measurement, as opposed to the full range of possible values. In addition to improving the nominal stop distance prediction, this reduction in variability can also work to reduce the amount of target offset necessary.

The previous proof-of-concept research project demonstrated the merit of using the adaptive functions to improve the operational efficiency of the enforcement algorithm. A number of simulations and field tests executed during this effort demonstrated the potential benefits of using these functions to improve the prediction and to reduce the variability in the resulting distribution of stopping locations.

The project also concluded that the train weight adaptive function was superfluous, given that the brake efficiency adaptive function could compensate for errors in train weight. During the project, it was observed that if an overestimate of the train weight was provided, the brake efficiency adaptive algorithm would estimate more brake force, which would balance the effect of the overestimate of the train weight, and the resulting stop distance prediction would be very close to that which would result if the correct train weight had been provided. One of the major areas of concern regarding the train weight adaptive function was that it relied on an accurate measure of tractive effort produced by the locomotives, which was identified as being difficult to obtain. By eliminating the train weight algorithm and allowing train weight to be compensated for by the brake efficiency adaptive function, this concern could also be eliminated. On the basis of that conclusion, the train weight adaptive function was not used in the enforcement algorithm developed in this project.

6.2 Brake Pipe Propagation Time Adaptive Function

The brake pipe propagation time adaptive function uses brake pipe pressures from the head and rear of the train during a service brake application to estimate the actual brake pipe propagation time for a PTC penalty enforcement. During the previous proof-of-concept project, it was observed that there were many similarities in the response of the brake pipe pressure between a service brake application and a penalty brake application, and these similarities were used to define the algorithm. However, there were several issues with this algorithm that were identified at the conclusion of the previous research effort, which were addressed in this project.

At the most fundamental level, the propagation time adaptive function measures two things:

- The delay between the initial brake pipe pressure reduction on the head end and the initial brake pipe pressure reduction on the rear end
- The rate of brake pipe pressure reduction on the rear end, from the initial reduction until the brake application is complete (i.e., when the brake pipe pressure at the rear end has reached steady state)

It then calculates the PTC penalty enforcement brake pipe propagation time by assuming the same initial delay between the head end reduction and rear end reduction and using the rate of brake pipe pressure reduction on the rear end to determine the length of time before the rear end brake pipe pressure would get to the point at which equalization would occur on the last car.

One of the challenges with the brake pipe propagation time adaptive function is in determining when the brake application is complete, specifically when measuring the rate of brake pipe pressure reduction on the rear end. If this is done improperly, the rate of rear end brake pipe pressure reduction, and therefore the brake pipe propagation time, cannot be accurately estimated. The brake pipe propagation time adaptive function developed in the previous project assumed that, since the rear end brake pipe pressure is only reported when a reduction of 2 psi is measured, if the rear end brake pipe pressure did not change for a period of 10 seconds after the initial reduction, the brake application was complete. This resulted in several issues that were not immediately identified. First, the time between 2 psi reductions in rear end brake pipe pressure could be more than 10 seconds during a brake application for long trains. Second, in certain ambient conditions, such as cold temperatures, the propagation of the brake signal is slowed significantly, which can result in the time between 2 psi reductions in rear end brake pipe pressure during the brake application. In either of these cases, the function would consider the brake application to be complete and attempt to calculate the rate of rear end brake pipe pressure reduction with an incomplete set of data, which generally leads to a poor estimation of the brake pipe propagation time.

To correct this issue, the function was modified to identify the point at which the rate of rear end brake pipe pressure changes from a constant rate of reduction to a constant brake pipe pressure. This was done by comparing the time elapsed for the most recent 2 psi reduction against the overall rate of reduction measured for the previous reductions. Using this methodology, the point at which the brake application is complete is based on when the rate changes, and it is not related to the rate of change itself. Therefore, even in extreme conditions, such as long trains or cold temperatures, the function will correctly determine the point at which the brake application is complete.

Another issue with the brake pipe propagation time adaptive function from the previous project was that the rate of rear end brake pipe pressure reduction was calculated solely on the basis of the point of the initial reduction in rear end brake pipe pressure and the point when the brake application is complete, without using any of the points between. The issue is that the rate of rear end brake pipe pressure reduction is not constant over the full range of the brake application. The rate of reduction does not instantly change at either the beginning or end of the brake application, but instead slowly transitions to a constant rate of reduction and then slowly levels off at the completion of the application. By using only the first and last points of the reduction, the rate of reduction may be estimated improperly. By using a least-squares line regression method on all of the points throughout the rear end brake pipe pressure reduction, a more accurate estimation of the rate of reduction can be obtained.

The final issue identified with the original brake pipe propagation time adaptive function relates to how the brake pipe pressure levels off differently for a service brake application than for a penalty brake application. During a service brake application, the locomotive engineer sets the target brake pipe pressure by moving the automatic brake handle to the desired position. This sets the pressure in the equalizing reservoir to the target brake pipe pressure, and the brake pipe is then exhausted to match the target pressure in the equalizing reservoir. As the brake pipe pressure approaches the target pressure, the rate of brake pipe pressure reduction slows and tapers off. This means that there is some additional time for the brake cylinder pressure to reach the target brake cylinder pressure. During a penalty brake application, the target brake pipe pressure is atmospheric pressure, meaning the rate of brake pipe pressure reduction does not slow and taper off until well past the point when the brake cylinder pressure reaches the target brake cylinder pressure (equalization pressure). The additional time needed for the brake cylinder pressure to reach the target for the service brake application does not occur with the penalty application. To compensate for this, the rate of brake pipe pressure reduction measured during a service brake application is adjusted by a slight factor before it is used to estimate the propagation time for the penalty brake application. This additional adjustment factor was developed from brake pipe pressure measurements taken for both service and penalty brake applications for a number of different configurations.

Each of the modifications discussed in this section was documented in the enforcement algorithm definition document and implemented in the test enforcement algorithm software for testing and evaluation. The final definition of the function is included in the enforcement algorithm definition document in Appendix F.

6.3 Brake Efficiency Adaptive Function

The brake efficiency adaptive function characterizes the response of the train to a service brake application to better predict the response of the train to a PTC penalty enforcement. In particular, it measures the acceleration of the train and uses it, along with assumed values for the other forces acting on the train, in solving the equation of motion to estimate the amount of brake force acting on the train. It then uses this estimated brake force to predict the amount of brake force available for a PTC penalty enforcement. Although the function technically estimates the train brake force, if there are errors in the other assumed forces acting on the train (e.g., resistive force), the function will naturally compensate for these by predicting a larger or smaller brake force, as appropriate.

There are several critical components to properly estimating the brake force using this methodology. Measuring the acceleration accurately is the primary challenge to estimating the brake force. The acceleration is calculated using measured speed data for the locomotive only. Therefore, forces from slack action within the train can result in the calculated acceleration not being representative of the acceleration of the train as a whole. Additionally, the speed data is reported at infrequent intervals (1 Hz), meaning that the acceleration must be filtered to eliminate spikes in the data, which requires that the brake application be held constant for long enough to allow the filter to provide a good estimation of the actual acceleration.

Several modifications were made to the brake efficiency adaptive function from the previous research project. The filter for the acceleration data was changed from a low-pass Butterworth filter to a two-step averaging smoothing filter. The Butterworth filter implemented in the original function produced undesirable end effects on the acceleration data. The acceleration data used at the beginning and end of the dataset produced brake shoe force values that diverged significantly from the mean value for the entire dataset because of the effect of the filter on these end points. Initially, to handle this issue, the data at either end of the dataset were removed. However, this resulted in additional acceleration data being required to have the same amount of data for processing. Instead, the acceleration dataset was artificially extended, both by adding samples with the mean value, and by adding samples extending the trend at the end of the data sample. Neither of these techniques provided the desired result, so a new filter was designed that averages the acceleration data in two steps. In the first step, the acceleration data is averaged over the previous three data points to handle short-term spikes in the data. The averaged acceleration dataset is then filtered according to a least-squares line regression method to further smooth over the entire set of data. This method of filtering resulted in a far better estimation of the actual acceleration over the entire dataset, and required less data to be collected to provide the same level of confidence in the resulting brake force estimation.

The algorithm was also modified to take into account the relative efficiency of the brake rigging. As brake cylinder pressure increases, the efficiency of the rigging also increases as the slack in the rigging is taken up. This results in a nonlinear relationship between brake cylinder pressure and brake shoe force. The relative efficiency of the brake rigging is the ratio of the efficiency at a given brake cylinder pressure to the efficiency of the brake rigging at the penalty brake cylinder pressure of 64 psi. This factor results in a more accurate prediction of penalty brake shoe force from the estimated brake shoe force at any other given brake cylinder pressure.

The other modifications to the brake efficiency adaptive function were related to using the other functions within the enforcement algorithm to provide better estimates to the function. For example, in the original function, brake cylinder pressure was estimated from a simplistic model using the current brake pipe pressure. Since brake cylinder pressure is already calculated in the enforcement algorithm according to a more sophisticated model of the air brake system, this value was incorporated to provide a better estimate of the current level of braking. Similarly, the original function determined that the brake application is being held by waiting for 10 seconds since the last change to the brake pipe pressure. Again, since the enforcement algorithm already determines the state of the air brake system according to a more sophisticated model, the new function simply waits until the enforcement algorithm determines that the brake system is in the holding application state.

Finally, the brake efficiency adaptive function was modified to refine the brake efficiency estimate using all data collected from any brake application, rather than only on a set number of data points. This allows for the estimate to be improved upon as additional data becomes available. The final function was documented in the enforcement algorithm definition document, in Appendix F, and implemented in the test software application.

6.4 Field Testing Adaptive Functions

To evaluate the performance of the enforcement algorithm with the adaptive functions, the enforcement algorithm was tested under a variety of scenarios, both with the base algorithm and with the adaptive algorithm. Table 14 shows the test scenarios as well as the resulting average stopping location, relative to the target, for both the base and adaptive algorithms. The algorithms were tested without the target offset function, and without the other modifications to the base algorithm, in order to provide a good indication of the improvement in the prediction due solely to the adaptive functions.

As Table 14 shows, the train stopped closer to the target stopping location in all cases, but still stopped short of the target in all cases. This indicates that the train used exhibited better braking characteristics than indicated by the assumptions in the base algorithm. The adaptive functions properly accounted for these characteristics and allowed the train to proceed closer to the target before enforcing a penalty application.

Table 14. Adaptive Function Field Test Results

Test Conditions			Average Stopping Location Relative to Target (ft)	
Consist	**Speed (mph)**	**Track Grade**	**Base Algorithm**	**Adaptive Algorithm**
74 Cars – Loaded	30	Decline	-1,709	-1,182
74 Cars – Loaded	10	Flat	-182	-87
40 Cars – Loaded	50	Flat	-573	-191
28 Cars – Empty	30	Flat	-459	-246
28 Cars – Empty	30	Decline	-783	-399

7. Emergency Brake Backup

One of the highest priority developments for the enforcement algorithm, as expressed by the railroad advisory group, was the emergency brake backup. This concept was seen by the industry as having the greatest potential benefit to the operational efficiency of the enforcement algorithm. One of the fundamental difficulties with PTC braking enforcement is that there is no opportunity for feedback and adjustment to the braking process once it has been initiated. With the concept of PTC braking enforcement, the enforcement algorithm must predict the stopping distance of the train in the given scenario, using limited data and a wide range of unknowns, and wait until the last moment before applying a full penalty brake application to stop the train short of the limit. If the concept instead allowed for a brake application to be initiated, but then allowed the system to use the feedback from the initial application to determine if additional braking is needed, it would be possible to improve both the safety and operational efficiency of the system. This is precisely the objective of the emergency brake backup function.

7.1 Overview of Emergency Brake Backup Concept

The benefit of incorporating emergency brake backup into the enforcement algorithm is that the initial penalty brake enforcement does not need to be as conservative in order to meet the same safety objective probability of stopping short of the target. If the enforcement algorithm assumes some probability of enforcements will use an emergency brake application in addition to the penalty brake application, it can assume that the probability of enforcements will not stop short of the target stopping position with a penalty brake application alone. The benefit of incorporating emergency brake backup into the enforcement algorithm is that the initial penalty brake enforcement does not need to be as conservative in order to meet the same probability of stopping short of the target. If the enforcement algorithm assumes some probability of enforcements will use an emergency brake application (in addition to the penalty brake application), it can assume that this probability of enforcements will not stop short of the target stopping position with a penalty brake application alone. The target offset can therefore be reduced. Although this would result in a higher probability of overshoot with a penalty application alone, the emergency brake will be used to mitigate these overshoots. Figure 9 illustrates this concept.

The first (top) illustration in Figure 9 illustrates the target offset necessary to meet the safety objective probability limit with penalty braking alone. The second (middle) illustration shows the same distribution with a reduced target offset, resulting in the distribution shifting relative to the target stopping location, with a larger probability of overshooting the target with penalty braking alone. The third (bottom) illustration shows the distribution with the target offset used in the second illustration, but with the emergency brake used to stop short of the target those that overshot in the second illustration, resulting in the same probability of overshooting the target stopping location as in the first illustration. As Figure 9 shows, the emergency brake backup concept allows for the safety objective probability limit to be met, but with a reduced target offset, and therefore, a less conservative enforcement algorithm than without it.

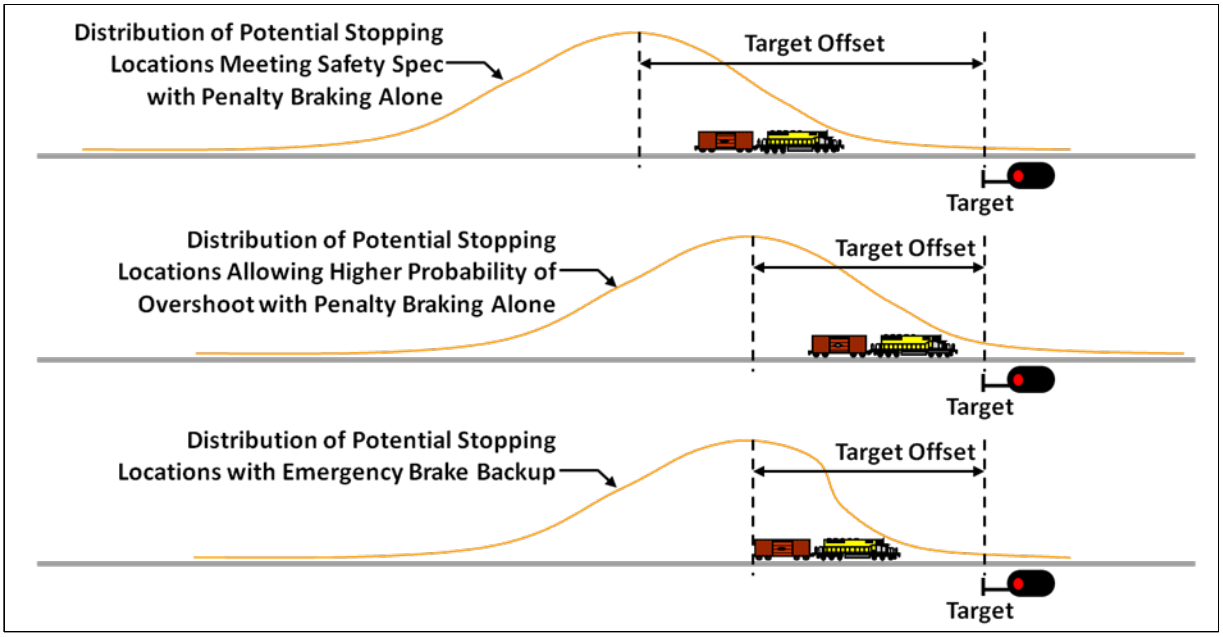


Figure 9. Emergency Brake Backup Concept

The emergency brake backup function also improves the safety of the enforcement algorithm. The emergency brake backup function is designed to apply the emergency brake any time the penalty brake enforcement does not appear sufficient for stopping the train short of the target stopping location. In essence, this provides a redundant check, with a different calculation method, that the train is going to stop short of the target, which provides additional confidence that the train will stop short of the target because the emergency brake will apply and add additional brake force to the train if there is a situation where the train is going to overrun the target with the penalty brake application.

7.2 Implementation Considerations for Emergency Brake Backup Function

The concept of adding an emergency brake backup to the traditional penalty brake enforcement introduces some new implementation factors that must be considered. The first is the amount of brake pipe pressure required to apply the emergency brake. When a service or penalty brake application is made, air exhausts from the brake pipe at what is known as a service rate. The brake pipe pressure is reduced at a relatively slow rate, and each control valve in the air brake system responds by allowing air in the auxiliary reservoir to flow into the brake cylinder. When an emergency brake application is made, air exhausts from the brake pipe at a much faster rate, and it is this faster rate that triggers each control valve to allow air from both the auxiliary and emergency reservoirs to flow into the brake cylinder, resulting in increased brake force. In order for the control valves to recognize the brake pipe pressure exhausting at the faster rate, there must be a sufficient amount of air in the brake pipe to exhaust. Although the exact amount of pressure required could vary from one scenario to the next, tests with a small sample of train consists indicate that the control valves could detect an emergency application reliably with 40 psi brake pipe pressure. Since a traditional penalty brake application exhausts the air in the brake pipe all the way to atmospheric pressure, it is conceivable that, following the initial penalty enforcement, there would not be enough air in the brake pipe to make an emergency brake application when needed.

Although the brake pipe pressure exhausts all the way to atmospheric pressure during a penalty brake application, because of the concept of equalization the brake cylinder pressure does not continue to increase past a certain point. At the point the pressure in the brake cylinder equalizes with that in the auxiliary reservoir, no additional air will flow from the auxiliary reservoir to the brake cylinder. Because of the volume relationship between the auxiliary reservoir and the brake cylinder, this will occur at a pressure greater than atmospheric pressure. The equalization pressure can be identified using Boyle's Law, which states that the product of the volume and the pressure of a system must remain constant:

$$V_{AR}P_{AR,1} + V_{BC}P_{BC,1} = V_{AR}P_{AR,2} + V_{BC}P_{BC,2} \tag{10}$$

Where:

- V_{AR}: Volume of auxiliary reservoir
- P_{AR}: Pressure in the auxiliary reservoir
- V_{BC}: Volume of the brake cylinder
- P_{BC}: Pressure in the brake cylinder

Assuming the system is initially fully charged, meaning the initial brake cylinder pressure is zero, and assuming that the final pressure is the pressure at which the auxiliary reservoir and brake cylinder equalize, this equation simplifies to:

$$V_{AR}P_{Init} = V_{AR}P_{Equalization} + V_{BC}P_{Equalization} \tag{11}$$

Where:

- P_{init}: Initial pressure in the system
- $P_{Equalization}$: Equalization pressure

Substituting the volume of the auxiliary reservoir to be 2.5 times that of the brake cylinder results in:

$$2.5V_{BC}P_{Init} = 2.5V_{BC}P_{Equalization} + V_{BC}P_{Equalization} \tag{12}$$

Dividing both sides of this equation by the volume of the brake cylinder gives the relationship between the initial auxiliary reservoir pressure and the pressure where the two will equalize as follows:

$$P_{Equalization} = \frac{2.5}{3.5}P_{Init} = \frac{5}{7}P_{Init} \tag{13}$$

According to this equation, because of the volume relationship between the auxiliary reservoir and the brake cylinder, the pressure in the two will equalize when it reaches 5/7 of the initial pressure in the auxiliary reservoir. Exhausting the pressure in the brake pipe past this point will, therefore, not result in any additional brake cylinder pressure or brake force.

To ensure enough air remains in the brake pipe for an emergency brake application, it would be logical, from this analysis, to limit the penalty brake pipe pressure reduction to 5/7 of the fully charged brake pipe pressure. However, if a case is considered where a service brake application is made and then released, it can be seen that there are cases where the equalization pressure could be lower than 5/7 of the fully charged brake pipe pressure.

When the brakes are released, the air compressor on the locomotive begins to charge the pressure in the brake pipe. At each control valve, the air pressure in the brake cylinder is exhausted as soon as the brake pipe pressure rises above the auxiliary reservoir pressure. However, it takes much longer for the pressure in the brake pipe and auxiliary reservoir to build all the way back up to the fully charged level. This could result in the system being less than fully charged at the time the penalty brake is applied. The worst case would be to assume that the brake cylinder pressure was exhausted instantaneously when the brakes were released following a full service brake application. In this case, the pressure in the auxiliary reservoir would be at the equalization pressure of 5/7 of the fully charged brake pipe pressure, and the brake cylinder pressure would be zero. The equalization pressure from a penalty application at this point would be 5/7 of the initial auxiliary reservoir pressure, which is already at 5/7 of the fully charged auxiliary reservoir pressure:

$$P_{Equalization} = \frac{5}{7} P_{Init} = \frac{5}{7} * \frac{5}{7} P_{Full} \approx \frac{1}{2} P_{Full} \tag{14}$$

Where:

- P_{Full}: Pressure in the auxiliary reservoir when fully charged

Therefore, to ensure that (a) equalization pressure is reached from the penalty brake application in any scenario and (b) there is enough brake pipe pressure remaining to initiate an emergency brake application if needed, the brake pipe pressure reduction for a PTC penalty enforcement should be limited to 1/2 of the fully charged brake pipe pressure. For a standard fully charged brake pipe pressure of 90 psi, this would mean limiting the brake pipe pressure for a PTC penalty enforcement to 45 psi, which is enough to initiate an emergency brake application, should it be required.

The second implementation area for consideration with regard to the use of emergency brake as a backup is the interface to the emergency brake. With the penalty brake, a brake test is performed as part of the PTC system initialization to ensure the interface is operating properly. An initialization test requiring an application of the emergency brake is not practical because the time required to recharge the train from the emergency brake application would result in significant operational delays. Currently, trains are dispatched with the assurance that the emergency brake is operational; this assurance is provided by locomotive inspections that are performed regularly by qualified locomotive technicians. It may be appropriate to inspect the PTC system interface to the emergency brake as part of these inspections to ensure the emergency brake is available when needed.

7.3 Evaluation of Safety Considerations Regarding Use of Emergency Braking

When the concept of using the emergency brake as a backup to the penalty was first introduced, there was concern from some of the railroad community that use of the emergency brake as a form of PTC enforcement could result in an increased probability of derailment during a PTC enforcement. According to the figures in Section 3, there are approximately 410 authority violations per year that would result in a PTC enforcement, which, using human factors analyses, should be reduced to, conservatively, 32.8 per year with the addition of the onboard display and audible warning. With the concept being that only a fraction of these enforcements would result in an application of the emergency brake, this is a relatively small number of emergency brake applications related to PTC enforcement, considering emergency brake applications occur on the railroad every day for a variety of other reasons. Nevertheless, an analysis was performed to evaluate any potential risks associated with use of the emergency brake.

The analysis consisted of modeling coupler forces throughout the train for a variety of scenarios, using the TOES model to identify where the magnitude of those forces may be of concern. The following three different operating scenarios were investigated during this analysis:

- Flat grade
- 1 percent constant decline grade
- Valley with undulating 1 percent grade

The flat grade provides a case where the locomotives are in throttle at the time of the brake application, whereas the 1 percent constant decline provides a case where the locomotives are in dynamic brake at the time of the brake application. For the valley case, the enforcement application occurs with the front half of the train decelerating up the hill with dynamic brake in use, while the back half of the train is in process of accelerating down the hill. This type of scenario is expected to result in the most significant compressive (buff) forces, with potentially the highest risk of causing a derailment.

The following five different train types were used in the modeling analysis:

- Loaded unit coal with distributed power, 130 cars, 4 locomotives
- Empty unit coal with distributed power, 130 cars, 4 locomotives
- Intermodal with head end power, 100 platforms, 3 locomotives
- Loaded mixed freight with head end power, 99 cars, 4 locomotives
- Empty mixed freight with head end power, 99 cars, 4 locomotives

In the case of the unit freight trains, the brakes were applied from both ends of the train with the use of distributed power. In the other cases, with head end power only, the penalty was applied from the head end, while the emergency was applied from both ends through the two-way end-of-train device. In the case of the loaded mixed freight train, a mix of loading conditions was used, and a significant number of cars were equipped with end of car cushioning draft gear devices in both mixed freight trains, which can contribute significantly to longitudinal motion, increased coupler forces, and derailment risk.

For each train and operating scenario discussed above, three different types of brake applications were modeled, as follows:

- Penalty brake application
- Emergency brake application
- Penalty brake application followed by emergency brake application after 25 seconds

The penalty brake application provides a baseline level of coupler forces against which to compare the emergency scenarios, since this form of enforcement is generally accepted from the standpoint of increased risk of derailment related to PTC enforcement. The emergency brake application is intended to demonstrate the worst potential scenario, and the penalty brake application followed by an emergency brake application after 25 seconds is intended to demonstrate a probable scenario where the emergency brake would be used as a backup to prevent a target overrun.

Figure 10 shows the maximum compressive (buff) force in the train for each combination of train, operating scenario, and type of brake application. It can be quickly observed from Figure 10 that the highest buff forces resulted from operating with dynamic brakes through the valley grade at the time the brake application was made. It can also quickly be observed that of the five different train types, the intermodal trains exhibited the lowest coupler forces. This is logical, given that the intermodal train consists of a large number of longitudinally rigid (solid), rotationally free connections (between the platforms of each articulated car), resulting in far less free slack than in the other train types.

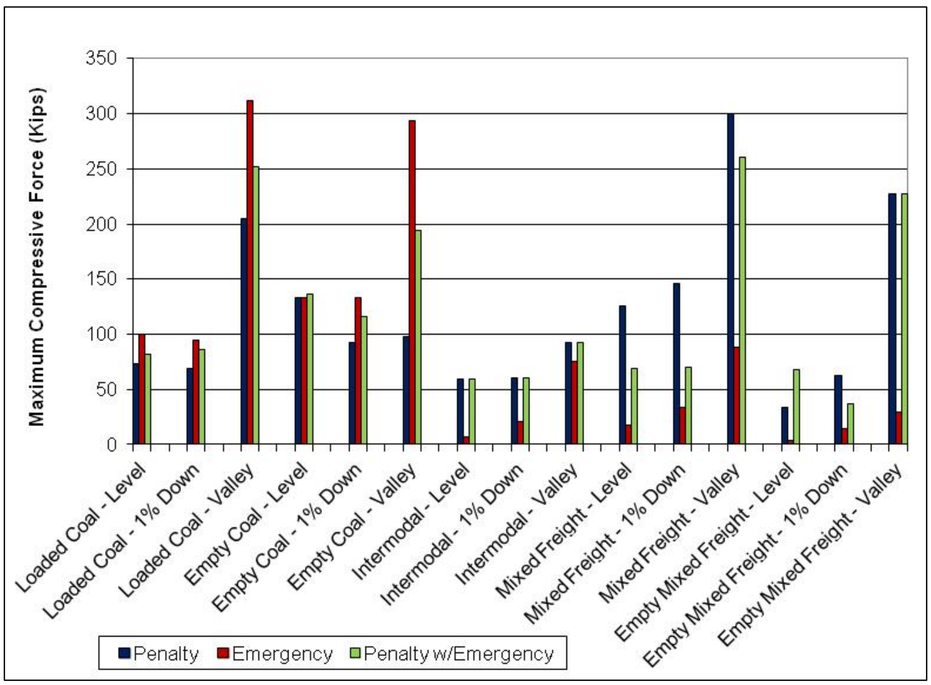


Figure 10. Maximum Coupler Forces Resulting from Brake Applications

Figure 10 also shows that, for the coal trains, the emergency application resulted in the highest coupler forces, whereas the penalty application resulted in the highest coupler forces for the other train types. This is a result of the two-way activation of the emergency brake. In the case of the unit trains, both the penalty and emergency brake applications occur from both ends, with the use of distributed power. In the case of the other train types, the penalty occurs from the head end only, but the emergency occurs from both ends, with the use of a two-way end-of-train device. Applying the brakes from both ends helps to control the slack in the train, particularly for the valley case, where the head-end application of the brakes helps to decelerate the train faster, while the rear of the train continues to accelerate, creating a run-in event. Because of the two-way application of the emergency brake, the coupler forces generated were shown to be generally smaller with the application of the emergency brake than with the application of the penalty brake from the head end only.

The largest coupler forces observed from the brake applications modeled were just over 300,000 lb (311,479 lb was the overall maximum, which occurred with an emergency brake application with the loaded coal train operating through the valley grade), which is not an overly alarming level of compressive force on the coupler. To put this in perspective, modern locomotives can apply approximately 100,000 lb of dynamic brake force each, which means if three locomotives were operating at the head end of a train, the first coupler in the train would see approximately the same coupler force of 300,000 lb.

There is no specific coupler force threshold above which derailment can occur. Rather, there are a number of contributing conditions that will result in a derailment. For example, if an empty car were to see a high coupler force while negotiating a relatively sharp curve or through a turnout, it could result in the car being forced off the rail or into a wheel-climb situation. However, the risk of derailment for a loaded car in the same situation, or the empty car on a tangent section of track, may be relatively low, despite experiencing the same coupler force. The results of the analysis performed do not show any indication that the use of the emergency brake as a backup to the penalty brake during a PTC enforcement scenario will result in increased risk of derailment or other safety issues.

7.4 Development of Initial Emergency Brake Backup Function

Initially, the emergency brake backup concept was designed to monitor the stopping progress of the train by measuring the acceleration of the train and using it to determine if the train would overshoot the target stopping location with the penalty brake application alone. In this design, the acceleration of the train is measured as the penalty brake is applied and is used to predict the acceleration profile for the remainder of the train stop. The acceleration profile is then used to predict where the train will stop with the current penalty brake application. If this prediction indicates that the train is still going to overshoot the target, the emergency brake is applied.

As with the brake efficiency adaptive function, the first challenge with this design is accurately measuring the acceleration of the train. In order to develop an accurate prediction of the stopping profile of the train, the raw acceleration data must be filtered to smooth out the spikes in the data related to the resolution and low frequency of data acquisition. The same method of filtering that was applied to the brake efficiency adaptive function was also applied to the emergency brake backup function. The most recent 3 raw acceleration data points are averaged and then the most recent 16 averaged acceleration data points are subjected to a least-squares regression method to determine the current acceleration of the train.

The next challenge is to predict the acceleration profile of the train going forward, given the fact that the brakes on the train are still in the act of applying, meaning the full force of the brakes has not yet been attained. In order to do this, the brake shoe force is calculated at each of the most recent 10 data samples, using the filtered acceleration and the estimated other forces acting on the train. The rate of change of the brake shoe force over this period is then determined using a simple linear regression formula. The brake shoe force profile is assumed to follow this rate of change up to the point where the brakes are fully applied. This brake shoe force profile is then used to predict the acceleration and speed profile for the rest of the penalty brake application.

Because this method of predicting the stopping location of the train is subject to various anomalies in the measured data, the emergency brake was designed only to apply when the average position for the most recent five predictions is beyond the target, and those predictions are within 200 ft. This method was tested using TOES simulations and was shown to have reasonable results. In all cases tested, the emergency brake was applied when necessary, and it was not applied when the penalty brake application was sufficient to stop the train. The function was documented and implemented in the test enforcement algorithm software for field evaluation.

7.5 Field Testing Emergency Brake Backup Function

To verify the proper operation of the emergency brake backup function with field testing, special field test procedures were necessary. The emergency brake backup function is designed to apply the emergency brake only in cases where the penalty brake application alone is not sufficient to stop the train short of the target. Typically, this will occur when conditions are extreme; for example, a train with braking characteristics far worse than typical. Given that the equipment available for field testing does not exhibit these worst-case type characteristics, the response of the train to the penalty application would be sufficient to stop the train without an emergency brake application. Therefore, to test the emergency brake backup function, the assumption within the enforcement algorithm for the amount of brake force available on the train was raised to a value far higher than that actually available on the test train. This resulted in the enforcement algorithm delaying the application of the penalty brake, such that an emergency brake application was necessary to prevent a target overrun.

The key criteria for evaluating the emergency brake backup function is that it (a) applies the emergency brake to stop the train short of the target when the penalty brake application would otherwise not, and (b) does not apply the emergency brake when the penalty brake application will stop the train short of the target without an emergency brake application. Therefore, two types of field tests were conceived:

- Overshoot — The brake force assumption within the enforcement algorithm was modified so that the train would stop approximately 200 ft beyond the target following a penalty brake application. This test is designed to address the first criteria.
- Undershoot — The brake force assumption within the enforcement algorithm was modified so that the train would stop approximately 200 ft short of the target following a penalty brake application. This test is designed to address the second criteria.

The value to which to set the brake force assumption in each case was determined through simulations conducted prior to executing the field tests.

Given the two types of tests, the emergency brake backup function was evaluated for a number of operating scenarios and compared against the results with the base enforcement algorithm. Table 15 provides a list of the test scenarios and the results of each. The base enforcement algorithm results indicate where the train stops in each test scenario without the emergency brake backup function. The base algorithm stopped beyond the target in all of the overshoot cases and stopped short of the target in all of the undershoot cases, as designed.

Table 15 shows that the emergency brake backup function applied the emergency brake in all of the overshoot cases. In all but one case, the train stopped short of the target when the emergency brake was applied. In the case that failed to stop the train short of the target, a run-in event occurred at the point at which the algorithm would have initiated an emergency brake application. This run-in caused severe fluctuations in the acceleration and in the predicted stopping distance. Because the algorithm could not get a fix on the actual stopping location of the train during this time, the application of the emergency brake was delayed until the acceleration settled, resulting in the emergency being applied too late. This issue, among others associated with the emergency brake backup function, is addressed in Section 7.6.

Table 15 also shows that the emergency brake was not applied in any of the undershoot cases. This indicates that the function only utilizes the emergency brake when the penalty application is not sufficient to stop the train short of the target, and not in other cases where it is unnecessary.

Table 15. Emergency Brake Backup Function Field Test Results

Test Conditions				Average Stopping Location Relative to Target (ft)	
Consist	**Speed (mph)**	**Track Grade**	**Test Case**	**Base Algorithm**	**Emergency Brake Backup**
40 Cars – Loaded	30	Decline	Overshoot	100	-600
40 Cars – Loaded	30	Decline	Undershoot	-200	-200*
40 Cars – Loaded	50	Flat	Overshoot	200	-40
40 Cars – Loaded	50	Flat	Undershoot	-200	-200*
90 Cars – Loaded	30	Decline	Overshoot	200	-200
90 Cars – Loaded	30	Decline	Undershoot	-175	-175*
90 Cars – Loaded	30	Flat	Overshoot	200	120
90 Cars – Loaded	30	Flat	Undershoot	-200	-200*

* Emergency brake was not applied

7.6 Development of Improved Emergency Brake Backup Function

Although the results from both simulation and field testing indicated reasonable performance, several issues were identified with the initial emergency brake backup design. First, because of the initial time it takes for the brakes to begin to apply, the rate of change of the brake shoe force cannot be reliably measured until several seconds after the penalty brake application. Second, because of the filtering necessary on the acceleration data, the function cannot begin to predict whether an emergency brake application is necessary or not until well into the penalty application. Third, because of slack run-in events that are typical following a penalty brake application for many scenarios, the acceleration data many times exhibits large anomalies that require sophisticated methods to identify and handle. Finally, because the function is designed to apply the emergency as soon as it is confident the penalty application is not sufficient, in many cases the emergency was applied so early that the train stopped well short of the target. Because of these deficiencies, the emergency brake backup function was redesigned using a different overall concept.

In the original concept, the function attempted to refine the stopping distance prediction with the penalty brake application, using empirically measured data. In the redesigned concept, the emergency brake profile of the train is computed and the stopping location is compared with the target to determine if the emergency brake is necessary. Because emergency braking can stop the train much faster than penalty braking, a more conservative emergency brake profile can be used to ensure that it will stop the train short of the target, without being applied when the penalty alone is sufficient. Using this concept, there is no dependency on measuring and filtering data, and the emergency will not be applied until it is absolutely necessary, resolving the issues identified with the original concept.

The development of the improved emergency brake backup function parallels many of the functions of the penalty brake prediction function. As with the penalty brake prediction, the function estimates the forces acting on the train at each time step of the prediction loop, which are then used to estimate the acceleration, velocity, and location. For the emergency brake prediction, the brake pipe pressure is assumed to reduce by 40 psi each second of the prediction. This forces the air brake model in the enforcement algorithm to respond as if an emergency brake application is underway, modeling the brake force accordingly.

To ensure that the emergency brake prediction is conservative, the brake force estimated by the air brake model is adjusted to 90 percent of the estimated value at each time step of the prediction loop. This adjustment value is intended to be system configurable, so that it and the penalty prediction target offset function can be adjusted to allow a higher or lower percentage of penalty brake enforcements that result in an emergency brake application, using simulation or empirical data. The 90 percent value results in a conservative prediction that ensures the emergency brake application is sufficient to stop the train short of the target.

The improved emergency brake backup function is documented in the enforcement algorithm description document in Appendix F. This function was also implemented in the test software for evaluation. In the initial project plan, it was expected that any modifications to any of the functions would be made prior to field testing the function. However, in the case of the emergency brake backup function, many of the deficiencies were not identified until analyzing the results of the field testing. Therefore, the project budget could not support an additional field test period dedicated to evaluating the improved function. However, the improved function was evaluated in the simulation test process for all three phases of development, as discussed in Sections 9, 12, and 15. The improved emergency brake backup function was also implemented in the software used during the field tests for each of the functions developed during Phases 2 and 3, which allowed for some level of indirect evaluation. As described in the sections for field testing each of these functions, the emergency brake backup did not apply when not necessary and was used successfully to mitigate certain other system faults, such as a failure of the dynamic brakes at the time the penalty brake was enforced.

8. Distributed Power

A significant percentage of freight trains operate with distributed power today. Distributed power refers to arranging groups of locomotives, known as locomotive consists, in various locations throughout the train. For example, a common distributed power configuration is to have one locomotive consist located at the head end of the train and another locomotive consist located at the rear end of the train. The locomotive engineer will typically operate the train from the lead locomotive at the head end of the train. The lead locomotive in the remote (distributed power) locomotive consist(s) receives control setting and brake system commands from the lead locomotive of the head end locomotive consist via signals over a radio frequency link. The other locomotives in each locomotive consist receive control setting commands from the lead locomotive in the locomotive consist via the 27-pin multiple-unit (MU) cable, and the brake systems are set up to operate as trailing units, as in typical operations. The remote (distributed power) locomotives can be set up to operate synchronously, meaning they follow the same control and brake settings as the lead locomotive, or asynchronously, meaning the locomotive engineer gives the remote locomotives commands independent of the commands given to the lead locomotive. When a PTC penalty brake enforcement is initiated at the head end, the brakes are applied at each locomotive consist, regardless of the mode of operation.

Distributed power offers several operational advantages over operating with head end power only, including improved control of the slack action within the train, reducing force on the couplers at the head end of the train, the capability to operate longer trains, and improved brake application and recharge times. With distributed power, the brakes are applied by exhausting the pressure from the brake pipe at each locomotive consist, rather than only from the lead locomotive. This results in a faster propagation of the air brake signal to the cars, and, therefore, a faster application of the brakes, which can have a significant effect on the stopping distance of the train. Understanding the effect of distributed power on the braking performance and incorporating this into the enforcement algorithm is crucial to reducing operational inefficiencies associated with PTC enforcement for these types of trains.

8.1 Overview of Enforcement Algorithm Issues Associated with Distributed Power

Traditionally, the reduction in brake application time for trains operating with distributed power has not been incorporated into PTC enforcement algorithms, meaning they assume the propagation time from the head end only. This can result in a significantly conservative prediction of the train braking distance for trains operating with distributed power. Figure 11 illustrates this issue with the results of TOES simulations for a typical example, a loaded, 135-car unit aluminum coal train operating on flat grade at 50 mph. The blue curve shows the stopping distance for this train operating with four locomotives at the head end only, a distance of 5,208 ft. The red curve shows the stopping distance for the same scenario, but operating with two locomotives at the head end and two locomotives at the rear end, a distance of 4,208 ft, 1,000 ft shorter than the case with head end power only. If the enforcement algorithm assumes for this train operating with distributed power that the brake pipe pressure is exhausted from the head end only, the prediction will be 1,000 ft more conservative than necessary, assuming all other assumptions within the algorithm are accurate. As this example shows, the assumption that all brake applications are propagated from the head end only contributes significantly to the operational inefficiency of the enforcement algorithm.

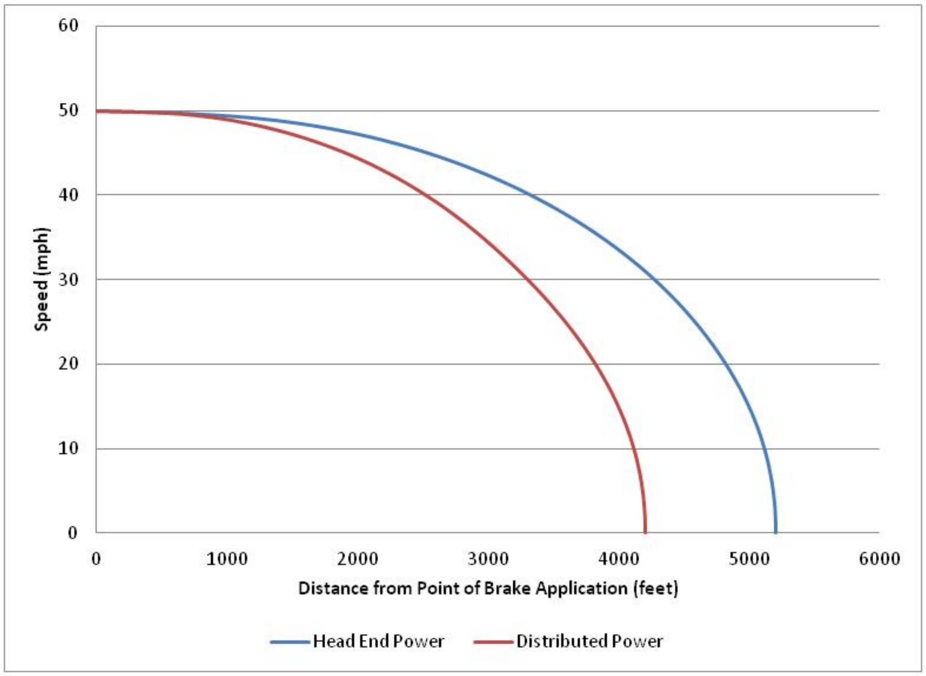


Figure 11. Comparison of Penalty Braking Distance with Head End Power and Distributed Power for Loaded 135-Car Unit Aluminum Coal Train on Flat Grade

8.2 Evaluation of Safety Considerations Regarding Distributed Power Communications Failures

One of the reasons that PTC enforcement algorithms may traditionally not have incorporated the benefit of distributed power is because the distributed power communications link can fail in certain circumstances, resulting in a potentially unsafe scenario if the enforcement algorithm assumes the distributed power link is active. This issue is manageable, however, by using feedback on the distributed power communications link status from the locomotive, and with the addition of the emergency brake backup function. If the enforcement algorithm uses the status of the distributed power communication link, it can assume distributed power propagation time if the status is active and the head end only propagation time if the status is inactive for any reason.

The only remaining issue arises in a situation where the distributed power communications status changes from active to inactive after the enforcement algorithm would have initiated a penalty if the status had been inactive at the time. In this case, the penalty would be initiated as quickly as is practical, but may be insufficient for stopping the train short of the target, if the distributed power communications link is not quickly restored. However, the emergency brake backup function, which would consider that the distributed power link is inactive, would apply the emergency brake to stop the train safely short of the target.

Figure 12 illustrates conceptually how the emergency brake backup function can be used to mitigate the safety concern with distributed power communications link failure with the results of TOES simulations for a typical example, a loaded, 135-car unit aluminum coal train operating on flat grade at 50 mph with distributed power. In the figure, the blue curve shows the stopping profile for this train if the algorithm assumes no distributed power even though the train is actually operating with distributed power, as traditionally assumed by PTC enforcement algorithms. The red curve shows the stopping profile if the algorithm assumes the train is operating with distributed power. In this case, the PTC enforcement would take place approximately 1,000 ft later than if no distributed power is assumed by the algorithm. The green curve shows the stopping profile if the algorithm assumes the train is operating with distributed power, but the distributed power communications link fails right at the point of enforcement. In this case, the point of enforcement is the same as the red curve, but the stopping distance is the same as in the blue curve. The result is that the train stops approximately 1,000 ft further than the algorithm predicted because it incorrectly assumed that distributed power would be active. Finally, the purple curve in the figure shows the stopping profile of the train if the algorithm assumes the train is operating with distributed power; the distributed power communications link fails right at the point of enforcement, but the algorithm uses the emergency brake to stop the train at the point it originally predicted. In this case, the emergency brake was applied 23 seconds after the penalty brake was applied, in order to stop the train at approximately the same location as if the distributed power communications link had been active.

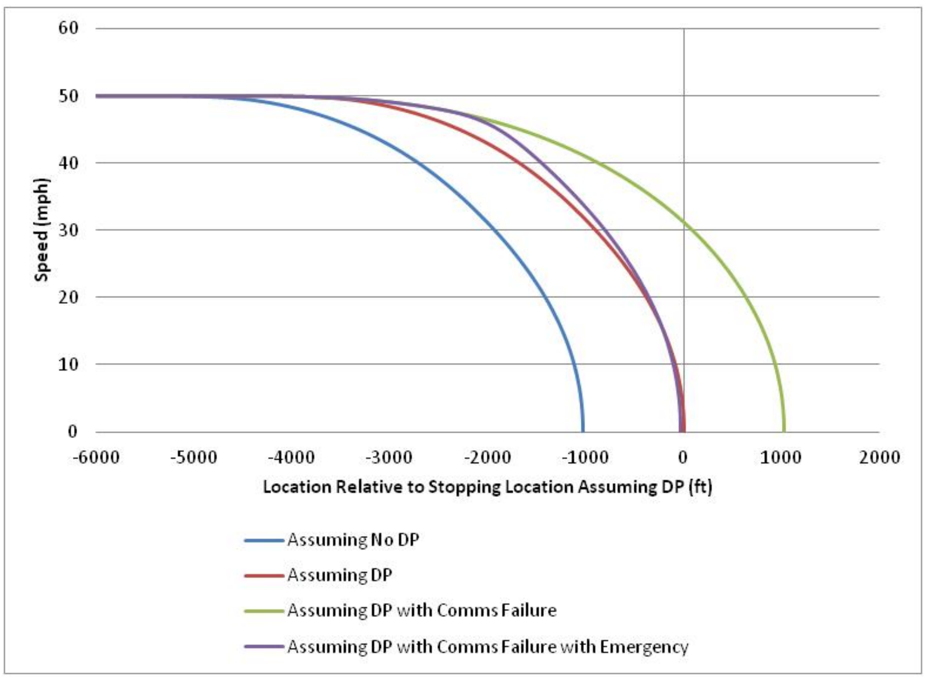


Figure 12. Comparison of Stopping Locations with Distributed Power Communications Failure and Emergency Brake Backup

The key to using the emergency brake as mitigation for the safety concern with cases where the distributed power communications link fails is that the emergency brake applied from the head end only will always stop the train at a shorter distance than the penalty brake applied from multiple locations within the train, and this is because an emergency brake application is approximately 5 times quicker than a penalty brake application. Therefore, if the communication link for distributed power fails after the location of enforcement for a head end only train, the emergency brake will apply and still stop the train short of the target.

8.3 Development of Enforcement Algorithm Modifications for Trains with Distributed Power

To develop a function for properly handling the improved brake pipe propagation time with distributed power, the relationship between the propagation time and the arrangement of the locomotives within the train consist must be understood. The following two characteristics of the arrangement of locomotives were identified as having the potential to affect the brake pipe propagation time:

- Number of locomotive consists in the train — This defines the number of locations where the air in the brake pipe is exhausted from during a penalty brake application.
- Distance between locomotive consists in the train — This defines the length of brake pipe that the air must travel through to get to an exhausting locomotive during a penalty brake application.

Parametric simulations with the TOES model were used to identify the relationships between these characteristics and the brake pipe propagation time for a penalty brake application. Table 16 shows the TOES simulations run to determine how the brake pipe propagation time is affected by the number of locomotive consists in the train. In each of the cases, a nominal train was built consisting of identical standard 50-foot hopper cars, equipped with ABDW type control valves. The number of cars, as well as the number and location of locomotive consists in the train were varied according to the values indicated in Table 16. For each test case, a penalty brake application was initiated at all locomotive consists, and the brake pipe propagation time was measured.

Table 16. Simulation Tests to Determine Effect of Number of Locomotive Consists on Brake Pipe Propagation Time

Test Case	Train Length (number of cars)	Number of Locomotive Consists	Location of Locomotive Consists	Ratio of Train Length to Number of Locomotive Consists	Brake Pipe Propagation Time(s)
1	50 cars	1	Head End	50	41
2	100 cars	2	Head/Rear	50	41
3	150 cars	3	Head/Mid/Rear	50	41
4	100 cars	1	Head End	100	70
5	200 cars	2	Head/Rear	100	70

The results shown in Table 16 indicate that the brake pipe propagation time is directly related to the ratio of the length of the train to the number of locomotives in the train, if the locomotive consists are evenly distributed throughout the length of the train, and all else being equal. In other words, the propagation time for a train operating with distributed power is equal to the propagation time of an identical train, except shorter by a factor of the number of locomotive consists, operating with head end power only.

The conclusions drawn from the results shown in Table 16 are intuitive. If there are locomotives located only at the head end, the air has to travel the length of the train to exhaust from a single location. If there are locomotives located at the head and rear of the train, the air can exhaust twice as fast, as there are two exhausting locations. Finally, if there are locomotives located at the head, middle, and rear of the train, the air can exhaust three times as fast, as there are three exhausting locations, spaced evenly throughout the train. Although this is a significant conclusion, the tests described in Table 16 do not cover cases where the locomotive consists are not distributed evenly throughout the length of the train.

To evaluate the effect of the location of the locomotive consists within the train on propagation time, the TOES simulations shown in Table 17 were run. For these tests, a nominal train was built consisting of 100 identical standard 50-foot hoppers equipped with ABDW type control brake valves. For one case, only locomotives at the head end were used, and for the other cases two locomotive consists were used. The location of one of the locomotive consists was varied from 10 cars behind the head end to the rear end of the train in 10 car increments, as indicated in table 17. As before, a penalty brake application was initiated at all locomotive consists and the brake pipe propagation time was measured.

Table 17. Simulation Tests to Determine Effect of the Location of Locomotive Consists, within the Train, on Brake Pipe Propagation Time

Test Case	Location of Locomotive Consists	Brake Pipe Propagation Time (s)
1	Head End Only	70
2	Head End and 10 Cars Back	58
3	Head End and 20 Cars Back	56
4	Head End and 30 Cars Back	53
5	Head End and 40 Cars Back	50
6	Head End and 50 Cars Back	46
7	Head End and 60 Cars Back	44
8	Head End and 70 Cars Back	41
9	Head End and 80 Cars Back	41
10	Head End and 90 Cars Back	41
11	Head End and Rear End	41

The results in Table 17 indicate that there is a benefit to having multiple locomotive consists, even if they are located very close together, but the benefit is greatest when they are separated by 70 percent or more of the train. Practically speaking, it is extremely unlikely that a train with two locomotive consists would be assembled with the locomotive consists closer than 50 percent of the length of the train, so test cases 2, 3, 4, and 5 are purely academic. With the locomotive consists separated by half of the length of the train, the propagation time is approximately 12 percent greater than with the locomotive consists separated by the full length of the train. Although this is not a trivial difference, this level of error in propagation time is far less than the level of potential error in propagation time attributed to differences in control valves, ambient temperature, and other factors. Because of this, combined with the fact that this configuration of locomotive consists is rare, it was determined that the propagation time for trains operating with distributed power could be estimated using the standard brake pipe propagation time formula for a train with a length equal to the train length divided by the number of locomotive consists.

For trains operating with distributed power, it is still desirable to utilize the brake pipe propagation time adaptive function to more accurately predict the brake pipe propagation time for a penalty brake application. However, because the brake pipe pressure exhausts from multiple locations, the rear of the train is not necessarily the point where equalization will occur the latest, as in the case with head end power only. Therefore, the brake pipe propagation time adaptive routine, which measures the brake pipe propagation time from the brake pipe pressure at the rear of the train, cannot reliably be used to estimate the brake pipe propagation time with distributed power being active.

If the brake pipe propagation time function is run with the distributed power cut out, however, a measurement can be made, and then an adjustment factor applied when the distributed power is cut in. Since it is envisioned that the brake pipe propagation time function would be run at train initialization, during a departure brake test, such a measurement could be made prior to cutting in distributed power. The brake pipe propagation time function would simply need to detect whether or not distributed power is cut in and only perform the brake pipe propagation time correction if it is cut out. When distributed power is cut in, the function would then apply the distributed power correction factor and proceed with the corrected propagation time.

The correction factor is derived by assuming that the ratio between the measured propagation time and the nominal estimated propagation time is the same for the same train operating with or without distributed power. Using this assumption, the propagation time with distributed power can be calculated as the nominal estimated propagation time with distributed power multiplied by the ratio of the measured propagation time to the nominal estimated propagation time without distributed power. For example, for a unit train with two locomotive consists that is 6,000 ft long, the nominal estimated propagation time without distributed power would be 93 seconds and the nominal estimated propagation time with distributed power would be 51 seconds (according to the new equation in Section 5.2.2). If the adaptive function measures a propagation time of 78 seconds for the train with distributed power cut out, the adaptive propagation time for the train with distributed power cut in would be 51 x (78/93) = 43 seconds. This method of calculating the correction factor was evaluated with TOES simulations for a number of cases and was shown to provide a good estimate of the actual brake pipe propagation time for these cases.

8.4 Field Testing Distributed Power Function

To verify the safety and performance of the distributed power function, a number of field tests were conducted. The field tests covered a range of operating scenarios and were executed with the base algorithm, the distributed power algorithm with assumed propagation time, and the distributed power algorithm with adaptive propagation time. The tests were run without the target offset function or the other modifications to the base algorithm, to provide an indication of the improvement in the prediction between the three versions of the algorithm.

Table 18 shows the test scenarios as well as the average stopping location relative to the target for each case and each version of the algorithm. The distributed power algorithm more accurately predicted the propagation time for the train in all cases, which resulted in the train stopping closer to the target, as shown in Table 18.

Table 18. Distributed Power Function Field Test Results

Test Conditions			Average Stopping Location Relative to Target (ft)		
Consist	**Speed (mph)**	**Track Grade**	**Base Algorithm**	**Distributed Power Function**	**Distributed Power Function with Adaptive Function**
78 Cars – Loaded	30	Flat	-786	-201	-2
78 Cars – Loaded	50	Flat	-1188	-231	101
78 Cars – Loaded	10	Flat	-150	-26	70
78 Cars – Loaded	30	Decline	-1000	-254	272
60 Cars – Loaded	30	Flat	-273	18	172
60 Cars – Loaded	30	Decline	-949	-158	122

In some cases, target overshoots were observed, particularly when the adaptive propagation time was used in conjunction with the new distributed power function, because neither the target offset function nor the brake efficiency adaptive function was used, which would bias the prediction accordingly. It is expected that, had the brake efficiency adaptive function be used in these tests, the stopping location would have been much closer to the target, because the prediction would have been much more accurate. It is also expected that, had the target offset been used, the train would have stopped safely short of the target, as this train did not represent a worst-case train. Finally, had the emergency brake backup function been used, the emergency would have been applied to stop the train short of the target. These functions were removed to provide a result that indicates the accuracy of the prediction related to the distributed power function. All tests with the distributed power function were shown to stop within 300 ft of the target; showing it more accurately represented the propagation time of the train than the base algorithm did.

9. Evaluation of Phase 1 Developmental Algorithm

The Phase 1 developmental algorithm consists of all the modifications and additions to the base algorithm described in Sections 5, 6, 7, and 8. This includes addition of train type input, modification of key assumptions, improvement of the target offset function, modification of the air brake model, and incorporation of adaptive, emergency brake backup, and distributed power functions. Appendix F defines each of the Phase 1 algorithm functions, within the context of the final developmental algorithm. Although the document included in Appendix F also includes modifications and new functions developed in Phases 2 and 3, these were not in place during the evaluation of the Phase 1 algorithm.

Simulation testing and analysis was performed on the Phase 1 algorithm using the methodology described in Section 2.2. The Phase 1 algorithm was only tested with unit trains, because improvements for manifest freight and intermodal freight trains were not incorporated until the third phase of development. Table 19 shows the overall results of simulation testing for unit trains with the Phase 1 algorithm. It shows the probability of stopping short of the target and the probability of stopping short of the performance limit, defined as stopping short of the target by less than 500 ft for speeds < 30 mph and 1,200 ft for speeds ≥ 30 mph. Appendix H contains the detailed results from simulation testing of the Phase 1 algorithm.

Table 19. Phase 1 Algorithm Simulation Test Results

Train Type	Probability of Stopping Short of Target	Probability of Stopping Short of Performance Limit
Unit Freight	99.69%	31.98%

The data in Table 19 shows the Phase 1 developmental algorithm maintains a probability of stopping short of the target greater than the objective of 99.5 percent and reduces the probability of stopping short of the performance limit to 31.98 percent from 83.57 percent in the base algorithm. This demonstrates the positive improvement in the operational efficiency of the enforcement algorithm, without impacting the level of safety, achieved through the modifications and new functions incorporated during the first phase of development.

10. Locomotive Braking

When a penalty brake application is initiated, the brake pipe pressure is reduced to atmospheric pressure at a service rate, which triggers the control valve on each car in the train to apply the brakes on that car. On locomotives there is an additional feature known as the actuating feature, which allows the locomotive engineer to release, or bail off, the locomotive brakes. Locomotives produce far more brake force than a typical freight car during a penalty brake application. As full application of the locomotive brakes can have undesirable effects, such as high coupler forces and the potential to slide locomotive wheels, locomotive engineers are trained to bail off the locomotive brakes to limit the amount of braking on the locomotives. Bailing of the locomotive brakes becomes a reflex reaction when the train brakes apply.

Locomotives are also capable of independent braking, allowing the locomotive engineer to apply some amount of locomotive brakes independently from the rest of the train, which can be useful in certain scenarios. The combination of bailing off the automatic brakes and applying the independent brakes on a locomotive allows the locomotive engineer the ability to very explicitly control the amount of locomotive braking to a desired level.

Although the locomotive brake force is only a small fraction of the total amount of brake force applied by the whole train during a penalty application for long trains, whether or not the locomotive engineer bails the locomotive automatic brake and applies the locomotive independent brake can have a significant effect on the stopping distance of short trains and light locomotives. How these scenarios are handled by the enforcement algorithm can be an important aspect of the system performance.

10.1 Background on Use of Locomotive Brakes during PTC Enforcement

The enforcement algorithm has no way of knowing what actions the locomotive engineer will take following a PTC penalty brake enforcement. However, because of the potential risks with allowing locomotive brakes to fully apply, it is common for locomotive engineers to reflexively bail off the locomotive brakes when the automatic air brakes are applied. It is also reasonable to assume that if the train were short enough to require locomotive brakes to stop the train in a practical distance, the locomotive engineer would either not bail the locomotive brakes or would apply some level of locomotive independent brakes. These assumptions form the basis for how PTC enforcement algorithms have traditionally handled locomotive brakes.

In the base algorithm, there is a configurable parameter that defines the number of cars for a "short" train. This number is used to determine whether locomotive braking will be assumed or not during PTC enforcement. The value suggested in the base case documentation for this parameter is eight cars. For trains with greater than eight cars, the enforcement algorithm assumes that the locomotive brakes will be fully bailed and no brake force will be contributed from the locomotives. For trains with eight or fewer cars, the enforcement algorithm assumes that the locomotive brakes will be fully applied, with no bail.

Although the assumptions used for the base algorithm are reasonable in terms of predicting what the locomotive engineer might do, there are obviously potential issues on short trains or light locomotives if the locomotive engineer bails the locomotive brakes reflexively. Additionally, in longer trains, if the locomotive brakes are not used to supplement the brakes on the trailing cars, there is some level of braking available that is not being used (or assumed), which contributes to additional algorithm conservatism. It should also be noted that, given the level of braking available to the locomotives, scenarios with short trains and light locomotives are historically not areas of high concern with regard to authority violations.

10.2 Development of Methodology for Handling Use of Locomotive Brakes

In order to ensure safe handling of short train and light locomotive scenarios, and provide additional braking to help reduce the operational inefficiencies associated with early warnings and enforcement for all trains, a consistent level of locomotive brakes must be applied for all PTC enforcements. Using this logic, a method for ensuring a consistent level of locomotive braking during PTC enforcement was conceived. In this concept, an appropriate level of locomotive braking is selected, below which the locomotive engineer cannot bail the locomotive automatic air brake application during a PTC enforcement. This requires either hardware and/or software modifications to the locomotive brake system to implement, but allows the enforcement algorithm to reliably predict the level of locomotive braking during the stopping distance prediction to provide a more accurate prediction, and safely delay the point of enforcement to give the locomotive engineer ample time to respond.

The key to this concept, other than the implementation challenge, is selecting an appropriate level of locomotive brake cylinder pressure to limit the bailing to. The level of brake cylinder pressure selected should be high enough that the operational impact to short trains and light locomotives is minimal, but also low enough to not impact braking performance for longer trains, or substantially increase the risk of locomotive wheel slide. It was determined that the most logical solution was to select a locomotive brake cylinder pressure that would result in a similar level of braking for the locomotives as for a typical freight car, relative to their weight. Although the overall average net brake ratio for a freight car varies between the train types, the need to get the level of locomotive braking to that level of precision is not necessary. Rather, it is important to get the level of locomotive braking close to the level of braking for the freight cars. Since a large majority of freight cars were designed to a loaded net brake ratio of between 8.5 percent and 13 percent, and it can be assumed that the net brake ratio can fade by up to 1 percent over time [7, 11], it is reasonable to select a nominal brake ratio of 10 percent for the purposes of aligning the level of locomotive braking to the level of freight car braking.

The AAR specifies a minimum net brake ratio for locomotives equipped with single high-friction composition brake shoes of 20 percent at 50 psi brake cylinder pressure [23]. Review of locomotive brake rigging designs for various locomotives and discussions with experts in the area of locomotive brake system design indicate that the gross brake ratio for a locomotive at 50 psi brake cylinder pressure can be as high as 30 percent, and that the efficiency of the locomotive brake rigging can generally be assumed at 80 percent. The net brake ratio is the gross brake ratio multiplied by the efficiency of the brake rigging. By taking the 80 percent efficiency factor into account the resulting maximum net brake ratio is equal to 24 percent at 50 psi brake cylinder pressure. The nominal net brake ratio can be assumed as the center of the range from the minimum of 20 percent to the maximum of 24 percent, which is 22 percent at 50 psi brake cylinder pressure. This equates to approximately a 28 percent net brake ratio at 64 psi brake cylinder pressure. This value was assumed to be the nominal net brake ratio for a locomotive at 64 psi brake cylinder pressure.

Using the assumption of the nominal locomotive net brake ratio of 28 percent at 64 psi and the nominal loaded net brake ratio of 10 percent at 64 psi for freight cars, a reasonable value for the brake cylinder pressure below which the locomotive engineer cannot bail during a PTC penalty application was selected as 10/28 x 64 ≈ 23 psi brake cylinder pressure. With the proper hardware and/or software modifications made to the locomotive brake system, the system would therefore not allow the locomotive engineer to bail the brakes to a brake cylinder pressure below 23 psi during a PTC penalty brake application. The brake system modifications would be designed to still allow a full bail of the locomotive brake cylinder pressure during brake applications initiated by the locomotive engineer or sources other than the PTC system. These modifications allow the train to be handled as currently done in normal operating conditions, but force a minimum level of locomotive braking during PTC enforcement, which improves the accuracy of the stopping distance prediction, allows additional time for the locomotive engineer to react before a PTC penalty enforcement occurs, and ensures that short trains and light locomotives will not violate the target stopping location during PTC enforcement because of reflexive actuation (bailing) of the locomotive brakes.

10.3 Field Testing Locomotive Brake Function

To test the concept of limiting the ability to bail the locomotive brakes during a PTC penalty application, modifications were made to the braking system on one of the test locomotives. The test locomotive was equipped with a pneumatic, 26-L brake system, allowing for hardware modifications to be made to the pneumatic system. For test purposes, the brake system was set up to automatically bail the locomotive brakes during the penalty brake application and reapply the independent brake with a limiting valve controlling the amount of independent brake cylinder pressure. Although actual implementations would still allow the locomotive engineer the ability to bail, forcing an automatic bail allowed for test consistency.

The limiting valve on the brake system was set up to allow adjustment for varying levels of brake cylinder pressure resulting from the application of the independent brake. A variety of brake cylinder pressure settings were evaluated during some of the tests, to determine if there were advantages or disadvantages to each. The following four locomotive brake cylinder pressure settings were used:

- 12 psi — corresponds to a brake ratio of ~ 5.25 percent
- 18.5 psi — corresponds to a brake ratio of ~8.1 percent
- 25 psi — corresponds to a brake ratio of ~10.9 percent
- 35 psi — corresponds to a brake ratio of ~15.3 percent

The tests were performed using a short train consist with a single locomotive and four loaded cars from the FAST train as well as a light engine consist with two locomotives. For each test case, the base algorithm was compared against the developmental algorithm. For the base algorithm tests, the locomotive brake cylinder setting was set to the 18.5 psi setting, which represents a conservative nominal level of braking that a locomotive engineer might use to stop a short train or light engine consist. For the developmental algorithm tests, the locomotive brake cylinder setting was set to one of the four settings listed above, and the algorithm software was adjusted to match.

Table 20 shows each of the test cases from the locomotive brake testing as well as the resulting average stopping location relative to the target for each. The results in the table show the train stopped further down the track with the base algorithm than with the developmental algorithm in all cases, because the base algorithm assumes full automatic brake cylinder pressure for the locomotive(s) during the penalty application when, in fact, the brake cylinder pressure was less because of the partial bail. In some cases, this resulted in a target overrun. For the developmental algorithm, which assumes the level of brake cylinder pressure selected by the automatic bail function, the train always stopped short of the target.

For the cases where multiple locomotive brake cylinder pressures were tested, the stopping location was consistent, regardless of which brake cylinder pressure was used. However, the higher the brake cylinder pressure, the longer the algorithm could wait before applying the penalty brake application. This suggests that a higher brake cylinder pressure would be desirable to delay the application of the penalty. This may be appropriate for shorter trains, but for longer trains, this higher brake force generated from the locomotives could result in undesirable train action. Additionally, higher brake forces on the locomotive increase the risk of damage to equipment, such as wheel flats from sliding wheels.

Table 20. Locomotive Brake Function Field Test Results

Test Conditions			Average Stopping Location Relative to Target (ft)				
Consist	Speed (mph)	Track Grade	Base Algorithm	Loco Brake Function 12 psi	18.5 psi	25 psi	35 psi
1 Locomotive, 4 Cars	60	Flat	45		-1425		
1 Locomotive, 4 Cars	30	Flat	-289	-586	-614	-620	-575
1 Locomotive, 4 Cars	10	Flat	-163		-198		-201
2 Locomotives, 0 Cars	30	Flat	-50	-336	-596	-596	-622
1 Locomotive, 4 Cars	30	Decline	27		-1227		
2 Locomotives, 0 Cars	30	Decline	272		-855		

This testing showed that this concept has merit for providing a safe method for ensuring that short trains and light engine consists stop short of the target, even when the locomotive engineer attempts to bail the automatic application. However, the complexities of implementing this type of functionality in the various locomotive braking systems (both pneumatic and electronic) combined with the relatively low risk associated with trains of this type, may mean that this functionality is not practical or necessary to provide a safe system.

11. Dynamic Braking

Dynamic braking refers to the use of the locomotive traction motors to assist with slowing the train. In essence, the traction motors are set to operate as generators with a large resistor grid acting as a load to provide resistance to the rotation of the motor, which slows the locomotive. The energy generated by the traction motors during dynamic braking is then dissipated as heat in the resistor grid. Dynamic braking is generally available on road locomotives in the railroad industry today and is used to supplement air braking during normal operations for a vast range of operating conditions. Dynamic braking offers several benefits, including reductions in wear on air brake system components such as brake shoes, consistent level of braking force on long grades where the air brake force may fade as the wheels and brake shoes heat up, faster application of the brakes, and improved control of the train.

The level of dynamic braking available is not consistent throughout the range of typical train operating speeds. As the train speed increases past approximately 25–30 mph, the level of dynamic braking available slowly decreases, and at low speeds the level of dynamic braking available drops dramatically. More recently, what is known as extended range dynamic brakes has been developed, which maintains a higher level of available dynamic braking force down to approximately 5 mph, before it drops off. Dynamic braking is also not considered a fail-safe form of braking, as air brakes are. With these deficiencies, dynamic braking has not replaced air braking, but the benefits of dynamic braking, particularly with the advent of extended range, have made it the primary method for slowing trains in the railroad industry today. In some cases, dynamic braking is essential for trains descending extended grades, and by operating practice the dynamic brakes must be checked prior to descending severe grades.

11.1 Overview of Issue with Assumption on Use of Dynamic Braking During PTC Enforcement

Because the use of dynamic braking is so prevalent, the PTC enforcement algorithm must consider that dynamic brakes may be in use to hold a train at a constant speed on a grade or to stop a train short of a given target stopping location before determining that a penalty air brake application is required. However, PTC enforcement algorithms to date have not considered that dynamic brakes may be in use at the time of potential enforcement. Figure 13 illustrates the issue without the use of dynamic brake when determining if a penalty brake application is necessary to stop the train short of a given stopping target.

In the figure, braking profiles produced from TOES simulations are shown for a loaded, 135-car unit aluminum coal train operating on a 1.1 percent decline at 25 mph. On this grade at this speed, the train speed is maintained with the use of dynamic brakes. The blue curve in the figure shows the stopping profile for this train if a locomotive engineer were to use additional dynamic brake supplemented with split service brake pipe pressure reductions to stop the train, as would typically be done. In this case, the locomotive engineer can bring the train to a stop in 2,920 ft. The red curve in the figure shows the stopping profile for this train calculated by the enforcement algorithm if it does not take into account the current state of the dynamic brake. Because of the time it takes for the air brake signal to propagate the length of the train and the brakes to apply, the force computations show acceleration, until enough brake force is supplied to begin decelerating the train to a stop. In this case, a train would have accelerated to 29 mph before decelerating to a stop over the course of 3,464 ft, which is 544 ft longer than the locomotive engineer would take to stop the train under the same circumstances.

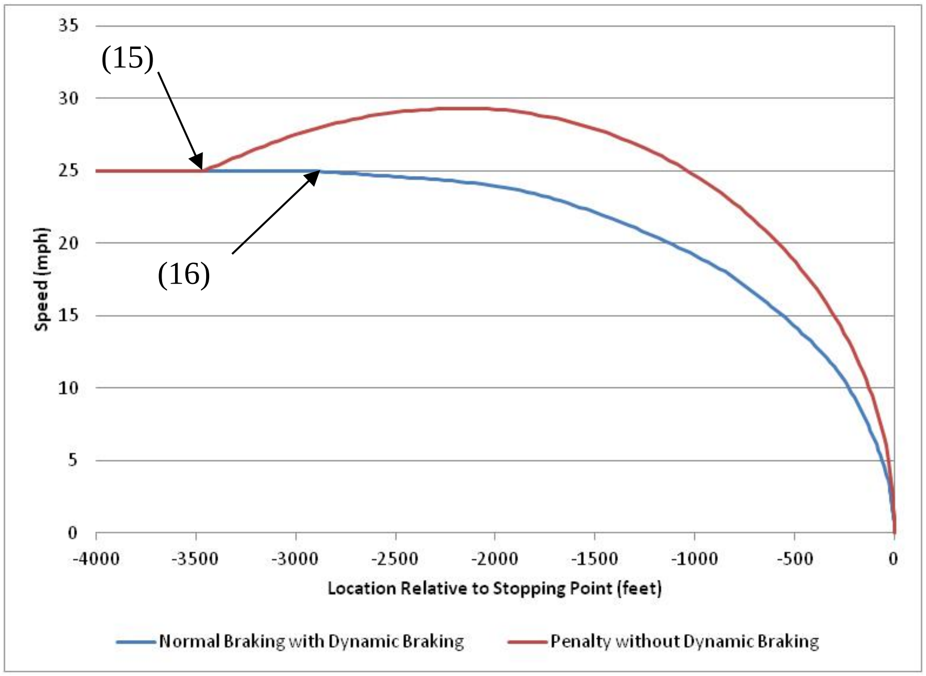


Figure 13. Comparison of Stopping Profiles for Normal Braking with Use of Dynamic Brake and Penalty Braking without Use of Dynamic Brake

Figure 13 shows that, by not taking dynamic brakes into account, the enforcement algorithm must enforce the train to a stop well before the locomotive engineer would begin to initiate the braking process under normal operating practice. With the additional target offset necessary to ensure the safety objective and the additional time for providing warning to the locomotive engineer, the additional distance required to stop the train could be significant, clearly contributing to the operational inefficiency of the system.

11.2 Safety Considerations Regarding Dynamic Brake Failure

The reason that PTC enforcement algorithms have traditionally not considered the use of dynamic brake is that, unlike the air brake system, there is the potential that the dynamic brake system would fail to a state where it would provide no braking. This is logical if no dynamic brake is being used prior to the PTC enforcement, where depending on the dynamic brake to be available for use as a method of enforcement could result in a significant risk. However, if the dynamic brakes are already being used to maintain the speed of the train on a decline grade, the likelihood of the dynamic brakes failing right at the point of PTC enforcement is extremely low. For this reason, it is practical to assume that any dynamic brake currently being used will remain following the PTC penalty enforcement, but that no additional dynamic brake will be assumed than is currently being used. For the example illustrated in Figure 13, it takes 1,901 ft to stop the train with a penalty brake application, if the dynamic brake setting is not changed from the setting required to maintain the speed on the grade, a distance 920 ft less than the locomotive engineer would take to stop the train using normal braking procedures.

Despite how unlikely it may be, it is still possible for the dynamic brake to fail, or for the locomotive engineer to release the dynamic brake right at the point of PTC enforcement. However, with the addition of the emergency brake backup function, the train can still be stopped short of the target stopping location in these unlikely scenarios. Using the example of a loaded, 135-car unit aluminum coal train operating on a 1.1 percent decline at 25 mph, the TOES simulation results demonstrate that this risk is mitigated with the emergency brake backup function as illustrated in Figure 14.

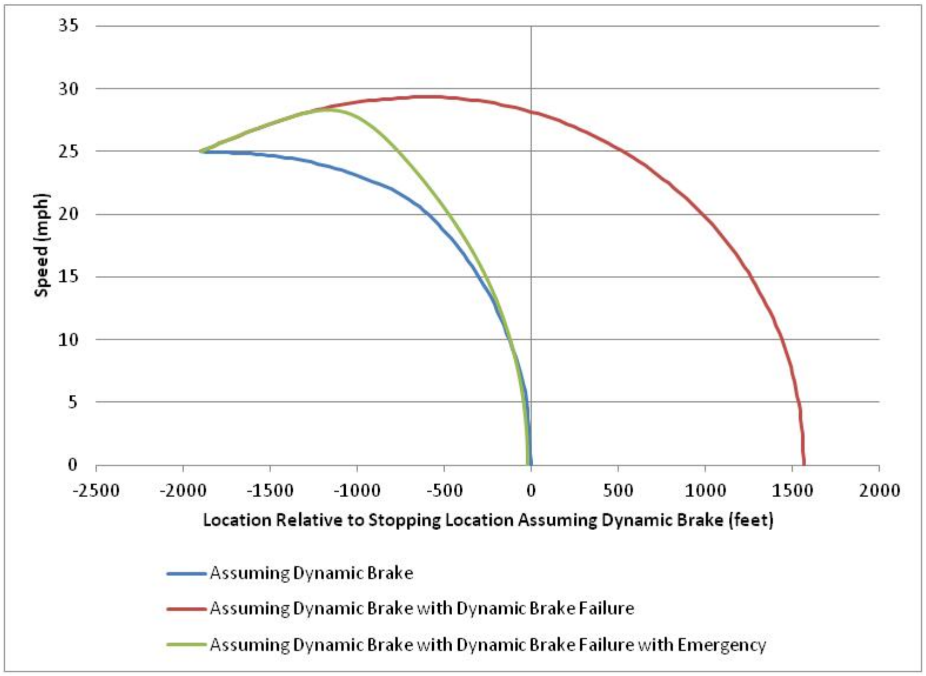


Figure 14. Comparison of Stopping Locations with Dynamic Brake Failure and Emergency Brake Backup

The blue curve shows the stopping profile for this scenario if the level of dynamic braking currently used to maintain the speed of the train is assumed to remain after the penalty brake enforcement. The red curve shows the stopping profile if the level of dynamic braking currently used to maintain the speed of the train is assumed to remain after the penalty brake enforcement, but the actual level of dynamic braking is zero, either from dynamic brake failure or from the locomotive engineer manually releasing the dynamic brake right at the point of penalty enforcement. In this case, the point of enforcement is the same as for the blue curve, but the stopping location is 1,564 ft past the stopping location if the dynamic braking had remained. The green curve shows the stopping profile if the level of dynamic braking falls to zero immediately following the penalty brake enforcement and the emergency brake function takes over. In this case, the emergency brake was applied 13 seconds after the initial penalty application to stop the train at approximately the same location as if the dynamic brake had been maintained.

Feedback from the locomotive on the status of the dynamic brake circuit is readily available, because it is passed from trailing locomotives using the 27-pin MU cable. If, for any reason, the dynamic brake circuit goes inactive after the penalty, the enforcement algorithm could enforce an emergency brake application before the train began accelerating uncontrollably. Furthermore, since the emergency brake backup function predicts the stopping location with an emergency brake application given the current conditions, it would still apply the emergency brake backup to stop the train safely short of the target stopping location even in the event the dynamic brake fails and the feedback from the locomotive indicates it is still active.

11.3 Development of Modifications for Handling Use of Dynamic Brake

Using the logic and rationale discussed above, a function was developed to estimate the current level of dynamic braking in use and use it in the stopping distance prediction of the enforcement algorithm. To develop the methodology for estimating the current level of dynamic braking in use, several options were considered, from the availability and accuracy of data that could be used. Data on the status of the dynamic brake circuit, as well as the dynamic brake control voltage are readily available, because they are transferred on the 27-pin MU cable. Estimated dynamic brake effort and/or traction motor current are more difficult to obtain, particularly from trailing or remote (distributed power) locomotives (the subject of available locomotive data and interfaces is discussed more thoroughly in Section 14). Because of this, it was determined that a function that could estimate the level of dynamic braking currently in use on the basis of the status of the dynamic brake circuit and the forces and acceleration of the train would be best suited.

The method for estimating the current acceleration of the train was designed from the development work performed on the brake efficiency adaptive function, discussed in Section 6.3. Similar to this function, the raw acceleration data is prone to noise from both the method and frequency of measurement. Therefore, the two-step averaging filter used in the brake efficiency adaptive function was implemented here to ensure a sufficient level of accuracy in the estimation of the acceleration. As described in Section 6.3, the acceleration data is averaged over the previous three data points to handle short-term spikes in the data as the first step in filtering. The averaged acceleration dataset is then filtered according to a least-squares line regression method to further smooth over the entire set of data. In the case of the brake efficiency adaptive function, data is collected over the entire time a brake application is held, to estimate the level of braking available for later stopping distance predictions. In the case of the dynamic brake estimation function, the data is used to estimate the level of dynamic braking at that point in time for use in the current stopping distance prediction. Therefore, the data collection period was minimized, so that the data could be available as soon as possible. It was determined that 10 data points were necessary to compute a reasonably accurate estimate of the actual train acceleration.

The current acceleration is then used, along with estimates of the other forces currently acting on the train, determined elsewhere in the enforcement algorithm, to compute any additional resistive force that is unaccounted for in the equation of motion. If the feedback from the locomotive indicates that the dynamic brake circuit is active, this additional resistive force can be attributed to the level of dynamic braking currently in use.

The setting of the dynamic brake is assumed to remain constant throughout the penalty stopping distance prediction, but the actual dynamic brake force varies as the speed changes. This is because the response of the dynamic brake system is not constant across all speeds. Figure 15 shows an example of the dynamic brake force produced over a range of speeds by a typical alternating current (AC) locomotive with extended range dynamic brakes, and Figure 16 shows an example of the dynamic brake force produced over a range of speeds by a typical direct current (DC) locomotive with extended range dynamic brakes. As both figures show, the dynamic brake force is zero at zero speed, but rises to a maximum level at a relatively low speed. For the AC locomotive in Figure 15, this level of dynamic brake force is maintained as speed increases until approximately 20 mph, at which point the dynamic brake force decays exponentially as speed increases. For the DC locomotive in Figure 16, there is a saw-tooth shape to the curve until approximately 25 mph, at which point the dynamic brake force decays exponentially as speed increases.

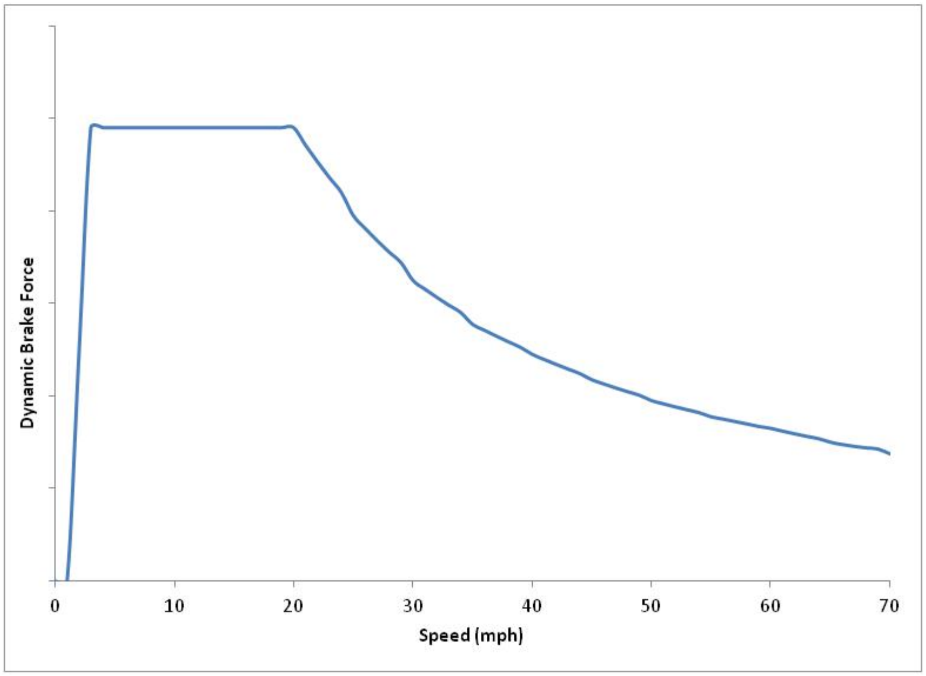


Figure 15. Example Dynamic Brake Curve for AC Locomotive

To properly estimate the amount of dynamic brake force in the stopping distance prediction, it is necessary to model the dynamic brake force response with regard to train speed at each time step in the prediction. The specific dynamic brake curves vary from one locomotive to another, but they all follow the same general shapes shown in Figures 15 and 16 for locomotives with extended range dynamic brakes. For locomotives without extended range dynamic brakes, the curves increase linearly from zero to the maximum point where the curve begins to decay exponentially. Because the vast majority of road locomotives today are equipped with extended range dynamic brakes, those without were not included in the development of the function.

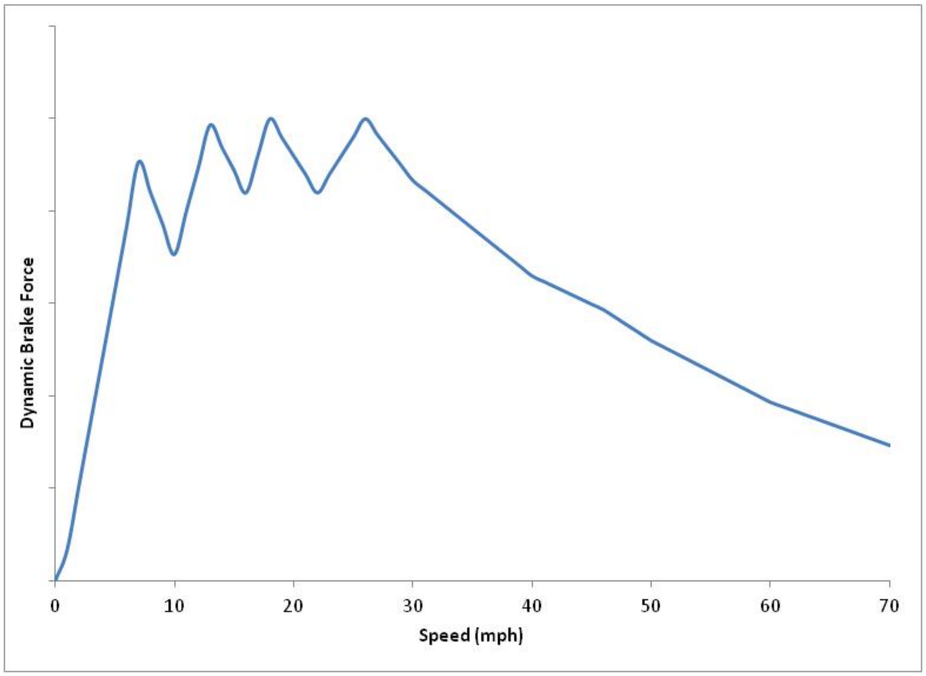


Figure 16. Example Dynamic Brake Curve for DC Locomotive

Using a set of best fit curves for a sample of dynamic brake curves from various different locomotive types, a dynamic brake force shape function was developed to scale the estimated dynamic brake force currently in use according to the predicted speed of the train at each time step in the prediction. The function assumes zero dynamic brake force up to 5 mph, a constant level of dynamic brake force between 5 and 20 mph, and an exponentially decaying level of dynamic brake force as speed increases beyond 20 mph. The dynamic brake force currently in use is divided by the value of this dynamic brake force shape function at the current train speed to generate a dynamic brake calculation coefficient. This coefficient is then multiplied at each time step of the stopping distance prediction by the value of the dynamic brake force shape function for the train speed at the given time step of the stopping distance prediction, to estimate the level of dynamic brake force at that time step of the prediction.

To ensure the function developed performed reasonably well in predicting the amount of dynamic brake force throughout the range of speeds, the function was tested using the TOES model for a variety of locomotive types, speed ranges, and dynamic brake settings. For each configuration, the train was stopped in the TOES model using locomotive dynamic brake only, and the function was used to determine the stopping distance with dynamic brake only. The two were compared and the function closely predicted the stopping distance in each case. Where there was error between the two, the dynamic brake force shape function always predicted less dynamic brake force for a longer stopping distance, showing that the function is a conservative estimate of the dynamic brake force actually produced throughout the stopping profile.

11.4 Field Testing Dynamic Brake Function

Field tests were performed using both the base enforcement algorithm and the developmental algorithm with the dynamic brake function, in order to demonstrate the performance benefits that can be seen by using the current dynamic brake status in the enforcement algorithm. Because dynamic brake is typically used to control the speed of the train on decline grades, all of these tests were performed on the decline grade on the RTT. In each case, the train was accelerated to the test speed and the dynamic brake notch was increased to that necessary to maintain the speed of the train with no use of the air brakes.

The following two types of tests were performed during the dynamic brake testing:

- Safety — These tests are designed to demonstrate that the algorithm safely stops the train short of the target. In these tests, the train is allowed to proceed toward the target with no intent to stop, such that the enforcement algorithm must enforce a penalty brake application to stop the train short.
- Performance — These tests are designed to demonstrate how the algorithm does or does not interfere with normal crew actions to stop the train safely short of the target. In these tests, the locomotive engineer stops the train short of the target using normal operating procedures, including the use of dynamic brake.

Table 21 shows the test cases that were used in the field testing of the dynamic brake function as well as the resulting stopping locations and penalty enforcement locations for both the base algorithm and the developmental algorithm with the dynamic brake function included.

Table 21. Dynamic Brake Function Field Test Results

Test Conditions			Average Stopping Location Relative to Target (ft)		Average Enforcement Location Relative to Target (ft)	
Consist	Speed (mph)	Test Type	Base Algorithm	Dynamic Brake Function	Base Algorithm	Dynamic Brake Function
10 Cars – Loaded	30	Safety	-3,013	-888	-5,489	-3,286
10 Cars – Loaded	30	Performance	-3,656	-655	-5,462	-955
40 Cars – Loaded	30	Safety	-2,360	-810	-5,114	-2,887
40 Cars – Loaded	50	Safety	-3,371	-1,640	-9,879	-7,115
80 Cars – Loaded	10	Safety	-1,169	-597	-1,950	-1,430
80 Cars – Loaded	10	Performance	-873	-243	-1,450	N/A
80 Cars – Loaded	30	Safety	-2,092	-1,137	-4,984	-4,045

As the data in Table 21 shows, the algorithm equipped with the dynamic brake function enforced the train later and stopped the train closer to the target in all cases, and dramatically so in many cases. For example, in the case with 40 cars traveling 50 mph, the developmental function enforced a penalty brake application over 2,700 ft later than the base algorithm, but still stopped the train safely short of the target. In an actual operation, this would give the train crew an additional 38 seconds to start acting to slow the train down before being enforced, which can have a significant impact on the line capacity. Additionally, in the slow speed (10 mph) performance case with 80 cars, the dynamic brake function did not interfere with the locomotive engineer, who stopped the train 243 ft short of the target, but enforced a penalty brake application nearly 1,500 ft short of the target with the base enforcement algorithm.

In addition to the test results shown in Table 21, each of the safety test scenarios was run with the development algorithm and simulating a failure of the dynamic brake at the point of enforcement. In each of these tests, the dynamic brake was reduced to idle directly following the penalty application. Table 22 shows the results of these tests. In all of these tests, the emergency brake backup function responded by applying the emergency brake and stopping the train safely short of the target. These tests both illustrate the need to consider dynamic brake in the enforcement algorithm and show that it can be done safely.

Table 22. Dynamic Brake Function with Simulated DB Failure Field Test Results

Test Conditions		Average Stopping Location Relative to Target (ft)	Average Enforcement Location Relative to Target (ft)
Consist	**Speed (mph)**		
10 Cars – Loaded	30	-415	-3,744
40 Cars – Loaded	30	-554	-2,856
40 Cars – Loaded	50	-294	-7,573
80 Cars – Loaded	10	-147	-1,321
80 Cars – Loaded	30	-772	-3,769

12. Evaluation of Phase 2 Developmental Algorithm

The Phase 2 developmental algorithm consists of all the modifications and additions to the base algorithm from the first phase of development, discussed in Sections 5, 6, 7, and 8, with the additional functions from the second phase of development, discussed in Sections 10 and 11. These additional functions include the dynamic brake and locomotive brake functions. Appendix F defines each of the Phase 2 algorithm functions within the context of the final developmental algorithm. Although the document included in Appendix F also includes modifications developed in Phase 3; these were not in place during the evaluation of the Phase 2 algorithm.

Simulation testing and analysis was performed on the Phase 2 algorithm using the methodology described in Section 2.2. As with the Phase 1 algorithm, the Phase 2 algorithm was only tested with unit trains, because improvements for manifest freight and intermodal freight trains were not included until the third phase of development. Table 23 shows the overall results of the simulation testing for unit trains with the Phase 2 algorithm. This table includes the probability of stopping short of the target and the probability of stopping short of the performance limit, defined as stopping short of the target by less than 500 ft for speeds < 30 mph and 1,200 ft for speeds ≥ 30 mph. Appendix I contains the detailed results from simulation testing of the Phase 2 algorithm.

Table 23. Phase 2 Algorithm Simulation Test Results

Train Type	Probability of Stopping Short of Target	Probability of Stopping Short of Performance Limit
Unit Freight	99.57%	7.59%

The data in Table 23 shows that the Phase 2 developmental algorithm meets the safety objective of stopping short of the target more than 99.5 percent of the time, and the probability of stopping short of the performance limit was reduced to 7.59 percent from 31.98 percent in the Phase 1 algorithm. A look into the details of the results of the analysis indicates that the improvement in the performance objective can be attributed primarily to incorporation of the dynamic brake function. This is apparent from the reduction in the probability of stopping short of the performance limit for scenarios on descending grades, where the dynamic brake is used to control the speed of the train. With the addition of this function, along with those developed in the first phase, the operational efficiency of the algorithm can improved to the point where trains will stop short of the performance limit only in very few circumstances.

13. Manifest Freight and Intermodal Freight

Having developed functionality to improve the safety and operational efficiency of the enforcement algorithm and demonstrated the improved performance for unit trains, the next task was to expand the scope of the enforcement algorithm to handle other typical train types including manifest freight and intermodal freight trains. The majority of the prediction logic remains the same for all train types; however, the braking performance and the variability in braking performance for these other train types can be significantly different than for unit trains. Additionally, more car types, including multiple-platform articulated cars must be handled by the enforcement algorithm for these train types.

13.1 Assumptions for Unknown Parameters for Manifest Freight and Intermodal Freight Equipment

The enforcement algorithm must make assumptions for some of the unknown parameters in predicting the stopping distance of the train, as discussed in Section 5.2. In the case of the base enforcement algorithm, these assumptions were generally more conservative, and modifications to these assumptions were made for unit trains to provide a more nominal prediction. Two of these assumptions, the nominal car brake force and the brake pipe propagation time, were modified to assume the center of the range of possible values. This same logic was applied to manifest freight and intermodal freight train types, as well.

13.1.1 Nominal Car Brake Force

In the case of nominal car brake force, several assumptions were made in the unit train analysis that do not necessarily apply to manifest freight and intermodal freight cars. First, the assumption that for a loaded train, every car is loaded to the maximum allowable GRL does not apply to train types other than unit freight. Many times, cars in these other train types are partially loaded, or the maximum volume is reached before the maximum weight is. Therefore, the average net brake ratio for the train type cannot be used to determine the nominal car brake force, because the trailing weight of the train may not be the maximum allowable GRL. Instead, the average net brake force for the possible car types must be assumed. However, with the introduction of multiple-platform articulated cars, assuming the average net brake force for the car can lead to problems as well. This is because the average net brake force for a multiple-platform articulated car may be much higher than a typical single-platform car, because of the increased load it can handle with the additional axles and platforms. Assuming the nominal brake force per axle, rather than by car, eliminates this problem, and the same assumption can apply to both single-platform and multiple-platform cars. Using this logic, the assumption for nominal brake force was changed from the nominal car brake force to the nominal axle brake force.

To determine the value for the nominal axle brake force for manifest freight and intermodal freight train types, the same basic process used for unit freight trains was followed. First, the average loaded net brake force for each train type was determined by individually examining each of the car types that can make up the given train type. For each of these car types, bins were defined according to the date ranges that a particular version of the AAR standard for net brake ratio was in effect for. For each of these bins, the minimum and maximum loaded net brake force per axle was determined, both for cars equipped with empty/loaded devices and for cars not equipped with empty/loaded devices, using the range of brake ratios allowed by the given version of the AAR standard, the assumption that the brake ratio can fade by 1 percent over time [7, 11], the average GRL and tare weight for the car type, and the number of axles for the car type.

For each car type, the average loaded net brake force per axle was determined by combining the average loaded net brake force per axle for each bin, using UMLER data for the probability that a given car of that type fits into each bin and the probability that the given car type is equipped with an empty/loaded device. The average empty net brake force was determined the same way, except that the loaded net brake force per axle was divided in two for the case where the car is equipped with an empty/loaded device, representing a 50 percent reduction in brake shoe force from the empty/loaded device when the car is empty.

Finally, to determine the nominal loaded and empty net brake force per axle for each train type, the average loaded and empty net brake force per axle were each averaged for all of the car types that could make up the given train type. In some cases, certain car types were left out of the average because they had an average net brake force per axle that was significantly higher than the other car types for the train type. These values were left out to ensure a safe assumption for all of the car types that make up the train type. For consistency, the loaded and empty nominal car brake forces for unit trains were converted into loaded and empty nominal brake forces per axle by dividing the nominal car brake forces determined earlier in the project (see table 13 in Section 5.2.1) by the number of axles on the unit car types, 4. Table 24 shows the final, revised assumption for the nominal brake force per axle for each train type, with W_{CARS} equal to the weight of the cars in lb and N_{AXLES} equal to the total number of car axles.

Table 24. Revised Nominal Car Brake Force for Unit Trains

Train Type	Nominal Loaded Car Brake Force	Nominal Empty Car Brake Force
Unit Aluminum Coal	$\frac{0.11 * W_{CARS}}{N_{AXLES}}$	3,975
Unit Freight	$\frac{0.093 * W_{CARS}}{N_{AXLES}}$	4,962
Manifest Freight	5,870	5,044
Intermodal Freight	6,895	3,746

13.1.2 Brake Pipe Propagation Time

As discussed in Section 5.2.2, the brake pipe propagation time is determined using a function of the length of the train. For unit trains, this function was determined by running a series of TOES simulations for each unit train type for a variety of train lengths. For each series of simulations, the control valve types and ambient conditions were varied according to the distributions of possible values for the given train type. This methodology was applied to manifest freight and intermodal freight train types as well. For these cases, a wider range of simulations were performed, however, to account for the wider variations in train makeup.

As with the development of the brake pipe propagation time for unit trains, the results of these simulations were analyzed using train length, and a best fit regression curve was developed. The final, revised brake pipe propagation time for all train types is:

$$T_{APPLY} = \begin{cases} 13 + 0.01179L_{TRAIN} + 0.000000256L_{TRAIN}^2 & for\ Unit\ Trains \\ 15.6 + 0.0084792L_{TRAIN} + 0.000000801L_{TRAIN}^2 & for\ Manifest\ Freight\ Trains \\ 16.66 + 0.006871L_{TRAIN} + 0.0000001331L_{TRAIN}^2 & for\ Intermodal\ Trains \end{cases}$$

Enforc

13.2 Development of Target Offset Functions for Manifest Freight and Intermodal Freight

An improved function for estimating the target offset necessary to offset the nominal stopping distance prediction to achieve the safety objective for unit trains was developed using Monte Carlo simulation techniques and statistical regression methods, as discussed in Section 5.3. This same process was used to develop similar functions for the manifest freight and intermodal freight train types.

As with the Monte Carlo simulation process for unit trains, a large test matrix covering a wide range of scenarios was necessary for manifest freight and intermodal freight train types, as well. Because of the wider variation of train makeup and loading conditions for these train types, the number of simulations was even greater than for unit train types. For manifest freight, the simulation test matrix included 114 different train makeup and loading conditions, 10 different train speeds, and eight different track grades, with a total of 4,207 test scenarios. For intermodal freight, the simulation test matrix included 70 different train makeup and loading conditions, 12 different train speeds, and eight different track grades, with a total of 3,570 test scenarios. For each scenario, 100 simulations were run with Monte Carlo variance of the parameters that can affect train stopping distance.

As for the unit train types, statistical analyses were used to identify the target offset necessary to achieve the safety objective for each manifest freight and intermodal freight test scenario simulated. A multiple-variable regression technique was then employed to develop the functions to estimate the target offset for any given scenario for all train types.

For manifest freight and intermodal freight trains, two functions were developed for each, depending on whether the train is operating with head end power only or distributed power. Each is a function of the velocity, v, the equivalent constant grade over the predicted stopping distance, g, the trailing weight in tons, W_{CARS}, the total number of axles on the train, n_{TOTAL}, the number of loaded cars, N_{LOAD}, and the number of empty cars, N_{EMPTY}.

For manifest freight trains operating with distributed power, the target offset, TO, is equal to:

$$TO = e^{0.0457v - 0.36g + 0.0000278W_{CARS} - 0.00795n_{TOTAL} + 0.03364N_{LOAD} + 0.03223N_{EMPTY} + 3.568}$$

Start

For manifest freight trains with head end power, the target offset, TO, is computed from one of three equations, depending on the equivalent constant percent grade over the predicted stopping distance, g:

$$TO = \begin{cases} TO_{DEC},\ if\ g \leq -0.5 \\ \left(1 + \frac{g}{0.5}\right) * TO_{INC} - \frac{g}{0.5} * TO_{DEC}\ ,\ if - 0.5 < g < 0 \\ TO_{INC},\ if\ g \geq 0 \end{cases} \tag{17}$$

Where the values for incline and decline are determined from the following two equations:

$$TO_{DEC} = \ (0.475v - 1.03g + 0.0004W_{CARS} + 0.0031n_{TOTAL})^2 \tag{18}$$

$$TO_{INC} = \ (0.436v - 2.12g + 0.00011W_{CARS} + 0.0037n_{TOTAL})^2 \tag{19}$$

For intermodal freight trains with distributed power, the target offset, TO, is equal to:

$$TO = \ (0.338v - 2.031g + 0.0000475W_{CARS} + 0.00605n_{TOTAL})^2 \tag{20}$$

For intermodal freight trains with head end power, the target offset, TO, is equal to:

$$TO = \ (0.335v - 2.412g + 0.0000415W_{CARS} + 0.00445n_{TOTAL} + 2.024)^2 \tag{21}$$

13.3 Field Testing with Manifest Freight Equipment

To verify the performance of the final developmental enforcement algorithm with train types other than unit, field testing was performed using manifest freight equipment. Unit freight equipment is generally available for testing at TTC, from the train used in the FAST program. However, manifest freight and intermodal equipment is not generally available as a complete train. Therefore, 74 empty general freight cars were sent to TTC by the UPRR to support this testing. The cars were a mix of covered hoppers, box cars, flat cars, gondolas, and refrigerated box cars used in general freight service. These cars had a variety of braking system components and configurations, making for a good range of car types to be included in the test consist. Because manifest freight trains generally have a mix of loaded and empty cars, some of the cars from the FAST train were used in combination with the empty manifest freight cars to create more realistic consists.

The enforcement algorithm was tested using the manifest freight train covering a wide range of test scenarios to demonstrate its safety and performance characteristics. The test scenarios included a range of train lengths, train speeds, track grades, as well as brake system states. Each of the test scenarios was repeated multiple times to demonstrate the consistency of the enforcement algorithm. Table 25 shows the test scenarios and resulting average stopping location relative to the target for each.

As the data in the table indicates, the train stopped short of the target stopping location in all test cases. Additionally, the train stopped within the performance target of stopping within 500 ft of the target when the train speed is < 30 mph and within 1,200 ft of the target when the train speed is $\geq$ 30 mph in all test cases. Both the safety and performance characteristics of the enforcement algorithm with the manifest freight test train was shown to be acceptable, and far better than that of the base algorithm.

Table 25. Manifest Freight Field Test Results

Test Conditions				
Consist	**Speed (mph)**	**Track Grade**	**Brake System State**	**Stopping Location Relative to Target (ft)**
94 Cars – 20 Loaded, 74 Empty	10	Flat	Fully Charged	-57
94 Cars – 20 Loaded, 74 Empty	30	Flat	Fully Charged	-334
94 Cars – 20 Loaded, 74 Empty	50	Flat	Fully Charged	-783
94 Cars – 20 Loaded, 74 Empty	30	Decline	Fully Charged	-230
94 Cars – 20 Loaded, 74 Empty	30	Decline	Applied	-233
94 Cars – 20 Loaded, 74 Empty	30	Incline	Fully Charged	-125
94 Cars – 20 Loaded, 74 Empty	30	Crest	Fully Charged	-163
40 Cars – 10 Loaded, 30 Empty	30	Flat	Fully Charged	-267
40 Cars – 10 Loaded, 30 Empty	50	Decline	Fully Charged	-719
10 Cars – 3 Loaded, 7 Empty	30	Flat	Fully Charged	-304
10 Cars – 3 Loaded, 7 Empty	30	Decline	Fully Charged	-700

14. Research on Available Locomotive Data and Interfaces

The enforcement algorithm software is contained within the locomotive onboard component of the PTC system. In order to function, the onboard component must interface with the locomotive in near real time to provide a variety of data elements to the enforcement algorithm. These data elements are required for stopping distance prediction and to initiate air brake applications when triggered by the enforcement algorithm to enforce an authority or speed limit. Although many of the data elements and interfaces required have been addressed by those involved with PTC system development and deployment, many of the functions proposed for improving the safety and operational performance of the enforcement algorithm involve additional data elements and interfaces that may not have been planned for.

Additionally, it is recognized that various types of locomotives of various vintages may be required to have PTC onboard equipment operating on them. Although some of the data elements and interfaces required by the enforcement algorithm may be readily available on certain types of locomotives, access to the information or system on other locomotives may require additional hardware or software components. In addition, some data elements must also be acquired from trailing or distributed power remote locomotives.

The purpose of this task was to identify the locomotive data elements and interfaces, both required and optional, for implementation of an improved enforcement algorithm, to define classes of locomotives using the availability of these data elements and interfaces, and to research and test methods for acquiring and using the identified data elements and interfaces on the various classes of locomotives defined.

14.1 Identification of Locomotive Data and Interfaces for Improved Enforcement Algorithm

The first component of this task was to identify which locomotive data elements are required for the enforcement algorithm, and which locomotive data elements could potentially be used to improve the performance of the enforcement algorithm, should they be available. The following elements were identified as being required by the enforcement algorithm:

- Head-end train location — Required for predicting the stopping location of the train
- Tail-end train location — Required for estimating the grade and curvature forces acting on the train throughout the predicted stopping profile of the train
- Train speed — Required in predicting the stopping location of the train
- Head-end brake pipe pressure — Required for determining the current state of the air brake system
- Tail-end brake pipe pressure — Required for estimating the pressure available in the air brake system

The following locomotive data elements were identified as having the potential to improve the enforcement algorithm performance, should they be available:

- Locomotive throttle notch — Could potentially be used to estimate tractive effort produced, which could be used to estimate train resistance

- Dynamic brake status — Could be used to determine if the dynamic brakes are active, which is necessary if the algorithm assumes that dynamic brakes will remain active after PTC enforcement
- Dynamic brake control voltage — Could potentially be used to estimate dynamic brake effort, which could be used to estimate train resistance, as well as to estimate the level of dynamic braking that will remain after PTC enforcement if the algorithm assumes such
- Tractive and dynamic brake effort — Could be used to estimate train resistance and to estimate the level of dynamic braking that will remain after PTC enforcement if the algorithm assumes such
- Status of distributed power communications — Necessary if the algorithm assumes faster propagation time when distributed power communication is active

In order to acquire the data elements listed above, and to initiate air brake applications, the following interfaces to the locomotive are, or may be, required:

- Brake system — Required for initiating PTC penalty brake application, emergency brake application (if the algorithm uses an emergency brake backup function), and for providing head-end brake pipe pressure
- End-of-train head end unit — Required for providing tail-end brake pipe pressure
- 27-pin MU cable data — Required for providing locomotive throttle notch, dynamic brake status, and dynamic brake voltage
- Location determination system — Required for providing accurate head-end location and train speed
- Locomotive computer — Required for providing current tractive effort and dynamic brake data, as well as train speed
- Locomotive traction motor electrical data — Required for estimating current tractive effort and dynamic brake data
- Distributed power communications status — Required for determining whether distributed locomotives will assist with propagation of brake signal

14.2 Definition of Classes of Locomotives for PTC Enforcement Algorithms

It was recognized that PTC onboard systems and enforcement algorithms may be required on a variety of types of locomotives, with potentially different data elements and interfaces available. The objective of this component of the research task was to identify the distinguishing features of the various locomotive types that define the different classes of locomotives with regard to data and interfaces available for PTC enforcement algorithms.

The following primary distinguishing features of locomotives currently in use by North American freight railroads were identified:

- Type of traction system, AC or DC
- Type of brake system, electronic or pneumatic

- Type of control system, computer-controlled (digital logic) or module-controlled (analog logic)

Each of these distinguishing features was considered with regard to each of the data elements and interfaces listed in the previous section to determine what, if any, implication the feature may have on the given data element or interface. Table 26 shows which of the data elements and interfaces are affected by each of the distinguishing locomotive characteristics. For the majority of the data elements, it was determined that the various locomotive distinguishing characteristics did not affect them measurably, with the exception of tractive effort/dynamic brake effort. In this case, the type of locomotive control system will affect the type of data available. For newer, computer-controlled (digital logic) locomotives, the locomotive computer measures and calculates the current tractive or dynamic brake effort, which could be used directly by the enforcement algorithm. For older, module-controlled (analog logic) locomotives, only the traction motor electrical data (e.g., traction motor current) is available for estimating tractive and dynamic brake effort. This difference has the potential to affect the performance of the enforcement algorithm, if the data is required.

Table 26. Data Elements/Interfaces Affected by Locomotive Characteristics

Data Element/Interface	Type of Traction System	Type of Brake System	Type of Control System
Head-end train location			
Tail-end train location			
Train speed			
Head-end brake pipe pressure			
Tail-end brake pipe pressure			
Throttle notch			
Dynamic brake status			
Dynamic brake voltage			
Tractive effort/dynamic brake effort			Type of data available is different
Distributed power communications status			
Brake system interface		Interface is different	
End-of-train head end unit interface			Interface may be different
27-pin MU cable data interface			Interface may be different
Location determination system interface			
Locomotive computer interface			No interface on module-controlled locomotives
Locomotive traction motor data interface			
Distributed power communications status interface			Interface may be different

In the case of the interfaces, many are affected by the type of control system. The interface to the end-of-train head end unit, 27-pin MU cable data, and distributed power communication status may all be different on computer-controlled (digital logic) locomotives than on module-controlled (analog logic) locomotives, because these functions may be integrated into the locomotive computer on computer-controlled (digital logic) locomotives. Additionally, the interface to the brake system is different depending on the type of brake system (electronic or pneumatic). Although the specific interfaces may be different in all of these cases, which will affect implementation of the onboard hardware, none of these differences are expected to have any effect on the performance of the enforcement algorithm.

From this analysis, there are effectively four classes of locomotives with regard to PTC enforcement algorithms, as follows:

- Computer-controlled (digital logic) locomotives with electronic brake systems
- Computer-controlled (digital logic) locomotives with pneumatic brake systems
- Module-controlled (analog logic) locomotives with electronic brake systems
- Module-controlled (analog logic) locomotives with pneumatic brake systems

14.3 Field Testing to Verify Potential Tractive Effort and Dynamic Brake Data

From the research described in the previous sections, the only data element with the potential to affect the performance of the enforcement algorithm using the class of locomotive it is operating on is tractive and dynamic brake effort data. To provide an indication of the accuracy of the tractive and dynamic brake effort data available with each of the types of locomotive control systems, field tests were performed at the TTC on a small sample of locomotives. The objective of the testing was to collect tractive and dynamic brake effort data and compare these to instrumented coupler data to quantify the accuracy of the available data. The test was not intended to fully evaluate the various options, but rather to qualitatively investigate their applicability to improve the accuracy of stopping distance predictions. This was a high-level study intended to identify what may be available to the braking enforcement algorithm, and how it may be used.

The three following Electro-Motive Diesel, Inc. (EMD) locomotives were selected for the field testing:

- UP3886, an EMD SD70M
- NS2595, an EMD SD70M
- CSX4762, an EMD SD70MAC

With the support of EMD, the computers on each of these locomotives were set up to record the computed tractive and dynamic brake effort data. Additionally, an instrumented coupler was installed in a freight car to measure the coupler force between the last locomotive coupler and the first coupler in the trailing consist.

The testing consisted of two components. In the first component, data was collected from the test locomotives during normal operations at FAST. The FAST train consists of the three locomotives and 80–115 loaded hopper/gondola cars. The FAST train operates on a 2.7-mile loop known as the HTL. The data collected during this component of testing was intended to identify a general level of accuracy, given multiple locomotives, including various types, in a full train application over multiple hours of continuous operation.

The second component consisted of collecting data under specific operating conditions with specific locomotives. In this component, each locomotive was evaluated separately, in operating scenarios including continuous pulling up a grade (measuring tractive effort), and constant braking down a grade (measuring dynamic brake effort). This component of testing was performed on the train dynamics track (TDT) at the TTC. The consist included a single locomotive and 25 loaded cars from the FAST consist. The data collected during this component of testing was intended to identify a general level of accuracy for a single locomotive in a specific operating scenario to help provide a high-level view of the relative accuracy from locomotive to locomotive, as well as to identify any significant differences between AC and DC locomotives. Each test scenario was run multiple times to provide repeatability data for comparison and to increase the overall dataset.

The test scenarios are listed in Table 27.

Table 27. Locomotive Data Test Scenarios

Test Case	Locomotives	Consist	Track
1	All FAST Locomotives	Full FAST Consist	HTL
2	1 SD70M (DC)	25 FAST cars	TDT (incline)
3	1 SD70MAC (AC)	25 FAST cars	TDT (incline)
4	1 SD70M (DC)	25 FAST cars	TDT (decline)
5	1 SD70MAC (AC)	25 FAST cars	TDT (decline)

Following testing, the data from the locomotives and the instrumented coupler was downloaded and some post processing was performed. Specifically, the data from the instrumented coupler exhibited a reasonable level of high frequency noise that was digitally filtered to provide a better comparison to the computed tractive and dynamic brake effort data. Figure 17 shows a comparison of the filtered instrumented coupler data and the tractive effort data computed by each of the three locomotives in the FAST train for approximately one hour of operation on the HTL. The data shows the train starting from a stop and accelerating over the course of several laps around the HTL to a steady-state operational cycle that repeats approximately every four minutes, as the train completes each lap. During each lap, the locomotives pull in throttle notch 8 for approximately 60 percent of the lap, before slowly notching down to throttle notch 4 as the train descends a hill and then notching back up to throttle notch 8 again. These changes in throttle notches account for the large variations in tractive effort throughout each lap. The more subtle variations are the result of the changing speed of the locomotives, where the tractive effort increases gradually as the train ascends the hill and the speed gradually decreases. As Figure 17 shows, the sum of the computed tractive effort for all of the locomotives correlates closely and repeatedly with the filtered instrumented coupler data.

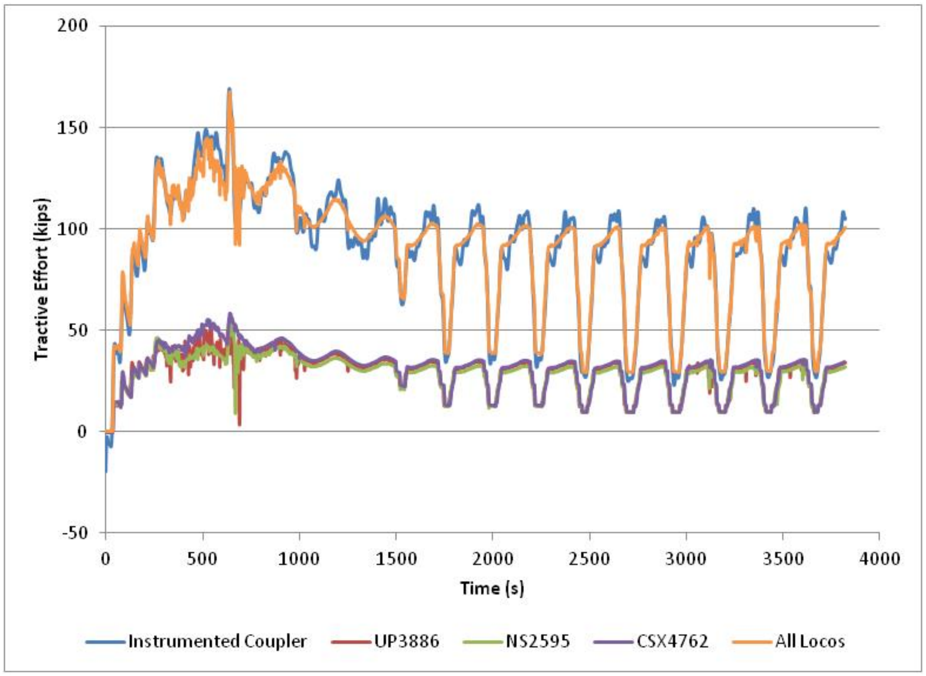


Figure 17. Comparison of Instrumented Coupler and Computed Tractive Effort Data for FAST Train over One Hour of Operation

The only exception to the close correlation is near the locations where the locomotive throttle is notched up or down, where there is a slight difference between the two sets of data. Figure 18 shows the same data as Figure 17, but for a single lap around the HTL. Figure 18 shows a distinct variance between the two datasets at these locations. This is likely the result of differences in the methodology in data acquisition, processing, and filtering that were not taken into account as part of this high-level effort. These differences are relatively small and of relatively short duration, meaning that, should the enforcement algorithm use a sample of data, rather than just a single data point, they should not cause significant issues with calculations from this data. On average, the two datasets are within 3 percent of each other across the range of the datasets that were compared, which is reasonable, given the high-level nature of the data acquisition and processing. The instrumented coupler itself has an accuracy of +/-1 percent of the full scale of 1,000,000 lb, meaning the majority of the differences are within the accuracy of the coupler.

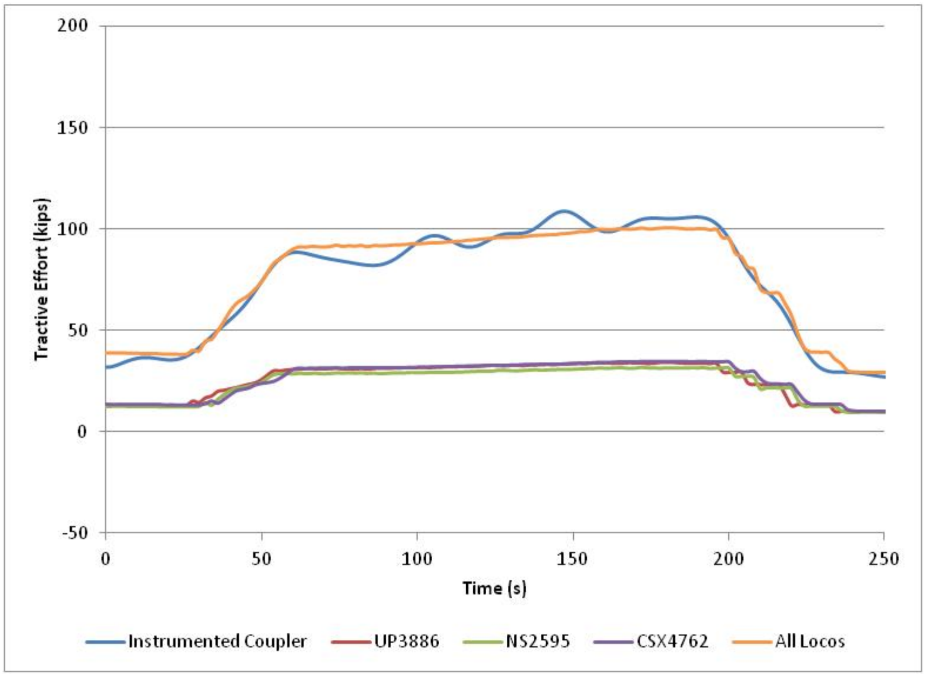


Figure 18. Comparison of Instrumented Coupler and Computed Tractive Effort Data for FAST Train over One Lap of the HTL

Figure 19 shows the filtered instrumented coupler data compared with the computed tractive and dynamic brake effort data for the UP3886 locomotive as it pulls 25 FAST cars over the hill on the TDT and slows the train to a stop. The UP3886 is an EMD SD70M locomotive equipped with a DC traction system. Figure 19 shows the tractive effort with the locomotive throttle notch gradually increasing as the train accelerates up to speed and then gradually increasing as the speed slowly decreases with the train ascending the hill. Near the end of the dataset, the tractive effort falls off quickly as the locomotive throttle notch is decreased to idle, and then dynamic brake is used to slow the train to a stop. The shape of the dataset through the dynamic braking section (the “saw-tooth” shape) is distinctive of the dynamic braking system of a DC locomotive across the speed range.

As with the data from Figure 17, Figure 19 shows good correlation between the instrumented coupler data and the tractive and dynamic brake effort data computed by the locomotive. The only area of any real discrepancy is when the locomotive is in idle at around the 500-second point on the graph. Here, the locomotive correctly shows no tractive effort produced, but the instrumented coupler shows some minimal amount of force. This is likely because the train was cresting the top of the hill at this point, meaning the locomotives were pulling down the hill, while some of the trailing cars were still being pulled up the other side, resulting in some amount of force between the locomotives and the trailing cars.

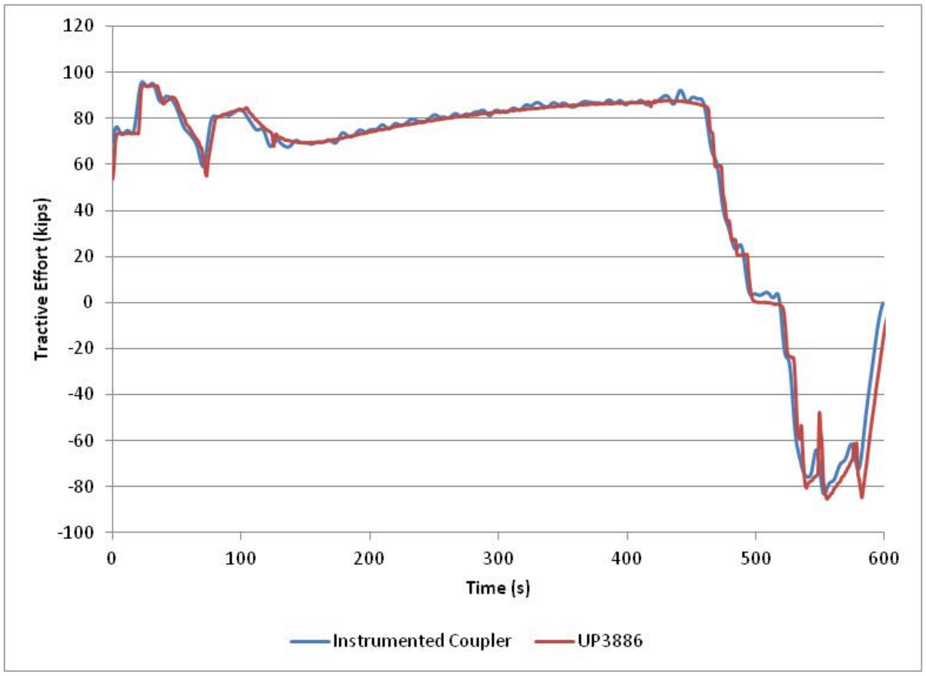


Figure 19. Comparison of Instrumented Coupler and Computed Tractive Effort Data for UP3886 (EMD SD70M)

Figure 20 shows a comparison of the filtered instrumented coupler data compared with the computed tractive and dynamic brake effort data for the CSX4762 locomotive over the same operation. The CSX4762 is an EMD SD70MAC locomotive equipped with an AC traction system. The data in Figures 19 and 20 are very similar, with two exceptions. One difference is the lack of the "saw-tooth" shape for the dynamic brake effort in figure 20. Extended range dynamic brakes exhibit a "flat-top" characteristic curve for AC traction systems. The other difference is there is some discrepancy between the computed dynamic brake effort and the filtered instrumented coupler data during dynamic braking in Figure 20. The reason for this difference is not immediately understood, and because of the high-level nature of this effort, it is not known whether it would occur on all AC locomotives or occurs only with this locomotive. Should this data be necessary for use in a PTC onboard braking enforcement algorithm application, further research should be done to identify implications of the difference observed here.

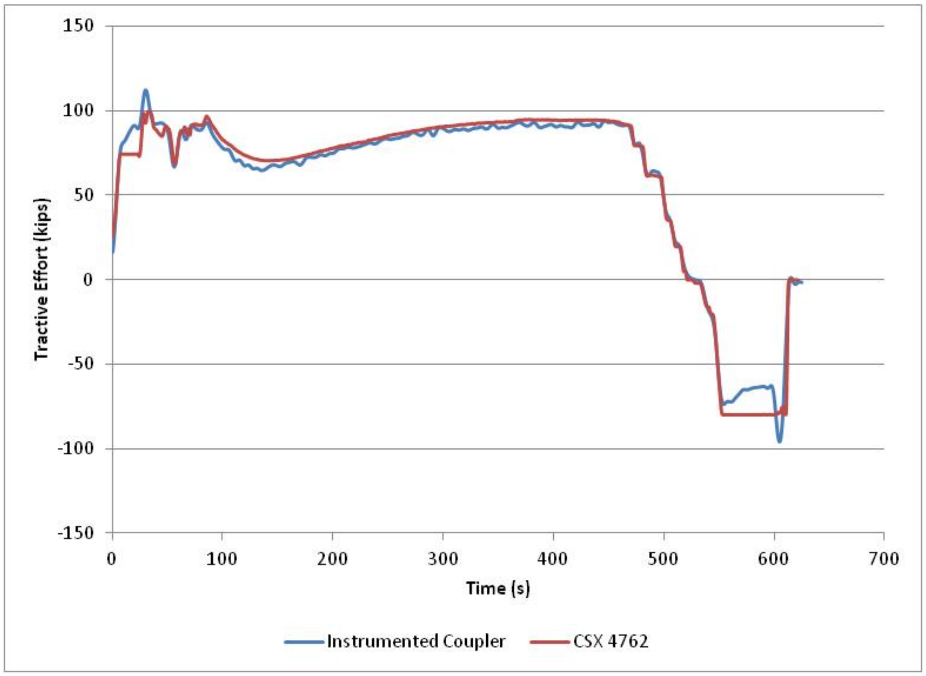


Figure 20. Comparison of Instrumented Coupler and Computed Tractive Effort Data for CSX4762 (EMD SD70MAC)

14.4 Conclusions and Other Considerations Regarding Locomotive Tractive Effort/Dynamic Brake Data

To summarize the results of the field testing, the tractive and dynamic brake effort computed by the locomotive computer was shown to be a very good representation of the actual pulling or resisting force of the locomotives. From this result, this data could be used in the enforcement algorithm for computer-controlled locomotives, if needed. However, to be effective, the data for all locomotives, including trailing locomotives and remote distributed power locomotives, would need to be sent to the onboard system in the lead locomotive. Presently, there is no method for achieving this. There is, however, a federal mandate that all new and rebuilt locomotives must report dynamic brake effort to the lead locomotive. As a result of this mandate, the AAR has developed Standard S-5509, for reporting both locomotive tractive and dynamic brake effort data to the lead locomotive for all trailing locomotives and remote distributed power locomotives in the consist [24]. As new locomotives are phased in and older ones replaced, this functionality will gradually become available.

For module-controlled locomotives where tractive and dynamic brake effort is not computed onboard, the tractive and dynamic brake effort could be estimated from the measured traction motor electrical data that is generally available. Module-controlled locomotives generally report the traction motor current for the second axle of the locomotive to a gauge in the cab, for use by the locomotive engineer during operation of the locomotive. If it is assumed that the same current applies to all traction motors on the locomotive, this value could be multiplied by the number of traction motors on the locomotive to estimate the total traction motor current. Multiplying this value by the main generator voltage will produce an estimate of the total power produced by the traction motors, in watts, when the locomotive is in a throttle notch. When the locomotive is in dynamic brake, the dynamic brake excitation voltage is multiplied by the total traction motor current to estimate the total resistive power of the traction motors, also in watts. Given that 746 watts = 1 horsepower = 550 ft-lb/s, it is possible to determine the force from the estimated power and speed of the locomotive as:

$$F = \frac{550 * \frac{P}{746}}{V * \frac{5280}{3600}} \tag{22}$$

Where F is tractive or dynamic brake force in lb, P is the power in watts, and V is the locomotive speed in mph. Using this methodology, it is conceivable that the tractive or dynamic brake effort for a module-controlled locomotive could be estimated. However, the difficulty of passing this data from trailing and remote distributed power locomotives to the lead locomotive is even more pronounced, because there are no current plans to provide this type of data for these older types of locomotives.

Locomotive tractive effort and dynamic brake effort data has been shown in an earlier study to be useful in estimating the resistance, or weight, of the train [1]. In this study, it was observed that accurately estimating the tractive and dynamic brake effort is the difficulty in performing this estimation. Additionally, if an accurate measure of dynamic brake effort could be made, it could be useful for estimating the level of dynamic braking during the stopping distance prediction.

The techniques researched as part of this task have shown that it is possible to accurately estimate tractive and dynamic brake effort data, particularly with newer computer-controlled locomotives, but that there is still some difficulty in acquiring the data from trailing and/or remote distributed power locomotives. However, it has also been determined, through other tasks of the research program, that the train resistance can be accounted for in the measurement of train braking efficiency, and that the level of dynamic brake effort can be estimated from train acceleration data. With these new developments, the need for accurately estimating the tractive and dynamic brake effort of the locomotive may be unnecessary. However, if future research and development in the area of PTC enforcement algorithms shows a need for this data, the results here indicate a path forward for acquiring it.

15. Evaluation of Final Developmental Enforcement Algorithm

The final developmental algorithm consists of all the modifications and additions from the first two phases of development, discussed in Sections 5-8 and 10-11, with additional modifications to handle manifest and intermodal freight trains. Appendix F defines the complete, final Phase 3 algorithm.

Simulation testing and analysis was performed on the final Phase 3 algorithm using the methodology described in Section 2.2. The final Phase 3 algorithm was tested with all freight train types, including unit, manifest, and intermodal freight trains. However, since none of the additional modifications made during the third phase apply to unit trains, the results of the analysis for the unit train type match those from the analysis completed for the Phase 2 algorithm. Table 28 shows the overall results of the simulation testing for all train types, both individually and combined into an overall result. This table includes the probability of stopping short of the target and the probability of stopping short of the performance limit, defined as stopping short of the target by < 500 ft for speeds < 30 mph and 1,200 ft for speeds ≥ 30 mph. Appendices I and J contain the detailed results from simulation testing of the final Phase 3 algorithm.

Table 28. Phase 3 Algorithm Simulation Test Results

Train Type	Probability of Stopping Short of Target	Probability of Stopping Short of Performance Limit
Unit Freight	99.57%	7.59%
Manifest Freight	97.49% (99.34%)	13.44% (12.62%)
Intermodal Freight	97.85%	3.26%
Overall	98.73% (98.91%)	9.77% (8.24%)

The results of the evaluation for manifest freight trains showed poor results in terms of the probability of stopping short of the target for light engine consists and very short trains (i.e., < 10 cars). An analysis of these cases indicated that an error in the final target offset function was the likely cause. It is recommended that the target offset be modified for these cases and the evaluation repeated as follow-on work to this project. So as not to skew the results of the evaluation for the rest of the analysis, the manifest freight results and overall results are presented in Table 28 without including the light locomotive or 3-car consists, in parentheses.

Table 28 shows that the algorithm ultimately fell short of the safety objective of stopping short of the target 99.5 percent of the time for both manifest and intermodal freight trains. To demonstrate how close the algorithm was to meeting the safety objective for these two train types, an additional metric was calculated to show the location at which there was a 99.5 percent probability of stopping short of, relative to the target. For the manifest freight trains, there was a 99.5 percent probability of stopping short of a location 6 ft past the target. For the intermodal freight trains, there was a 99.5 percent probability of stopping short of a location 31 ft past the target.

A more detailed look at the results reveals there are a few concentrated areas where the probability of overrun was greater than desired that will need to be addressed in order to meet the safety objective. A significant number of overruns occurred with longer trains, which were ultimately attributed to the adaptive brake pipe propagation time function. In these cases, the function calculated a brake pipe propagation time that was well short of the actual brake pipe propagation time. A closer look revealed that this was because the function calculates the brake pipe propagation time with the remote distributed power locomotives cut out, resulting, for these cases, in extreme brake pipe pressure differentials from head end to rear end (i.e., greater than 20 psi), which had unpredictable effects on the function. In actual railroad operations, a train is not allowed to depart the terminal with a brake pipe pressure differential of this magnitude; however, when run with distributed power cut in, the brake pipe pressure differential for these cases was acceptable. This presents an interesting case, where the brake pipe propagation time adaptive function cannot properly calculate the propagation time, because the magnitude of the brake pipe pressure differential is too large with distributed power cut out, yet the train can still operate with distributed power cut in. It is recommended that these issues be looked at and addressed as follow-on work to this project.

The data in Table 28 also shows the operational efficiency of the final developmental enforcement algorithm, with manifest freight trains having a 12.62 percent probability of stopping short of the performance limit and intermodal freight trains having a 3.26 percent probability of stopping short of the performance limit. Although there are a few issues that need to be investigated further, this evaluation shows that the algorithm developed comes very close to meeting both the safety and performance objectives for all cases in the evaluation matrix. This illustrates that a PTC braking enforcement algorithm that is both safe and results in minimal impact on railroad operations is technically feasible.

16. Evaluation of Wabtec Enforcement Algorithm

The primary objective of this program was to develop techniques for an improved braking enforcement algorithm for PTC systems with the goal of applying these techniques to production systems planned for implementation in the North American freight rail industry. As such, one of the tasks of the project was to support implementation of the techniques and evaluation of the resulting enforcement algorithm for a cooperating railroad and their suppliers. BNSF Railway's Electronic Train Management System (ETMS) is a PTC system that has been functioning in both pilot and production modes on select territories for many years. Wabtec, the supplier of the onboard component of ETMS, has also developed the onboard component for what is known as the I-ETMS®, which is currently the PTC system planned for implementation by all of the major Class I railroads in the United States. Therefore, the railroad advisory group and Wabtec supported the effort for implementation of improved methods for predictive braking enforcement and evaluation of the algorithm.

16.1 Development Support

Throughout the project, TTCI, Wabtec, and the railroad advisory group worked together to implement concepts developed to improve the performance of the braking enforcement algorithm. However, because Wabtec is working to develop production software and hardware for supporting PTC implementation on a large scale in accordance with a Federal mandate, the techniques chosen for near-term implementation included only those with a high level of support from railroads and regulators alike. These included a modified target offset function, emergency brake backup, and a function for handling trains with distributed power. It is recognized that other methods may be implemented in time, but these were seen as having the most significant impact on the performance, enabling the successful implementation of the technology while also supporting the implementation schedule.

In parallel with, and independent of TTCI's algorithm research, Wabtec implemented techniques to improve the target offset, add emergency brake backup, and improve distributed power support for use in I-ETMS. With the use of TTCI's recently published research, Wabtec intends to review its algorithm for the potential of additional improvements. Through the course of development at both TTCI and Wabtec, open discussion on performance requirements, conceptual implementation solutions, and design recommendations between TTCI, Wabtec, and the railroad advisory group members worked to contribute to an improved solution.

In addition to supporting the development of new functionality through these discussions, TTCI worked to support Wabtec and the railroads by providing essential feedback on new enforcement algorithm software builds through informal simulation testing. As new functions and modifications to the algorithm logic were made, a number of interim software builds were produced by Wabtec and provided as black box software applications to TTCI for checkout. By running these interim builds through a relatively small batch of simulations representing a variety of operating scenarios, it was possible to provide quick, higher-level feedback on the safety and performance characteristics of the algorithm. The batch of simulations was small enough to be run and produce results quickly, but was broad enough to highlight areas of potential concern. As these areas were identified, more focused batches of simulations could be run to help diagnose and address these concerns. This process of black box simulation testing to support development and troubleshooting was identified as an important benefit of the simulation environment and test process developed from this work.

Initially, the intent was to support implementation of the functions and evaluation of the algorithm following each phase of development. However, because only some of the functions were implemented and because the timing associated with getting the algorithm software application and the test environment working, it was not useful or practical to perform evaluations on multiple versions of the software. However, a new feature added to the Wabtec algorithm offered the opportunity to provide useful data from multiple evaluations of the algorithm. This new feature allows the train brake force to be provided to the onboard system at train initialization. The concept is that information available in the back office server, but not to the onboard system could be used to provide a more accurate estimate of brake force. If this data is not provided, the algorithm reverts to using the original internal assumptions for brake force. It was decided that evaluation of the algorithm both with this data provided, as well as without, would provide the most useful data to the industry.

16.2 Simulation Testing

Simulation testing and analysis was performed on two different configurations of the Wabtec algorithm for unit trains, manifest trains, and intermodal freight trains. The methodology described in Section 2.2 was used to test and analyze both simulation sets. The first set of simulation testing included providing the algorithm with an externally calculated value for the estimated brake force of the train. Table 29 shows the summary results for these simulations and the detailed results are provided in Appendix K. The second set of simulation testing was performed without providing the algorithm with the externally calculated value for brake force. Table 29 shows the summary results for these simulations, and Appendix L provides the detailed results. The summary tables include the probability of stopping short of the target and the probability of stopping short of the performance limit, defined as stopping short of the target by less than500 ft for speeds < 30 mph and 1,200 ft for speeds ≥ 30 mph.

Table 29. Wabtec Algorithm Simulation Test Results (Brake Force Provided)

Train Type	Probability of Stopping Short of Target	Probability of Stopping Short of Performance Limit
Unit Freight	99.00%	25.30%
Manifest Freight	98.51%	29.66%
Intermodal	99.87%	41.67%
Overall	99.03%	32.31%

The data in Table 29 shows that the algorithm met the safety objective of stopping short of the target 99.5 percent of the time for intermodal freight trains, but fell short for both unit and manifest freight trains. To demonstrate how close the algorithm was to meeting the safety objective for these two train types, an additional metric was calculated to show the location at which there was a 99.5 percent probability of stopping short of, relative to the target. For unit freight trains there was a 99.5 percent probability of stopping short of a location 11 ft past the target. For the manifest freight trains, there was a 99.5 percent probability of stopping short of a location 34 ft past the target.

From the detailed results of the simulations where brake force was provided to the algorithm, a few concentrated areas can be identified where a high probability of overrun was observed for both unit and manifest freight trains. Wabtec is presently addressing the changes required to reach the safety objective of 99.5 percent, but the simulation data with those changes was not available at the time of publication of this report. From Table 29 it can also be shown that the probability of stopping short of the performance objective for unit and manifest freight trains has improved greatly over the base algorithm. For unit freight trains, the algorithm had a probability of stopping short of the performance limit of 25.30 percent compared to 83.57 percent for the base algorithm and for manifest freight trains, the algorithm had a probability of stopping short of the performance limit of 29.66 percent compared to 70.89 percent for the base algorithm.

The second set of simulation testing was with the algorithm calculating a value for the estimated brake force of the train. Table 30 shows the summary results for these simulations and the detailed results are provided in Appendix L.

Table 30. Wabtec Algorithm Simulation Test Results (Brake Force Not Provided)

Train Type	Probability of Stopping Short of Target	Probability of Stopping Short of Performance Limit
Unit Freight	99.4276%	38.75%
Manifest Freight	99.6711%	38.88%
Intermodal	99.8190%	43.60%
Overall	99.6620%	40.27%

The data in Table 30 shows that, overall, the algorithm met the safety objective of stopping short of the target 99.5 percent of the time. The algorithm met the safety objective for manifest freight and intermodal trains, but fell just short of the objective for unit freight trains. For the unit freight trains, there was a 99.5 percent probability of stopping short of a point located 2 ft past the target. The probability of stopping short of the performance limit was greater when brake force was not provided to the algorithm. This was not unexpected, because the consist information available to the algorithm is not as detailed as that which is available in the back office server; therefore, this calculation must be more conservative. However, the probability of stopping short of the performance level is still significantly better than that observed with the base algorithm.

16.3 Field Testing at TTC

Field tests were performed with unit freight trains and manifest freight trains, in order to demonstrate the performance of the current Wabtec algorithm. The field test setup included a locomotive equipped with a Wabtec I-ETMS® onboard system, which housed the enforcement algorithm, and a laptop used as a back office server simulator, which was used to send consist and authority information to the onboard system. As with simulation testing, two configurations of the algorithm were tested during this field test, as follows:

1. Brake force provided from off-board processor
2. Brake force calculated by onboard system

Three types of tests were performed during the testing of the Wabtec algorithm:

- Safety — These tests are designed to demonstrate that the algorithm safely stops the train short of the target. In these tests, the train is allowed to proceed toward the target with no intent to stop, such that the enforcement algorithm must enforce a penalty brake application to stop the train short.
- Safety with Application — These tests are designed to demonstrate that the algorithm safely stops the train short of the target when a brake application is applied, which is insufficient for stopping the train before the target. In these tests, the train is allowed to proceed toward the target and a brake application is made that will not bring the train to a stop before the target, such that the enforcement algorithm must enforce a penalty brake application to stop the train short.
- Performance — These tests are designed to demonstrate whether the algorithm does or does not interfere with normal crew actions to stop the train safely short of the target. In these tests, the locomotive engineer stops the train short of the target using normal operating procedures, including the use of dynamic brake.

Tables 31 and 32 show each of the test scenarios and the resulting average stopping locations relative to the target for the unit freight test and the manifest freight test, respectively.

Table 31. Field Test Summary of Wabtec Algorithm with Unit Freight Train

Test Conditions				Average Stopping Location Relative to Target (ft)	
Consist	**Speed (mph)**	**Track Grade**	**Test Type**	**With Brake Force Provided**	**Without Brake Force Provided**
90 Loaded Cars	10	Flat	Safety	-70	-140
90 Loaded Cars	10	Flat	Performance	-100	N/A
90 Loaded Cars	30	Flat	Safety	-226	-491
90 Loaded Cars	50	Flat	Safety	-590	-1095
90 Loaded Cars	30	Decline	Safety	-1183	-1890*
90 Loaded Cars	30	Decline	Safety with Application	-586	N/A
90 Loaded Cars	30	Decline	Performance	N/A	-250
40 Loaded Cars	30	Flat	Safety	-80*	-335*
40 Loaded Cars	30	Decline	Performance	-385	N/A
40 Loaded Cars	50	Decline	Safety	-265	-3170*
16 Loaded Cars	30	Flat	Safety	-65*	-300*
16 Loaded Cars	30	Flat	Performance	-221	N/A
16 Loaded Cars	30	Decline	Safety	-580	N/A

*Emergency Brake Applied

Table 32. Field Test Summary of Wabtec Algorithm with Manifest Freight Train

Test Conditions				Average Stopping Location Relative to Target (ft)	
Consist	**Speed (mph)**	**Track Grade**	**Test Type**	**With Brake Force Provided**	**Without Brake Force Provided**
96 Cars – 20 Loaded, 76 Empty	10	Flat	Safety	-184	N/A
96 Cars – 20 Loaded, 76 Empty	10	Flat	Performance	-84	-56
96 Cars – 20 Loaded, 76 Empty	30	Flat	Safety	-660	-1,106
96 Cars – 20 Loaded, 76 Empty	50	Flat	Safety	-1,219	-1,219
96 Cars – 20 Loaded, 76 Empty	30	Decline	Safety	-1,203	-2,139
96 Cars – 20 Loaded, 76 Empty	30	Decline	Safety with Application	-583	N/A
96 Cars – 20 Loaded, 76 Empty	30	Flat	Performance	-250	N/A
96 Cars – 20 Loaded, 76 Empty	30	Incline	Safety	-315	-582
96 Cars – 20 Loaded, 76 Empty	30	Crest	Safety	-495	-911
40 Cars – 10 Loaded, 30 Empty	30	Flat	Safety	-273	-580
40 Cars – 10 Loaded, 30 Empty	30	Decline	Performance	-109	N/A
40 Cars – 10 Loaded, 30 Empty	50	Decline	Safety	-1,145	N/A
16 Cars – 4 Loaded, 12 Empty	30	Flat	Safety	-202	-575
16 Cars – 4 Loaded, 12 Empty	30	Flat	Performance	-98	N/A
16 Cars – 4 Loaded, 12 Empty	30	Decline	Safety	-770	-2,293

As the data shows in Tables 31 and 32, the Wabtec algorithm stopped the train short of the target in all of the safety cases that were performed. It also shows that the algorithm is more conservative if brake force is not provided to the system, which is consistent with expectations and the results seen in the simulation data. Also, the Wabtec algorithm did not enforce a penalty application during any of the performance test cases.

Overall, the field evaluation of the Wabtec algorithm was shown to compare well with the simulation testing. The results showed that the algorithm stops the train safely short of the target for a broad range of test cases, and it does not adversely interfere with the locomotive engineer during normal operations. The performance of the algorithm overall was shown to be far better than the base algorithm, demonstrating the improvement achieved with the concepts implemented for improving the accuracy and operational efficiency of the algorithm.

17. Development and Testing of V-PTC Enforcement Algorithm

One of the objectives of this effort was to develop enforcement algorithm logic that is ready for implementation in a PTC system. To support this objective, the complete enforcement algorithm logic was documented in an enforcement algorithm description document at the completion of each phase of development. Near the completion of the first phase of enforcement algorithm development, there was an opportunity to implement and test this enforcement algorithm logic in a developmental PTC system to the mutual benefit of this project and another FRA project: the V-PTC Research and Development project [5].

The objective of the V-PTC Research and Development project was to develop, test, and demonstrate a V-PTC system with a centralized architecture and moving-block capability. As part of this project, FRA funded the development of system specifications as well as testing and demonstration activities, and LMC provided in-kind services to design and develop the system components. The system development was organized into a number of functional builds to incrementally demonstrate system functionality. One of these builds included predictive enforcement of authority and speed limits, which requires a braking enforcement algorithm.

Evaluation of the developmental enforcement algorithm logic implemented in the V-PTC onboard system was conceived to benefit the V-PTC project as well as the enforcement algorithm research and development project by demonstrating the safety and performance characteristics of the enforcement algorithm logic implemented in a functional PTC system. As such, FRA provided funding to support the development and evaluation of the Phase 1 enforcement algorithm logic in the V-PTC system.

17.1 Development and Simulation Test Support

The schedule for development and testing of the enforcement algorithm in the V-PTC system was driven by the V-PTC project. In order to support the schedule for that project, development efforts had to begin before the Phase 1 enforcement algorithm developmental logic was completed. The development and testing efforts were broken into the following four stages to allow development efforts on the V-PTC software to begin prior to completing the Phase 1 logic:

- Stage 1 — Development and simulation testing of the revised base enforcement algorithm
- Stage 2 — Development and simulation testing of the Phase 1 enforcement algorithm
- Stage 3 — Field testing of the Phase 1 enforcement algorithm with externally supplied stopping targets
- Stage 4 — Field testing of the Phase 1 enforcement algorithm with system generated stopping targets from authorities provided by a simulated dispatch system

The four stages offered a progressive buildup of functionality, allowing development to begin while the algorithm logic, as well as supporting system functionality was completed, and testing of each of the progressively more complex builds was conducted.

To begin implementation of the enforcement algorithm in the V-PTC system, a draft version of the developmental enforcement algorithm definition document was provided to LMC with only the revisions to the base enforcement algorithm logic included. LMC implemented this functionality into a standalone brake enforcement algorithm application that could interface the simulation test environment according to the communications protocol specified in the document included in Appendix B. TTCI supported the implementation by providing source code snippets and further descriptions where necessary to clarify specific items in the documentation. This feedback from a PTC supplier was also used to improve the algorithm definition document.

Throughout the development process, simulations were run for a wide variety of test cases to verify that the enforcement algorithm was functioning as expected. The simulation results were compared against the results with the developmental test version of the algorithm software to ensure that the algorithm logic was implemented consistent to the test application. This provided a redundant check to ensure that the test software developed by TTCI matched the documented logic and the software developed by LMC.

After the design and documentation of the Phase 1 functions was complete, the updated document was provided to LMC for implementation in the V-PTC software. Again, a standalone brake enforcement algorithm application was developed for verification with simulation testing. The enforcement algorithm was also implemented in the V-PTC onboard system software for field testing.

17.2 Field Testing at TTC

After the Phase 1 developmental algorithm was implemented in the V-PTC onboard software, a series of field tests were performed to verify the performance of the algorithm logic as implemented in a functional PTC onboard system. The field tests were run using the algorithm incorporated in the V-PTC onboard system, with the algorithm developmental test application running in the background on a separate computer for comparison purposes.

Three types of tests were performed during the testing of the V-PTC algorithm, as follows:

- Safety — These tests are designed to demonstrate that the algorithm safely stops the train short of the target. In these tests, the train is allowed to proceed toward the target with no intent to stop, such that the enforcement algorithm must enforce a penalty brake application to stop the train short.
- Safety emergency brake backup — These tests are designed to demonstrate that the algorithm safely stops the train short of the target by using the emergency brake backup function when the initial penalty brake application is insufficient for stopping the train before the target. In these tests, the train is allowed to proceed toward the target with no intent to stop, such that the enforcement algorithm must enforce a penalty brake application. At this point, the test crew controls the trailing locomotives to power against the penalty brake application, simulating a train that is not stopping as expected, such that the enforcement algorithm must enforce an emergency brake application to stop the train short.
- Performance — These tests are designed to demonstrate whether the algorithm does or does not interfere with normal crew actions to stop the train safely short of the target. In these tests, the locomotive engineer stops the train short of the target using normal operating procedures, including the use of dynamic brake.

Table 33 shows each of the test scenarios and the resulting average stopping locations relative to the target.

Table 33. Field Test Summary of LMC V-PTC Algorithm

Consist	Test Conditions: Speed (mph)	Test Conditions: Track Grade	Test Type	Average Stopping Location Relative to Target (ft)
40 Loaded Cars	30	Flat	Safety	-418
40 Loaded Cars	30	Flat	Performance	-171
40 Loaded Cars	30	Flat	Safety Emergency Brake Backup	-424
40 Loaded Cars	60	Flat	Safety	-86*
40 Loaded Cars	30	Decline	Safety	-675
40 Loaded Cars	30	Decline	Performance	499*
40 Loaded Cars	60	Decline	Safety	1,880* (-1,051)
40 Loaded Cars	30	Varying	Safety	-171
90 Loaded Cars	10	Flat	Safety	-151
90 Loaded Cars	10	Flat	Performance	-139
90 Loaded Cars	30	Flat	Safety	-447
90 Loaded Cars	10	Decline	Safety	-376
90 Loaded Cars	30	Decline	Safety	-1,121
90 Loaded Cars	30	Varying	Safety	-366
10 Loaded Cars	30	Flat	Safety	-751
10 Loaded Cars	30	Flat	Performance	-681
10 Loaded Cars	30	Decline	Safety	-1,858

* Hardware on locomotive prevented proper application of emergency brake
(the stopping location relative to the target with the emergency applied)

The V-PTC implementation of the Phase 1 algorithm correlated well to the developmental test application of the algorithm running in the background on a separate computer. The enforcement locations for each test case were, in most cases, at the exact same time for both applications, and within a few seconds of each other for the rest. For some of the test cases, there was an issue with the hardware on the locomotive that prevented proper application of the emergency brake, although the algorithm attempted to apply it. These cases are indicated in Table 33 with an asterisk next to the value for the average stopping location relative to the target. In two of these cases, the train exceeded the target stopping location, and in the third case, the train stopped very close to the target, particularly given the test speed (i.e., 86 ft short of the target from 60 mph), indicating that the emergency brake application was indeed justified for these cases. The hardware issue was resolved and the emergency brake properly applied on the remaining cases. Time and budget allowed for the one of these test cases (the 40-car, 60 mph, decline grade case) to be rerun after the issue was resolved to demonstrate the stopping location was short of the target when the emergency was properly applied. For this case, the stopping location relative to the target with the emergency applied is indicated in parentheses.

The field testing of the V-PTC braking enforcement algorithm implemented by LMC successfully demonstrated the safety and performance characteristics of the Phase 1 developmental enforcement algorithm as implemented in a functional PTC onboard component. This supports the applicability of the algorithm developed in a fully functional PTC system, as opposed to operating as a standalone application. The testing also demonstrated that the documentation of the developmental algorithm was sufficient for developing a working implementation of the algorithm logic matching that intended during the development of the algorithm. Overall, this task helps to demonstrate the feasibility of developing these techniques as an implementation ready set of logic to improve the operational performance of the algorithm for an independently developed PTC system.

18. Conclusions

Throughout the course of the project, several techniques for improving the safety and performance of enforcement algorithms for PTC systems were researched and tested. Results of these tests showed that improvements in operational performance are indeed possible, without negatively affecting the safety of the system. Further, a formal methodology was developed for demonstrating the safety and performance characteristics of any PTC enforcement algorithm, which will allow for future versions of algorithms from various sources to be reliably tested to confirm their suitability for use in a functional system without the expense of lengthy field test processes.

In the first phase of the project, it was shown that the safety objective for the enforcement function of a PTC system need not be excessive. The safety benefits of PTC not related to the enforcement function, combined with the already safe nature of the railroad operation, lessen the need for an excessively conservative enforcement algorithm. The analysis presented allows for a probability of 99.5 percent for stopping the train short of the target, which can ultimately result in a significant reduction in early warnings and enforcements over the previously suggested 99.9995 percent probability and still provide considerable improvement in safety over the traditional signal systems used today. The impact of this analysis can be shown with the dramatic reduction in target offset levels used in the developmental algorithm as compared with the base algorithm.

Enforcement algorithm development in the first phase included improvements to the base algorithm logic, an improved target offset function, adaptive features, emergency brake backup, and functionality for handling trains with distributed power. The second phase expanded further with functions for handling use of locomotive braking, including dynamic braking and independent/automatic braking during PTC penalty enforcement. Finally, in the third phase, the functions previously developed were expanded to work on all train types. Each of these functions was shown to improve the performance of the algorithm individually through field testing, as well as aggregately through simulation testing. Although simulation testing of the final version of the developmental algorithm showed that it falls just short of the objective for stopping short of the target (98.91 percent), TTCI knows the minor modifications and tweaks required to bring the algorithm into conformance with the requirements. These will be done as part of the follow-on work.

The safety of the algorithm is paramount, but the operational performance improvements seen from the developments employed cannot be overlooked. The base enforcement algorithm had an overall probability of stopping short of the performance limit of 75.06 percent. Although this measure is not a precise indication of the level of operational impact the algorithm will ultimately have, it can be generally stated that the lower this probability, the less impact the algorithm will have. The final developmental algorithm had a probability of stopping short of the performance limit of just 8.24 percent, a tremendous improvement over the base algorithm. This shows the enormous potential the concepts and techniques researched here can have on PTC systems and their impact on railroad operations.

Each of the techniques researched has its own pros and cons, but it is apparent from this project that some have more potential to improve the safety and performance of the system, with potentially less effort, than others. For example, the emergency brake backup function significantly improves the performance of the algorithm, and it also has safety benefits. Furthermore, it enables many of the other functions developed. For instance, the distributed power function relies on the emergency brake backup function to mitigate the risk of overrun in the case the distributed power communications link fails at the point of enforcement. This enabling feature of the emergency brake backup function makes it an almost essential improvement to the algorithm. The only drawback of this function is the requirement of an additional interface to the brake system, but this is a minor drawback, considering the amount of additional hardware that already needs to be installed on locomotives for PTC to function.

It is expected that railroads and their suppliers may initially adopt only some of the concepts introduced in this project. This has been shown to be the case to date with the algorithm Wabtec is developing for the I-ETMS® system. However, the concepts added to this algorithm have also shown dramatic improvement over the base algorithm. The algorithm developed by Wabtec was shown to have a probability of stopping short of the performance limit of 40.27 percent. The operational areas where the algorithm performed less efficiently were primarily those on steep downgrades, where dynamic brake is used extensively to control the speed of the train. As PTC system deployment is continued, this may be an area where further improvement can be seen by adopting other concepts investigated under this project.

Although many of the techniques developed as part of this project have not yet been adopted into systems currently in use, the results of this project are significant, because they have advanced the state of PTC enforcement algorithm technology and have shown the potential for improvement over traditional methods. The groundwork laid here will set the expectations for the level of performance for PTC enforcement algorithms as the technology continues moving forward.

19. References

1. Brosseau, J., Moore Ede, B. (June 2009) "Development of an Adaptive Predictive Braking Enforcement Algorithm," DOT-FRA-ORD-09/13, U.S. Department of Transportation, Federal Railroad Administration, Office of Research and Development, Washington, D.C.
2. Manos, W.P., Hawthorne, K.L., Misner, G., Brown, T. (April 1981) "Brake Shoe Performance," Research Report R-469, AAR Technical Center, Chicago, IL
3. Anderson, G.B., Manos, W.P., Wilson, N.G. (December 1983) "Brake Shoe Performance Test II: 1982-83 Pueblo, Colorado Test Series," Research Report R-565A, AAR Technical Center, Chicago, IL
4. Association of American Railroads. (2002) *AAR Manual of Standards and Recommended Practices*. Section K. "End-of-Train Communications." Standard S-5701, Washington, D.C.
5. Morgan, R., Mauger, D., Brosseau, J. (March 2011) "Vital-Positive Train Control Research and Development Final Report." DOT/FRA/ORD-11/14, U.S. Department of Transportation, Federal Railroad Administration, Office of Research and Development, Washington, D.C.
6. Association of American Railroads. (2007) *AAR Manual of Standards and Recommended Practices*. Section E. "Brake Design Requirements." Standard S-401, Washington, D.C.
7. Carlson, F. (October 2002) "Body-mounted Brake Rigging." *Technology Digest* TD-02-022. Association of American Railroads, Transportation Technology Center, Inc., Pueblo, CO.
8. Grenci, L. and Nese, J. (2001) *A World of Weather: Fundamentals of Meterology*. Dubuque: Kendall/Hunt. p. 95
9. National Oceanic Atmospheric Administration. http://ols.nndc.noaa.gov/plolstore/plsql/olstore.prodspecific?prodnum=C00095-PUB-A0001. Climatological normals for 1971-2000.
10. Dynisco. (2012) *Dynisco Model PT311JA Flush Diaphragm Pressure Transducer Datasheet*. Franklin, MA.
11. Carriere, K., Gallagher, B. (2011) "What's the Force? Degradation of Brake Forces." *Proc. 103rd Annual Convention and Technical Conference of Air Brake Association*.
12. Hay, William W. (1982) *Railroad Engineering.* Second Edition, John Wiley & Sons, Inc.
13. Association of American Railroads (2012) *Field Manual of the AAR Interchange Rules.* Washington, D.C.
14. Statsoft. (2011) *STATISTICA.* Version 10. Tulsa, OK.
15. Rychlik, I. Ryden, J. (2006) *Probability and Risk Analysis: An Introduction for Engineers.* Heidelburg: Springer.
16. Annapurva, R. Butar, F.B. (2010) "An Insight into Heavy-Tailed Distribution." *Journal of Mathematical Sciences and Mathematical Education.* Vol. 5.

17. Conort, X. (2010 Jan.-Jun.) "Quantile Estimation of Heavy Tail Distributions and Model Risks of EVT Techniques." *Bulletin Facais D' Actuariat.* Vol. 10, n19, pp. 63-109.

18. MathWave Technologies. (2010, Dec 3) *Easy Fit Professional.* Version 5.5. Spokane, WA

19. ICF Consulting (2006) "Technology Driven Operations Comparative Risk Assessment." Report to Association of American Railroads, Washington, D.C.

20. IEC 61508. "Functional Safety of Electrical/Electronic/Programmable Electronic Safety-related Systems." International Standard of Rules.

21. Wabtec Railway Electronics. (2003, Jan. 10) "IDOT PTC Project Braking and Prediction Algorithm Definition." Revision C. Cedar Rapids, IA.

22. Kutner, M.H., Nachtscheim, C.J., Neter, J. (2004) *Applied Linear Regression Models.* 4th Edition. Chicago: McGraw Hill/Irwin.

23. Association of American Railroads. (2010) *AAR Manual of Standards and Recommended Practices,* Section M. "Braking Ratios for Locomotives." Standard RP-509 and "Basic Brake Design Data for Freight Locomotives." Standard RP-5209, Washington, D.C.

24. Association of American Railroads. (2010) *AAR Manual of Standards and Recommended Practices,* Section M. "Locomotive Dynamic Brake Status Reporting." Standard S-5509, Washington, D.C.

25. Montgomery, Douglas C. and Runger, George C. (2007) A*pplied Statistics and Probability for Engineers*. Fourth Edition, John Wiley & Sons, Inc.

26. StatSoft, Inc. (2013). Electronic Statistics Textbook. Tulsa, OK: StatSoft. WEB: http://www.statsoft.com/textbook/

Appendix A.
Enforcement Algorithm Evaluation Methodology Document

Methodology for Evaluation of PTC Freight Train Braking Enforcement Algorithms

Version 1.2

9/1/2011

Prepared by:

Transportation Technology Center, Inc.
a subsidiary of the Association of American Railroads

With funding from:

Federal Railroad Administration

Revision History

Date	Revision	Description
8/4/11	1.0	Initial draft
8/5/11	1.1	Incorporated comments from internal review
9/1/11	1.2	Incorporated comments from advisory group

Table of Contents

A1. Introduction

A1.1 Purpose

The purpose of this document is to provide a technical description of the proposed methodology for evaluation of braking enforcement algorithms for positive train control (PTC) applications. The intent of this methodology is to specify the empirical and analytical processes of generating and analyzing data in support of the comprehensive safety and performance analysis of a particular PTC implementation.

A1.2 Intended Audience

This document is intended for developers, suppliers and end users of positive train control systems that require data generation and analysis to verify the safety and performance of the enforcement function of the system as well as for regulators responsible for the approval and acceptance of these systems.

A1.3 Definitions and Acronyms

A1.3.1 Definitions

The following terms are used in the document:

- Degree of curvature – The central angle turned over a 100 foot chord length, expressed in degrees.
- Distributed power – A descriptive term for a train that includes more than a single group of locomotives distributed throughout the train, separated by groups of non-powered cars
- Emergency air brake application – A rapid reduction of the brake pipe pressure to atmospheric pressure. An emergency brake application results in higher brake force as a result of the control valve directing air from both the auxiliary and emergency reservoirs to the brake cylinder.
- Monte Carlo simulation method – A method of modeling physical systems with many coupled degrees of freedom through the use of repeated random sampling and analysis of the combined results.
- Onboard computer – The computer onboard the locomotive used for collecting train status and enforcement test target information and applying brake enforcements.
- Penalty air brake application – A reduction of the brake pipe pressure at a service rate that results in the control valve directing air from the auxiliary reservoir to the brake cylinder until equalization is reached.
- Positive Train Control (PTC) – A form of train control where train movement authorities and speed limits are transmitted electronically and automatically enforced to prevent violations. FRA has defined four minimum requirements for a PTC system. The system must prevent:
  - Train-to-train collisions,
  - Over-speed derailments,
  - Incursions into established work zone limits, and
  - Movement of a train through a switch left in the wrong position.

- Predictive braking enforcement algorithm – A computational algorithm that predicts the braking profile of a train and, if necessary, enforces a penalty brake application to prevent a violation of a movement authority or speed limit. Also described as "enforcement algorithm" or simply "algorithm".
- Target – A location where the train must be at or below a given speed. The target locations are used by the enforcement algorithm to determine if a penalty air brake application is necessary.

A1.3.2 Acronyms

The following is a list of acronyms used within this document:

- AAR – Association of American Railroads
- ALD – Automatic Location Detector
- COFC – Container on Flat Car
- EDA – Exploratory Data Analysis
- GPD – Generalized Pareto Distribution
- POT – Peaks-over-Threshold
- PTC – Positive Train Control
- TCL – Test Controller/Logger
- TOES – Train Operations and Energy Simulator
- TOFC – Trailer on Flat Car

A2. Overview

Successful implementation of positive train control demands a safe and operationally efficient braking enforcement algorithm. In order to verify that a braking enforcement algorithm meets specified safety and performance objectives, a test methodology must be defined to quantify the safety and performance of the algorithm according to defined measures.

From a safety standpoint, the objective of such a methodology is to demonstrate a high degree of confidence that any given train, in any given operational scenario, will stop short of a given target stopping location as a result of PTC brake enforcement. Historically, this objective has been expressed as a probability that a train will stop short of a target stopping location with a given confidence level, as shown in figure 1. Research has shown an appropriate safety objective as a 0.995 probability of stopping short of the target with a 0.99 confidence level. As such, the methodology described within this document aims to quantify the probability of stopping short of the target for the particular PTC braking enforcement algorithm under evaluation for comparison against this objective, among other performance measures.

Figure A21: PTC Predictive Braking Enforcement Algorithm Safety Objective

Evaluation of PTC braking enforcement algorithms has generally been accomplished through field testing of the enforcement function on revenue service track. While this may be appropriate for final verification of the enforcement function, it presents several disadvantages. First, it is costly and time-consuming. It impacts the operation of the railroad, in terms of affecting capacity and causing interference to other revenue traffic. It also does not provide the highest level of statistical confidence in the safety and performance of the algorithm, as it is not possible to perform a sufficient number of live field tests within the timeframe required for system deployment. There is limited control over test conditions, in terms of boundary condition (e.g. worst-case) scenarios. While specific operating conditions, such as track grades and train speeds may be possible, it is unlikely that a given test train will exhibit boundary condition characteristics. The potential for repeatability testing is also very limited, and the quantity of field tests practically achievable generally falls short of what is needed for adequate statistical significance.

The methodology presented within this document seeks to overcome these disadvantages, through a combination of computer simulation testing in a lab environment and field testing in a controlled test environment, resulting in a reduced amount of revenue service field testing. As part of this methodology, the simulation testing is used to statistically quantify the safety and performance of the enforcement function by running large batches of simulations with Monte Carlo variation of train and environmental characteristics that affect train stopping distance. Limited field testing in a controlled environment provides validation of the simulation results using actual hardware inputs to the enforcement algorithm. The final verification of the enforcement algorithm safety and performance is provided on only the necessary boundary conditions (e.g. steep grades) through revenue service testing.

The focus of this evaluation methodology is on the results of the simulation testing. This testing provides the capability to test the enforcement algorithm over a wide range of operating scenarios, including boundary conditions, in a safe and efficient manner. It also provides more comprehensive statistical data on the safety and performance of the enforcement algorithm when compared to the alternative.

The key to using the simulation data as the core of the evaluation is to provide adequate empirical data to ensure that it properly represents how the enforcement algorithm will perform in the field. The evaluation methodology provides this verification through three types of field testing. The first is enforcement field testing, both in a controlled environment and revenue service, which is compared to results of simulation testing. The second is repeatability testing to establish the consistency in freight train stopping distance for a given set of conditions, which is used to verify the parameters selected for Monte Carlo variation in the simulation testing process and quantify any variability in stopping distance not captured through the Monte Carlo variation. The final type of field testing is stop distance testing where all practical parameters are precisely measured for direct comparison to simulation testing, to verify the accuracy of the model used, and quantify any systematic error between the model and the actual performance of the field hardware.

The results of the enforcement algorithm simulation testing are combined with the results from the enforcement algorithm field testing, repeatability testing, and stop distance testing and analyzed to quantify the safety and performance of the enforcement algorithm. Finally, the results are compared against pass/fail criteria to demonstrate the safety and performance of the enforcement function.

The specific details of each of the components of the enforcement algorithm evaluation methodology are further described in the remaining sections of this document.

A3. Simulation Testing

The objective of the simulation testing portion of the enforcement algorithm evaluation methodology is to provide data for statistically quantifying the safety and performance of the enforcement algorithm being evaluated. This is achieved by running large batches of enforcement simulations that are representative of the distribution of possible enforcement outcomes for a range of operating conditions.

A3.1 Overview of Simulation Testing Process

Figure 2 shows a conceptual diagram of the components used for simulation testing. The simulation testing process makes use of the Train Operations and Energy Simulator (TOES™), a longitudinal train dynamics and energy model developed and fully validated by the Association of American Railroads (AAR). The TOES™ model includes a complete fluid dynamics model of the air brake system, which allows for accurate modeling of a wide variety of air brake equipment, making it the ideal tool for performing braking enforcement algorithm testing.

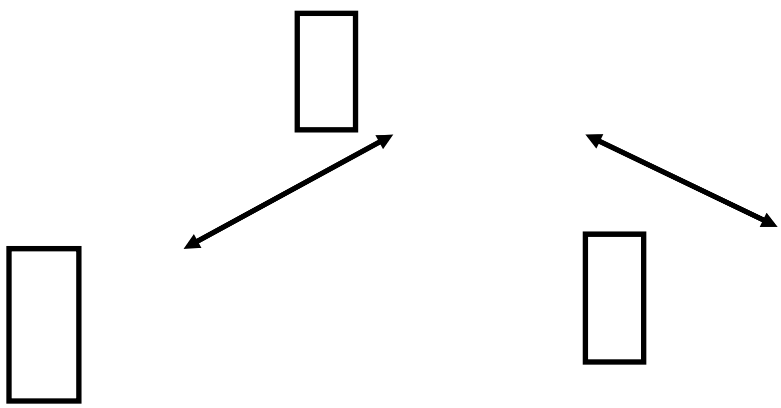


Figure A2: Simulation Testing Components

The simulation testing process also makes use of a test controller and logger (TCL) software component, which sets up and executes batches of TOES™ simulations. Each batch of simulations represents a single operating scenario and each simulation within the batch represents a possible random outcome of the given operating scenario. The operating scenarios are defined by the train make-up, longitudinal track profile (i.e., grade and curvature), and initial train speed. Each unique simulation within the batch is defined by randomly varying the key parameters that affect the train stopping distance, according to predefined input distributions, in a Monte Carlo process.

The TCL software executes each simulation within the TOES™ model by approaching the given target location at the test speed and providing feedback from TOES™ to the enforcement algorithm, implemented as a black-box software component. TCL provides the enforcement algorithm with the required data over a pre-defined interface at regular simulated time intervals. The enforcement algorithm commands a penalty brake enforcement to TCL, over the pre-defined interface, to prevent a violation of the target stopping location provided. The enforcement is initiated in the TOES™ model by the TCL software and the simulation continues until the train is stopped. In some cases, the enforcement algorithm may also command an emergency brake enforcement, also initiated in the TOES™ model by the TCL software. The output of each simulation is logged by the TCL software for later analysis.

There are a total of 4286 batches (operating scenarios) in the simulation testing methodology. 100 unique simulations are run for each of these batches (operating scenarios), where the key parameters that affect the stopping location of the train are varied randomly for each simulation, for a total of 428,600 simulations. The results of each individual simulation are combined for all the simulations within each batch (operating scenario) and used to determine the safety and performance characteristics of the enforcement algorithm for each given operating scenario. These results can then be combined to determine the overall safety and performance characteristics of the enforcement algorithm.

A3.2 Simulation Testing Operating Scenarios

The operating scenarios defined for simulation testing are intended to capture the range of operating conditions that the PTC system will regularly and frequently encounter. It is recognized that it is neither possible nor necessary to simulate or test every possible operating scenario, and specific scenarios that vary greatly from those defined may need additional focus beyond what is defined in this methodology. The operating scenarios are defined by the test consist and the operating conditions, as described in the following sections.

A3.2.1 Test Consists

Simulation testing is performed using a range of test consists, based on railroad historical data on revenue service train consists. These are broken down into three logical groups:

1. Unit freight trains
2. Manifest freight trains
3. Intermodal freight trains

Unit Freight Trains

Unit freight trains are defined as those consisting entirely of a single car type. There are a total of 60 unit train consists. Each unit train consist represents a unique combination of train makeup, length, loading condition and power arrangement.

There are six types of unit trains, defined by the car type, as follows:

- Unit aluminum hopper
- Unit steel hopper
- Unit covered hopper
- Unit tank
- Unit refrigerated boxcar
- Unit multilevel (vehicular flat car)

There are four train lengths defined for unit freight operations, as follows:

- 100 cars
- 135 cars
- 200 cars (unit aluminum hopper and unit steel hopper trains only)
- 260 cars (unit aluminum hopper and unit steel hopper trains only)

There are two types of loading conditions defined for unit freight trains:

- Fully loaded
- Fully empty

There are three types of power arrangements defined for unit freight trains:

- Head end power only (100-car trains only)
- Head and rear end distributed power (100-car, 135-car, and 200-car trains only)
- Head, mid, and rear end distributed power (135-car, 200-car, and 260-car trains only)

Manifest Freight Trains

Manifest freight trains are defined as having a mix of car types and loads throughout the train. There are a total of 114 manifest freight train consists. The number of manifest freight train consists represents a unique combination of train length, power arrangement, locomotive type, and train make-up/loading.

There are seven train lengths defined for manifest freight operations:

- 0 cars (light locomotives)
- 3 cars
- 10 cars
- 40 cars
- 100 cars
- 150 cars
- 200 cars

There are three types of power arrangements defined for manifest freight trains:

- Head end power only (0 car, 3-car, 10-car, 40-car, and 100-car trains only)
- Head and rear end distributed power (100-car, 150-car, and 200-car trains only)
- Head, mid, and rear end distributed power (150-car, and 200-car trains only)

For short trains, where locomotive weight becomes a significant factor and locomotive brakes may be applied, it is necessary to test the algorithm performance with various locomotive types. There are two types of locomotives for manifest freight trains:

- 4000-horsepower, 6-axle SD70MAC locomotives
- 3000-horsepower, 4-axle GP40-2 locomotives (0-car, 3-car, and 10-car trains only)

The manifest freight trains are made up of a pseudo-random mix of potential car types and contain varying loading conditions throughout the train, based on actual railroad train manifest data. The car types include:

- Box cars
- Covered hoppers
- Gondolas
- Flat cars
- Open-top hoppers
- Aluminum coal gondolas
- Tank cars

- TOFC/COFC flat cars
- Multilevels

For each combination of train length, power arrangement, and locomotive type, ten unique consists are generated using the pseudo-random car type selection process. Of these, one consist contains all fully loaded cars, one contains all empty cars, and the remaining eight contain cars loaded based on the pseudo-random car load selection process. For the case of light locomotives, train make-up and car loads do not apply, so there are only two consists for each locomotive type; one with a single locomotive, and the other with three locomotives.

Intermodal Freight Trains

Intermodal freight trains are defined as being made up entirely of intermodal well cars. There are a total of 70 intermodal freight train consists. The number of intermodal freight train consists represents a unique combination of train length, base loading condition, power arrangement, and train make-up/loading condition.

There are four train lengths defined for intermodal freight operations:

- Short – approximately 5,000 feet
- Medium – approximately 7,500 feet
- Long – approximately 10,000 feet
- Very long – approximately 15,000 feet

There are two types of base loading conditions defined for intermodal freight trains:

- Loaded
- Empty

There are three types of power arrangements defined for intermodal freight trains:

- Head end power only (short and medium length trains only)
- Head and rear end distributed power (short, medium, and long train lengths only)
- Head, mid, and rear end distributed power (long and very long train lengths only)

The intermodal trains are made up of a pseudo-random mix of potential car types and contain varying loading conditions throughout the train, based on actual railroad train manifest data. The car types include:

- Single platform intermodal well cars
- Three-pack intermodal well cars
- Five-pack intermodal well cars

For each combination of train length, base loading condition, and power arrangement, five unique consists are generated using the pseudo-random car type selection process. For the cases where the base loading condition is loaded, one of the five consists contains all fully loaded cars, and the remaining four contain cars loaded based on the pseudo-random car load selection process for loaded intermodal consists. For the cases where the base loading condition is empty, one of the five consists contains all empty cars, and the remaining four contain cars loaded based on the pseudo-random car load selection process for empty intermodal consists (in many cases, trains are designated empty, but actually contain variations in loading due to empty containers, etc.).

A3.2.2 Operating Conditions

Each test consist is simulated under a number of operating conditions. Each operating condition represents a unique combination of train speed, track grade, and track curvature. The operating conditions are based on the boundary conditions of allowable operating conditions. Figure 3 illustrates how the boundary speed/grade conditions were determined based on the allowable speeds for various train types on various sustained grades. The X's in figure 3 show speed/grade combinations that are simulated on declining grades.

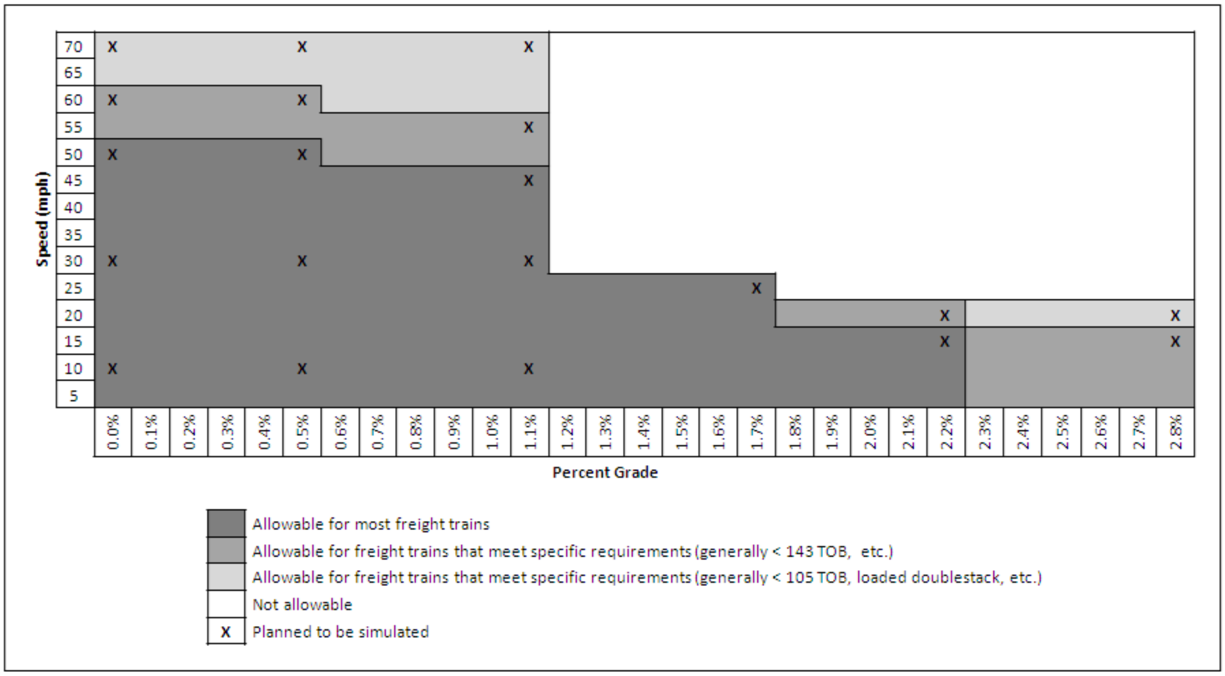


Figure A3: Boundary Operating Conditions for Simulation Testing

In addition to the decline grades, simulations are run on inclines and undulating (crest and trough) grades. Table 1 shows the test speeds for simulation testing for each of the grade scenarios and train types. In some cases, two speeds are shown, indicating that the test speed is based on the specific consist.

Table A1: Simulation Testing Speeds by Track Grade and Train Type

	Grade									
	Flat	0.50%	1.50%	-0.50%	-1.10%	-1.70%	-2.20%	-2.80%	1% Crest	1% Trough
Loaded Intermodal	70, 30, 10	70, 10	25	70, 30, 10	70, 30, 10	25	20	15	70	70
Empty Intermodal	60, 30, 10	60, 10	25	60, 30, 10	60, 30, 10	25	20	20	60	60
Manifest Freight	60, 30, 10	60, 10	25	60, 30, 10	45/55, 30, 10	25	15	15/0	45/55	45/55
Loaded Unit	50, 30, 10	50, 10	25	50, 30, 10	45, 30, 10	25	0	0	45	45
Empty Unit	60, 30, 10	60, 10	25	60, 30, 10	55, 30, 10	25	20	0	55	55

These operating scenarios represent all of the practical consist, speed, and grade combinations on tangent track. In addition, to evaluate the ability of the enforcement algorithm to properly handle operating scenarios on curved track, a subset of the consist, speed, and grade combinations are run on curves. This subset represents the three train types over a variety of grades and speeds, and is tested on 2-degree, 4-degree, 8-degree, and 15-degree curves, as allowable for the specific test speed.

A3.3 Simulation Testing Variable Parameters

There are a number of parameters that affect the stopping distance of a train in a PTC enforcement scenario. Simulation testing is used to quantify the variability in train stopping location during a PTC enforcement scenario by varying these parameters using a Monte Carlo method, according to input distributions that are representative of their actual, real-world variability. These parameters and associated input distributions are based on a combination of research, literature review, field measurements, and expert opinion, in order to represent reality as accurately as possible.

A total of 28 parameters have been identified as having an impact on train stopping location during a PTC enforcement scenario. Of these, 22 have been identified as having the potential to have a significant effect on train stopping location. Input distributions have been defined for these 22 parameters, which are varied in simulation testing.   The remaining six parameters have been determined to have a relatively insignificant effect and may be impractical to vary in the simulation. Table 2 shows all 28 parameters, along with the source of their input distribution for the 22 parameters that are varied in simulation testing. The six parameters that are not varied in simulation testing are indicated in the table, as well.

Table 2: Varied Parameters for Simulation Testing

	PARAMETER	UNITS	SOURCE
TRAIN AND EVNIRONMENTAL PARAMETERS	Ambient Pressure	psi	Historical NOAA weather data for US
	Ambient Temperature	deg F	Historical NOAA weather data for US
	Brake Pipe Leakage Rate	psi / min	Expert opinion and limited measured data
	Coefficient of Friction Between Brake Shoe and Wheel	N/A	Expert opinion and data from AAR Reports R-469, "Brake Shoe Performance Evaluation" and R-565A, "Brake Shoe Performance Test II"
	Length of Time of Distributed Power Communcations Link Outage	seconds	Expert opinion and information provided by railroads
	Error in EOT Pressure as Reported by EOT Device	psi	Accuracy of +/-3 psig per AAR Standard S-5701
	Error in HOT Pressure as Reported by Pressure Sensor	psi	Variability as specified by accuracy of Dynisco Model PT311JA pressure transducer
	Error in Reported Head End Location	feet	V-PTC Build 1A testing results
	Percent Operable Brakes	percent	Expert opinion and information provided by railroads
	Error in Reported Train Speed	mph	V-PTC Build 1A testing results
	Error in Reported Track Grade	percent grade	Based on accuracy of grade data in track database
	Error in Reported Degree of Track Curvature	degree curvature	Not varied - Variability not found to significantly affect results
	Nominal Brake Pipe Pressure	psi	Not varied - Slight variation expected and taken care of with other BPP parameters (e.g. leakage)
	Wind Speed	mph	Not varied - Variability not found to significantly affect results
CAR PARAMETERS	Car Tare Weight	pounds	Historical consist data provided by railroads and Wheel Impcat Load Detector (WILD) data
	Davis resistance equation aerodynamic coefficient (v^2 dependent term)	pounds / mph^2	Expert opinion, data from energy testing, and Modified Davis Equation
	Davis resistance equation bearing resistance coefficient (# of axles dependent term)	pounds / axle	Expert opinion, data from energy testing, and Modified Davis Equation
	Davis resisitance equation rolling resisitance coefficient (constant term)	pounds / ton	Expert opinion, data from energy testing, and Modified Davis Equation
	Davis resisitance equation rolling resisitance coefficient (v dependent term)	pounds / ton*mph	Expert opinion, data from energy testing, and Modified Davis Equation
	Brake Force Per Brake Shoe with 50psi Brake Cylinder Pressure, when E/L equipped	pounds	UMLER (combination of car build date and whether or not car is E/L equipped), AAR Manual of Standards and Recommended Practices (S-401), and Report by Fred Carlson
	Brake Force Per Brake Shoe with 50psi Brake Cylinder Pressure, when not E/L equipped	pounds	UMLER (combination of car build date and whether or not car is E/L equipped), AAR Manual of Standards and Recommended Practices (S-401), and Report by Fred Carlson
	Car Load	percent error	Historical consist data provided by railroads and Wheel Impcat Load Detector (WILD) data
	Brake Cylinder Piston Stroke	inches	Measurements provided by railroads and performed by TTCI
	Control Valve Type	N/A	UMLER (based on car build date in relation to year when each model brake valve was introduced), Air Brake Association Proceedings
	Percent empty/load valve equipped	N/A	UMLER
	Brake Rigging Type	N/A	Not varied - Variability not found to significantly affect results and taken care of in other parameters (e.g. Brake Force Per Brake Shoe)
	Brake Pipe Length	feet	Not varied - Variability not found to significantly affect results
	Car Length	feet	Not varied - Variability not found to significantly affect results

A4. Field Testing

The objectives of the field testing portion of the enforcement algorithm evaluation methodology are to:

(a) provide enforcement test data to demonstrate the safety and performance of the enforcement algorithm using actual PTC hardware and railroad equipment
(b) verify that the parameters varied in simulation testing are appropriate by demonstrating the level of repeatability in stopping distance, given identical inputs for the parameters varied in simulation testing
(c) verify that the simulation results are representative of actual, real-world enforcement results

Each of these objectives is achieved through a different set of field tests. The first objective aims to provide additional data used in the verification of the enforcement algorithm safety and performance, and needs to be included in evaluating any particular enforcement algorithm. The second two objectives are aimed at providing the necessary justification for the simulation testing results. Since they are not tied to a specific version of a specific enforcement algorithm, these tests need only be performed a single time.

A4.1 Enforcement Algorithm Field Testing

The purpose of enforcement algorithm field testing is to supplement the simulation testing results with enforcement data using actual PTC hardware in a field implementation on actual railroad equipment. This will occur in two stages, as necessary. In the first stage, the enforcement algorithm, implemented as a black-box software application is integrated with field test hardware in a highly controlled test environment where specific conditions can be tested and tests can be repeated to show consistency. In the second stage, the enforcement algorithm, implemented in a complete PTC system is tested on revenue track where conditions not found in the controlled test environment can be tested.

A4.1.1Stage 1 – Testing in a Controlled Environment

The purpose of the first stage of enforcement algorithm field testing is to evaluate the enforcement algorithm, under a practical range of conditions, using real-world inputs on actual railroad equipment in a controlled environment, where repeatability tests can be performed at relatively low cost with no impact to railroad operations. The intent is not to perform the quantity of enforcements necessary to statistically evaluate the safety and performance of the enforcement algorithm, as this is only practical to demonstrate through the results of the simulation testing. The intent is also not to verify the accuracy of the model used or the parameters varied in simulation testing, as these are achieved through other field tests (although these tests may be used to provide additional confidence in the simulation testing results).

For the first stage of enforcement algorithm field testing, the enforcement algorithm is implemented as a black-box software application, just as for the simulation testing. The enforcement algorithm is initialized for each test by manually providing train and target stop location data to the software. The test hardware is set up to provide those inputs required by the enforcement algorithm (e.g. location, speed, brake pipe pressures, etc.) at regular time intervals over the identical interface used in simulation testing. The test train is operated towards the given target stopping location at the given test speed and the enforcement algorithm commands a penalty air brake application to prevent a violation of the given stopping target location. The enforcement algorithm may also command an emergency brake enforcement, as necessary, following the initial penalty brake enforcement. The test hardware is set up to initiate both the penalty and emergency application on the test locomotive. Enforcement of the air brakes brings the train to a stop, which completes the test.

Due to the practical availability of equipment, the specific test scenarios cannot be precisely defined for the first stage of enforcement algorithm field testing. However, it is expected that a range of operating conditions will be covered, as follows:

- Train make-up. If practical, multiple train types and loading conditions will be used, however, it may only be practical to test with loaded unit train equipment. It may be practical to test with some amount of manifest freight equipment.
- Train length. If practical, various train lengths will be tested, up to 100 cars. In some cases, shorter trains may be tested, in order to allow for more test cases to be practically evaluated.
- Train speed. A range of test speeds will be tested, up to 70 mph, if practical.
- Track grade. A range of track grades will be tested, up to -1.47%.

Additionally, a variety of the test cases will be repeated up to three times to demonstrate the consistency of the safety and performance of the enforcement algorithm in a field environment. It is expected that approximately 30-40 enforcement tests will be performed.

A4.1.2Stage 2 – Testing in Revenue Service

The purpose of the second stage of enforcement algorithm field testing is to provide additional confidence, as necessary, in the safety and performance of the enforcement algorithm under specific conditions, as in the implemented PTC system. The second stage of enforcement algorithm field testing will occur on revenue track, using PTC-equipped, test trains.

For the second stage of enforcement algorithm field testing, the enforcement algorithm is implemented in the onboard component of the PTC system. For each test, initialization is performed to include train, track, and authority information. The train is then operated towards the boundary of an artificial work zone, with the onboard system providing the required data to the enforcement algorithm. The enforcement algorithm commands a penalty air brake application to prevent a violation of the given stopping target location. The enforcement algorithm may also command an emergency brake enforcement, as necessary, following the initial penalty brake enforcement. The onboard system initiates the penalty and, if necessary, emergency applications and the train is brought to a stop.

The specific test scenarios will be generally defined, as necessary, following the first stage of enforcement algorithm field testing, to provide any additional field test data required. The precise test consists, speeds and grades will depend on the practically available locations and test trains at those locations, based on the generally defined test scenarios. It is expected that a total of approximately 20 enforcement tests will be performed that will cover the range of boundary conditions found on all freight railroads that cannot be performed in the controlled test environment.

A4.2 Repeatability Field Testing

The purpose of repeatability testing in the field is to demonstrate consistency in freight train stopping distance, given that the key varied parameters from simulation testing are held constant. This will verify that the variation in freight train stopping distance is due primarily to the parameters varied in the simulation testing, and the effects of the parameters not varied is minimal and, therefore, do not need to be considered. Because this testing is not associated with a specific enforcement algorithm, it only needs to be performed one time.

The repeatability field testing provides data on the variation in freight train stopping distance by repeating each test case multiple times with identical conditions, as practical. A minimum of six test runs for each test case provides statistical significance. Consistent location of the penalty brake application is ensured through the use of an automatic location detector (ALD) system. An ALD tag is placed on the track at the desired location of the penalty brake application and the ALD tag reader, installed on the locomotive, is wired to trigger a penalty brake application when it senses the ALD tag on the track.

For each test run, the train crew operates the train, with a fully charged air brake system, to achieve the given test speed at the location of the ALD tag. The system triggers the penalty brake application, the train is brought to a stop, and stopping distance data is recorded. The test cases for repeatability field testing represent a mix of train length, train speed, and track grade.

A4.3 Field Testing for Comparison against Simulation Results

The purpose of performing stopping distance field tests and comparing against simulation results is to demonstrate the accuracy of the model used for simulation testing and to quantify any systematic error in the model. Because this testing is not associated with a specific enforcement algorithm, it only needs to be performed one time.

Stopping distance field tests are performed to determine the actual stopping performance of the given test train. For each test case, the train is operated to the test speed and a penalty brake application is initiated at a pre-defined point. The train is brought to a stop and the dynamic speed and location data are recorded. Prior to testing, measurements of all of the key parameters that affect stopping distance are performed on the train to be used as inputs to the model. For parameters where measurement of every car in the train is impractical, measurements are performed on a sample of cars in the train, to provide statistical data to be used in the model.

Each stopping distance field test is replicated in the TOES™ model to determine the simulated stopping performance for the given test train. The exact measurements for each parameter from the field test are input and the exact operating control settings are replicated in the simulation. The results from the field tests and the simulation tests are then compared to demonstrate the accuracy of the model, given the accuracy of the inputs. The test cases for stopping distance field and simulation testing comparisons represent a mix of train length, train speed, and track grade.

A5. Analysis and Reporting

The data produced from the testing methodology described in the previous sections is analyzed to demonstrate the safety and performance of the enforcement algorithm under evaluation. The primary output of this analysis is the probability that a given train will stop short of a given target stopping location. This output, along with a number of other performance characteristics, is quantified through a statistical analysis of the results of the simulation testing. Analysis of the field testing results is used to support the conclusions drawn from the analysis of the simulation testing.

There are four components to the test data analysis:

- Statistical evaluation of the simulation data to quantify the safety and performance characteristics of the enforcement algorithm
- Comparison of field enforcement tests to simulated enforcement tests to demonstrate correlation
- Analysis of field stopping distance repeatability tests to evaluate consistency in freight train stopping distance
- Comparison of field stopping distance tests to simulated stopping distance tests to verify accuracy of model used for simulation testing

These components are described in further detail in the following sub-sections.

A5.1 Simulation Testing Analysis

The analysis of the results from the simulation testing is intended to statistically quantify the safety and performance characteristics of the enforcement algorithm for each scenario tested, based on the simulation results. There are a number of key safety and performance characteristics that are evaluated:

- Probability of target overshoot. The maximum statistical probability that the given train, under the given operating conditions, will stop beyond the given stopping target, following an air brake enforcement by the enforcement algorithm under evaluation.
- Average target overshoot. The expected average distance, in feet, beyond the given stopping target that the given train, under the given operating conditions, will stop, for those situations where the train stops beyond the stopping target
- Standard deviation of target overshoot. The expected standard deviation, in feet, of the stopping location for the given train, under the given operating conditions, for those situations where the train stops beyond the stopping target, following an air brake enforcement by the enforcement algorithm under evaluation.
- Probability of excessive target undershoot. The statistical probability range that the given train, under the given operating conditions, will stop short of the target, following an air brake enforcement by the enforcement algorithm under evaluation, by greater than:
    - 500 feet, if the initial speed at enforcement is < 30mph, or
    - 1200 feet, if the initial speed at enforcement is ≥ 30mph

- Probability of emergency brake application. The expected statistical probability that the enforcement algorithm under evaluation will apply an emergency air brake application, following the initial penalty air brake application for the given train, under the given operating conditions.
- Average enforcement location. The average location, in feet, relative to the given target stopping location, that the enforcement algorithm under evaluation will initiate a penalty air brake application for the given train, under the given operating conditions.
- Standard deviation of enforcement location. The standard deviation, in feet, of the location the enforcement algorithm under evaluation will initiate a penalty air brake application for the given train, under the given operating conditions.

The above characteristics are estimated, using a variety of statistical evaluation methods. The statistical evaluation process can be described generally as a two part analysis method. These parts are differentiated as being an objective analysis phase, followed by a subjective analysis phase.

A5.1.1Exploratory Data Analysis (objective analysis phase)

Exploratory Data Analysis (EDA) is termed “an approach/philosophy for data analysis that employs a variety of techniques (mostly graphical) to:

1. maximize insight into a data set;
2. uncover underlying structure;
3. extract important variables;
4. detect outliers and anomalies;
5. test underlying assumptions.” (NIST, 2010)

Often, 80% of the desired results are determined during EDA. The data are characterized by generating common descriptive statistics plus a variety of graphical analysis outputs. Graphical outputs include box plots, scatter (runs) plots, histograms and quantile-quantile (Q-Q) plots. The primary software tool used to perform all analyses is Statistica, Version 10 (Statsoft, 2011).

One of the tasks of EDA is data augmentation and validation. This portion of EDA assures completeness of the expected datasets and that no extraneous data were unintentionally extracted from the simulation result database. Certain required data for subsequent analysis steps must be generated (computed or derived) from the simulation results. These data field additions are completed and verified as part of the validation process. Simulated as well as generated numeric variables are evaluated to assure that the analyses are not done while data are missing or extraneous. Frequency tables, cross-tabulations and dot plots reveal all expected combinations and/or unexpected data presence.

Data consistency is confirmed using a combination of breakdown tables and various plots. Statistica breakdown tables can isolate unique combinations of factors that match each batch or operating scenario (i.e., each set of 100 simulated enforcements). The statistical parameters generated for these tables can include all standard parameters (mean, standard deviation, min, max, median, quartiles) plus variation evaluation parameters (skewness, kurtosis, standard errors, normality test statistics, variance, mean confidence interval, standard deviation confidence interval, trimmed mean, etc.).

Should any data cleanup be required, such actions are completed and the data validation outputs are rerun. Should the data prove to be reliable with review but certain characteristics remain that stand out, these are noted. Such characteristics include: outliers that are deemed reliable data; bimodal distribution patterns; and large numbers of repeated values (typical of very low speed, short trains).

A5.1.2Specific Statistical Analysis (subjective analysis phase)

Analytical methods applied during this phase produce any statistical characteristics, parameters or outcomes not available from the EDA. Typical outputs may include results such as difference tests, regressions, correlations or specialized statistical parameters. For evaluation of the enforcement algorithm, several probabilities are generated. These are considered specialized statistical parameters given the uncertainty in their determination. The problem of uncertainty in extreme quantile estimation exists where the estimated quantile (i.e. 0.995) is beyond the observed sample data range (Mhamed-Ali El-Arouia, 2002). In this case, parts-per-thousand precision is required from parts-per-hundred-sized data samples.

Probabilities are estimated both empirically and via extreme quantile estimation methods (Igor Rychlik and Rydén, 2006). The empirical probability is directly calculated from the sample. A long term probability is estimated based on observations of the distribution tail characteristics using the Peaks-over-Threshold (POT) method as defined by Rychlik and Rydén to be a Generalized Pareto Distribution (GPD). If the right distribution tail is upward-turning as observed in a Q-Q plot then the empirical probability will be an underestimate of the true probability (Ravi Annapurva and Butar, 2010), (CONORT, 2010). For these cases, the extreme quantile estimate is made using a modified POT method. A more specific and reliable distribution function is substituted following a direct data fitting evaluation. EasyFit Professional, Version 5.5 is used for data fit evaluation and distribution function and parameter generation (MathWave, 2010).

A5.2 Comparison of Field and Simulated Enforcements

Enforcement tests evaluate the performance of the enforcement algorithm in stopping the train short of the target stopping location. The specific purpose of this analysis is to assess a sample of stopping locations achieved by the algorithm, relative to a given target location across the varied set of operating scenarios (combinations of train, speed, and track profile).

Difficulties with this analysis are in comparing the sample size of one stopping distance data point produced from a field test, to a simulated stopping distance sample set of 100 data points. The uncertainty in this comparison is that, with a sample size of one, no variation exists for comparison to the simulated sample. The number of difference tests available for making this one-sample type of comparison is limited. However, using a properly defined hypothesis statement, the method used is well established. The approach is to support a null hypothesis of No Difference where the field test sample stopping distance cannot be proven to be from a different distribution than that of the simulated sample.

A5.3 Analysis of Stopping Distance Repeatability

Stopping distance repeatability tests evaluate field test data gathered while actually stopping trains representing a cross-section of potential operating scenarios. This analysis determines the consistency and variation in stopping distance, given identical conditions. This verifies that these field test stopping distance data are suitable for comparing with simulated stopping distance data. The possibility of any causes of variation that are not considered in the simulations would be revealed and assessed.

In addition to the descriptive statistics provided by the EDA, tests for homogeneity of variance are made to assess the suitability of the data for establishing a conclusion of being repeatable. The simple definition of this result is that the data come from the same distribution (are repeatable), given a high level of confidence (Montgomery, 2003). If it is true that all causes of variation are controlled or accounted for (typically, velocity, load, track grade, etc.) then the data will pass this test. If some cause of variation exists that is not considered or accounted for, the test will fail; ergo, the stopping distance data are not repeatable.

A5.4 Comparison of Identical Field and Simulated Stopping Distance Tests

Stopping distance comparisons between field tests and simulations show how closely the overall simulated results represent reality. The comparisons (statistical difference tests applied) are not between individual simulated stopping distance outcomes vs. the relative field test result. The evaluation is of the aggregate performance of the field tested enforcement algorithm vs. the aggregate performance of the simulations for the scenarios tested.

The comparison's null hypothesis is that there is no difference when comparing the differences between the pairs of the respective data sets. The relatively small sample sizes acquired from field testing add some analysis limitations in that the difference tests to be applied must be tolerant of small sample sizes. The EDA establishes the likely distribution identification for differences which, in turn, establishes the acceptable assumptions for choosing which statistical tests to use (Montgomery, 2003 and Statsoft, Inc., 2011). The primary consideration is whether the difference data are normally distributed or not. To allow additional tests to be applied, the data can be transformed to a normal distribution (NIST, 2010). A useful practice is to perform multiple, suitable tests to build a case toward supporting or rejecting the null hypothesis.

A5.5 Reporting

The final component of the test methodology is the reporting of the conclusions drawn from the analysis of the test data. The statistical measures of performance, described in section 5.1 are reported for each of the simulated test scenarios. Overall measures of performance are also reported, by combining the results of the individual test scenarios. This combination can be weighted by the likelihood of encountering each test scenario, although the weighting process can be subjective. Finally, the supporting conclusions from the analysis of the field test data are reported to demonstrate the validity of the conclusions drawn from the analysis of the simulation test data.

A6. References

1. Conort, X. (2010). “Quantile Estimation Of Heavy Tail Distributions And Model Risks Of Evt Techniques.” *Bulletin Français D’Actuariat, Vol. 10, n°19* , 63-109.
2. Rychlik, I. and Rydén, J. (2006). *Probability and Risk Analysis: An Introduction for Engineers.* Heidelburg: Springer.
3. MathWave. (2010, Dec 3). *EasyFit Professional, Version 5.5 (Released 2010-12-03)* .
4. Mhamed-Ali El-Arouia, J. D. (2002). “On the use of the peaks overthresholds method forestimating out-of-sample quantiles.” *Computational Statistics & Data Analysis,* 453-475.
5. NIST, D. o. (2010, 03 23). *NIST/SEMATECH e-Handbook of Statistical Methods.* Retrieved 01 17, 2009, from Engineering Statistics Handbook: http://www.itl.nist.gov/div898/handbook/
6. Annapurva, R. and Butar, F. B. (2010). An Insight into Heavy-Tailed Distrution. *Journal of Mathematical Sciences and Mathematical Education, Vol. 5* .
7. StatSoft, Inc. (2011). *STATISTICA, version 10* . Tulsa, OK.

Appendix B.
Enforcement Algorithm Evaluation Process Overview and Communications Interface Specification

Enforcement Algorithm
Evaluation Process Overview
and
Communications Interface Specification

Revision 6

January 25, 2011

Transportation Technology Center, Inc.
A subsidiary of the Association of American Railroads

Modification Log

Description	Date
Revision 2 - First Draft	June 2010
Revision 3 – Changes to termination logic	August 24, 2010
Revision 4 – Formatting and restructuring; added data message specification and field testing overview	September 13, 2010
Revision 5 – Added target speed to init message	September 15, 2010
Revision 6 – added description of installation test procedures in Appendix B.	January 25, 2011

Document Description

This document describes the concept of operations for the evaluation of PTC braking enforcement algorithm (EA) software in both a simulation and field test environment. The document also includes interface protocol specifications for the integration of supplier provided EA software into the TTCI testing environment.

Definitions and Acronyms

Definitions:

- Enforcement Algorithm (EA) - software designed to predict train stopping distance to enforce externally defined limits on train movement.
- Test Controller and Logger (TCL) –software used to evaluate PTC enforcement algorithm performance in a simulation test environment by running batches of simulation tests using the Train Operations and Energy Simulator (TOES™) software. The TCL software manages execution of the EA and TOES™ components and acts as a gateway between the two applications during each simulation. TCL determines consist, track, and target stopping location inputs for each test. Simulated train inputs are passed from TOES™ to EA via TCL at regular time intervals throughout the simulation and TCL initiates a penalty brake application in TOES™ upon receiving the command from EA.
- EA Initialization Module (EA-Init) – A software application used to initialization the test process with EA software. This module is started by TCL at the beginning of each simulation, or manually at the beginning of each field test. The purpose of this module is to transmit consist, track, and target stopping location data to the EA software using a TCP/IP connection.
- Virtual Machine (VM) – virtual machine software containing the supplier's EA software.

Acronyms:

- BPP – Brake Pipe Pressure
- EA – Enforcement Algorithm
- IP – Internet Protocol
- OBC – Onboard Computer
- RAM – Random Access Memory
- TCL – Test Controller/Logger
- TCP – Transmission Control Protocol
- TOES™ – Train Operations and Energy Simulator
- TTCI – Transportation Technology Center, Inc.
- VM – Virtual Machine

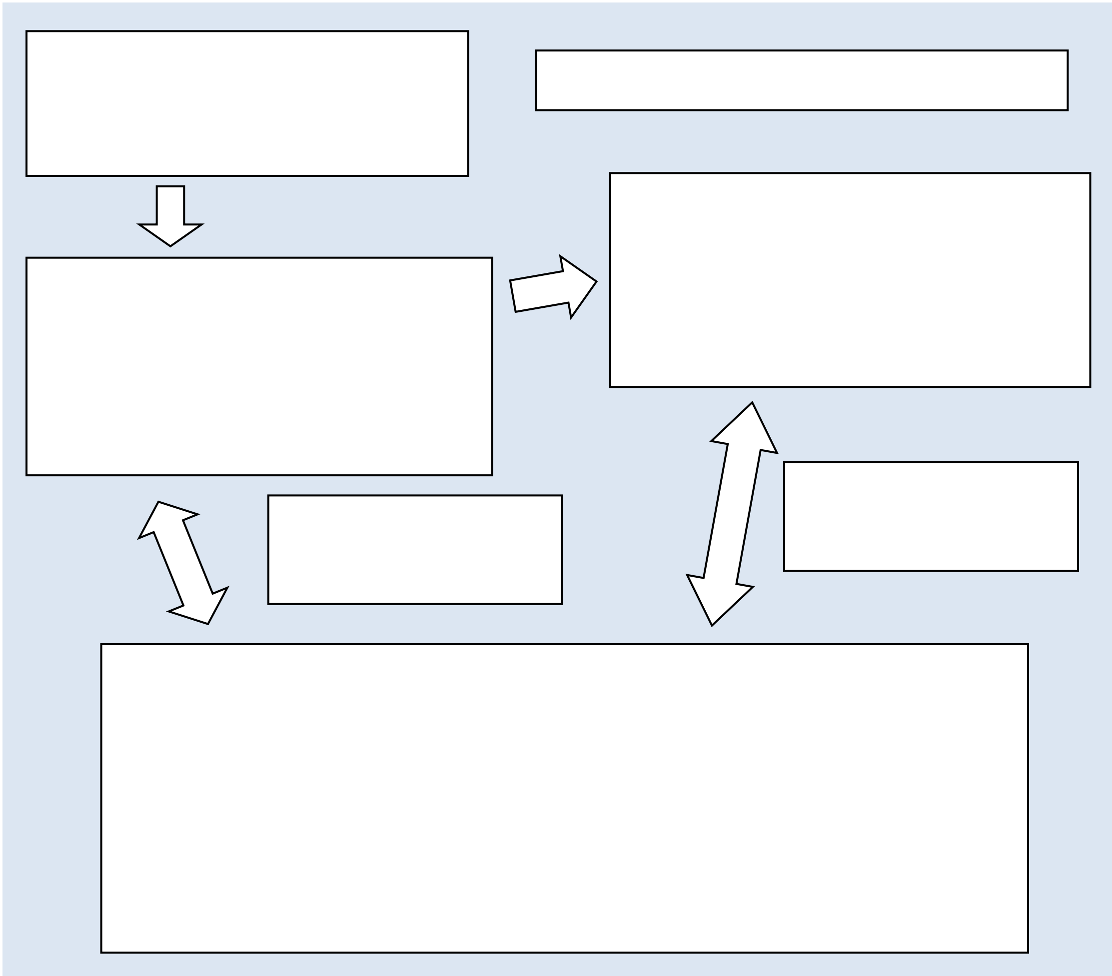
B1. Concept of Operations

This section describes the concept of operations for enforcement algorithm evaluation in both a simulation and field test environment.

B1.1 Simulation Testing

This section describes the simulation test process and required interfaces. The simulation testing process flow is illustrated in Figure B1. To start the process, TCL is configured to execute a batch of simulations and the EA application is started and configured to communicate with TCL and EA-Init using a specified IP address and two distinct ports. The simulation testing then proceeds as follows:

1. TCL starts EA-Init and TOES™ at the beginning of each simulation.
2. EA-Init sends an initialization message to EA over TCP/IP using the admin port.
3. EA sends a status message to TCL over TCP/IP using the data port.
4. TCL propagates the TOES™ simulation by one second, receives train status data and sends this data to EA over TCP/IP using the data port.
5. Steps 3 and 4 are repeated until EA determines a penalty brake application is necessary. At this time EA updates the status code in the status message sent in Step 3 to instruct TCL to apply the penalty brake. TCL then initiates the penalty application in TOES™ and steps 3 and 4 continue until the train speed is less than 0.5 mph.
6. EA sends a terminate message to both TCL (using the data port) and EA-Init (using the admin port).
7. EA-Init shuts down and TCL proceeds with the next test until the end of the test batch.

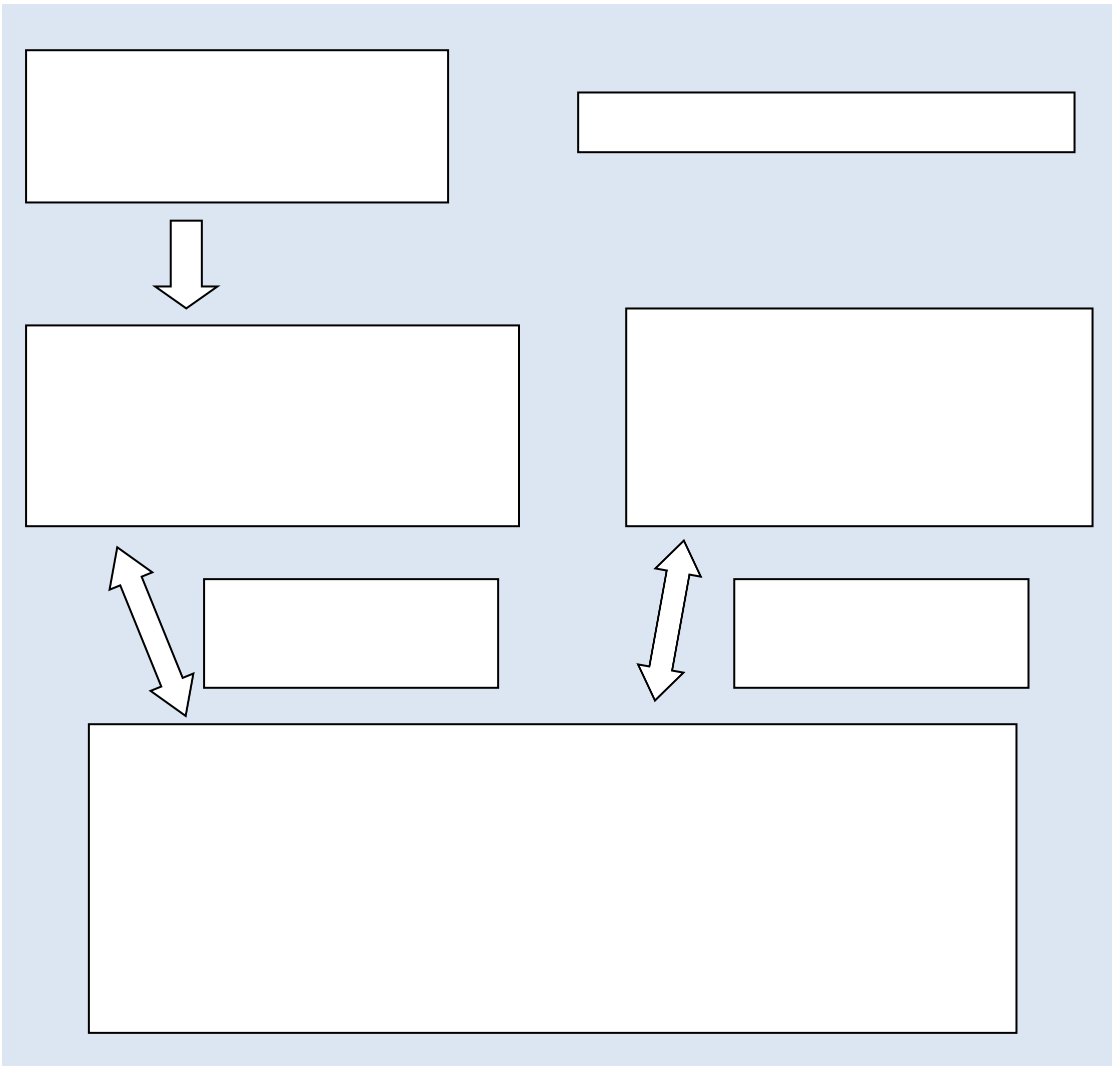


The TCL software has the ability to run multiple simulations on a single test machine. For this reason, the supplier EA software should have the ability to set both the admin port and data port using configuration files.

B1.2 Field Testing

This section describes the field test process and required interfaces. The general process flow for field testing is designed to be very similar to simulation testing and the interfaces are identical. The process flow for field testing is illustrated in Figure B2. The primary difference is that, during field testing, the EA software and the EA-Init application reside on a test computer that is connected through an Ethernet cable to the locomotive onboard computer (OBC). As in simulation testing, the EA is started and configured to interface the EA-Init application and the locomotive OBC through a specified IP address and two distinct ports.

The EA-Init application is then started and used to send an initialization message to the EA software over TCP/IP using the admin port. Once initialized, EA sends a status message to the locomotive OBC application over TCP/IP using the data port. The test is then run, with the locomotive OBC application sending data to the EA software at 1 Hz frequency and the EA software responding with a status message using the data port. When the EA software determines a penalty application is necessary, it sends the appropriate status message to the locomotive OBC, which then initiates the penalty application on the train. When the train comes to a stop, the EA software sends a terminate message to the locomotive OBC (using the data port) and to the EA-Init application (using the admin port).



B1.3 Track Data

TTCI and the EA supplier will coordinate the development of track data that will be used by the supplier provided EA software. TTCI will provide track profile data for each track section that will be utilized in testing. The supplier will use this track profile data to generate the track data store to be used by their EA software. Specific track sections for each individual test will be identified in the initialization message using an agreed upon identifier.

B1.4 Machine Configuration

Supplier provided EA software shall be delivered in one of three forms:

- as a virtual machine image that can be run on the test machines, or
- as a software executable that can run on the test machines, or
- as hardware that can be installed in the TTCI test environment (note that for simulation testing, multiple simulations are planned to be run concurrently)

The current test machines run Windows XP operating system with 4GB of RAM. TTCI and the EA supplier shall create a mutually agreeable machine configuration for running the provided EA software.

B1.4.1 Protocol Test Application

TTCI will provide a protocol test application for the EA supplier to use in development of software that can communicate using protocols developed by TTCI (See Appendix BA).

B2. Interface Specifications

This section specifies the format for the various messages used in the enforcement algorithm evaluation processes described in the previous section.

B2.1 Initialization Message Specification

Table B1 specifies the format for the initialization message to be sent from the EA-Init application to the supplier's EA application at the beginning of each simulation and field test.

Table B34 - Initialization Message

Field Name	Description	Data Length	Data Type	Notes
START_BYTES	Bytes for Framing	2 bytes	21930 (0x55aa)	Static
MESSAGE_ID	Message Identifier	1 byte	3 (0x03)	Static
TRACK_FILE_ID	The track file number	2 bytes	unsigned short	None
TARGET_LOCATION	The Target stopping Location (footage)	4 bytes	unsigned Integer	None
TARGET_SPEED	The target speed (mph)	1 byte	Unsigned integer	None
START_LOCATION	The initial starting track location (in feet)	4 bytes	Unsigned Integer	None
TRAIN_TYPE	Train Type 0 – Unknown 1 – General Freight 2 – Unit Freight 3 – Intermodal 4 – Passenger 5 – High speed Passenger 6 – Tilt train	1 byte	UINT	0-6
ORIENTATION	Lead Loco Orientation 0 – Unknown 1 – Front 2 – Back	1 byte	UINT	0-2
TRAILING_TONS	Trailing Tonnage (cars only)	2 bytes	unsigned short	0-30000
CARS_NO_BRAKES	Number of cars with inoperative brakes	2 bytes	unsigned short	0-999
AXLES	Number of axles (cars and locomotives)	2 bytes	unsigned short	0-3996
TOTAL_LENGTH	Train length (feet) – including locomotives	2 bytes	unsigned short	60-15000
LOADS	Loaded car count	2 bytes	unsigned short	0-999
EMPTIES	Empty car count	2 bytes	unsigned short	0-999
CAR_BRAKE_FORCE	Car Braking Force (lb) (optional) – not including locomotives	4 bytes	unsigned integer	0-2000000
LOCOMOTIVES	The number of locomotives	1 byte	UINT	0-24

Field Name	Description	Data Length	Data Type	Notes
For each Loco				
POSITION	The locomotive position in the train	2 bytes	unsigned short	0-999
TONNAGE	The tonnage of the locomotive	2 bytes	unsigned short	20-300
STATUS	Locomotive Status 0 – Unknown 1 – Run 2 – Isolated	1 byte	UINT	0-2
LENGTH	The length of the locomotive (feet)	1 byte	UINT	60-90
HORSEPOWER	Locomotive Horsepower	2 bytes	unsigned short	0-10000
End For				
CRC 32	CRC32 over data (not implemented)	4 bytes	UINT	Not used
END_BYTES	Bytes for Framing	2 bytes	30875 (0x789b)	Static

The TRACK_FILE_ID field identifies the section of track according to an agreed upon identifier.

The TARGET_LOCATION field specifies the target stop position in feet from the beginning of the track section for the simulation. The track section for the simulation is defined in the track file indicated by the TRACK_FILE_ID field, as discussed above.

The CAR_BRAKE_FORCE field is an optional input designed for cases when the RR customer plans to supply the enforcement algorithm with a total train braking force that is calculated offline by a preprocessor. In these cases, the RR or EA supplier can provide the algorithm for calculating the total train braking force and this field can be populated. Otherwise, this field can be ignored.

B2.2 Train Data Message Specification

Table B2 specifies the format for the train data message that is sent to the EA software. This message is sent from the TCL application during simulation testing and from the locomotive OBC application during field testing. In simulation testing, this will occur at 1 Hz frequency simulation time (i.e. faster than real time) and in field testing, this will occur at 1 Hz frequency real time.

Table B35 – Train Data Message

Field Name	Description	Data Length	Data Type	Notes
START_BYTES	Bytes for Framing	2 bytes	21930 (0x55aa)	Static
TRN_LOC	Current Train Location (footage)	8 bytes	Double	Sent as feet, must be within limits defined in track data file
TRN_SPD	Current Train Speed (mph)	8 bytes	Double	MPH

Field Name	Description	Data Length	Data Type	Notes
				0 to 999.99
BPP_HEAD	Current Brake Pipe Pressure at Head of train (psi)	8 bytes	Double	Range from 0 to 999.99
BPP_END	Current Brake Pipe Pressure at End of Train (psi)	8 bytes	Double	Range from 0 to 999.99
NOTCH	Current locomotive throttle position	8 bytes	Double	0-8
DYN_BRAKE_V	Dynamic Braking Voltage	8 bytes	Double	0 to 80V
HW_DISC1	Hardware Discrete Byte 1 • Bit A: TL01 - Slow Speed • Bit B: TL03 - Throttle D • Bit C: TL06 - Generator Field • Bit D: TL07 - Throttle C • Bit E: TL08 - Fwd Ctl • Bit F: TL09 - Rev Ctl • Bit G: TL10 - Wheel Slip • Bit H: TL12 - Throttle B	1 byte	Byte	HGFEDCBA (LSB) 1 = High 0 = Low
HW_DISC2	Hardware Discrete Byte 2 • Bit A: TL15 - Throttle A • Bit B: TL16 - Engine Run • Bit C: TL17 - Dyn Brake Setup • Bit D: TL21 - Dyn Brake Circuit Active • Bit E: TL05 - Emg Sand • Bit F: Alternator (Engine Running) • Bit G: TL23 Sand • Bit H: ISOLATE	1 byte	Byte	HGFEDCBA (LSB) 1 = High 0 = Low
HW_DISC3	Hardware Discrete Byte 3 - (spare) • Bit A: (NOT SUPPLIED) • Bit B: (NOT SUPPLIED) • Bit C: (NOT SUPPLIED) • Bit D: (NOT SUPPLIED) • Bit E: (NOT SUPPLIED) • Bit F: (NOT SUPPLIED) • Bit G: (NOT SUPPLIED) • Bit H: Brakes Cut Out	1 byte	Byte	HGFEDCBA (LSB) 1 = High 0 = Low
SPARE	(not used)	1 byte	Byte	Not used
CRC 32	CRC32 over data (not required in V3.4)	4 bytes	UINT32	Not used
END_BYTES	Bytes for Framing	2 bytes	30875 (0x789b)	Static

B2.3 EA Status Message Specification

Table B3 specifies the format for the EA status message. This message is sent by the EA software to the TCL application (simulation testing) or the locomotive OBC application (field testing) once at the beginning of the test and then again after each time a train data message is received.

Table B36 – EA Status Message

Field Name	Description	Data Length	Data Type	Notes
START_BYTES	Bytes for Framing	2 bytes	Byte (0x55aa)	Static
STATUS	Health Status 00 – OK 01 – Error 02 – Completed	2 bytes	short	Values 0 thru 2
APPLY_BR	Apply service brake	1 byte	Boolean	0 – false 1 – true
APPLY_EB	Apply emergency brake	1 byte	Boolean	0 – false 1 – true
CRC 32	CRC32 over data (not required in V3.4)	4 bytes	UINT32	Not used
END_BYTES	Bytes for Framing	2 bytes	30875 (0x789b)	Static

B.3 Protocol Test Application

The protocol test application is provided to EA developers to assist in the development of interfaces to the TCL and locomotive OBC software. The protocol test application has the following features:

- Simulates TCL/Locomotive OBC inputs
- Uses current TTCI EA protocol specifications
- Allows the user to test input values
- Sends sample initialization message to EA software

The Microsoft Visual C# 2008 source code for this application will be provided to the EA supplier to assist in development and testing.

The following two figures illustrate the operation of the test application. The first shows the train data message screen and the second shows the initialization message screen.

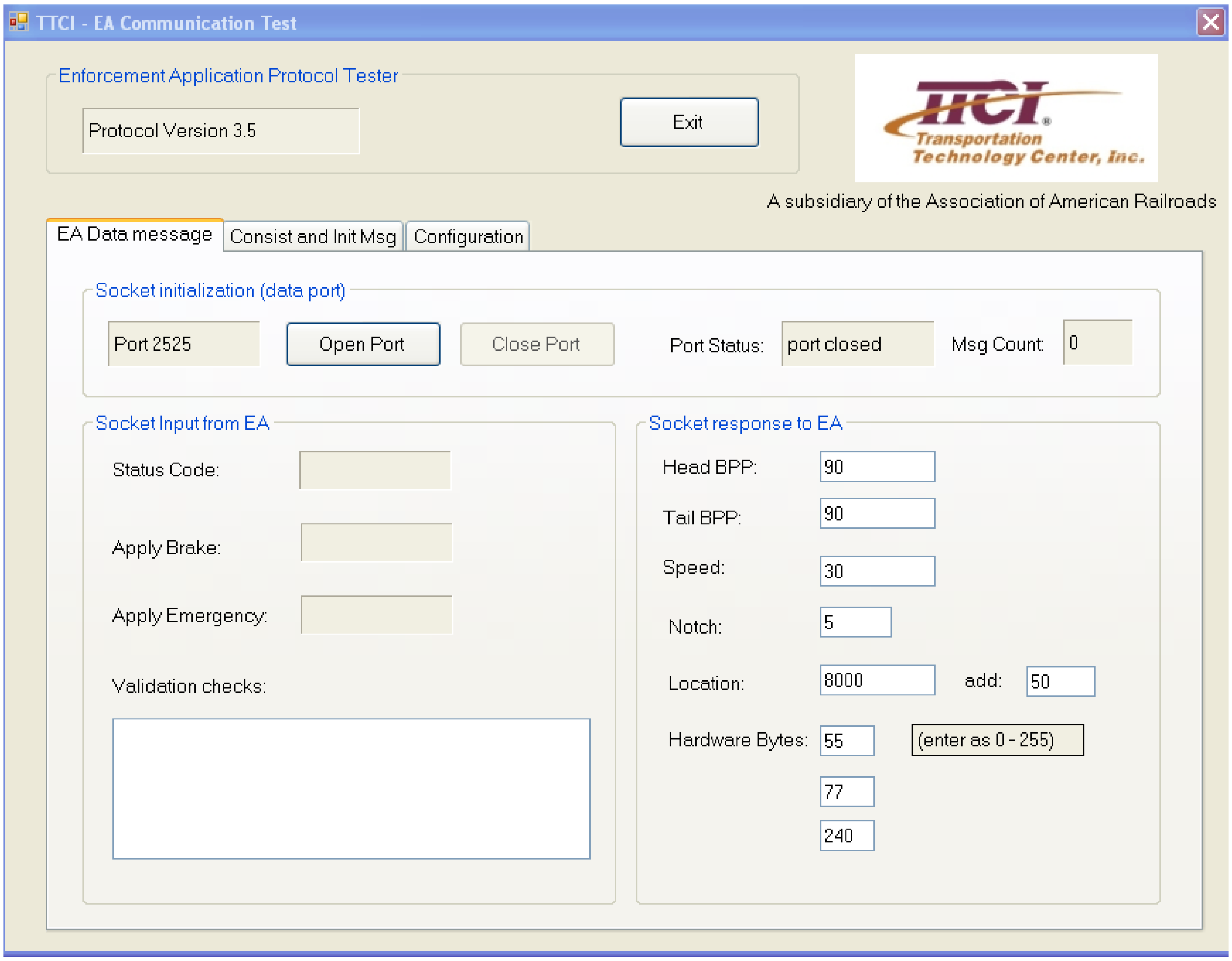


Figure B22 - EA Protocol Test Application – Data Message Tab

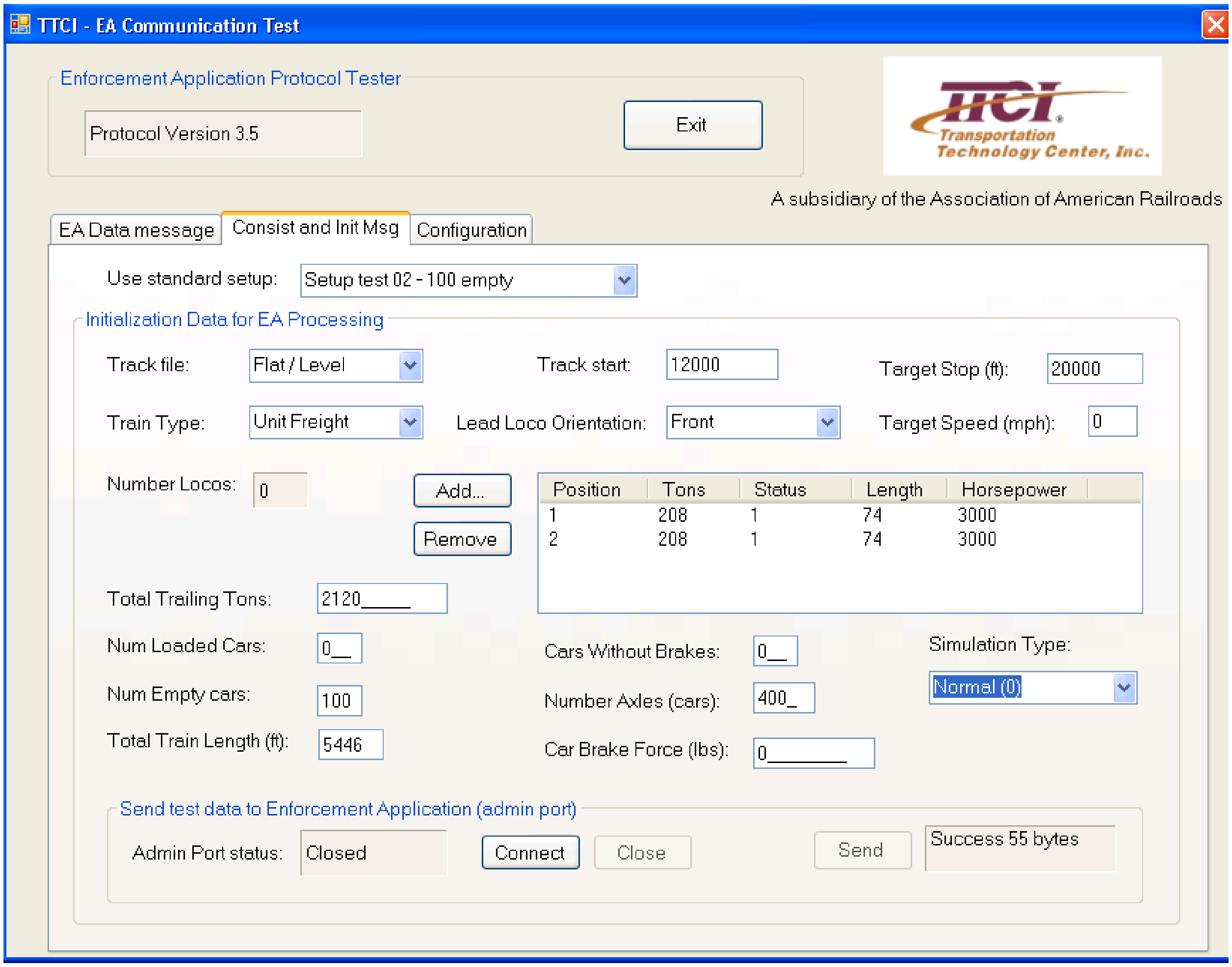
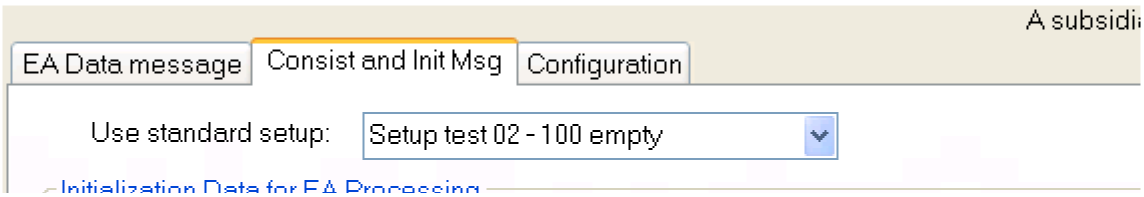


Figure B23 – EA Protocol Test Application – Initialization Message Tab

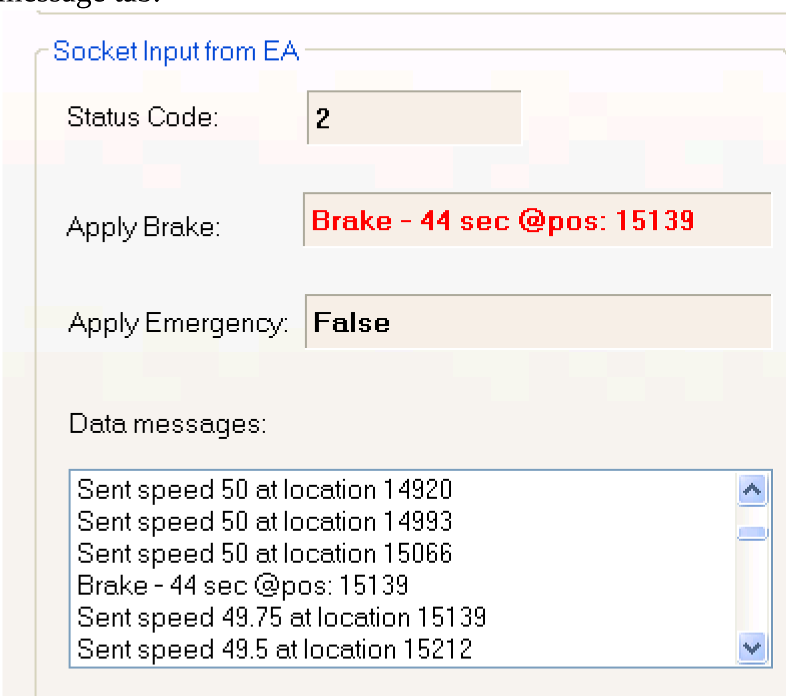
B.4 Installation and Setup Testing

This section describes how the protocol test application is used to validate the machine setup and to ensure that the EA software is installed and configured properly. The process is described as follows:

1) There are several test scenarios described in this section. These scenarios match test scenarios in the TTCI simulation environment.
2) Using the protocol test app the input parameters are entered by selecting a setup test using the EA Comms test application. This causes the loading of parameters to the screen fields.



3) Then after starting the simulation test, the application sends test date to the EA software, and the EA software should trigger a brake application this is displayed on the EA Data message tab.



4) The brake position should be recorded for each of the test scenarios in the test matrix.
5) After installation of the VM image or EA software at the TTCI test lab the test matrix is executed to validate the installation process.
6) As a final step a TCL test batch matching the test matrix is executed and the results are compared to those supplied in step 4. The test results should be similar to those in step 4, but will vary slightly due to TOES variations and TCL's use of the cruise control feature to maintain train speed.

Setup Test Matrix

Test 1	Unit Coal – 100 cars, 2 locomotives, 30 mph, flat track,
Test 2	Unit coal – 100 cars (empty), 2 locomotives, 50 mph, flat track
Test 3	General freight – 20 loads, 20 empty, 2 locomotives, 40 mph, 1.5 percent decline (TrackId = 8034)
Test 4	General freight – 20 loads, 2 locomotives, 20 mph, 1.5 percent incline (TrackId= 8036)

This test must match a test batch in the TTCI test environment.

Appendix C.
Simulation Test Matrix Details

Table C-1 describes the test consists generated for simulation testing as part of the enforcement algorithm evaluation methodology. The consist name is a unique identifier for each consist. Figures C-1, C-2, and C-3 show the naming conventions for unit, manifest freight, and intermodal trains, respectively.

Consist Naming Convention - Unit Train	
Example: U100LCWHE	
U	Unit Train
110	Number of Cars
L	Loaded (E = Empty)
CW	Coal [Western] (CE = Coal [Eastern], CH = Covered Hopper, TK = Tank, RB = Refrigerated Boxcar, ML = Multilevel)
HE	Head-end Power (DE = DP with units at end of train, DM = DP with units at head, mid, and end of train)

Figure C-1. Unit Train Consist Naming Convention

Consist Naming Convention - Manifest Train	
Example: M040AHE	
M	Manifest Train
040	Number of Cars
A	Consist identifier (10 unique consists will be tested for each length of train)
HE	Head-end Power (DE = DP with units at end of train, DM = DP with units at head, mid, and end of train)

Figure C-2. Manifest Freight Train Consist Naming Convention

Consist Naming Convention - Intermodal Train

Example: ISLAHE

I	Intermodal Train
S	Short [5,000 ft] (M = Medium [7,500 ft], L = Long [10,000 ft], V = Very Long [15,000 ft])
L	Loaded (E = Empty)
A	Consist identifier
	(5 unique consists will be tested for each length/load combination)
HE	Head-end Power (DE = DP with units at end of train, DM = DP with units at head, mid, and end of train)

Figure C-3. Intermodal Freight Train Consist Naming Convention

Table C-1. Simulation Test Consist Descriptions

Consist Name	Type	Length	Makeup	Loading	Power	Trailing Tonnage	Number of Locomotives
IVEADM	Intermodal	Very Long	A	Empty	DP - H/M/E	5169	10
IVEBDM	Intermodal	Very Long	B	Empty	DP - H/M/E	5398	10
IVECDM	Intermodal	Very Long	C	Empty	DP - H/M/E	5536	10
IVEDDM	Intermodal	Very Long	D	Empty	DP - H/M/E	5512	10
IVEEDM	Intermodal	Very Long	E	Empty	DP - H/M/E	5361	10
IVLADM	Intermodal	Very Long	A	Loaded	DP - H/M/E	20743	15
IVLBDM	Intermodal	Very Long	B	Loaded	DP - H/M/E	12105	10
IVLCDM	Intermodal	Very Long	C	Loaded	DP - H/M/E	13336	10
IVLDDM	Intermodal	Very Long	D	Loaded	DP - H/M/E	13517	10
IVLEDM	Intermodal	Very Long	E	Loaded	DP - H/M/E	11947	10
ILEADE	Intermodal	Long	A	Empty	DP - H/E	3437	7
ILEADM	Intermodal	Long	A	Empty	DP - H/M/E	3437	7
ILEBDE	Intermodal	Long	B	Empty	DP - H/E	3614	7
ILEBDM	Intermodal	Long	B	Empty	DP - H/M/E	3614	7

Consist Name	Type	Length	Makeup	Loading	Power	Trailing Tonnage	Number of Locomotives
ILECDE	Intermodal	Long	C	Empty	DP - H/E	3687	7
ILECDM	Intermodal	Long	C	Empty	DP - H/M/E	3687	7
ILEDDE	Intermodal	Long	D	Empty	DP - H/E	3613	7
ILEDDM	Intermodal	Long	D	Empty	DP - H/M/E	3613	7
ILEEDE	Intermodal	Long	E	Empty	DP - H/E	3630	7
ILEEDM	Intermodal	Long	E	Empty	DP - H/M/E	3630	7
ILLADE	Intermodal	Long	A	Loaded	DP - H/E	14858	11
ILLADM	Intermodal	Long	A	Loaded	DP - H/M/E	14858	11
ILLBDE	Intermodal	Long	B	Loaded	DP - H/E	9160	7
ILLBDM	Intermodal	Long	B	Loaded	DP - H/M/E	9160	7
ILLCDE	Intermodal	Long	C	Loaded	DP - H/E	9987	7
ILLCDM	Intermodal	Long	C	Loaded	DP - H/M/E	9987	7
ILLDDE	Intermodal	Long	D	Loaded	DP - H/E	9077	7
ILLDDM	Intermodal	Long	D	Loaded	DP - H/M/E	9077	7
ILLEDE	Intermodal	Long	E	Loaded	DP - H/E	9592	7
ILLEDM	Intermodal	Long	E	Loaded	DP - H/M/E	9592	7
IMEADE	Intermodal	Medium	A	Empty	DP - H/E	2658	5
IMEAHE	Intermodal	Medium	A	Empty	Head End	2658	5
IMEBDE	Intermodal	Medium	B	Empty	DP - H/E	2781	5
IMEBHE	Intermodal	Medium	B	Empty	Head End	2781	5
IMECDE	Intermodal	Medium	C	Empty	DP - H/E	2648	5
IMECHE	Intermodal	Medium	C	Empty	Head End	2648	5
IMEDDE	Intermodal	Medium	D	Empty	DP - H/E	2738	5
IMEDHE	Intermodal	Medium	D	Empty	Head End	2738	5
IMEEDE	Intermodal	Medium	E	Empty	DP - H/E	2681	5
IMEEHE	Intermodal	Medium	E	Empty	Head End	2681	5

Consist Name	Type	Length	Makeup	Loading	Power	Trailing Tonnage	Number of Locomotives
IMLADE	Intermodal	Medium	A	Loaded	DP - H/E	10447	9
IMLAHE	Intermodal	Medium	A	Loaded	Head End	10447	9
IMLBDE	Intermodal	Medium	B	Loaded	DP - H/E	6846	5
IMLBHE	Intermodal	Medium	B	Loaded	Head End	6846	5
IMLCDE	Intermodal	Medium	C	Loaded	DP - H/E	6397	5
IMLCHE	Intermodal	Medium	C	Loaded	Head End	6397	5
IMLDDE	Intermodal	Medium	D	Loaded	DP - H/E	5891	5
IMLDHE	Intermodal	Medium	D	Loaded	Head End	5891	5
IMLEDE	Intermodal	Medium	E	Loaded	DP - H/E	6414	5
IMLEHE	Intermodal	Medium	E	Loaded	Head End	6414	5
ISEADE	Intermodal	Short	A	Empty	DP - H/E	1770	4
ISEAHE	Intermodal	Short	A	Empty	Head End	1770	4
ISEBDE	Intermodal	Short	B	Empty	DP - H/E	1793	4
ISEBHE	Intermodal	Short	B	Empty	Head End	1793	4
ISECDE	Intermodal	Short	C	Empty	DP - H/E	1793	4
ISECHE	Intermodal	Short	C	Empty	Head End	1793	4
ISEDDE	Intermodal	Short	D	Empty	DP - H/E	1822	4
ISEDHE	Intermodal	Short	D	Empty	Head End	1822	4
ISEEDE	Intermodal	Short	E	Empty	DP - H/E	1842	4
ISEEHE	Intermodal	Short	E	Empty	Head End	1842	4
ISLADE	Intermodal	Short	A	Loaded	DP - H/E	7002	6
ISLAHE	Intermodal	Short	A	Loaded	Head End	7002	6
ISLBDE	Intermodal	Short	B	Loaded	DP - H/E	5129	4
ISLBHE	Intermodal	Short	B	Loaded	Head End	5129	4
ISLCDE	Intermodal	Short	C	Loaded	DP - H/E	3937	4
ISLCHE	Intermodal	Short	C	Loaded	Head End	3937	4

Consist Name	Type	Length	Makeup	Loading	Power	Trailing Tonnage	Number of Locomotives
ISLDDE	Intermodal	Short	D	Loaded	DP - H/E	4736	4
ISLDHE	Intermodal	Short	D	Loaded	Head End	4736	4
ISLEDE	Intermodal	Short	E	Loaded	DP - H/E	4328	4
ISLEHE	Intermodal	Short	E	Loaded	Head End	4328	4
M0AHE	Manifest Freight	Light Locomotive	A	N/A	N/A	0	1
M0BHE	Manifest Freight	3 Light Locomotives	B	N/A	N/A	0	3
M0AHEG	Manifest Freight	Light Locomotive	A	N/A	N/A	0	1
M0BHEG	Manifest Freight	3 Light Locomotives	B	N/A	N/A	0	3
M3AHE	Manifest Freight	003	A	N/A	Head End	398	1
M3BHE	Manifest Freight	003	B	N/A	Head End	99	1
M3CHE	Manifest Freight	003	C	N/A	Head End	384	1
M3DHE	Manifest Freight	003	D	N/A	Head End	107	1
M3EHE	Manifest Freight	003	E	N/A	Head End	381	1
M3FHE	Manifest Freight	003	F	N/A	Head End	380	1
M3GHE	Manifest Freight	003	G	N/A	Head End	360	1
M3HHE	Manifest Freight	003	H	N/A	Head End	222	1
M3IHE	Manifest Freight	003	I	N/A	Head End	136	1
M3JHE	Manifest Freight	003	J	N/A	Head End	117	1
M3AHEG	Manifest Freight	003	A	N/A	Head End	398	1
M3BHEG	Manifest Freight	003	B	N/A	Head End	99	1
M3CHEG	Manifest Freight	003	C	N/A	Head End	384	1
M3DHEG	Manifest Freight	003	D	N/A	Head End	107	1
M3EHEG	Manifest Freight	003	E	N/A	Head End	381	1
M3FHEG	Manifest Freight	003	F	N/A	Head End	380	1
M3GHEG	Manifest Freight	003	G	N/A	Head End	360	1
M3HHEG	Manifest Freight	003	H	N/A	Head End	222	1

Consist Name	Type	Length	Makeup	Loading	Power	Trailing Tonnage	Number of Locomotives
M3IHEG	Manifest Freight	003	I	N/A	Head End	136	1
M3JHEG	Manifest Freight	003	J	N/A	Head End	117	1
M10AHE	Manifest Freight	010	A	N/A	Head End	1315	2
M10BHE	Manifest Freight	010	B	N/A	Head End	344	2
M10CHE	Manifest Freight	010	C	N/A	Head End	560	2
M10DHE	Manifest Freight	010	D	N/A	Head End	921	2
M10EHE	Manifest Freight	010	E	N/A	Head End	1072	2
M10FHE	Manifest Freight	010	F	N/A	Head End	800	2
M10GHE	Manifest Freight	010	G	N/A	Head End	686	2
M10HHE	Manifest Freight	010	H	N/A	Head End	389	2
M10IHE	Manifest Freight	010	I	N/A	Head End	1379	2
M10JHE	Manifest Freight	010	J	N/A	Head End	1005	2
M10AHEG	Manifest Freight	010	A	N/A	Head End	1315	2
M10BHEG	Manifest Freight	010	B	N/A	Head End	344	2
M10CHEG	Manifest Freight	010	C	N/A	Head End	560	2
M10DHEG	Manifest Freight	010	D	N/A	Head End	921	2
M10EHEG	Manifest Freight	010	E	N/A	Head End	1072	2
M10FHEG	Manifest Freight	010	F	N/A	Head End	800	2
M10GHEG	Manifest Freight	010	G	N/A	Head End	686	2
M10HHEG	Manifest Freight	010	H	N/A	Head End	389	2
M10IHEG	Manifest Freight	010	I	N/A	Head End	1379	2
M10JHEG	Manifest Freight	010	J	N/A	Head End	1005	2
M40AHE	Manifest Freight	040	A	N/A	Head End	5131	4
M40BHE	Manifest Freight	040	B	N/A	Head End	1318	2
M40CHE	Manifest Freight	040	C	N/A	Head End	3741	3
M40DHE	Manifest Freight	040	D	N/A	Head End	5026	4

Consist Name	Type	Length	Makeup	Loading	Power	Trailing Tonnage	Number of Locomotives
M40EHE	Manifest Freight	040	E	N/A	Head End	4090	3
M40FHE	Manifest Freight	040	F	N/A	Head End	2909	2
M40GHE	Manifest Freight	040	G	N/A	Head End	2505	2
M40HHE	Manifest Freight	040	H	N/A	Head End	4183	3
M40IHE	Manifest Freight	040	I	N/A	Head End	2174	2
M40JHE	Manifest Freight	040	J	N/A	Head End	2958	2
M100ADE	Manifest Freight	100	A	N/A	DP - H/E	13290	9
M100AHE	Manifest Freight	100	A	N/A	Head End	13290	9
M100BDE	Manifest Freight	100	B	N/A	DP - H/E	3338	4
M100BHE	Manifest Freight	100	B	N/A	Head End	3338	4
M100CDE	Manifest Freight	100	C	N/A	DP - H/E	6810	5
M100CHE	Manifest Freight	100	C	N/A	Head End	6810	5
M100DDE	Manifest Freight	100	D	N/A	DP - H/E	11500	7
M100DHE	Manifest Freight	100	D	N/A	Head End	11500	7
M100EDE	Manifest Freight	100	E	N/A	DP - H/E	8382	5
M100EHE	Manifest Freight	100	E	N/A	Head End	8382	5
M100FDE	Manifest Freight	100	F	N/A	DP - H/E	8709	5
M100FHE	Manifest Freight	100	F	N/A	Head End	8709	5
M100GDE	Manifest Freight	100	G	N/A	DP - H/E	8918	5
M100GHE	Manifest Freight	100	G	N/A	Head End	8918	5
M100HDE	Manifest Freight	100	H	N/A	DP - H/E	9069	5
M100HHE	Manifest Freight	100	H	N/A	Head End	9069	5
M100IDE	Manifest Freight	100	I	N/A	DP - H/E	10007	6
M100IHE	Manifest Freight	100	I	N/A	Head End	10007	6
M100JDE	Manifest Freight	100	J	N/A	DP - H/E	10462	6
M100JHE	Manifest Freight	100	J	N/A	Head End	10462	6

Consist Name	Type	Length	Makeup	Loading	Power	Trailing Tonnage	Number of Locomotives
M150ADE	Manifest Freight	150	A	N/A	DP - H/E	19748	9
M150ADM	Manifest Freight	150	A	N/A	DP - H/M/E	19748	9
M150BDE	Manifest Freight	150	B	N/A	DP - H/E	4942	6
M150BDM	Manifest Freight	150	B	N/A	DP - H/M/E	4942	6
M150CDE	Manifest Freight	150	C	N/A	DP - H/E	13891	7
M150CDM	Manifest Freight	150	C	N/A	DP - H/M/E	13891	7
M150DDE	Manifest Freight	150	D	N/A	DP - H/E	10796	6
M150DDM	Manifest Freight	150	D	N/A	DP - H/M/E	10796	6
M150EDE	Manifest Freight	150	E	N/A	DP - H/E	9753	6
M150EDM	Manifest Freight	150	E	N/A	DP - H/M/E	9753	6
M150FDE	Manifest Freight	150	F	N/A	DP - H/E	12542	6
M150FDM	Manifest Freight	150	F	N/A	DP - H/M/E	12542	6
M150GDE	Manifest Freight	150	G	N/A	DP - H/E	10884	6
M150GDM	Manifest Freight	150	G	N/A	DP - H/M/E	10884	6
M150HDE	Manifest Freight	150	H	N/A	DP - H/E	16043	7
M150HDM	Manifest Freight	150	H	N/A	DP - H/M/E	16043	7
M150IDE	Manifest Freight	150	I	N/A	DP - H/E	13721	7
M150IDM	Manifest Freight	150	I	N/A	DP - H/M/E	13721	7
M150JDE	Manifest Freight	150	J	N/A	DP - H/E	14991	7
M150JDM	Manifest Freight	150	J	N/A	DP - H/M/E	14991	7
M200ADE	Manifest Freight	200	A	N/A	DP - H/E	26535	12
M200ADM	Manifest Freight	200	A	N/A	DP - H/M/E	26535	12
M200BDE	Manifest Freight	200	B	N/A	DP - H/E	7108	8
M200BDM	Manifest Freight	200	B	N/A	DP - H/M/E	7108	8
M200CDE	Manifest Freight	200	C	N/A	DP - H/E	18565	9
M200CDM	Manifest Freight	200	C	N/A	DP - H/M/E	18565	9

Consist Name	Type	Length	Makeup	Loading	Power	Trailing Tonnage	Number of Locomotives
M200DDE	Manifest Freight	200	D	N/A	DP - H/E	15649	8
M200DDM	Manifest Freight	200	D	N/A	DP - H/M/E	15649	8
M200EDE	Manifest Freight	200	E	N/A	DP - H/E	17315	8
M200EDM	Manifest Freight	200	E	N/A	DP - H/M/E	17315	8
M200FDE	Manifest Freight	200	F	N/A	DP - H/E	19152	9
M200FDM	Manifest Freight	200	F	N/A	DP - H/M/E	19152	9
M200GDE	Manifest Freight	200	G	N/A	DP - H/E	20566	9
M200GDM	Manifest Freight	200	G	N/A	DP - H/M/E	20566	9
M200HDE	Manifest Freight	200	H	N/A	DP - H/E	19139	9
M200HDM	Manifest Freight	200	H	N/A	DP - H/M/E	19139	9
M200IDE	Manifest Freight	200	I	N/A	DP - H/E	20049	9
M200IDM	Manifest Freight	200	I	N/A	DP - H/M/E	20049	9
M200JDE	Manifest Freight	200	J	N/A	DP - H/E	17541	8
M200JDM	Manifest Freight	200	J	N/A	DP - H/M/E	17541	8
U100ECEDE	Unit	100	Coal - Eastern	Empty	DP - H/E	2955	4
U100ECEHE	Unit	100	Coal - Eastern	Empty	Head End	2955	4
U100ECHDE	Unit	100	Grain	Empty	DP - H/E	3125	4
U100ECHHE	Unit	100	Grain	Empty	Head End	3125	4
U100ECWDE	Unit	100	Coal - Western	Empty	DP - H/E	2120	4
U100ECWHE	Unit	100	Coal - Western	Empty	Head End	2120	4
U100EMLDE	Unit	100	Multilevel	Empty	DP - H/E	5200	4
U100EMLHE	Unit	100	Multilevel	Empty	Head End	5200	4
U100ERBDE	Unit	100	Refrigerated Box	Empty	DP - H/E	5115	4
U100ERBHE	Unit	100	Refrigerated Box	Empty	Head End	5115	4
U100ETKDE	Unit	100	Tank	Empty	DP - H/E	3100	4
U100ETKHE	Unit	100	Tank	Empty	Head End	3100	4

Consist Name	Type	Length	Makeup	Loading	Power	Trailing Tonnage	Number of Locomotives
U100LCEDE	Unit	100	Coal - Eastern	Loaded	DP - H/E	14300	4
U100LCEHE	Unit	100	Coal - Eastern	Loaded	Head End	14300	4
U100LCHDE	Unit	100	Grain	Loaded	DP - H/E	14300	4
U100LCHHE	Unit	100	Grain	Loaded	Head End	14300	4
U100LCWDE	Unit	100	Coal - Western	Loaded	DP - H/E	14300	4
U100LCWHE	Unit	100	Coal - Western	Loaded	Head End	14300	4
U100LMLDE	Unit	100	Multilevel	Loaded	DP - H/E	11000	4
U100LMLHE	Unit	100	Multilevel	Loaded	Head End	11000	4
U100LRBDE	Unit	100	Refrigerated Box	Loaded	DP - H/E	14300	4
U100LRBHE	Unit	100	Refrigerated Box	Loaded	Head End	14300	4
U100LTKDE	Unit	100	Tank	Loaded	DP - H/E	13150	4
U100LTKHE	Unit	100	Tank	Loaded	Head End	13150	4
U135ECEDE	Unit	135	Coal - Eastern	Empty	DP - H/E	3989	6
U135ECEDM	Unit	135	Coal - Eastern	Empty	DP - H/M/E	3989	6
U135ECHDE	Unit	135	Grain	Empty	DP - H/E	4219	6
U135ECHDM	Unit	135	Grain	Empty	DP - H/M/E	4219	6
U135ECWDE	Unit	135	Coal - Western	Empty	DP - H/E	2862	6
U135ECWDM	Unit	135	Coal - Western	Empty	DP - H/M/E	2862	6
U135EMLDE	Unit	135	Multilevel	Empty	DP - H/E	7020	6
U135EMLDM	Unit	135	Multilevel	Empty	DP - H/M/E	7020	6
U135ERBDE	Unit	135	Refrigerated Box	Empty	DP - H/E	6905	6
U135ERBDM	Unit	135	Refrigerated Box	Empty	DP - H/M/E	6905	6
U135ETKDE	Unit	135	Tank	Empty	DP - H/E	4185	6
U135ETKDM	Unit	135	Tank	Empty	DP - H/M/E	4185	6
U135LCEDE	Unit	135	Coal - Eastern	Loaded	DP - H/E	19305	6
U135LCEDM	Unit	135	Coal - Eastern	Loaded	DP - H/M/E	19305	6

Consist Name	Type	Length	Makeup	Loading	Power	Trailing Tonnage	Number of Locomotives
U135LCHDE	Unit	135	Grain	Loaded	DP - H/E	19305	6
U135LCHDM	Unit	135	Grain	Loaded	DP - H/M/E	19305	6
U135LCWDE	Unit	135	Coal - Western	Loaded	DP - H/E	19305	6
U135LCWDM	Unit	135	Coal - Western	Loaded	DP - H/M/E	19305	6
U135LMLDE	Unit	135	Multilevel	Loaded	DP - H/E	14850	6
U135LMLDM	Unit	135	Multilevel	Loaded	DP - H/M/E	14850	6
U135LRBDE	Unit	135	Refrigerated Box	Loaded	DP - H/E	19305	6
U135LRBDM	Unit	135	Refrigerated Box	Loaded	DP - H/M/E	19305	6
U135LTKDE	Unit	135	Tank	Loaded	DP - H/E	17753	6
U135LTKDM	Unit	135	Tank	Loaded	DP - H/M/E	17753	6
U200ECEDE	Unit	200	Coal - Eastern	Empty	DP - H/E	5910	8
U200ECEDM	Unit	200	Coal - Eastern	Empty	DP - H/M/E	5910	8
U200ECWDE	Unit	200	Coal - Western	Empty	DP - H/E	4240	8
U200ECWDM	Unit	200	Coal - Western	Empty	DP - H/M/E	4240	8
U200LCEDE	Unit	200	Coal - Eastern	Loaded	DP - H/E	28600	8
U200LCEDM	Unit	200	Coal - Eastern	Loaded	DP - H/M/E	28600	8
U200LCWDE	Unit	200	Coal - Western	Loaded	DP - H/E	28600	8
U200LCWDM	Unit	200	Coal - Western	Loaded	DP - H/M/E	28600	8
U260ECEDM	Unit	260	Coal - Eastern	Empty	DP - H/M/E	7683	12
U260ECWDM	Unit	260	Coal - Western	Empty	DP - H/M/E	5512	12
U260LCEDM	Unit	260	Coal - Eastern	Loaded	DP - H/M/E	37180	12
U260LCWDM	Unit	260	Coal - Western	Loaded	DP - H/M/E	37180	12

Table C-2 lists the maximum operating speed for each consist on each grade used in the simulation test matrix. A "*" in the table indicates that an air brake application is required to maintain the given speed, in addition to use of dynamic brake. A "^" in the table indicates that the maximum operating speed is less than the maximum allowable speed, for cases where it is not possible to maintain the maximum allowable speed.

Table C-2. Maximum Speeds

Consist Name	Flat	0.5%	1.5%	-0.5%	-1.1%	-1.7%	-2.2%	-2.8%	1% Crest	1% Trough
IVEADM	60	60	25	60	60	25	20	15	52^	60
IVEBDM	60	60	25	60	60	25	20	15	52^	60
IVECDM	60	60	25	60	60	25	20	15	52^	60
IVEDDM	60	60	25	60	60	25	20	15	52^	60
IVEEDM	60	60	25	60	60	25	20	15	52^	60
IVLADM	60	50^	21^	60	60	25	20	15*	30^	60
IVLBDM	60	50^	21^	60	60	25	20	15*	30^	60
IVLCDM	60	50^	21^	60	60	25	20	15*	30^	60
IVLDDM	60	50^	21^	60	60	25	20	15*	30^	60
IVLEDM	60	50^	21^	60	60	25	20	15*	30^	60
ILEADE	60	60	25	60	60	25	20	20	53^	60
ILEADM	60	60	25	60	60	25	20	20	53^	60
ILEBDE	60	60	25	60	60	25	20	20	53^	60
ILEBDM	60	60	25	60	60	25	20	20	53^	60
ILECDE	60	60	25	60	60	25	20	20	53^	60
ILECDM	60	60	25	60	60	25	20	20	53^	60
ILEDDE	60	60	25	60	60	25	20	20	53^	60
ILEDDM	60	60	25	60	60	25	20	20	53^	60
ILEEDE	60	60	25	60	60	25	20	20	53^	60
ILEEDM	60	60	25	60	60	25	20	20	53^	60
ILLADE	60	48^	20^	60	60	25	20	15*	30^	60
ILLADM	60	48^	20^	60	60	25	20	15*	30^	60
ILLBDE	60	48^	20^	60	60	25	20	15*	30^	60
ILLBDM	60	48^	20^	60	60	25	20	15*	30^	60
ILLCDE	60	48^	20^	60	60	25	20	15*	30^	60
ILLCDM	60	48^	20^	60	60	25	20	15*	30^	60
ILLDDE	60	48^	20^	60	60	25	20	15*	30^	60
ILLDDM	60	48^	20^	60	60	25	20	15*	30^	60
ILLEDE	60	48^	20^	60	60	25	20	15*	30^	60
ILLEDM	60	48^	20^	60	60	25	20	15*	30^	60
IMEADE	60	60	25	60	60	25	20	20	52^	60
IMEAHE	60	60	25	60	60	25	20	20	52^	60
IMEBDE	60	60	25	60	60	25	20	20	52^	60

Consist Name	Flat	0.5%	1.5%	-0.5%	-1.1%	-1.7%	-2.2%	-2.8%	1% Crest	1% Trough
IMEBHE	60	60	25	60	60	25	20	20	52^	60
IMECDE	60	60	25	60	60	25	20	20	52^	60
IMECHE	60	60	25	60	60	25	20	20	52^	60
IMEDDE	60	60	25	60	60	25	20	20	52^	60
IMEDHE	60	60	25	60	60	25	20	20	52^	60
IMEEDE	60	60	25	60	60	25	20	20	52^	60
IMEEHE	60	60	25	60	60	25	20	20	52^	60
IMLADE	70	50^	25	70	70	25	20	15*	33^	70
IMLAHE	70	50^	25	70	70	25	20	15*	33^	70
IMLBDE	70	50^	25	70	70	25	20	15*	33^	70
IMLBHE	70	50^	25	70	70	25	20	15*	33^	70
IMLCDE	70	50^	25	70	70	25	20	15*	33^	70
IMLCHE	70	50^	25	70	70	25	20	15*	33^	70
IMLDDE	70	50^	25	70	70	25	20	15*	33^	70
IMLDHE	70	50^	25	70	70	25	20	15*	33^	70
IMLEDE	70	50^	25	70	70	25	20	15*	33^	70
IMLEHE	70	50^	25	70	70	25	20	15*	33^	70
ISEADE	60	60	25	60	60	25	20	20	57^	60
ISEAHE	60	60	25	60	60	25	20	20	57^	60
ISEBDE	60	60	25	60	60	25	20	20	57^	60
ISEBHE	60	60	25	60	60	25	20	20	57^	60
ISECDE	60	60	25	60	60	25	20	20	57^	60
ISECHE	60	60	25	60	60	25	20	20	57^	60
ISEDDE	60	60	25	60	60	25	20	20	57^	60
ISEDHE	60	60	25	60	60	25	20	20	57^	60
ISEEDE	60	60	25	60	60	25	20	20	57^	60
ISEEHE	60	60	25	60	60	25	20	20	57^	60
ISLADE	70	55^	25	70	70	25	20	15*	35^	70
ISLAHE	70	55^	25	70	70	25	20	15*	35^	70
ISLBDE	70	55^	25	70	70	25	20	15*	35^	70
ISLBHE	70	55^	25	70	70	25	20	15*	35^	70
ISLCDE	70	55^	25	70	70	25	20	15*	35^	70
ISLCHE	70	55^	25	70	70	25	20	15*	35^	70
ISLDDE	70	55^	25	70	70	25	20	15*	35^	70
ISLDHE	70	55^	25	70	70	25	20	15*	35^	70
ISLEDE	70	55^	25	70	70	25	20	15*	35^	70
ISLEHE	70	55^	25	70	70	25	20	15*	35^	70
M0AHE	60	60	25	60	55	25	20	20	55	55
M0BHE	60	60	25	60	55	25	20	20	55	55

Consist Name	Flat	0.5%	1.5%	-0.5%	-1.1%	-1.7%	-2.2%	-2.8%	1% Crest	1% Trough
M0AHEG	60	60	25	60	55	25	20	20	55	55
M0BHEG	60	60	25	60	55	25	20	20	55	55
M3AHE	60	60	25	60	45	25	20	15	45	45
M3BHE	60	60	25	60	45	25	20	15	45	45
M3CHE	60	60	25	60	45	25	20	15	45	45
M3DHE	60	60	25	60	45	25	20	15	45	45
M3EHE	60	60	25	60	45	25	20	15	45	45
M3FHE	60	60	25	60	45	25	20	15	45	45
M3GHE	60	60	25	60	45	25	20	15	45	45
M3HHE	60	60	25	60	45	25	20	15	45	45
M3IHE	60	60	25	60	45	25	20	15	45	45
M3JHE	60	60	25	60	45	25	20	15	45	45
M3AHEG	60	60	25	60	45	25	20	15	45	45
M3BHEG	60	60	25	60	45	25	20	15	45	45
M3CHEG	60	60	25	60	45	25	20	15	45	45
M3DHEG	60	60	25	60	45	25	20	15	45	45
M3EHEG	60	60	25	60	45	25	20	15	45	45
M3FHEG	60	60	25	60	45	25	20	15	45	45
M3GHEG	60	60	25	60	45	25	20	15	45	45
M3HHEG	60	60	25	60	45	25	20	15	45	45
M3IHEG	60	60	25	60	45	25	20	15	45	45
M3JHEG	60	60	25	60	45	25	20	15	45	45
M10AHE	60	60	25	60	45	25	20	15	45	45
M10BHE	60	60	25	60	45	25	20	15	45	45
M10CHE	60	60	25	60	45	25	20	15	45	45
M10DHE	60	60	25	60	45	25	20	15	45	45
M10EHE	60	60	25	60	45	25	20	15	45	45
M10FHE	60	60	25	60	45	25	20	15	45	45
M10GHE	60	60	25	60	45	25	20	15	45	45
M10HHE	60	60	25	60	45	25	20	15	45	45
M10IHE	60	60	25	60	45	25	20	15	45	45
M10JHE	60	60	25	60	45	25	20	15	45	45
M10AHEG	60	60	25	60	45	25	20	15	45	45
M10BHEG	60	60	25	60	45	25	20	15	45	45
M10CHEG	60	60	25	60	45	25	20	15	45	45
M10DHEG	60	60	25	60	45	25	20	15	45	45
M10EHEG	60	60	25	60	45	25	20	15	45	45
M10FHEG	60	60	25	60	45	25	20	15	45	45
M10GHEG	60	60	25	60	45	25	20	15	45	45

Consist Name	Flat	0.5%	1.5%	-0.5%	-1.1%	-1.7%	-2.2%	-2.8%	1% Crest	1% Trough
M10HHEG	60	60	25	60	45	25	20	15	45	45
M10IHEG	60	60	25	60	45	25	20	15	45	45
M10JHEG	60	60	25	60	45	25	20	15	45	45
M40AHE	60	46^	20^	60	45*	25*	20*	15*	28^	45
M40BHE	60	46^	20^	60	45*	25*	20*	15*	28^	45
M40CHE	60	46^	20^	60	45*	25*	20*	15*	28^	45
M40DHE	60	46^	20^	60	45*	25*	20*	15*	28^	45
M40EHE	60	46^	20^	60	45*	25*	20*	15*	28^	45
M40FHE	60	46^	20^	60	45*	25*	20*	15*	28^	45
M40GHE	60	46^	20^	60	45*	25*	20*	15*	28^	45
M40HHE	60	46^	20^	60	45*	25*	20*	15*	28^	45
M40IHE	60	46^	20^	60	45*	25*	20*	15*	28^	45
M40JHE	60	46^	20^	60	45*	25*	20*	15*	28^	45
M100ADE	60	45^	18^	60	45*	25*	20*	15*	26^	45
M100AHE	60	45^	18^	60	45*	25*	20*	15*	26^	45
M100BDE	60	45^	18^	60	45*	25*	20*	15*	26^	45
M100BHE	60	45^	18^	60	45*	25*	20*	15*	26^	45
M100CDE	60	45^	18^	60	45*	25*	20*	15*	26^	45
M100CHE	60	45^	18^	60	45*	25*	20*	15*	26^	45
M100DDE	60	45^	18^	60	45*	25*	20*	15*	26^	45
M100DHE	60	45^	18^	60	45*	25*	20*	15*	26^	45
M100EDE	60	45^	18^	60	45*	25*	20*	15*	26^	45
M100EHE	60	45^	18^	60	45*	25*	20*	15*	26^	45
M100FDE	60	45^	18^	60	45*	25*	20*	15*	26^	45
M100FHE	60	45^	18^	60	45*	25*	20*	15*	26^	45
M100GDE	60	45^	18^	60	45*	25*	20*	15*	26^	45
M100GHE	60	45^	18^	60	45*	25*	20*	15*	26^	45
M100HDE	60	45^	18^	60	45*	25*	20*	15*	26^	45
M100HHE	60	45^	18^	60	45*	25*	20*	15*	26^	45
M100IDE	60	45^	18^	60	45*	25*	20*	15*	26^	45
M100IHE	60	45^	18^	60	45*	25*	20*	15*	26^	45
M100JDE	60	45^	18^	60	45*	25*	20*	15*	26^	45
M100JHE	60	45^	18^	60	45*	25*	20*	15*	26^	45
M150ADE	60	40^	15^	60	45*	25*	20*	0	23^	40^
M150ADM	60	40^	15^	60	45*	25*	20*	0	23^	40^
M150BDE	60	40^	15^	60	45*	25*	20*	0	23^	40^
M150BDM	60	40^	15^	60	45*	25*	20*	0	23^	40^
M150CDE	60	40^	15^	60	45*	25*	20*	0	23^	40^
M150CDM	60	40^	15^	60	45*	25*	20*	0	23^	40^

Consist Name	Flat	0.5%	1.5%	-0.5%	-1.1%	-1.7%	-2.2%	-2.8%	1% Crest	1% Trough
M150DDE	60	40^	15^	60	45*	25*	20*	0	23^	40^
M150DDM	60	40^	15^	60	45*	25*	20*	0	23^	40^
M150EDE	60	40^	15^	60	45*	25*	20*	0	23^	40^
M150EDM	60	40^	15^	60	45*	25*	20*	0	23^	40^
M150FDE	60	40^	15^	60	45*	25*	20*	0	23^	40^
M150FDM	60	40^	15^	60	45*	25*	20*	0	23^	40^
M150GDE	60	40^	15^	60	45*	25*	20*	0	23^	40^
M150GDM	60	40^	15^	60	45*	25*	20*	0	23^	40^
M150HDE	60	40^	15^	60	45*	25*	20*	0	23^	40^
M150HDM	60	40^	15^	60	45*	25*	20*	0	23^	40^
M150IDE	60	40^	15^	60	45*	25*	20*	0	23^	40^
M150IDM	60	40^	15^	60	45*	25*	20*	0	23^	40^
M150JDE	60	40^	15^	60	45*	25*	20*	0	23^	40^
M150JDM	60	40^	15^	60	45*	25*	20*	0	23^	40^
M200ADE	60	38^	14^	60	45*	25*	20*	0	21^	36^
M200ADM	60	38^	14^	60	45*	25*	20*	0	21^	36^
M200BDE	60	38^	14^	60	45*	25*	20*	0	21^	36^
M200BDM	60	38^	14^	60	45*	25*	20*	0	21^	36^
M200CDE	60	38^	14^	60	45*	25*	20*	0	21^	36^
M200CDM	60	38^	14^	60	45*	25*	20*	0	21^	36^
M200DDE	60	38^	14^	60	45*	25*	20*	0	21^	36^
M200DDM	60	38^	14^	60	45*	25*	20*	0	21^	36^
M200EDE	60	38^	14^	60	45*	25*	20*	0	21^	36^
M200EDM	60	38^	14^	60	45*	25*	20*	0	21^	36^
M200FDE	60	38^	14^	60	45*	25*	20*	0	21^	36^
M200FDM	60	38^	14^	60	45*	25*	20*	0	21^	36^
M200GDE	60	38^	14^	60	45*	25*	20*	0	21^	36^
M200GDM	60	38^	14^	60	45*	25*	20*	0	21^	36^
M200HDE	60	38^	14^	60	45*	25*	20*	0	21^	36^
M200HDM	60	38^	14^	60	45*	25*	20*	0	21^	36^
M200IDE	60	38^	14^	60	45*	25*	20*	0	21^	36^
M200IDM	60	38^	14^	60	45*	25*	20*	0	21^	36^
M200JDE	60	38^	14^	60	45*	25*	20*	0	21^	36^
M200JDM	60	38^	14^	60	45*	25*	20*	0	21^	36^
U100ECEDE	60	60	25	60	55	25	20	0	46^	55
U100ECEHE	60	60	25	60	55	25	20	0	46^	55
U100ECHDE	60	60	25	60	55	25	20	0	45^	55
U100ECHHE	60	60	25	60	55	25	20	0	45^	55
U100ECWDE	60	60	25	60	55	25	20	0	52^	55

Consist Name	Flat	0.5%	1.5%	-0.5%	-1.1%	-1.7%	-2.2%	-2.8%	1% Crest	1% Trough
U100ECWHE	60	60	25	60	55	25	20	0	52^	55
U100EMLDE	60	50^	25	60	55	25	20	0	34^	55
U100EMLHE	60	50^	25	60	55	25	20	0	34^	55
U100ERBDE	60	50^	25	60	55	25	20	0	34^	55
U100ERBHE	60	50^	25	60	55	25	20	0	34^	55
U100ETKDE	60	60	25	60	55	25	20	0	47^	55
U100ETKHE	60	60	25	60	55	25	20	0	47^	55
U100LCEDE	50	27^	10^	50	45*	15*^	15	0	15^	24^
U100LCEHE	50	27^	10^	50	45*	15*^	15	0	15^	24^
U100LCHDE	50	26^	10^	50	45*	15*^	15	0	14^	23^
U100LCHHE	50	26^	10^	50	45*	15*^	15	0	14^	23^
U100LCWDE	50	26^	10^	50	45*	15*^	15	0	14^	23^
U100LCWHE	50	26^	10^	50	45*	15*^	15	0	14^	23^
U100LMLDE	50	34^	13^	50	45*	25*	15*^	0	19^	33^
U100LMLHE	50	34^	13^	50	45*	25*	15*^	0	19^	33^
U100LRBDE	50	30^	11^	50	45*	15*^	15	0	16^	26^
U100LRBHE	50	30^	11^	50	45*	15*^	15	0	16^	26^
U100LTKDE	50	30^	10^	50	45*	20*^	15	0	15^	25^
U100LTKHE	50	30^	10^	50	45*	20*^	15	0	15^	25^
U135ECEDE	60	60	25	60	55	25	20	0	50^	55
U135ECEDM	60	60	25	60	55	25	20	0	50^	55
U135ECHDE	60	60	25	60	55	25	20	0	47^	55
U135ECHDM	60	60	25	60	55	25	20	0	47^	55
U135ECWDE	60	60	25	60	55	25	20	0	55	55
U135ECWDM	60	60	25	60	55	25	20	0	55	55
U135EMLDE	60	53^	25	60	55	25	20	0	36^	55
U135EMLDM	60	53^	25	60	55	25	20	0	36^	55
U135ERBDE	60	52^	25	60	55	25	20	0	35^	55
U135ERBDM	60	52^	25	60	55	25	20	0	35^	55
U135ETKDE	60	60	25	60	55	25	20	0	48^	55
U135ETKDM	60	60	25	60	55	25	20	0	48^	55
U135LCEDE	50	30^	11^	50	45*	25*	15	0	16^	27^
U135LCEDM	50	30^	11^	50	45*	25*	15	0	16^	27^
U135LCHDE	50	30^	11^	50	45*	25*	15	0	15^	27^
U135LCHDM	50	30^	11^	50	45*	25*	15	0	15^	27^
U135LCWDE	50	30^	11^	50	45*	25*	15	0	15^	27^
U135LCWDM	50	30^	11^	50	45*	25*	15	0	15^	27^
U135LMLDE	50	37^	14^	50	45*	25*	15*^	0	21^	37^
U135LMLDM	50	37^	14^	50	45*	25*	15*^	0	21^	37^

Consist Name	Flat	0.5%	1.5%	-0.5%	-1.1%	-1.7%	-2.2%	-2.8%	1% Crest	1% Trough
U135LRBDE	50	31^	12^	50	45*	25*	15	0	17^	30^
U135LRBDM	50	31^	12^	50	45*	25*	15	0	17^	30^
U135LTKDE	50	31^	12^	50	45*	25*	15	0	16^	30^
U135LTKDM	50	31^	12^	50	45*	25*	15	0	16^	30^
U200ECEDE	60	60	25	60	45	25	20	0	45	45
U200ECEDM	60	60	25	60	45	25	20	0	45	45
U200ECWDE	60	60	25	60	45	25	20	0	45	45
U200ECWDM	60	60	25	60	45	25	20	0	45	45
U200LCEDE	50	27^	10^	50	45*	20*^	15	0	15^	27^
U200LCEDM	50	27^	10^	50	45*	20*^	15	0	15^	27^
U200LCWDE	50	26^	10^	50	45*	20*^	15	0	14^	25^
U200LCWDM	50	26^	10^	50	45*	20*^	15	0	14^	25^
U260ECEDM	60	60	25	60	45*	25	20	0	45	45
U260ECWDM	60	60	25	60	45*	25	20	0	45	45
U260LCEDM	50	31^	12^	50	45*	20*^	15	0	17^	28^
U260LCWDM	50	30^	11^	50	45*	20*^	15	0	16^	27^

Below are the intermodal cars used to make up the intermodal consists and their nominal values

Car	Parameter	Nominal Value
Intermodal Single Platform	Weight GRL	220,000 lb
	Tare Weight	71,596 lb
	Brake Force (64psi)	25,060 (Loaded) 13,673 (Empty)
	Piston Travel	7.5"
	Length	71.69'

Car	Parameter	Nominal Value
Intermodal 3-Pack	Weight GRL	486,000 lb
	Tare Weight	159,569 lb
	Brake Force (64psi)	55,471 (Loaded) 30,316 (Empty)
	Piston Travel	7.5"
	Length	203.98'

Car	Parameter	Nominal Value
Intermodal 5-Pack	Weight GRL	801,200 lb
	Tare Weight	212,142 lb
	Brake Force (64psi)	89,864 (Loaded) 48,394 (Empty)
	Piston Travel	7.5"
	Length	265.13'

Below are the manifest cars used to make up the manifest consists and their nominal values

Car	Parameter	Nominal Value
Covered Hopper Cars	Weight GRL	263,000 lb
	Tare Weight	65,750 lb
	Brake Force (64psi)	24,128 (Loaded) 20,039 (Empty)
	Piston Travel	7.5"
	Length	65.08'

Car	Parameter	Nominal Value
Equipped Hopper Cars	Weight GRL	286,000 lb
	Tare Weight	51,200 lb
	Brake Force (64psi)	31,630 (Loaded) 15,815 (Empty)
	Piston Travel	7.5"
	Length	53.04

Car	Parameter	Nominal Value
Refrigerator Box Cars	Weight GRL	286,000 lb
	Tare Weight	102,300 lb
	Brake Force (64psi)	29,097 (Loaded) 28,437 (Empty)
	Piston Travel	7.5"
	Length	83.75'

Car	Parameter	Nominal Value
Tank Cars	Weight GRL	263,000 lb
	Tare Weight	62,000 lb
	Brake Force (64psi)	23,136 (Loaded) 20,669 (Empty)
	Piston Travel	7.5"
	Length	43.06'

Car	Parameter	Nominal Value
Equipped Box Cars	Weight GRL	263,000 lb
	Tare Weight	84,000 lb
	Brake Force (64psi)	26,153 (Loaded) 25,418 (Empty)
	Piston Travel	7.5"
	Length	68.06'

Car	Parameter	Nominal Value
Unequipped Box Cars	Weight GRL	222,000 lb
	Tare Weight	61,600 lb
	Brake Force (64psi)	19,993 (Loaded) 19,608 (Empty)
	Piston Travel	7.5"
	Length	55.42'

Car	Parameter	Nominal Value
Equipped Gondola	Weight GRL	263,000 lb
	Tare Weight	67,000 lb
	Brake Force (64psi)	23,192 (Loaded) 21,763 (Empty)
	Piston Travel	7.5"
	Length	58.13'

Car	Parameter	Nominal Value
Flat Cars	Weight GRL	263,000 lb
	Tare Weight	75,122 lb
	Brake Force (64psi)	25,678 (Loaded) 21,596 (Empty)
	Piston Travel	7.5"
	Length	66.00'

Car	Parameter	Nominal Value
Unequipped Hopper	Weight GRL	263,000 lb
	Tare Weight	58,500 lb
	Brake Force (64psi)	22,501 (Loaded) 19,014 (Empty)
	Piston Travel	7.5"
	Length	53.08'

Car	Parameter	Nominal Value
Conventional Intermodal Cars	Weight GRL	220,000 lb
	Tare Weight	66,900 lb
	Brake Force (64psi)	22,589 (Loaded) 19,515 (Empty)
	Piston Travel	7.5"
	Length	92.75'

Car	Parameter	Nominal Value
Vehicular Flat Cars	Weight GRL	220,000 lb
	Tare Weight	104,000 lb
	Brake Force (64psi)	22,374 (Loaded) 22,374 (Empty)
	Piston Travel	7.5"
	Length	93.83'

Car	Parameter	Nominal Value
Gondola Cars	Weight GRL	286,000 lb
	Tare Weight	42,400 lb
	Brake Force (64psi)	31,104 (Loaded) 15,552 (Empty)
	Piston Travel	7.5"
	Length	53.08'

Car	Parameter	Nominal Value
Equipped Gondola	Weight GRL	263,000 lb
	Tare Weight	67,800 lb
	Brake Force (64psi)	24,450 (Loaded) 21,021 (Empty)
	Piston Travel	7.5"
	Length	57.04'

Below are the unit cars used to make up the unit consists and their nominal values

Car	Parameter	Nominal Value
Unit Aluminum Hoppers	Weight GRL	286,000 lb
	Tare Weight	42,400 lb
	Brake Force (64psi)	31,801 (Loaded) 15,901 (Empty)
	Piston Travel	7.5"
	Length	53.08'

Car	Parameter	Nominal Value
Unit Covered Hopper	Weight GRL	286,000 lb
	Tare Weight	63,790 lb
	Brake Force (64psi)	27,903 (Loaded) 19,148 (Empty)
	Piston Travel	7.5"
	Length	59.00'

Car	Parameter	Nominal Value
Unit Multilevel	Weight GRL	220,000 lb
	Tare Weight	102,170 lb
	Brake Force (64psi)	22,489 (Loaded) 22,489 (Empty)
	Piston Travel	7.5"
	Length	93.83'

Car	Parameter	Nominal Value
Unit Refrigerated Boxcar	Weight GRL	286,000 lb
	Tare Weight	103,548 lb
	Brake Force (64psi)	29,120 (Loaded) 28,460 (Empty)
	Piston Travel	7.5"
	Length	83.75'

Car	Parameter	Nominal Value
Unit Steel Hopper	Weight GRL	286,000 lb
	Tare Weight	64,360 lb
	Brake Force (64psi)	25,619 (Loaded) 20,018 (Empty)
	Piston Travel	7.5"
	Length	48.71'

Car	Parameter	Nominal Value
Unit Tank Cars	Weight GRL	263,000 lb
	Tare Weight	64,641 lb
	Brake Force (64psi)	23,945 (Loaded) 20,386 (Empty)
	Piston Travel	7.5"
	Length	43.06'

Appendix D.
Distributions Used for Variable Parameters in Simulation Testing

The detailed distributions for each car are shown in the tables below.

<table>
<tr><th>Car</th><th colspan="2">Distribution Type</th><th>Distribution Details</th></tr>
<tr><td rowspan="22">Covered Hopper Cars</td><td rowspan="6">Weight
Min: 42000 lb
Max: 289300 lb</td><td rowspan="6">Discrete Uniform</td><td>23% - 95% (3%)</td></tr>
<tr><td>95% - 100% (27%)</td></tr>
<tr><td>100% - 105% (55%)</td></tr>
<tr><td>105% - 110% (12%)</td></tr>
<tr><td>110% - 115% (2%)</td></tr>
<tr><td>115% - 170% (1%)</td></tr>
<tr><td rowspan="5">Brake Force
Empty Load Equipped: 28%</td><td rowspan="5">Discrete Uniform</td><td>1808 - 3288 (10%)</td></tr>
<tr><td>1808 - 3288 (26%)</td></tr>
<tr><td>1918 - 3324 (9%)</td></tr>
<tr><td>2557 - 3324 (1%)</td></tr>
<tr><td>2557 - 3580 (54%)</td></tr>
<tr><td rowspan="3">Brake Force
Not Empty Load Equipped: 72%</td><td rowspan="3">Discrete Uniform</td><td>1808 - 2491 (65%)</td></tr>
<tr><td>1808 - 2491 (24%)</td></tr>
<tr><td>1918 - 2454 (11%)</td></tr>
<tr><td rowspan="3">Brake Valve</td><td rowspan="3">Discrete Uniform</td><td>ABD (36%)</td></tr>
<tr><td>ABDW (19%)</td></tr>
<tr><td>ABDX (45%)</td></tr>
<tr><td>Piston Travel</td><td>Normal</td><td>Mean = 7.5" SD = 0.87"</td></tr>
<tr><td rowspan="4">Davis Equation Variables</td><td>Aerodynamic:
Nominal</td><td>Mean = 0.07 SD = 0</td></tr>
<tr><td>Bearing Resistance:
Normal</td><td>Mean = 18 SD = 3</td></tr>
<tr><td>Constant:
Normal</td><td>Mean = 0.6 SD = 0.1</td></tr>
<tr><td>Velocity Dependent:
Normal</td><td>Mean = 0.01 SD = .0017</td></tr>
</table>

Car	Distribution Type		Distribution Details
Equipped Hopper Cars	Weight Min: 48000 lb Max: 314600 lb	Discrete Uniform	86% - 90% (6%)
			90% - 100% (42%)
			100% - 105% (39%)
			105% - 110% (9%)
			110% - 125% (3%)
			125% - 190% (1%)
	Brake Force Empty Load Equipped: 100%	Discrete Uniform	1966 - 3575 (4%)
			1966 - 3575 (26%)
			2085 - 3615 (18%)
			2781 - 3615 (3%)
			2781 - 3893 (49%)
	Brake Valve	Discrete Uniform	ABD (25%)
			ABDW (15%)
			ABDX (60%)
	Piston Travel	Normal	Mean = 7.5" SD = 0.87"
	Davis Equation Variables	Aerodynamic: Nominal	Mean = 0.07 SD = 0
		Bearing Resistance: Normal	Mean = 18 SD = 3
		Constant: Normal	Mean = 0.6 SD = 0.1
		Velocity Dependent: Normal	Mean = 0.01 SD = .0017

Car	Distribution Type		Distribution Details
Refrigerator Box Cars	Weight Min: 74000 lb Max: 314600 lb	Discrete Uniform	35% - 85% (2%)
			85% - 95% (21%)
			95% - 105% (65%)
			105% - 110% (9%)
			110% - 270% (3%)
	Brake Force Empty Load Equipped: 4%	Discrete Uniform	1966 - 3575 (18%)
			2085 - 3615 (6%)
			2781 - 3893 (76%)
	Brake Force Not Empty Load Equipped: 96%	Discrete Uniform	1966 - 3575 (76%)
			1966 - 3575 (2%)
			2085 - 3615 (8%)
			2781 - 3615 (2%)
			2781 - 3221 (12%)
	Brake Valve	Discrete Uniform	ABD (69%)
			ABDW (8%)
			ABDX (23%)
	Piston Travel	Normal	Mean = 7.5" SD = 0.87"
	Davis Equation Variables	Aerodynamic: Nominal	Mean = 0.07 SD = 0
		Bearing Resistance: Normal	Mean = 18 SD = 3
		Constant: Normal	Mean = 0.6 SD = 0.1
		Velocity Dependent: Normal	Mean = 0.01 SD = .0017

Car	Distribution Type		Distribution Details
Tank Cars	Weight Min: 52000 lb Max: 289600 lb	Discrete Uniform	80% - 95% (3%)
			95% - 100% (18%)
			100% - 105% (64%)
			105% - 110% (12%)
			110% - 175% (3%)
	Brake Force Empty Load Equipped: 16%	Discrete Uniform	1808 - 3288 (4%)
			1808 - 3288 (5%)
			1918 - 3324 (1%)
			2557 - 3324 (1%)
			2557 - 3580 (85%)
	Brake Force Not Empty Load Equipped: 84%	Discrete Uniform	1808 - 2394 (53%)
			1808 - 2394 (31%)
			1918 - 2358 (16%)
	Brake Valve	Discrete Uniform	ABD (27%)
			ABDW (18%)
			ABDX (55%)
	Piston Travel	Normal	Mean = 7.5" SD = 0.87"
	Davis Equation Variables	Aerodynamic: Nominal	Mean = 0.07 SD = 0
		Bearing Resistance: Normal	Mean = 18 SD = 3
		Constant: Normal	Mean = 0.6 SD = 0.1
		Velocity Dependent: Normal	Mean = 0.01 SD = .0017

Car	Distribution Type		Distribution Details
Equipped Box Cars	Weight Min: 50000 lb Max: 289300 lb	Discrete Uniform	25% - 40% (1%)
			70% - 95% (4%)
			95% - 100% (19%)
			100% - 105% (50%)
			105% - 110% (22%)
			110% - 120% (3%)
			120% - 140% (1%)
	Brake Force Empty Load Equipped: 5%	Discrete Uniform	1808 - 3288 (9%)
			1918 - 3324 (34%)
			2557 - 3324 (9%)
			2557 - 3580 (48%)
	Brake Force Not Empty Load Equipped: 95%	Discrete Uniform	1808 - 3207 (72%)
			1808 - 3207 (10%)
			1918 - 2358 (10%)
			2557 - 3159 (3%)
			2557 - 2660 (5%)
	Brake Valve	Discrete Uniform	ABD (54%)
			ABDW (19%)
			ABDX (27%)
	Piston Travel	Normal	Mean = 7.5" SD = 0.87"
	Davis Equation Variables	Aerodynamic: Nominal	Mean = 0.07 SD = 0
		Bearing Resistance: Normal	Mean = 18 SD = 3
		Constant: Normal	Mean = 0.6 SD = 0.1
		Velocity Dependent: Normal	Mean = 0.01 SD = .0017

Car	Distribution Type		Distribution Details
Unequipped Box Cars	Weight Min: 50000 lb Max: 242000 lb	Discrete Uniform	30% - 35% (2%)
			80% - 95% (6%)
			95% - 100% (27%)
			100% - 105% (46%)
			105% - 110% (15%)
			110% - 120% (3%)
			120% - 155% (1%)
	Brake Force Empty Load Equipped: 3%	Discrete Uniform	1604 - 2781 (10%)
			2139 - 2781 (31%)
			2139 - 2994 (59%)
	Brake Force Not Empty Load Equipped: 97%	Discrete Uniform	1513 - 2320 (70%)
			1513 - 2320 (2%)
			1604 - 2285 (27%)
			2139 - 2285 (1%)
	Brake Valve	Discrete Uniform	ABD (38%)
			ABDW (29%)
			ABDX (23%)
	Piston Travel	Normal	Mean = 7.5" SD = 0.87"
	Davis Equation Variables	Aerodynamic: Nominal	Mean = 0.07 SD = 0
		Bearing Resistance: Normal	Mean = 18 SD = 3
		Constant: Normal	Mean = 0.6 SD = 0.1
		Velocity Dependent: Normal	Mean = 0.01 SD = .0017

Car	Distribution Type		Distribution Details
Equipped Gondola	Weight Min: 50000 lb Max: 289300 lb	Discrete Uniform	25% - 55% (2%)
			70% - 95% (3%)
			95% - 100% (22%)
			105% - 105% (50%)
			105% - 110% (14%)
			110% - 120% (5%)
			120% - 170% (4%)
	Brake Force Empty Load Equipped: 10%	Discrete Uniform	1808 - 3288 (5%)
			1808 - 3288 (33%)
			1918 - 3324 (20%)
			2577 - 3324 (2%)
			2577 - 3580 (40%)
	Brake Force Not Empty Load Equipped: 90%	Discrete Uniform	1808 - 2577 (72%)
			1808 - 2577 (17%)
			1918 - 2539 (11%)
	Brake Valve	Discrete Uniform	ABD (52%)
			ABDW (15%)
			ABDX (33%)
	Piston Travel	Normal	Mean = 7.5" SD = 0.87"
	Davis Equation Variables	Aerodynamic: Nominal	Mean = 0.07 SD = 0
		Bearing Resistance: Normal	Mean = 18 SD = 3
		Constant: Normal	Mean = 0.6 SD = 0.1
		Velocity Dependent: Normal	Mean = 0.01 SD = .0017

Car	Distribution Type		Distribution Details
Flat Cars	Weight Min: 50000 lb Max: 289300 lb	Discrete Uniform	20% - 30% (2%)
			75% - 95% (6%)
			95% - 100% (26%)
			100% - 105% (46%)
			105% - 110% (13%)
			110% - 140% (3%)
			140% - 210% (4%)
	Brake Force Empty Load Equipped: 28%	Discrete Uniform	1808 - 3288 (5%)
			1808 - 3288 (22%)
			1918 - 3324 (19%)
			2557- 3324 (7%)
			2557 - 3580 (47%)
	Brake Force Not Empty Load Equipped: 72%	Discrete Uniform	1808 - 2897 (63%)
			1808 - 2897 (18%)
			1918 - 2859 (17%)
			2557 - 2854 (2%)
	Brake Valve	Discrete Uniform	ABD (39%)
			ABDW (11%)
			ABDX (50%)
	Piston Travel	Normal	Mean = 7.5" SD = 0.87"
	Davis Equation Variables	Aerodynamic: Nominal	Mean = 0.07 SD = 0
		Bearing Resistance: Normal	Mean = 18 SD = 3
		Constant: Normal	Mean = 0.6 SD = 0.1
		Velocity Dependent: Normal	Mean = 0.01 SD = .0017

Car	Distribution Type		Distribution Details
Unequipped Hopper	Weight Min: 48000 lb Max: 289300 lb	Discrete Uniform	75% - 90% (6%)
			90% - 95% (20%)
			95% - 100% (41%)
			100% - 110% (28%)
			110% - 120% (4%)
			120% - 131% (1%)
	Brake Force Empty Load Equipped: 24%	Discrete Uniform	1808 - 3288 (23%)
			1808 - 3288 (17%)
			1918 - 3324 (8%)
			2557 - 3580 (52%)
	Brake Force Not Empty Load Equipped: 76%	Discrete Uniform	1808 - 2165 (93%)
			1808 - 2165 (7%)
	Brake Valve	Discrete Uniform	ABD (62%)
			ABDW (20%)
			ABDX (18%)
	Piston Travel	Normal	Mean = 7.5" SD = 0.87"
	Davis Equation Variables	Aerodynamic: Nominal	Mean = 0.07 SD = 0
		Bearing Resistance: Normal	Mean = 18 SD = 3
		Constant: Normal	Mean = 0.6 SD = 0.1
		Velocity Dependent: Normal	Mean = 0.01 SD = .0017

Car	Distribution Type		Distribution Details
Conventional Intermodal Cars	Weight Min: 60000 lb Max: 242000 lb	Discrete Uniform	20% - 30% (2%)
			75% - 95% (6%)
			95% - 100% (26%)
			100% - 105% (46%)
			105% - 110% (13%)
			110% - 140% (3%)
			140% - 210% (4%)
	Brake Force Empty Load Equipped: 25%	Discrete Uniform	1513 - 2750 (21%)
			2139 - 2781 (77%)
			2139 - 2781 (2%)
	Brake Force Not Empty Load Equipped: 75%	Flat	1513 - 2750
	Brake Valve	Discrete Uniform	ABD (69%)
			ABDW (15%)
			ABDX (16%)
	Piston Travel	Normal	Mean = 7.5" SD = 0.87"
	Davis Equation Variables	Aerodynamic: Nominal	Mean = 0.07 SD = 0
		Bearing Resistance: Normal	Mean = 18 SD = 3
		Constant: Normal	Mean = 0.6 SD = 0.1
		Velocity Dependent: Normal	Mean = 0.01 SD = .0017

Car	Distribution Type		Distribution Details
Vehicular Flat Cars	Weight Min: 82000 lb Max: 242000 lb	Discrete Uniform	49% - 85% (6%)
			85% - 90% (20%)
			90% - 105% (41%)
			105% - 110% (28%)
			110% - 115% (4%)
			115% - 130% (1%)
	Brake Force Not Empty Load Equipped: 100%	Discrete Uniform	1513 - 2750 (71%)
			1513 - 2750 (6%)
			1604 - 2781 (15%)
			2139 - 2994 (8%)
	Brake Valve	Discrete Uniform	ABD (59%)
			ABDW (14%)
			ABDX (27%)
	Piston Travel	Normal	Mean = 7.5" SD = 0.87"
	Davis Equation Variables	Aerodynamic: Nominal	Mean = 0.07 SD = 0
		Bearing Resistance: Normal	Mean = 18 SD = 3
		Constant: Normal	Mean = 0.6 SD = 0.1
		Velocity Dependent: Normal	Mean = 0.01 SD = .0017

Car	Distribution Type		Distribution Details
Gondola Cars	Weight Min: 42000 lb Max: 314600 lb	Discrete Uniform	30% - 85% (10%)
			85% - 95% (13%)
			95% - 100% (28%)
			100% - 105% (19%)
			105% - 110% (11%)
			110% - 125% (14%)
			125% - 155% (5%)
	Brake Force Empty Load Equipped: 100%	Discrete Uniform	1966 - 3575 (11%)
			1966 - 3575 (30%)
			2085 - 3615 (16%)
			2781 - 3615 (2%)
			2781 - 3893 (41%)
	Brake Valve	Discrete Uniform	ABD (33%)
			ABDW (15%)
			ABDX (42%)
	Piston Travel	Normal	Mean = 7.5" SD = 0.87"
	Davis Equation Variables	Aerodynamic: Nominal	Mean = 0.07 SD = 0
		Bearing Resistance: Normal	Mean = 18 SD = 3
		Constant: Normal	Mean = 0.6 SD = 0.1
		Velocity Dependent: Normal	Mean = 0.01 SD = .0017

Car	Distribution Type		Distribution Details
Equipped Gondola	Weight Min: 48000 lb Max: 289300 lb	Discrete Uniform	35% - 90% (20%)
			90% - 95% (9%)
			95% - 100% (19%)
			100% - 110% (24%)
			110% - 120% (10%)
			120% - 185% (14%)
			185% - 225% (4%)
	Brake Force Empty Load Equipped: 24%	Discrete Uniform	1808 - 3288 (5%)
			1808 - 3288 (33%)
			1918 - 3324 (20%)
			2557 - 3324 (2%)
			2557 - 3580 (40%)
	Brake Force Not Empty Load Equipped: 76%	Discrete Uniform	1808 - 2685 (72%)
			1808 - 2685 (17%)
			1918 - 2645 (11%)
	Brake Valve	Discrete Uniform	ABD (34%)
			ABDW (13%)
			ABDX (53%)
	Piston Travel	Normal	Mean = 7.5" SD = 0.87"
	Davis Equation Variables	Aerodynamic: Nominal	Mean = 0.07 SD = 0
		Bearing Resistance: Normal	Mean = 18 SD = 3
		Constant: Normal	Mean = 0.6 SD = 0.1
		Velocity Dependent: Normal	Mean = 0.01 SD = .0017

Car	Distribution Type		Distribution Details
Unit Aluminum Hoppers	Weight Loaded	Normal	Mean = 101% SD = 0.03%
	Weight Empty	Normal	Mean = 100% SD = 0.03%
	Brake Force Empty Load Equipped: 100%	Discrete Uniform	1966 - 3575 (3%)
			1966 - 3575 (20%)
			2085 - 3615 (23%)
			2781 - 3615 (2%)
			2781 - 3893 (52%)
	Brake Valve	Discrete Uniform	ABD (27%)
			ABDW (18%)
			ABDX (55%)
	Piston Travel	Normal	Mean = 7.5" SD = 0.87"
	Davis Equation Variables	Aerodynamic: Nominal	Mean = 0.07 SD = 0
		Bearing Resistance: Normal	Mean = 18 SD = 3
		Constant: Normal	Mean = 0.6 SD = 0.1
		Velocity Dependent: Normal	Mean = 0.01 SD = .0017

Car	Distribution Type		Distribution Details
Unit Tank Cars	Weight Loaded	Discrete Uniform	92.1% - 94.8% (1%)
			94.8% - 100% (19%)
			100% - 102.6% (22%)
			102.6% - 105.2% (40%)
			105.2% - 107.9% (17%)
			107.9% - 113.1% (1%)
	Weight Empty	Discrete Uniform	92.1% - 94.0% (1%)
			94.0% - 95.9% (4%)
			95.9% - 101.7% (73%)
			101.7% - 103.6% (12%)
			103.6% - 109.3% (8%)
			109.3% - 122.8% (2%)
	Brake Force Empty Load Equipped: 23%	Discrete Uniform	1808 - 3288 (3%)
			1808 - 3288 (3%)
			1918 - 3324 (6%)
			2557 - 3324 (1%)
			2557 - 3580 (87%)
	Brake Force Not Empty Load Equipped: 77%	Discrete Uniform	1808 - 2424 (50%)
			1808 - 2424 (27%)
			1918 - 2388 (23%)
	Brake Valve	Discrete Uniform	ABD (27%)
			ABDW (18%)
			ABDX (55%)
	Piston Travel	Normal	Mean = 7.5" SD = 0.87"
	Davis Equation Variables	Aerodynamic: Nominal	Mean = 0.07 SD = 0
		Bearing Resistance: Normal	Mean = 18 SD = 3
		Constant: Normal	Mean = 0.6 SD = 0.1
		Velocity Dependent: Normal	Mean = 0.01 SD = .0017

Car	Distribution Type		Distribution Details
Unit Multilevel	Weight Loaded	Discrete Uniform	49% - 85% (6%)
			85% - 90% (20%)
			90% - 105% (41%)
			105% - 110% (28%)
			110% - 115% (4%)
			115% - 130% (1%)
	Weight Empty	Discrete Uniform	49% - 85% (6%)
			85% - 90% (20%)
			90% - 105% (41%)
			105% - 110% (28%)
			110% - 115% (4%)
			115% - 130% (1%)
	Brake Force Not Empty Load Equipped: 100%	Discrete Uniform	1513 - 2750 (69%)
			1513 - 2750 (2%)
			1604 - 2781 (19%)
			2139 - 2994 (10%)
	Brake Valve	Discrete Uniform	ABD (59%)
			ABDW (14%)
			ABDX (27%)
	Piston Travel	Normal	Mean = 7.5" SD = 0.87"
	Davis Equation Variables	Aerodynamic: Nominal	Mean = 0.07 SD = 0
		Bearing Resistance: Normal	Mean = 18 SD = 3
		Constant: Normal	Mean = 0.6 SD = 0.1
		Velocity Dependent: Normal	Mean = 0.01 SD = .0017

Car	Distribution Type		Distribution Details
Unit Covered Hopper	Weight Loaded	Discrete Uniform	96.2% - 98.7% (22%)
			98.7% - 101.3% (1%)
			101.3% - 102.6% (8%)
			102.6% - 103.8% (16%)
			103.8% - 105.1% (33%)
			105.1% - 106.4% (17%)
			106.4% - 107.7% (3%)
	Weight Empty	Discrete Uniform	93.08% - 95.04% (2%)
			95.04% - 97% (16%)
			97% - 98.96% (39%)
			98.96% - 100.92% (18%)
			100.92% - 106.8% (18%)
			106.8% - 115.61% (6%)
			115.61% - 122.47% (1%)
	Brake Force Empty Load Equipped: 54%	Discrete Uniform	1966 - 3575 (4%)
			1966 - 3575 (18%)
			2085 - 3615 (12%)
			2781 - 3615 (1%)
			2781 - 3893 (65%)
	Brake Force Not Empty Load Equipped: 46%	Discrete Uniform	1966 - 2392 (14%)
			1966 - 2392 (44%)
			2085 - 2357 (42%)
	Brake Valve	Discrete Uniform	ABD (36%)
			ABDW (19%)
			ABDX (45%)
	Piston Travel	Normal	Mean = 7.5" SD = 0.87"
	Davis Equation Variables	Aerodynamic: Nominal	Mean = 0.07 SD = 0
		Bearing Resistance: Normal	Mean = 18 SD = 3
		Constant: Normal	Mean = 0.6 SD = 0.1
		Velocity Dependent: Normal	Mean = 0.01 SD = .0017

Car	Distribution Type		Distribution Details
Unit Refrigerated Boxcar	Weight Loaded	Discrete Uniform	53.3% - 65.7% (3%)
			65.7% - 75.1% (12%)
			75.1% - 90.7% (23%)
			90.7% - 96.9% (19%)
			96.9% - 103.1% (31%)
			103.1% - 106.2% (7%)
			106.2% - 115.6% (5%)
	Weight Empty	Discrete Uniform	89% - 95% (7%)
			95% - 97% (9%)
			97% - 101% (26%)
			101% - 107% (56%)
			107% - 109% (2%)
	Brake Force Empty Load Equipped: 4%	Discrete Uniform	1966 - 3575 (18%)
			2085 - 3615 (6%)
			2781 - 3893 (76%)
	Brake Force Not Empty Load Equipped: 96%	Discrete Uniform	1966 - 3575 (75%)
			1966 - 3575 (2%)
			2085 - 3615 (8%)
			2781 - 3615 (2%)
			2781 - 3221 (13%)
	Brake Valve	Discrete Uniform	ABD (69%)
			ABDW (8%)
			ABDX (23%)
	Piston Travel	Normal	Mean = 7.5" SD = 0.87"
	Davis Equation Variables	Aerodynamic: Nominal	Mean = 0.07 SD = 0
		Bearing Resistance: Normal	Mean = 18 SD = 3
		Constant: Normal	Mean = 0.6 SD = 0.1
		Velocity Dependent: Normal	Mean = 0.01 SD = .0017

Car	Distribution Type		Distribution Details
Unit Steel Hopper	Weight Loaded	Discrete Uniform	53.3% - 65.7% (3%)
			65.7% - 75.1% (12%)
			75.1% - 90.7% (23%)
			90.7% - 96.9% (19%)
			96.9% - 103.1% (31%)
			103.1% - 106.2% (7%)
			106.2% - 115.6% (5%)
	Weight Empty	Normal	Mean = 64360 SD = 2679
	Brake Force Empty Load Equipped: 36%	Discrete Uniform	1966 - 3575 (29%)
			1966 - 3575 (25%)
			2085 - 3615 (1%)
			2781 - 3615 (1%)
			2781 - 3893 (44%)
	Brake Force Not Empty Load Equipped: 64%	Discrete Uniform	1966 - 2414 (88%)
			1966 - 2414 (11%)
			2085 - 2378 (1%)
	Brake Valve	Discrete Uniform	ABD (62%)
			ABDW (20%)
			ABDX (18%)
	Piston Travel	Normal	Mean = 7.5" SD = 0.87"
	Davis Equation Variables	Aerodynamic: Nominal	Mean = 0.07 SD = 0
		Bearing Resistance: Normal	Mean = 18 SD = 3
		Constant: Normal	Mean = 0.6 SD = 0.1
		Velocity Dependent: Normal	Mean = 0.01 SD = .0017

Car	Distribution Type		Distribution Details
Intermodal 3-Pack	Weight Loaded	Discrete Uniform	60% - 90% (21%)
			90% - 95% (11%)
			95% - 100% (18%)
			100% - 105% (18%)
			105% - 110% (5%)
			110% - 145% (12%)
			145% - 165% (15%)
	Weight Empty	Discrete Uniform	76.99% - 81.27% (5%)
			81.27% - 85.54% (17%)
			85.54% - 89.82% (50%)
			89.82% - 94.1% (14%)
			94.1% - 136.87% (4%)
			171.09% - 239.52% (10%)
	Brake Force Empty Load Equipped: 90%	Discrete Uniform	1671 - 3038 (8%)
			2278 - 3038 (22%)
			2363 - 3072 (26%)
			2363 - 3072 (8%)
			2363 - 3308 (36%)
	Brake Force Not Empty Load Equipped: 10%	Discrete Uniform	1671 - 2992 (43%)
			2278 - 2992 (35%)
			2363 - 2948 (16%)
			2363 - 2948 (6%)
	Brake Valve	Discrete Uniform	ABD (12%)
			ABDW (12%)
			ABDXL (76%)
	Piston Travel	Normal	Mean = 7.5" SD = 0.87"
	Davis Equation Variables	Aerodynamic: Nominal	Mean = 0.07 SD = 0
		Bearing Resistance: Normal	Mean = 18 SD = 3
		Constant: Normal	Mean = 0.6 SD = 0.1
		Velocity Dependent: Normal	Mean = 0.01 SD = .0017

Car	Distribution Type		Distribution Details
Intermodal 5-Pack	Weight Loaded	Discrete Uniform	100% - 105% (15%)
			105% - 110% (57%)
			110% - 120% (28%)
	Weight Empty	Discrete Uniform	80.92% - 85.18% (5%)
			85.18% - 89.44% (73%)
			89.44% - 93.7% (9%)
			93.7% - 97.96% (5%)
			195.91% - 281.09% (8%)
	Brake Force Empty Load Equipped: 90%	Discrete Uniform	1836 - 3338 (8%)
			2504 - 3338 (22%)
			2596 - 3375 (26%)
			2596 - 3375 (8%)
			2596 - 3635 (36%)
	Brake Force Not Empty Load Equipped: 10%	Flat	1836 - 2652
	Brake Valve	Discrete Uniform	ABD (12%)
			ABDW (12%)
			ABDXL (76%)
	Piston Travel	Normal	Mean = 7.5" SD = 0.87"
	Davis Equation Variables	Aerodynamic: Nominal	Mean = 0.07 SD = 0
		Bearing Resistance: Normal	Mean = 18 SD = 3
		Constant: Normal	Mean = 0.6 SD = 0.1
		Velocity Dependent: Normal	Mean = 0.01 SD = .0017

Car	Distribution Type		Distribution Details
Intermodal Single Platform	Weight Loaded	Discrete Uniform	60% - 90% (21%)
			90% - 95% (11%)
			95% - 100% (18%)
			100% - 105% (18%)
			105% - 110% (5%)
			110% - 145% (12%)
	Weight Empty	Discrete Uniform	72.98% - 76.82% (10%)
			76.82% - 80.66% (33%)
			80.66% - 103.71% (43%)
			153.64% - 230.46% (14%)
	Brake Force Empty Load Equipped: 90%	Discrete Uniform	1836 - 3338 (8%)
			2504 - 3338 (22%)
			2596 - 3375 (26%)
			2596 - 3375 (8%)
			2596 - 3635 (36%)
	Brake Force Not Empty Load Equipped: 10%	Flat	1836 - 2652
	Brake Valve	Discrete Uniform	ABD (12%)
			ABDW (12%)
			ABDXL (76%)
	Piston Travel	Normal	Mean = 7.5" SD = 0.87"
	Davis Equation Variables	Aerodynamic: Nominal	Mean = 0.07 SD = 0
		Bearing Resistance: Normal	Mean = 18 SD = 3
		Constant: Normal	Mean = 0.6 SD = 0.1
		Velocity Dependent: Normal	Mean = 0.01 SD = .0017

Below is the table of varied train parameters:

	Distribution Type		Distribution Details
Train Parameters	Ambient Pressure	Half Normal	Mean = 14.7 psi SD = 1.5 psi
	Ambient Pressure	Normal	Mean = 54.1°F SD = 10.8°F
	Brake Pipe Pressure Leakage	Normal	Mean = 2.5 psi/min SD = 0.83 psi/min
	Coefficient of Friction between Brake Shoe and Wheel	Normal	Mean = 0% SD = 6.67%
	DP Comms Link Outage	Half Normal	Mean = 2 sec SD = 2 sec
	Reported HOT Pressure	Flat	(+/-) 0.5 psi
	Reported EOT Pressure	Flat	(+/-) 3 psi
	Location Error	Normal	Mean = 0' SD = 3.6'
	Percent Operable Brakes	Normal	Mean = 99% SD = 0.33%
	Speed Error	Normal	Mean = 0 mph SD = 0.16 mph
	Track Grade	Flat	(+/-) 0.05°

Task Order 242: Development of a PTC Enforcement Algorithm for Freight Trains

Enforcement with Brake System States Other Than Fully Charged

Field Test Implementation Plan

November 2009

Approval:____

Terry Tse, COTM **Date**

Presented By:

Transportation Technology Center, Inc.

A Subsidiary of the **Association of American Railroads**

55500 D.O.T. Road

P.O. Box 11130

Pueblo, Colorado, USA 81001

1.0 Project Title

Development of an Implementation-Ready Enforcement Braking Algorithm for Freight Trains

2.0 Introduction

Positive Train Control (PTC) is an emerging train control technology intended to enhance safety and possibly improve train performance and plant capacity. The underlying concept of the technology is that movement authorities are transmitted digitally to the controlling locomotive of each train. The locomotive tracks the train's location with respect to its authority and speed limits and the train's stopping ability based on known train parameters and brake pipe pressure and automatically applies brakes to prevent the train from violating any limit in the event of human failure. Enforcement braking is an event of last recourse when the locomotive engineer has failed to take adequate action. A full service brake application is used for enforcement in today's PTC systems.

The current enforcement algorithm takes the state of the train's brake system into account and uses that information to predict the stopping distance. The stopping point after enforcement should not change for the same train with the brakes either fully charged or at states other than fully charged unless there is some additional conservatism built in. Enforcement should also happen sooner in trains with other than fully charged brakes if the current enforcement algorithm performs correctly.

The objective of this test is to evaluate the existing enforcement algorithm at brake states other than fully charged and compare the results with brakes fully charged to determine how the current algorithm performs. The results will be used to determine what changes, if any, are needed to improve the algorithm with brakes states other than fully charged.

2.1 Key Personnel

Customer Contact, Ruben Pena, Assistant Director, Business Acquisition / DC

Telephone: 719-584-0543

Fax: 719-584-0770

Email: ruben_pena@ttci.aar.com

Program Manager, Dingqing Li, Principal Investigator II / FRA Program Manager

Telephone: 719-584-0740

Fax: 719-584-0791

Email: dingqing_li@ttci.aar.com

Project Manager, Joe Brosseau, Senior Engineer I

Telephone: 719-584-7128

Fax: 719-584-0771

Email: joe_brosseau@ttci.aar.com

Test Engineer, <u>Shad Pate, Engineer</u>

Telephone: 719-584-7116

Fax: 719-584-0771

Email: shad_pate@ttci.aar.com

2.2 Responsibilities

The project manager for this project is Joe Brosseau. He is responsible for ensuring that the test is completed on time, within budget, and will ensure all deliverables meet or exceed FRA requirements. The test engineer for this test is Shad Pate. He will be responsible for ensuring that the test is executed according to the test plan, that all data is collected properly, and that the test is completed safely.

2.3 Documentation

The results of this test will be documented within the final report for this project.

3.0 Preparation

In preparation for field testing of the enforcement algorithm, the following tasks will be completed:

- Test locomotive setup/checkout. This includes the installation of a locomotive control unit (LCU) capable of determining locomotive location and speed, head end brake pipe pressure, tail end brake pipe pressure from an end of train (EOT) device and throttle notch. The LCU will be capable of interacting with the enforcement algorithm operating on a separate test machine.
- Enforcement algorithm software setup/checkout. This includes software modifications necessary for this test and testing of the software in a simulation environment to determine that the algorithm will operate as expected.
- Test consist setup. This includes determining the specific consist to be used, making measurements on the brake system components, scaling the test consist and installing the test instrumentation.

4.0 Implementation

4.1 Constraints

None.

4.2 Operation Sequence

4.2.1 Track Testing

The field test configuration is shown in Figure 1. The lead locomotive of the test consist will have a standard laptop PC containing the base case enforcement algorithm (EA). The lead locomotive will also be instrumented with a Locomotive Control Unit (LCU) that communicates train speed, position, head and tail end brake pipe pressure, and locomotive notch to the EA PC. Head end brake pipe pressure is measured by a pressure transducer and the tail end brake pipe pressure is measured using a two-way End-of-Train (EOT) device. The LCU and the EA PC will be used to record speed, location, locomotive notch, and brake pipe pressure data throughout each test for use in determining when the brakes were applied, where the train stopped, etc.

A track file loaded on the enforcement algorithm PC will contain surveyed grade and curve data for the Railroad Test Track (RTT), and will be accessed by the enforcement algorithm as needed for stopping distance prediction.

The enforcement algorithm PC will interface with the LCU over an Ethernet connection to enforce a penalty brake application when necessary.

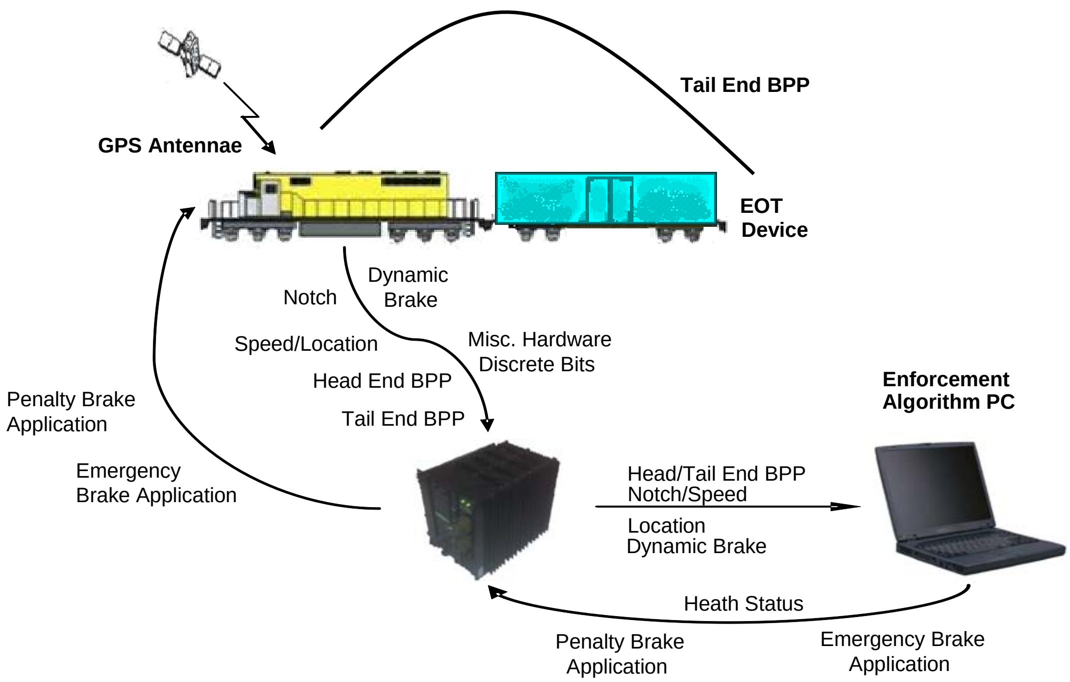


Figure 1 – Test Configuration

The field testing will test the base case enforcement algorithm at brake states other than fully charged over a number of test scenarios, which will cover a range of operating conditions. The test scenarios are determined by varying the following independent test variables:

- Train length
- Train speed
- Track grade
- State of brake system

For the state of the brake system, there are four possibilities:

- Charged – the brake system is fully charged to 90 psi.

- Applied – a brake application has been made, but not sufficient to bring the train to a stop before reaching the target.
- Releasing – A brake application has been made followed by a brake release, but the system has not recharged completely.
- Applied to stop – a brake application has been made sufficient for stopping the train before reaching the target. This case is to ensure that the algorithm will not enforce the train if it is not necessary to.

The specific test scenarios are listed in table 1, below.

Table 1 – Test Scenarios

Test ID	Train length	Train speed	Track grade	Brake system state
1a	40 cars	30 mph	Flat	Charged
1b	40 cars	30 mph	Flat	Applied
1c	40 cars	30 mph	Flat	Releasing
1d	40 cars	30 mph	Flat	Applied to stop
2a	40 cars	50 mph	Flat	Charged
2b	40 cars	50 mph	Flat	Applied
2c	40 cars	50 mph	Flat	Releasing
2d	40 cars	50 mph	Flat	Applied to stop
3a	80 cars	30 mph	Decline	Charged
3b	80 cars	30 mph	Decline	Applied
3c	80 cars	30 mph	Decline	Releasing
3d	80 cars	30 mph	Decline	Applied to stop
4a	80 cars	10 mph	Flat	Charged
4b	80 cars	10 mph	Flat	Applied
4c	80 cars	10 mph	Flat	Releasing
4d	80 cars	10 mph	Flat	Applied to stop
5a	10 cars	30 mph	Flat	Charged
5b	10 cars	30 mph	Flat	Applied
5c	10 cars	30 mph	Flat	Releasing
5d	10 cars	30 mph	Flat	Applied to stop

For each test scenario, a target stopping location will be selected on the RTT that will provide the proper track grade for the scenario. This location will be entered into the enforcement algorithm, along with the generic consist information and other required inputs. An appropriate starting location will be determined, and the train will be moved to this location to start each test run.

The train will be accelerated to the specified test speed and the brakes will be applied by the locomotive engineer based on the detailed test plan for that scenario. The train will proceed towards the target stopping location, with the enforcement algorithm monitoring the speed, location, and brake pipe pressure of the train. When the enforcement algorithm determines that an enforcement brake application is necessary, it will send a signal to the LCU, which will drop power to the locomotives and apply a penalty brake application. The locomotive engineer will bail off the locomotive brakes as soon as the penalty application has been made.

Once the train has stopped, the absolute stopping location will be recorded and the location relative to the target will be measured and recorded before resetting the train for the next test run.

4.2.2 Validation Testing

N/A

4.2.3 Endurance Testing

N/A

4.2.4 Safety Margin Tests

N/A

4.3 Operation Locations

The stop tests will occur between Post 100 and R-24 on the RTT. However, in some cases, the entire RTT loop will be utilized to get the train up to speed for the test zone.

4.4 Special Support

N/A

4.5 Instrumentation Types

See section 5.0.

4.6 Measurement Definitions

The following measurements will be taken during the field test for each test run:

- Stopping location. The location in footage relative to a specific point on the track will be measured by the LCU and recorded by the enforcement algorithm software once the train has come to a stop.
- Stopping location relative to the target. The difference in footage between the stopping location and the target location will be calculated in post-processing.
- Stopping distance. The difference in footage between the point of penalty brake application and stopping location will be calculated in post-processing.

4.7 Data Collection Schematics

None.

5.0 Instrumentation Identification

5.1 On-Board Instrumentation List

The on-board instrumentation includes:

- Locomotive control unit (LCU)
- Laptop computer containing enforcement algorithm software
- Locomotive brake pipe pressure transducer
- Locomotive head end unit (HEU)
- GPS antennas
- Penalty brake valve
- End of train (EOT) unit
- Unmanned data acquisition computer (UDAC)
- Rear end brake pipe pressure transducer
- Rear end brake cylinder pressure transducer

5.2 Wayside Instrumentation List

None.

5.3 Special Instrumentation List

None.

6.0 Photography and Video

6.1 Photography Requirements

None.

6.2 Video Requirements

None.

7.0 Transportation Technology Center, Inc. Requirements

7.1 Facility Requirements

None.

7.2 Track Requirements

The enforcement algorithm will be tested at various locations around the 13.5 mile Railroad Test Track (RTT) at the Transportation Technology Center (TTC). On days when multiple test consists will be used, other tracks may be needed for switching and storage of test cars.

7.3 Labor/Personnel Requirements

The following personnel will be required to setup, perform, and analyze the results from the tests planned:

- Test engineer(s): The test engineer(s) will be responsible for organizing and managing the test activities, including providing test plans, procedures, and data sheets to test personnel, and ensuring test activities can be performed in a safe manner. It will also be the responsibility of the test engineer(s) to oversee setup of the instrumentation, running the enforcement algorithm software, and recording or ensuring necessary data is recorded. Post test, the test engineer(s) will analyze the data collected for use in other tests and future developments of the enforcement algorithm.
- Test controller: The test controller will be in charge of the actual tests and all movements of the test consist. This includes ensuring all safety rules, test plans, and other instructions are followed by all test personnel. The test controller will be the point of communication between the test engineers and the locomotive engineer and any other test personnel. The test controller will coordinate all train moves with the proper personnel in the Operations Control Center (OCC), and ensure safe test conditions at all times. Finally, the test controller will keep a detailed log of the test activities.
- Locomotive engineer: The locomotive engineer will execute train moves as necessary for test setup, switching, and test functions.
- Instrumentation engineer(s): The instrumentation engineer(s) will work closely with the test engineer(s) to set up all test instrumentation, and ensure the proper operation of the instrumentation and data collection system during testing.

7.4 Equipment Requirements

The following equipment will be required for the field tests:

- Four locomotives, including two GP40-2 and two SD60MAC locomotives
- 80 test cars from the Facility for Accelerated Service Testing (FAST) train

7.5 Material Requirements

None.

7.6 Special Requirements

None.

8.0 Restoration and/or Dismantling

8.1 Facility Restoration

None.

8.2 Track Restoration

Tribometer readings will be taken on the RTT following the field tests to ensure that lubrication from the FAST cars does not affect the friction characteristics of the track. If any negative effects are measured from the test, they will be remedied.

8.3 Equipment Disposition

None.

8.4 Material Disposition

None.

8.5 Special Equipment Disposition

None.

9.0 Data Requirements

9.1 Data Types

The following data will be collected during this field test:

- Locomotive location
- Locomotive speed
- Locomotive brake pipe pressure
- Tail end brake pipe pressure through an end of train (EOT) device
- Locomotive notch
- Tail end brake pipe pressure through a pressure transducer
- Tail end (last car) brake cylinder pressure

9.2 Recording Techniques

Locomotive location, speed, brake pipe pressure, EOT brake pipe pressure and locomotive notch will be collected once per second by the locomotive control unit (LCU). Tail end brake pipe pressure and brake cylinder pressure will be collected once per second using an unmanned data acquisition computer (UDAC).

9.3 Data Analysis

The data collected will be used to evaluate the performance of the enforcement algorithm. For all tests where enforcement occurs, the stopping location will be compared to the same test with the brake system fully charged. The objective is for the train to stop at approximately the same location, regardless of brake state.

The actual brake pipe and brake cylinder data, stop distance and stop time will also be compared to the prediction data from the enforcement algorithm to determine the accuracy of the prediction and identify any flaws in the algorithm logic that need to be investigated.

9.4 Reports

Documentation of the field test will be included in a final report for the project.

10.0 Safety

TTCI has a very successful safety record. Strict operating and safety rules will be followed during the work described in this proposal.

A pre-test meeting will be held before any physical work is started. Safety and quality issues will be addressed at this meeting.

11.0 Work Schedule

The field testing will occur during the week of November 23, 2009.

12.0 Quality Assurance

TTCI is committed to providing products and/or services that meet and/or exceed the customers' specified contractual and project requirements. TTCI recognizes that in order to provide and maintain a consistently high quality in the work it undertakes, an effective Quality Management System is necessary so as to ensure that proper communication, work control and accountable records are generated for all work undertaken.

It is the policy, therefore, of TTCI to control and conduct its business of consultancy and test services in the railway transportation arena by means of a formalized system of modern quality management that conforms to the requirements of ISO 9001–2000. Through the QMS, TTCI is able to ensure that our products and services meet or exceed our customers' expectations.

In order to ensure our entire organization supports the quality process, TTCI sponsors an employee led Quality Resource Team (QRT). The mission of the QRT is to "To promote customer satisfaction by providing effective training, education, and communication tools for Team TTCI." The QRT works directly with TTCI's marketing team to identify customer satisfaction issues and help resolve them. The QRT also provides period refresher training to TTCI employees in science of Continuous Quality Improvement, Customer Satisfaction, and the implementation of problem solving tools.

13.0 Support Specialties

N/A

Task Order 242: Development of a PTC Enforcement Algorithm for Freight Trains

Enforcement with Distributed Power

Field Test Implementation Plan

December 2009

Approval:____

Terry Tse, COTM   Date

Presented By:

Transportation Technology Center, Inc.

A Subsidiary of the **Association of American Railroads**

55500 D.O.T. Road

P.O. Box 11130

Pueblo, Colorado, USA 81001

1.0 Project Title

Development of an Implementation-Ready Enforcement Braking Algorithm for Freight Trains

2.0 Introduction

Positive Train Control (PTC) is an emerging train control technology intended to enhance safety and possibly improve train performance and plant capacity. The underlying concept of the technology is that movement authorities are transmitted digitally to the controlling locomotive of each train. The locomotive tracks the train's location with respect to its authority and speed limits and the train's stopping ability based on known train parameters and brake pipe pressure and automatically applies brakes to prevent the train from violating any limit in the event of human failure. Enforcement braking is an event of last recourse when the locomotive engineer has failed to take adequate action. A full service brake application is used for enforcement in today's PTC systems.

The base case enforcement algorithm determines brake propagation time based on the length of the train. The assumption is that the brake signal is propagated from the head end of the train only. A new development of the algorithm uses the location of remote locomotives in addition to the length of the train to estimate a more accurate propagation time for trains with distributed power.

To further improve the accuracy of the propagation time used by the enforcement algorithm, modifications to the propagation time adaptive routine allow for a propagation time measurement to be used to more accurately estimate the propagation time.

The objective of this test is to evaluate the enforcement algorithm with the modifications made for trains with distributed power against the base case algorithm.

2.1 Key Personnel

Customer Contact, Ruben Pena, Assistant Director, Business Acquisition / DC

Telephone: 719-584-0543

Fax: 719-584-0770

Email: ruben_pena@ttci.aar.com

Program Manager, Dingqing Li, Principal Investigator II / FRA Program Manager

Telephone: 719-584-0740

Fax: 719-584-0791

Email: dingqing_li@ttci.aar.com

Project Manager, Joe Brosseau, Senior Engineer I

Telephone: 719-584-7128

Fax: 719-584-0771

Email: joe_brosseau@ttci.aar.com

Test Engineer, W. David Mauger, Engineer

Telephone: 719-584-0758

Fax: 719-584-0758

Email: dave_mauger@ttci.aar.com

2.2 Responsibilities

The project manager for this project is Joe Brosseau. He is responsible for ensuring that the test is completed on time, within budget, and will ensure all deliverables meet or exceed FRA requirements. The test engineer for this test is David Mauger. He will be responsible for ensuring that the test is executed according to the test plan, that all data is collected properly, and that the test is completed safely.

2.3 Documentation

The results of this test will be documented within the final report for this project.

3.0 Preparation

In preparation for field testing of the enforcement algorithm, the following tasks will be completed:

- Test locomotive setup/checkout. This includes the installation of a locomotive control unit (LCU) capable of determining locomotive location and speed, head end brake pipe pressure, and throttle notch. The LCU will be capable of interacting with the enforcement algorithm operating on a separate test machine.
- Enforcement algorithm software setup/checkout. This includes software modifications necessary for this test and testing of the software in a simulation environment to determine that the algorithm will operate as expected.
- Test consist setup. This includes determining the specific consist to be used, making measurements on the brake system components, scaling the test consist and installing the test instrumentation.

4.0 Implementation

4.1 Constraints

None.

4.2 Operation Sequence

4.2.1 Track Testing

The field test configuration is shown in Figure 1. The lead locomotive of the test consist will have a standard laptop PC containing the enforcement algorithm (EA). The lead locomotive will also be instrumented with a Locomotive Control Unit (LCU) that communicates train speed, position, head end brake pipe pressure, and locomotive notch to the EA PC. The LCU and the

EA PC will be used to record speed, location, locomotive notch, and brake pipe pressure data throughout each test for use in determining when the brakes were applied, where the train stopped, etc.

A track file loaded on the enforcement algorithm PC will contain surveyed grade and curve data for the Railroad Test Track (RTT), and will be accessed by the enforcement algorithm as needed for stopping distance prediction.

The enforcement algorithm PC will interface with the LCU over an Ethernet connection to enforce a penalty brake application when necessary. The penalty application will be transmitted to the remote (distributed) locomotive, resulting in application of the penalty brake by both the lead and remote (distributed) locomotives.

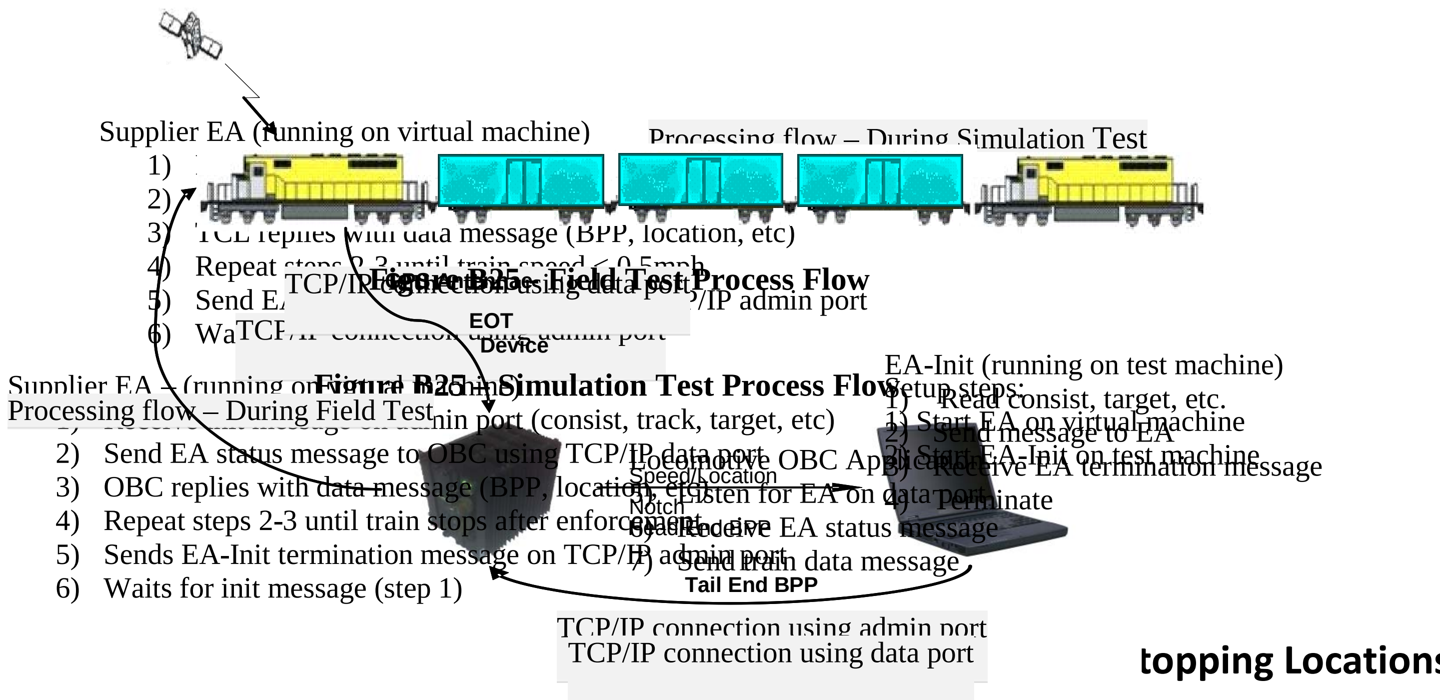


Figure 1 – Test Configuration

The field testing will test the both the base case and current enforcement algorithm with distributed power in the consist over a number of test scenarios, which will cover a range of operating conditions. The test scenarios are determined by varying the following independent test variables:

- Train length
- Train speed
- Track grade

The specific test scenarios are listed in table 1, below.

Table 1 – Test Scenarios

Test ID	Train Length	Train Speed	Track Grade
1	80 cars	30 mph	Flat
2	80 cars	50 mph	Flat
3	80 cars	10 mph	Flat
4	80 cars	30 mph	Decline
5	80 cars	30 mph	Incline
6	60 cars	30 mph	Flat
7	60 cars	30 mph	Decline

Each test scenario will be used to evaluate the base case algorithm, and the developmental algorithm both with and without the adaptive function.

For each test scenario, a target stopping location will be selected on the RTT that will provide the proper track grade for the scenario. This location will be entered into the enforcement algorithm, along with the generic consist information and other required inputs. An appropriate starting location will be determined, and the train will be moved to this location to start each test run.

The train will be accelerated to the specified test speed and the train will proceed towards the target stopping location, with the enforcement algorithm monitoring the speed, location, and brake pipe pressure of the train. When the enforcement algorithm determines that an enforcement brake application is necessary, it will send a signal to the LCU, which will drop power to the locomotives and apply a penalty brake application. The penalty application will be transmitted to the remote (distributed) locomotive to apply the penalty brake from both locations. The locomotive engineer will bail off the locomotive brakes as soon as the penalty application has been made.

Once the train has stopped, the absolute stopping location will be recorded and the location relative to the target will be measured and recorded before resetting the train for the next test run.

4.2.2 Validation Testing

N/A

4.2.3 Endurance Testing

N/A

4.2.4 Safety Margin Tests

N/A

4.3 Operation Locations

The stop tests will occur at various locations around the RTT.

4.4 Special Support

N/A

4.5 Instrumentation Types

See section 5.0.

4.6 Measurement Definitions

The following measurements will be taken during the field test for each test run:

- Stopping location. The location in footage relative to a specific point on the track will be measured by the LCU and recorded by the enforcement algorithm software once the train has come to a stop.
- Stopping location relative to the target. The difference in footage between the stopping location and the target location will be calculated in post-processing.
- Stopping distance. The difference in footage between the point of penalty brake application and stopping location will be calculated in post-processing.

4.7 Data Collection Schematics

None.

5.0 Instrumentation Identification

5.1 On-Board Instrumentation List

The on-board instrumentation includes:

- Locomotive control unit (LCU)
- Laptop computer containing enforcement algorithm software
- Locomotive brake pipe pressure transducer
- GPS antennas
- Penalty brake valve
- Mid-Train test car with brake pipe pressure transducer
- Mid-Train test car with brake cylinder pressure transducer
- Unmanned data acquisition computer (UDAC)

5.2 Wayside Instrumentation List

None.

5.3 Special Instrumentation List

None.

6.0 Photography and Video

6.1 Photography Requirements

None.

6.2 Video Requirements

None.

7.0 Transportation Technology Center, Inc. Requirements

7.1 Facility Requirements

None.

7.2 Track Requirements

The enforcement algorithm will be tested at various locations around the 13.5 mile Railroad Test Track (RTT) at the Transportation Technology Center (TTC). Other tracks may be needed for switching and storage of test cars.

7.3 Labor/Personnel Requirements

The following personnel will be required to setup, perform, and analyze the results from the tests planned:

- Test engineer(s): The test engineer(s) will be responsible for organizing and managing the test activities, including providing test plans, procedures, and data sheets to test personnel, and ensuring test activities can be performed in a safe manner. It will also be the responsibility of the test engineer(s) to oversee setup of the instrumentation, running the enforcement algorithm software, and recording or ensuring necessary data is recorded. Post test, the test engineer(s) will analyze the data collected for use in other tests and future developments of the enforcement algorithm.
- Test controller: The test controller will be in charge of the actual tests and all movements of the test consist. This includes ensuring all safety rules, test plans, and other instructions are followed by all test personnel. The test controller will be the point of communication between the test engineers and the locomotive engineer and any other test personnel. The test controller will coordinate all train moves with the proper personnel in the Operations Control Center (OCC), and ensure safe test conditions at all times. Finally, the test controller will keep a detailed log of the test activities.
- Locomotive engineer: The locomotive engineer will execute train moves as necessary for test setup, switching, and test functions.
- Instrumentation engineer(s): The instrumentation engineer(s) will work closely with the test engineer(s) to set up all test instrumentation, and ensure the proper operation of the instrumentation and data collection system during testing.

7.4 Equipment Requirements

The following equipment will be required for the field tests:

- Four locomotives, including two SD70MAC locomotives equipped and capable of operating with distributed power
- 80 loaded test cars from the Facility for Accelerated Service Testing (FAST) train

7.5 Material Requirements

None.

7.6 Special Requirements

None.

8.0 Restoration and/or Dismantling

8.1 Facility Restoration

None.

8.2 Track Restoration

None.

8.3 Equipment Disposition

None.

8.4 Material Disposition

None.

8.5 Special Equipment Disposition

None.

9.0 Data Requirements

9.1 Data Types

The following data will be collected during this field test:

- Locomotive location
- Locomotive speed
- Locomotive brake pipe pressure
- Locomotive notch
- Mid-Train brake pipe pressure
- Mid-Train (test car) brake cylinder pressure

9.2 Recording Techniques

Locomotive location, speed, brake pipe pressure and locomotive notch will be collected once per second by the locomotive control unit (LCU). Mid-train brake pipe pressure and brake cylinder pressure will be collected at 256 Hz using an unmanned data acquisition computer (UDAC).

9.3 Data Analysis

The data collected will be used to evaluate the performance of the enforcement algorithm. For each test, the stopping location with the current algorithm will be compared to the same test with the base case enforcement algorithm. The objective is to determine the improvement in stopping distance prediction for trains with distributed power. The results will also be compared against the safety and performance objectives for each test scenario.

The actual brake pipe and brake cylinder data, stop distance and stop time will also be compared to the prediction data from the enforcement algorithm to determine the accuracy of the prediction and identify any flaws in the algorithm logic that need to be investigated.

9.4 Reports

Documentation of the field test will be included in a final report for the project.

10.0 Safety

TTCI has a very successful safety record. Strict operating and safety rules will be followed during the work described in this proposal.

A pre-test meeting will be held before any physical work is started. Safety and quality issues will be addressed at this meeting.

11.0 Work Schedule

The field testing will occur during the week of December 21, 2009.

12.0 Quality Assurance

TTCI is committed to providing products and/or services that meet and/or exceed the customers' specified contractual and project requirements. TTCI recognizes that in order to provide and maintain a consistently high quality in the work it undertakes, an effective Quality Management System is necessary so as to ensure that proper communication, work control and accountable records are generated for all work undertaken.

It is the policy, therefore, of TTCI to control and conduct its business of consultancy and test services in the railway transportation arena by means of a formalized system of modern quality management that conforms to the requirements of ISO 9001–2000. Through the QMS, TTCI is able to ensure that our products and services meet or exceed our customers' expectations.

In order to ensure our entire organization supports the quality process, TTCI sponsors an employee led Quality Resource Team (QRT). The mission of the QRT is to "To promote customer satisfaction by providing effective training, education, and communication tools for Team TTCI." The QRT works directly with TTCI's marketing team to identify customer satisfaction issues and help resolve them. The QRT also provides period refresher training to TTCI employees in science of Continuous Quality Improvement, Customer Satisfaction, and the implementation of problem solving tools.

13.0 Support Specialties

N/A

Task Order 242: Development of a PTC Enforcement Algorithm for Freight Trains

Enforcement with Emergency Brake Back-Up

Field Test Implementation Plan

July 2010

Approval:____

Terry Tse, COTM **Date**

Presented By:

Transportation Technology Center, Inc.

A Subsidiary of the **Association of American Railroads**

55500 D.O.T. Road

P.O. Box 11130

Pueblo, Colorado, USA 81001

1.0 Project Title

Development of an Implementation-Ready Enforcement Braking Algorithm for Freight Trains

2.0 Introduction

Positive Train Control (PTC) is an emerging train control technology intended to enhance safety and possibly improve train performance and plant capacity. The underlying concept of the technology is that movement authorities are transmitted digitally to the controlling locomotive of each train. The locomotive tracks the train's location with respect to its authority and speed limits and the train's stopping ability based on known train parameters and automatically applies brakes to prevent the train from violating any limit in the event of human failure. Enforcement braking is an event of last recourse when the locomotive engineer has failed to take adequate action. A full service brake application is used for enforcement in today's PTC systems.

The base case enforcement algorithm predicts train braking distance based on a number of assumed or calculated train and environmental parameters, such as brake propagation time, brake ratio, ambient temperature, etc. In order to achieve the safety objectives of the PTC system, a target (safety) offset is added to the stopping distance prediction to ensure that a given train stops short of the target, even if the assumptions in the prediction calculation are inaccurate and result in a predicted stopping distance that is shorter than the actual stopping distance. However, by adding this target (safety) offset, there is also the possibility of negatively affecting the performance of the system in the case where the assumptions in the prediction calculation result in a predicted stopping distance that is longer than the actual stopping distance.

A new development of the algorithm uses the input data from the onboard computer after an enforcement has been initiated and monitors the actual stopping progress of the train. If it is determined that the train is going to overrun the target the enforcement algorithm will then initiate an emergency brake application to prevent a violation. This added capability allows for less target (safety) offset to be used in the algorithm, thereby lessening the impact on system performance without negatively affecting the safety objective.

The primary objective of this test is to evaluate the enforcement algorithm with the modifications made for emergency brake back-up against the base case algorithm. Additional data collection will also be performed during the test to support other enforcement algorithm developments.

2.1 Key Personnel

Customer Contact, <u>Ruben Pena, Assistant Director, Business Acquisition / DC</u>

Telephone: 719-584-0543

Fax: 719-584-0770

Email: ruben_pena@ttci.aar.com

Program Manager, <u>Dingqing Li, Principal Investigator II / FRA Program Manager</u>

Telephone: 719-584-0740

Fax: 719-584-0791

Email: dingqing_li@ttci.aar.com

Project Manager, Joe Brosseau, Senior Engineer II

Telephone: 719-584-7128

Fax: 719-584-0771

Email: joe_brosseau@ttci.aar.com

Test Engineer, Shad Pate, Engineer

Telephone: 719-584-7116

Fax: 719-584-7116

Email: shad_pate@ttci.aar.com

2.2 Responsibilities

The project manager for this project is Joe Brosseau. He is responsible for ensuring that the test is completed on time, within budget, and will ensure all deliverables meet or exceed FRA requirements. The test engineer for this test is Shad Pate. He will be responsible for ensuring that the test is executed according to the test plan, that all data is collected properly, and that the test is completed safely.

2.3 Documentation

The results of this test will be documented within the final report for this project.

3.0 Preparation

In preparation for field testing of the enforcement algorithm, the following tasks will be completed:

- Test locomotive setup/checkout. This includes the installation of a locomotive control unit (LCU) capable of determining locomotive location and speed, head end brake pipe pressure, and throttle notch. The LCU will be capable of interacting with the enforcement algorithm operating on a separate test machine.
- Enforcement algorithm software setup/checkout. This includes software modifications necessary for this test and testing of the software in a simulation environment to determine that the algorithm will operate as expected.
- Test consist setup. This includes determining the specific consist to be used, making measurements on the brake system components, scaling the test consist and installing the test instrumentation.

4.0 Implementation

4.1 Constraints

None.

4.2 Operation Sequence

4.2.1 Track Testing

The field test configuration is shown in Figure 1. The lead locomotive of the test consist will have a standard laptop PC containing the enforcement algorithm (EA). The lead locomotive will also be instrumented with a Locomotive Control Unit (LCU) that communicates train speed, position, head end brake pipe pressure, and locomotive notch to the EA PC. The LCU and the EA PC will be used to record speed, location, locomotive notch, and brake pipe pressure data throughout each test for use in determining when the brakes were applied, where the train stopped, etc.

A track file loaded on the enforcement algorithm PC will contain surveyed grade and curve data for the Railroad Test Track (RTT), and will be accessed by the enforcement algorithm as needed for stopping distance prediction.

The enforcement algorithm PC will interface with the LCU over an Ethernet connection to enforce a penalty brake application when necessary. The enforcement algorithm will then continue to monitor the train's stopping progress and enforce an emergency brake application if/when necessary.

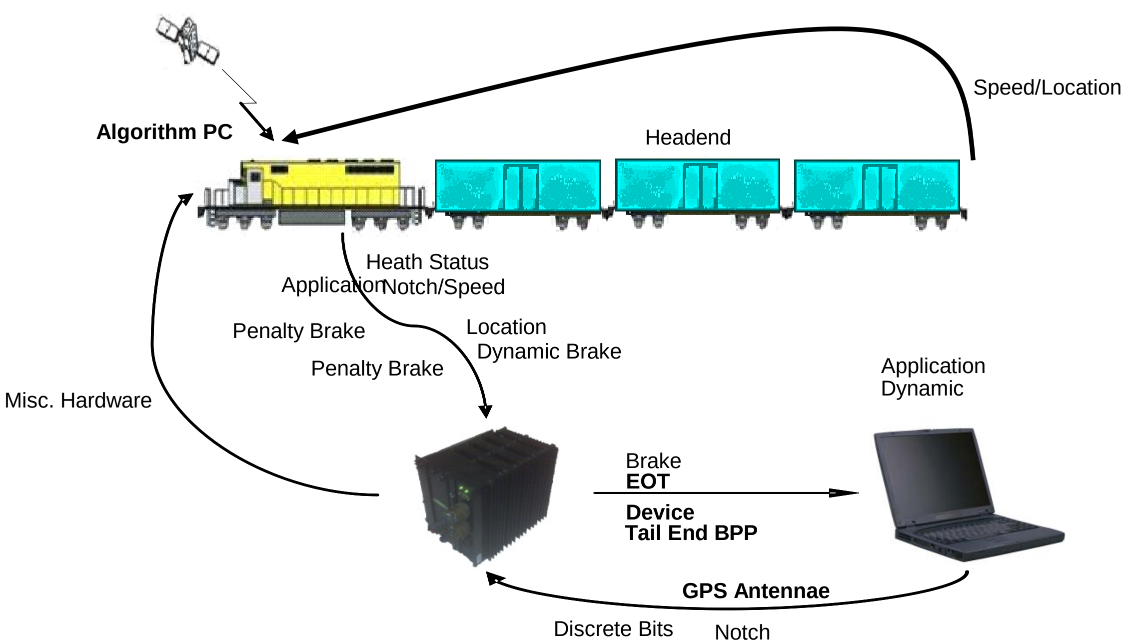


Figure 1 – Test Configuration

The field testing will test both the base case and current enforcement algorithm with emergency brake back-up over a number of test scenarios, which will cover a range of operating conditions. The test scenarios are determined by varying the following independent test variables:

- Train length
- Train speed

- Track grade

The specific test scenarios are listed in table 1, below.

Table 1 – Test Scenarios

Test ID	Train length	Train speed	Track grade
1	40 cars	30 mph	Decline
2	40 cars	30 mph	Flat
3	40 cars	50 mph	Decline
4	40 cars	30 mph	Incline
5	100 cars	30 mph	Decline
6	100 cars	30 mph	Flat
7	10 cars	30 mph	Decline
8	10 cars	50 mph	Flat

For each of the above test scenarios, the emergency brake back-up algorithm will be evaluated based on its ability to stop the train short of a target when the penalty is not sufficient, but also to ensure that emergency applications are not unnecessarily initiated when the penalty is sufficient for stopping the train short of the target.

For each test scenario, a target stopping location will be selected on the RTT that will provide the proper track grade for the scenario. This location will be entered into the enforcement algorithm, along with the generic consist information and other required inputs. The inputs to the enforcement algorithm for the train will be modified in such a way that it will enforce the train to stop approximately 200 feet short of the target or 200 feet beyond the target, as appropriate for the test case. An appropriate starting location will be determined, and the train will be moved to this location to start each test run.

The train will be accelerated to the specified test speed and the train will proceed towards the target stopping location, with the enforcement algorithm monitoring the speed, location, and brake pipe pressure of the train. When the enforcement algorithm determines that an enforcement brake application is necessary, it will send a signal to the LCU, which will drop power to the locomotives and apply a penalty brake application. The enforcement algorithm will then monitor the stopping progress and determine if an emergency brake application in necessary. The locomotive engineer will bail off the locomotive brakes as soon as the penalty or emergency application has been made.

Once the train has stopped, the absolute stopping location will be recorded and the location relative to the target will be measured and recorded before resetting the train for the next test run.

4.2.2 Validation Testing

N/A

4.2.3 Endurance Testing

N/A

4.2.4 Safety Margin Tests

N/A

4.3 Operation Locations

The stop tests will occur at various locations around the RTT.

4.4 Special Support

N/A

4.5 Instrumentation Types

See section 5.0.

4.6 Measurement Definitions

The following measurements will be taken during the field test for each test run:

- Penalty enforcement location. The location in footage relative to a specific point on the track will be measured by the LCU and recorded by the enforcement algorithm software once the train has received a penalty application.
- Emergency enforcement location. The location in footage relative to a specific point on the track will be measured by the LCU and recorded by the enforcement algorithm software once the train has received an emergency application.
- Stopping location. The location in footage relative to a specific point on the track will be measured by the LCU and recorded by the enforcement algorithm software once the train has come to a stop.
- Stopping location relative to the target. The difference in footage between the stopping location and the target location will be calculated in post-processing.
- Stopping distance. The difference in footage between the point of penalty brake application and stopping location will be calculated in post-processing.

4.7 Data Collection Schematics

None.

5.0 Instrumentation Identification

5.1 On-Board Instrumentation List

The on-board instrumentation includes:

- Locomotive control unit (LCU)
- Laptop computer containing enforcement algorithm software
- Locomotive brake pipe pressure transducer

- GPS antennas
- Penalty brake valve
- Emergency brake valve
- Three test cars with a brake pipe pressure transducer spaced throughout the train
- Three test cars with a brake cylinder pressure transducer spaced throughout the train
- Three Unmanned data acquisition computers (UDAC)

5.2 Wayside Instrumentation List

None.

5.3 Special Instrumentation List

None.

6.0 Photography and Video

6.1 Photography Requirements

None.

6.2 Video Requirements

None.

7.0 Transportation Technology Center, Inc. Requirements

7.1 Facility Requirements

None.

7.2 Track Requirements

The enforcement algorithm will be tested at various locations around the 13.5 mile Railroad Test Track (RTT) at the Transportation Technology Center (TTC). Other tracks may be needed for switching and storage of test cars.

7.3 Labor/Personnel Requirements

The following personnel will be required to setup, perform, and analyze the results from the tests planned:

- Test engineer(s): The test engineer(s) will be responsible for organizing and managing the test activities, including providing test plans, procedures, and data sheets to test personnel, and ensuring test activities can be performed in a safe manner. It will also be the responsibility of the test engineer(s) to oversee setup of the instrumentation, running the enforcement algorithm software, and recording or ensuring necessary data is recorded. Post test, the test engineer(s) will analyze the data collected for use in other tests and future developments of the enforcement algorithm.

- Test controller: The test controller will be in charge of the actual tests and all movements of the test consist. This includes ensuring all safety rules, test plans, and other instructions are followed by all test personnel. The test controller will be the point of communication between the test engineers and the locomotive engineer and any other test personnel. The test controller will coordinate all train moves with the proper personnel in the Operations Control Center (OCC), and ensure safe test conditions at all times. Finally, the test controller will keep a detailed log of the test activities.
- Locomotive engineer: The locomotive engineer will execute train moves as necessary for test setup, switching, and test functions.
- Instrumentation engineer(s): The instrumentation engineer(s) will work closely with the test engineer(s) to set up all test instrumentation, and ensure the proper operation of the instrumentation and data collection system during testing.

7.4 Equipment Requirements

The following equipment will be required for the field tests:

- Four locomotives, including at least one of the three locomotives equipped with the necessary LCU used for enforcement algorithm testing
- 100 loaded test cars from the Facility for Accelerated Service Testing (FAST) train

7.5 Material Requirements

None.

7.6 Special Requirements

None.

8.0 Restoration and/or Dismantling

8.1 Facility Restoration

None.

8.2 Track Restoration

None.

8.3 Equipment Disposition

None.

8.4 Material Disposition

None.

8.5 Special Equipment Disposition

None.

9.0 Data Requirements

9.1 Data Types

The following data will be collected during this field test:

- Locomotive location
- Locomotive speed
- Locomotive brake pipe pressure
- Locomotive notch
- Train brake pipe pressure at three locations throughout the train (test cars)
- Brake cylinder pressure on three tests cars located throughout the train

9.2 Recording Techniques

Locomotive location, speed, brake pipe pressure and locomotive notch will be collected once per second by the locomotive control unit (LCU) and transmitted to the enforcement algorithm PC, which will keep a record of these data items. Train brake pipe pressure and brake cylinder pressure from the test cars will be collected at 256 Hz using an unmanned data acquisition computer (UDAC).

9.3 Data Analysis

The data collected will be used to evaluate the performance of the enforcement algorithm. For each test, the stopping location with the current algorithm will be compared to the same test with the base case enforcement algorithm. The objective is to determine the improvement in authority violations for trains equipped with emergency brake back-up algorithm. The results will also be compared against the safety and performance objectives for each test scenario.

The actual brake pipe and brake cylinder data, stop distance and stop time will also be compared to the prediction data from the enforcement algorithm to determine the accuracy of the prediction and identify any flaws in the algorithm logic that need to be investigated.

9.4 Reports

Documentation of the field test will be included in a final report for the project.

10.0 Safety

TTCI has a very successful safety record. Strict operating and safety rules will be followed during the work described in this proposal.

A pre-test meeting will be held before any physical work is started. Safety and quality issues will be addressed at this meeting.

11.0 Work Schedule

The field testing will occur during the week of July 12, 2010.

12.0 Quality Assurance

TTCI is committed to providing products and/or services that meet and/or exceed the customers' specified contractual and project requirements. TTCI recognizes that in order to provide and maintain a consistently high quality in the work it undertakes, an effective Quality Management System is necessary so as to ensure that proper communication, work control and accountable records are generated for all work undertaken.

It is the policy, therefore, of TTCI to control and conduct its business of consultancy and test services in the railway transportation arena by means of a formalized system of modern quality management that conforms to the requirements of ISO 9001–2000. Through the QMS, TTCI is able to ensure that our products and services meet or exceed our customers' expectations.

In order to ensure our entire organization supports the quality process, TTCI sponsors an employee led Quality Resource Team (QRT). The mission of the QRT is to "To promote customer satisfaction by providing effective training, education, and communication tools for Team TTCI." The QRT works directly with TTCI's marketing team to identify customer satisfaction issues and help resolve them. The QRT also provides period refresher training to TTCI employees in science of Continuous Quality Improvement, Customer Satisfaction, and the implementation of problem solving tools.

13.0 Support Specialties

N/A

Task Order 242: Development of a PTC Enforcement Algorithm for Freight Trains

Lockheed Martin Phase 1 Field Test

Field Test Implementation Plan

November/December 2010

Approval:____

Terry Tse, COTM **Date**

Presented By:

Transportation Technology Center, Inc.

A Subsidiary of the **Association of American Railroads**

55500 D.O.T. Road

P.O. Box 11130

Pueblo, Colorado, USA 81001

1.0 Project Title

Development of an Implementation-Ready Enforcement Braking Algorithm for Freight Trains

2.0 Introduction

Positive Train Control (PTC) is an emerging train control technology intended to enhance safety and possibly improve train performance and plant capacity. The underlying concept of the technology is that movement authorities are transmitted digitally to the controlling locomotive of each train. The locomotive tracks the train's location with respect to its authority and speed limits and the train's stopping ability based on known and assumed train parameters and brake pipe pressure, and automatically applies brakes to prevent the train from violating any limit in the event of human failure. Enforcement braking is an event of last recourse when the locomotive engineer has failed to take adequate action. A full service penalty brake application is used for enforcement in today's PTC systems.

As part of the first phase of work under this task order, a number of new functions have been developed and tested that are intended to improve the operational performance of the enforcement algorithm without negatively affecting the safety performance. These developments include:

- Modifications to the algorithm logic
- Modifications to the assumptions within the algorithm
- An improved target offset function
- Adaptive functions that adjust the assumed parameters based on measured braking characteristics
- Distributed power function that adjusts the prediction for trains with distributed power
- Emergency brake back-up function that monitors the braking progress after the initial penalty enforcement and applies the emergency brake if a target overrun is predicted

To evaluate the practical application of the functions and techniques developed in the first phase of work, the enforcement algorithm will be tested as implemented in a functional PTC system developed by Lockheed Martin. To fully quantify the performance of the enforcement algorithm implemented by Lockheed Martin, a series of simulation and field tests will be performed. This document describes the field test plan for this evaluation.

The objective of this test is to evaluate the Lockheed Martin implementation of the phase 1 enforcement algorithm. The results of this test will be used, in conjunction with the results of simulation testing, to quantify the overall performance of the enforcement algorithm. The test will be conducted in two stages. In the first stage, the PTC onboard system will receive stop targets directly from the test personnel to evaluate the performance of the enforcement algorithm as a standalone function. In the second stage, authorities will be provided to the PTC system through a simulated dispatching system, and the PTC system will be responsible for generating the stop targets to evaluate the performance of the enforcement algorithm as a component of the overall PTC onboard system.

2.1 Key Personnel

Customer Contact, <u>Ruben Pena, Assistant Director, Business Acquisition / DC</u>

Telephone: 719-584-0543

Fax: 719-584-0770

Email: ruben_pena@ttci.aar.com

Program Manager, <u>Dingqing Li, Principal Investigator II / FRA Program Manager</u>

Telephone: 719-584-0740

Fax: 719-584-0791

Email: dingqing_li@ttci.aar.com

Project Manager, <u>Joe Brosseau, Senior Engineer I</u>

Telephone: 719-584-7128

Fax: 719-584-0771

Email: joe_brosseau@ttci.aar.com

Test Engineer, <u>Jeremy Dasher, Engineering Aid</u>

Telephone: 719-584-0758

Fax: 719-584-0758

Email: Jeremy_Dasher@ttci.aar.com

2.2 Responsibilities

The project manager for this project is Joe Brosseau. He is responsible for ensuring that the test is completed on time, within budget, and will ensure all deliverables meet or exceed FRA requirements. The test engineer for this test is Jeremy Dasher. He will be responsible for ensuring that the test is executed according to the test plan, that all data is collected properly, and that the test is completed safely.

2.3 Documentation

The results of this test will be documented within the final report for this project.

3.0 Preparation

In preparation for field testing of the enforcement algorithm, the following tasks will be completed:

- Test locomotive setup/checkout. This includes the installation of a PTC locomotive control unit (LCU) that contains the Lockheed Martin (LM) implementation of the enforcement algorithm. The LCU will also be capable of interfacing with the TTCI enforcement algorithm test application operating on a separate test machine. The TTCI enforcement algorithm test application will primarily be used for data collection purposes, but will also be used in selected test cases as an enforcement algorithm for direct comparison to the LM implementation.

- Enforcement algorithm software setup/checkout. This includes testing of the enforcement algorithm software in a simulation environment to determine that the algorithm will operate as expected.
- Test consist setup. This includes determining the specific consist to be used and installing the test instrumentation.
- Tribometer reading will be taken before and after testing to document track conditions.

4.0 Implementation

4.1 Constraints

None.

4.2 Operation Sequence

Track Testing

The test will be conducted in two stages. In the first stage, the PTC onboard system will receive stop targets directly from the test personnel to evaluate the performance of the enforcement algorithm as a standalone function. In the second stage, a simulated dispatching system will be used to provide movement authorities to the onboard system to evaluate the performance of the enforcement function as contained within the overall onboard system.

During the first stage of testing, the LM implementation of the enforcement algorithm will be tested over a variety of test scenarios. For a select number of these test scenarios, the TTCI implementation of the enforcement algorithm will also be tested to verify that the results are consistent between the TTCI and Lockheed Martin implementations.

The field test configuration for the first stage of testing of the LM implementation is shown in Figure 1. The lead locomotive of the test consist will house a Locomotive Control Unit (LCU) and a standard laptop PC. The LCU will contain the Lockheed Martin implementation of the enforcement algorithm (EA) and the laptop PC will contain the TTCI enforcement algorithm test application.

The enforcement algorithm contained within the LCU will be initialized with consist data and stop target data by test personnel prior to each test. Track data loaded on the LCU will contain surveyed grade and curve data for the Railroad Test Track (RTT), to be accessed by the enforcement algorithm during the test. The enforcement algorithm will then collect train status data, including train speed, position, head end brake pipe pressure, tail end brake pipe pressure as reported by an EOT device and locomotive notch, in real time as the test is run, and use this data to enforce penalty and emergency brake applications, as necessary to avoid a target overrun.

The train status data will also be sent to the TTCI enforcement algorithm test application via an Ethernet connection. The TTCI enforcement algorithm test application will be used to record data throughout each test for use in determining when the brakes were applied, where the train stopped, etc.

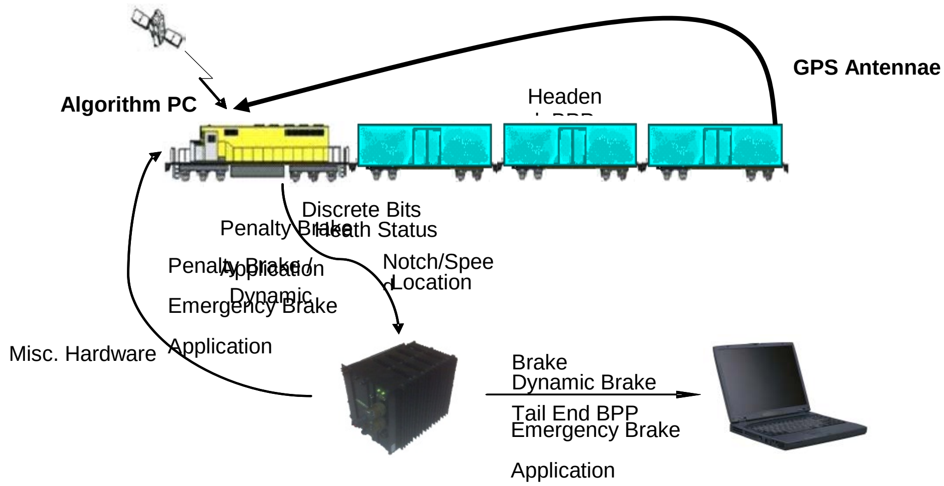


Figure 1 – First Stage Test Configuration – LM EA

The test configuration for testing the TTCI implementation of the enforcement algorithm is shown in Figure 2. For these cases, the TTCI implementation of the enforcement algorithm, contained on the laptop PC, will be initialized with consist and target stop data. The enforcement algorithm will then interface with the LCU over an Ethernet connection to receive train status data and enforce penalty and emergency brake applications, as necessary to avoid a target overrun.

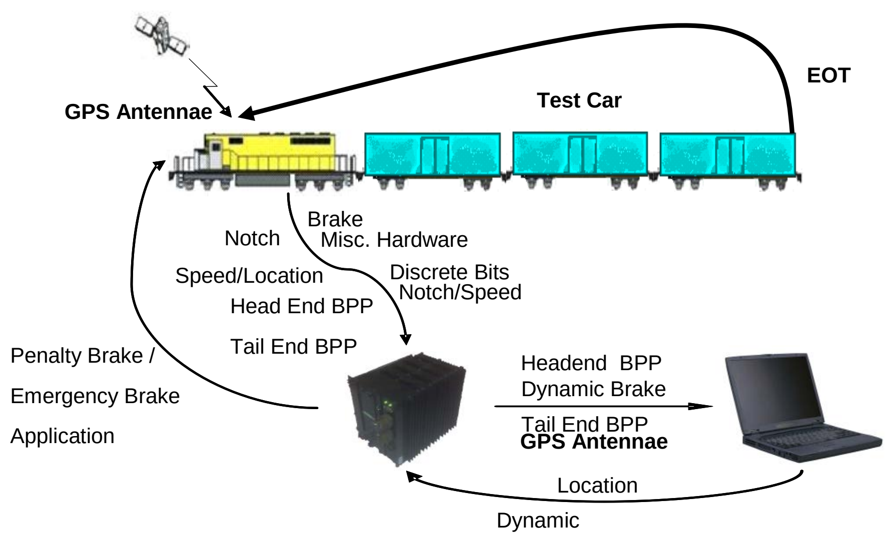


Figure 2 – First Stage Test Configuration – TTCI EA

The first stage of field testing will test enforcement algorithm over a number of test scenarios, which will cover a range of operating conditions. The test scenarios are determined by varying the following independent test variables:

- Consist – The field tests will use the consist from the Facility for Accelerated Service Testing (FAST). The length of the consist is specified for each test scenario as one of the following:
    - Long – 85 to 90 cars (based on availability of cars)
    - Medium – 40 cars
    - Short – 10 cars
- Track – The approximate track grade over the braking distance:
    - Flat – 0% grade
    - Decline – 1.5% grade
    - Incline – 0.7% grade
    - Crest – 0.6 % incline and 0.6 % decline
    - Varying – 0% to 0.7% incline
- Speed – The approximate train speed at enforcement. In some cases, two speeds are listed, which indicates there will be a speed restriction in addition to an absolute stop target or authority limit.
- 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.

Some of the tests will be run multiple times to evaluate repeatability, as indicated by the "Number of Runs" column in the test matrix. The specific test scenarios are listed in Table 1. Test cases sixteen and seventeen will test the performance of the enforcement algorithm with a speed restriction in addition to an absolute stop target.

For test case 21, the emergency brake back-up function of the enforcement algorithm will be evaluated. For this test case, the train will be artificially forced to overrun the target by a small margin following the penalty enforcement to evaluate whether the emergency brake back-up function enforces an emergency brake application to stop the train short of the target.

Table 1 – First Stage Test Scenarios

Test Case	Consist	Track	Speed	Brake State	Type of Test	Target Pt	Number of Runs	Algorithm
1	Long	Flat	10	Fully Charged	Safety	R24	3	LM
2	Long	Flat	10	Fully Charged	Performance	R24	2	LM
3	Long	Flat	30	Fully Charged	Safety	R24	3	LM
4	Long	Flat	60	Fully Charged	Safety	R24	1	LM
5	Long	Decline	30	Fully Charged	Safety	R14	3	LM
6	Long	Decline	30	Fully Charged	Performance	R14	2	LM
7	Long	Varying	30	Fully Charged	Safety	R27	1	LM
8	Med	Decline	60	Fully Charged	Safety	R14	1	LM
9	Med	Decline	60	Fully Charged	Performance	R14	2	LM
10	Short	Flat	30	Fully Charged	Safety	R24	3	LM
11	Short	Flat	30	Fully Charged	Performance	R24	2	LM
12	Long	Flat	30	Applied	Safety	R24	3	LM
13	Long	Incline	10	Fully Charged	Safety	R48	1	LM
14	Long	Incline	30	Fully Charged	Safety	R48	3	LM
15	Long	Crest	30	Fully Charged	Safety	R69	1	LM
16	Long	Flat	60,30	Fully Charged	Safety	R30 30 at R24	1	LM
17	Long	Flat	60,30	Fully Charged	Performance	R30 30 at R24	2	LM
18	Long	Flat	60	Fully Charged	Safety	R24	1	TTCI
19	Short	Flat	30	Fully Charged	Safety	R24	1	TTCI
20	Med	Decline	60	Fully Charged	Safety	R14	1	TTCI
21	Long	Flat	30	Fully Charged	Safety	R24	2	LM

Each test case will begin with a standing air brake test, in which a 15 psi brake pipe pressure reduction will be made by the locomotive crew to allow the enforcement algorithm an opportunity to correct for the actual propagation time of the train. The train will then be accelerated to a speed of approximately 30 mph, and a running brake test will be performed, in which the locomotive crew will make a 15 psi brake pipe pressure reduction to allow the enforcement algorithm an opportunity to correct for the actual braking efficiency of the train.

Following the standing and running brake tests, the enforcement algorithm test runs for the test case will be executed. The train will be moved to the starting position appropriate for the specific test case. The train will then be accelerated to the specified test speed and proceed towards the target stopping location, with the enforcement algorithm monitoring the speed, location, and brake pipe pressure of the train. When the enforcement algorithm determines that an enforcement brake application is necessary, the LCU will drop power to the locomotives and apply a penalty brake application. The locomotive engineer will bail off the locomotive brakes as soon as the penalty application has been made.

For the performance tests, the locomotive crew will stop the train prior to the target using normal train handling procedures. The enforcement algorithm may or may not enforce a penalty brake application in these test cases.

Once the train has stopped, the absolute stopping location will be recorded and the location relative to the target will be measured and recorded before resetting the train for the next test run.

For the second stage of testing, movement authorities will be provided to the PTC onboard system through a simulated dispatching system, and the onboard system will be responsible for generating the stop targets to evaluate the performance of the enforcement algorithm as a component of the overall PTC onboard system. The field test configuration for the second stage is shown in Figure 3.

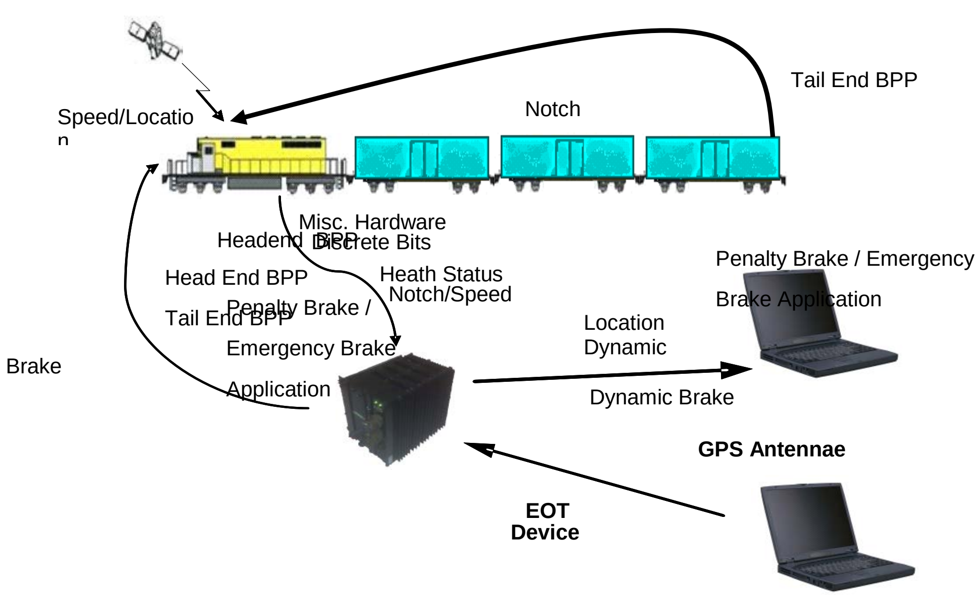


Figure 3 – Second Stage Test Configuration

The specific test scenarios for the second stage of testing are listed in Table 2.

Table 2 – Second Stage Test Scenarios

Test Case	Consist	Track	Speed	Brake State	Type of Test	Begin Authority	Target Pt	Number of Runs	Algorithm
1	Long	Flat	10	Fully Charged	Safety	R66	R24	3	LM
2	Long	Flat	10	Fully Charged	Performance	R66	R24	2	LM
3	Long	Flat	30	Fully Charged	Safety	R66	R24	3	LM
4	Long	Flat	60	Fully Charged	Safety	R66	R24	1	LM
5	Long	Decline	30	Fully Charged	Safety	R66	R14	3	LM
6	Long	Decline	30	Fully Charged	Performance	R66	R14	2	LM
7	Long	Varying	30	Fully Charged	Safety	R66	R27	1	LM
8	Med	Decline	60	Fully Charged	Safety	R66	R14	1	LM
9	Med	Decline	60	Fully Charged	Performance	R66	R14	2	LM
10	Short	Flat	30	Fully Charged	Safety	R66	R24	3	LM
11	Short	Flat	30	Fully Charged	Performance	R66	R24	2	LM
12	Long	Flat	30	Applied	Safety	R66	R24	3	LM
13	Long	Decline	10	Fully Charged	Safety	R66	R14	1	LM
14	Med	Flat	30	Fully Charged	Safety	R66	R24	1	LM
15	Long	Flat	30,20	Fully Charged	Safety	R66	R30 20 at R24	1	LM
16	Long	Flat	30,20	Fully Charged	Performance	R66	R30 20 at R24	2	LM
17	Med	Flat	60,30	Fully Charged	Safety	R66	R30 30 at R24	1	LM
18	Med	Flat	60,30	Fully Charged	Performance	R66	R30 30 at R24	2	LM
19	Short	Decline	30	Fully Charged	Safety	R66	R14	1	LM
20	Long	Flat	30	Fully Charged	Safety	R66	R24	2	LM

4.2.1 Validation Testing

N/A

4.2.2 Endurance Testing

N/A

4.2.3 Safety Margin Tests

N/A

4.3 Operation Locations

The stop tests will occur at various locations, as per Tables 1 & 2, around the Railroad Test Track (RTT), located at the Transportation Technology Center (TTC) in Pueblo, CO.

4.4 Special Support

N/A

4.5 Instrumentation Types

See section 5.0.

4.6 Measurement Definitions

The following measurements will be taken during the field test for each test run:

- Penalty enforcement location. The location in footage relative to a specific point on the track will be measured by the LCU and recorded by the enforcement algorithm software once the train has received a penalty application.
- Emergency enforcement location. The location in footage relative to a specific point on the track will be measured by the LCU and recorded by the enforcement algorithm software once the train has received an emergency application.
- Stopping location. The location in footage relative to a specific point on the track will be measured by the LCU and recorded by the enforcement algorithm software once the train has come to a stop.
- Stopping location relative to the target. The difference in footage between the stopping location and the target location will be calculated in post-processing.
- Stopping distance. The difference in footage between the point of penalty brake application and stopping location will be calculated in post-processing.

4.7 Data Collection Schematics

None.

5.0 Instrumentation Identification

5.1 On-Board Instrumentation List

The on-board instrumentation includes:

- Locomotive control unit (LCU)
- Laptop computer containing enforcement algorithm software
- Locomotive brake pipe pressure transducer
- GPS antennas
- Penalty brake valve
- Emergency brake valve
- Three test cars with brake pipe pressure transducers spaced throughout the train behind the 10th, 40th and last car
- Three test cars with brake cylinder pressure transducers spaced throughout the train on the 10th, 40th and last car
- Three unmanned data acquisition computers (UDAC)

5.2 Wayside Instrumentation List

None.

5.3 Special Instrumentation List

A hand-operated tribometer will be used for recording adhesion coefficients at test locations around the RTT.

6.0 Photography and Video

6.1 Photography Requirements

None.

6.2 Video Requirements

None.

7.0 Transportation Technology Center, Inc. Requirements

7.1 Facility Requirements

None.

7.2 Track Requirements

The enforcement algorithm will be tested at various locations, as per Tables 1 & 2, around the 13.5 mile Railroad Test Track (RTT) at the Transportation Technology Center (TTC). Other tracks may be needed for switching and storage of test cars.

7.3 Labor/Personnel Requirements

The following personnel will be required to setup, perform, and analyze the results from the tests planned:

- Test engineer(s): The test engineer(s) will be responsible for organizing and managing the test activities, including providing test plans, procedures, and data sheets to test personnel, and ensuring test activities can be performed in a safe manner. It will also be the responsibility of the test engineer(s) to oversee setup of the instrumentation, running the enforcement algorithm software, and recording or ensuring necessary data is recorded. Post test, the test engineer(s) will analyze the data collected for use in other tests and future developments of the enforcement algorithm.
- Test controller: The test controller will be in charge of the actual tests and all movements of the test consist. This includes ensuring all safety rules, test plans, and other instructions are followed by all test personnel. The test controller will be the point of communication between the test engineers and the locomotive engineer and any other test personnel. The test controller will coordinate all train moves with the proper personnel in the Operations Control Center (OCC), and ensure safe test conditions at all times. Finally, the test controller will keep a detailed log of the test activities.
- Locomotive engineer: The locomotive engineer will execute train moves as necessary for test setup, switching, and test functions.
- Instrumentation engineer(s): The instrumentation engineer(s) will work closely with the test engineer(s) to set up all test instrumentation, and ensure the proper operation of the instrumentation and data collection system during testing.
- Lockheed Martin test personnel: The Lockheed Martin test support personnel will be responsible for ensuring the Lockheed Martin hardware and software operate properly and will work with the Test engineer(s) to ensure that the test procedures are executed properly.

7.4 Equipment Requirements

The following equipment will be required for the field tests:

- Four locomotives, including at least one of the three locomotives equipped with the necessary LCU used for enforcement algorithm testing
- 85-90 loaded test cars from the Facility for Accelerated Service Testing (FAST) train

7.5 Material Requirements

None.

7.6 Special Requirements

None.

8.0 Restoration and/or Dismantling

8.1 Facility Restoration

None.

8.2 Track Restoration

None.

8.3 Equipment Disposition

None.

8.4 Material Disposition

None.

8.5 Special Equipment Disposition

None.

9.0 Data Requirements

9.1 Data Types

The following data will be collected during this field test:

- Locomotive location
- Locomotive speed
- Locomotive brake pipe pressure
- Locomotive notch
- Train brake pipe pressure at three locations throughout the train (test cars)
- Train brake cylinder pressure at three locations throughout the train (test cars)
- Specific test consist makeup

9.2 Recording Techniques

Locomotive location, speed, brake pipe pressure and locomotive notch will be collected once per second by the locomotive control unit (LCU). Train brake pipe pressure and brake cylinder pressure from three of the test cars will be collected at 256 Hz using an unmanned data acquisition computer (UDAC).

9.3 Data Analysis

The data collected will be used to evaluate the performance of the enforcement algorithm. For each test, the data collected will be reprocessed using the TTCI enforcement algorithm test application. The stopping location and the time of the penalty application from the Lockheed Martin algorithm will be compared to the results of reprocessing the data through the TTCI enforcement algorithm test application. The objective is to determine how the Lockheed Martin implementation compares to the test application of the enforcement algorithm.

The results will also be compared against the safety and performance objectives for each test scenario, and used to validate the results of simulation testing that will support the evaluation of the algorithm against these objectives.

The actual brake pipe and brake cylinder data, stop distance and stop time will also be compared to the prediction data from the enforcement algorithm to determine the accuracy of the prediction and identify any flaws in the algorithm logic that need to be investigated.

9.4 Reports

Documentation of the field test will be included in a final report for the project.

10.0 Safety

TTCI has a very successful safety record. Strict operating and safety rules will be followed during the work described in this proposal.

A pre-test meeting will be held before any physical work is started. Safety and quality issues will be addressed at this meeting.

A safety and job briefing will be held prior to start of testing each day, with subsequent job briefings throughout the day if required by a change in the work plan.

11.0 Work Schedule

The first stage of field testing will occur during the week of November 29, 2010 and the second stage will occur during the week of December 13, 2010.

12.0 Quality Assurance

TTCI is committed to providing products and/or services that meet and/or exceed the customers' specified contractual and project requirements. TTCI recognizes that in order to provide and maintain a consistently high quality in the work it undertakes, an effective Quality Management System is necessary so as to ensure that proper communication, work control and accountable records are generated for all work undertaken.

It is the policy, therefore, of TTCI to control and conduct its business of consultancy and test services in the railway transportation arena by means of a formalized system of modern quality management that conforms to the requirements of ISO 9001–2000. Through the QMS, TTCI is able to ensure that our products and services meet or exceed our customers' expectations.

In order to ensure our entire organization supports the quality process, TTCI sponsors an employee led Quality Resource Team (QRT). The mission of the QRT is to "To promote customer satisfaction by providing effective training, education, and communication tools for Team TTCI." The QRT works directly with TTCI's marketing team to identify customer satisfaction issues and help resolve them. The QRT also provides period refresher training to TTCI employees in science of Continuous Quality Improvement, Customer Satisfaction, and the implementation of problem solving tools.

13.0 Support Specialties

N/A

Task Order 242: Development of a PTC Enforcement Algorithm for Freight Trains

Enforcement with Dynamic Brake Field Test

Field Test Implementation Plan

April 2011

Approval:____

Terry Tse, COTM **Date**

Presented By:

Transportation Technology Center, Inc.

A Subsidiary of the **Association of American Railroads**

55500 D.O.T. Road

P.O. Box 11130

Pueblo, Colorado, USA 81001

1.0 Project Title

Development of an Implementation-Ready Enforcement Braking Algorithm for Freight Trains

2.0 Introduction

The objective of this test is to evaluate the performance of a PTC braking enforcement algorithm modified to consider the use of dynamic brake applications made prior to the enforcement. The modified algorithm will be compared to the base algorithm to demonstrate the potential safety and performance benefits. This document describes the field test plan for this evaluation.

Positive Train Control (PTC) is an emerging train control technology intended to enhance safety and possibly improve train performance and plant capacity. The underlying concept of the technology is that movement authorities are transmitted digitally to the controlling locomotive of each train. The locomotive tracks the train's location with respect to its authority and speed limits and the train's stopping ability based on known and assumed train parameters and brake pipe pressure, and automatically applies brakes to prevent the train from violating any limit in the event of human failure. Enforcement braking is an event of last recourse when the locomotive engineer has failed to take adequate action. A full service penalty brake application is used for enforcement in today's PTC systems.

Historically, PTC braking enforcement algorithms do not take the retarding force due to dynamic brake into account during the stopping prediction. This is due to the fact that the dynamic brakes are not designed for fail-safe operation. However, this has an adverse effect on the performance of the braking prediction in cases where dynamic brake is being used to control the train. By ignoring the force generated by the dynamic brake, enforcement occurs earlier than necessary, resulting in unnecessary use of the air brakes, interference with normal, crew-initiated braking, and potentially excessive warnings and enforcements.

To resolve these issues, the PTC braking enforcement algorithm needs to account for the retarding force resulting from a dynamic brake application made prior to a PTC penalty enforcement. The ability to account for this force is essential to achieving the performance goals of the PTC system.

It is therefore desirable to design a system where the retarding force resulting from a dynamic brake application is included in the calculation of the penalty enforcement location. The algorithm will assume that the force due to dynamic brake that is present before an enforcement occurs will remain throughout the penalty enforcement. If the dynamic brake fails during a PTC penalty enforcement the emergency brake backup routine will trigger an emergency brake application if it determines the train will not come to a stop before the target.

As part of the second phase of work under this task order, this dynamic brake subroutine has been incorporated into the braking enforcement algorithm test application to evaluate the practical application of this concept.

2.1 Key Personnel

Customer Contact, <u>Ruben Pena, Assistant Director, Business Acquisition / DC</u>

Telephone: 719-584-0543

Fax: 719-584-0770

Email: ruben_pena@ttci.aar.com

Program Manager, Dingqing Li, Principal Investigator II / FRA Program Manager

Telephone: 719-584-0740

Fax: 719-584-0791

Email: dingqing_li@ttci.aar.com

Project Manager, Joe Brosseau, Senior Engineer II

Telephone: 719-584-7128

Fax: 719-584-0771

Email: joe_brosseau@ttci.aar.com

Test Engineer, Jeremy Dasher, Engineering Aid

Telephone: 719-584-0758

Fax: 719-584-0758

Email: Jeremy_Dasher@ttci.aar.com

2.2 Responsibilities

The project manager for this project is Joe Brosseau. He is responsible for ensuring that the test is completed on time, within budget, and will ensure all deliverables meet or exceed FRA requirements. The test engineer for this test is Jeremy Dasher. He will be responsible for ensuring that the test is executed according to the test plan, that all data is collected properly, and that the test is completed safely.

2.3 Documentation

The results of this test will be documented within the final report for this project.

3.0 Preparation

In preparation for field testing of the enforcement algorithm, the following tasks will be completed:

- Test locomotive setup/checkout. This includes the installation of a PTC locomotive control unit (LCU). The LCU will be capable of interfacing with the TTCI enforcement algorithm test application operating on a separate test machine. The TTCI enforcement algorithm test application will be used as an enforcement algorithm and for data collection purposes.

- Enforcement algorithm software setup/checkout. This includes testing of the enforcement algorithm software in a simulation environment to determine that the algorithm will operate as expected.
- Test consist setup. This includes determining the specific consist to be used and installing the test instrumentation.
- Tribometer readings will be taken before and after testing to document track conditions.

4.0 Implementation

4.1 Constraints

None.

4.2 Operation Sequence

4.2.1 Track Testing

The field test configuration is shown in Figure 1. The lead locomotive of the test consist will house a Locomotive Control Unit (LCU) and a standard laptop PC. The LCU will be used as interface to the locomotive's brake and computer systems. The laptop PC will contain the TTCI enforcement algorithm test application.

The enforcement algorithm will collect 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 will be collected by the enforcement algorithm application, in real time as the test is run, and used to enforce penalty and emergency brake applications, as necessary, to avoid a target overrun. The enforcement algorithm test application will also be used to record the data throughout each test for use in determining when the brakes were applied, where the train stopped, etc.

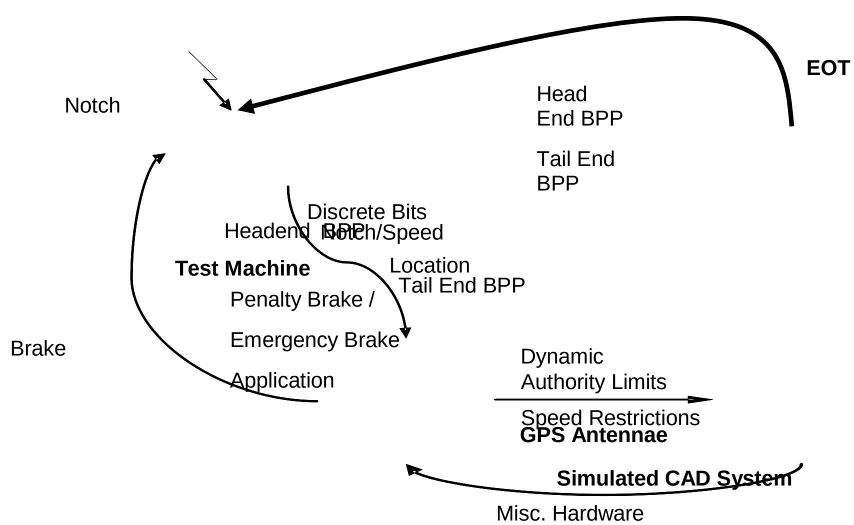


Figure 1 – First Stage Test Configuration – TTCI EA

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

- Consist – The field tests will use the consist from the Facility for Accelerated Service Testing (FAST). The length of the consist is specified for each test scenario as one of the following:
  - Long – 85 to 90 cars (based on availability of cars)
  - Medium – 40 cars
  - Short – 10 cars
- Track – The approximate track grade over the braking distance:
  - Flat – 0% grade
  - Decline – 1.5% grade
- Speed – The target train speed at the time enforcement braking is activated.
- 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.
  - EBB-Safety – Test to ensure that the emergency brake backup routine stops the train short of the target when penalty braking is insufficient to do so. This situation is forced by having some locomotives continue to apply tractive effort after penalty braking is invoked.
  - Safety w/ DB Failure – Test to ensure the emergency brake backup routine stops the train short of the target if the dynamic brakes fail after a penalty enforcement or if dynamic braking is reduced by the operator after penalty enforcement is initiated. This situation is forced by having the locomotive engineer remove dynamic braking once the penalty is enforced by the LCU.

The specific test cases are listed in Table 1. Tests will be run multiple times to evaluate repeatability, up to three tests per test case. Each test case will be performed using the base case algorithm as well as the current algorithm with the dynamic brake modifications. The level of dynamic braking applied prior to enforcement will be determined by the locomotive engineer for each of the test cases.

For the EBB-Safety test case, the emergency brake back-up function of the enforcement algorithm will be evaluated. For this test case, the train will be artificially forced to overrun the target by a small margin following the penalty enforcement to evaluate whether the emergency brake back-up function enforces an emergency brake application to stop the train short of the target.

Table 1 –Test Scenarios

Test Case	Consist	Track	Speed	Type of Test	Target Pt
1	Short	Decline	30	Safety	R14
2	Short	Decline	30	Safety w/ DB Failure	R14
3	Short	Flat	30	Performance	R24
4	Short	Decline	30	Performance	R14
5	Med	Decline	30	Safety	R14
6	Med	Decline	30	Safety w/ DB Failure	R14
7	Med	Decline	50	Safety	R14
8	Med	Decline	50	Safety w/ DB Failure	R14
9	Med	Flat	30	Performance	R24
10	Med	Decline	30	Performance	R14
11	Med	Flat	30	EBB -safety	R24
12	Long	Decline	10	Safety	R14
13	Long	Decline	10	Safety w/ DB Failure	R14
14	Long	Flat	10	Performance	R24
15	Long	Decline	10	Performance	R14
16	Long	Decline	30	Safety	R14
17	Long	Decline	30	Safety w/ DB Failure	R14

For each test, the train will be moved to the starting position appropriate for the specific test case. The train will then be accelerated to the specified test speed and proceed 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. When the enforcement algorithm determines that a penalty brake application is necessary, the LCU will apply the penalty brake. When this occurs, the locomotive engineer will bail off the locomotive brakes. In the case of the safety with DB failure test cases, the locomotive engineer will also respond by removing the dynamic brake. In all other cases, the dynamic brake will remain at its current setting for the remainder of the test.

For the performance tests, the locomotive crew will stop the train prior to the target using normal train handling procedures. The enforcement algorithm may or may not enforce a penalty brake application in these test cases.

Once the train has stopped, the absolute stopping location will be recorded and the location relative to the target will be measured and recorded before resetting the train for the next test run.

4.2.2 Validation Testing

N/A

4.2.3 Endurance Testing

N/A

4.2.4 Safety Margin Tests

N/A

4.3 Operation Locations

The stop tests will occur at various locations, as per Table 1, around the Railroad Test Track (RTT), located at the Transportation Technology Center (TTC) in Pueblo, CO.

4.4 Special Support

N/A

4.5 Instrumentation Types

See section 5.0.

4.6 Measurement Definitions

The following measurements will be taken during the field test for each test run:

- Penalty enforcement location. The location in footage relative to a specific point on the track will be measured by the LCU and recorded by the enforcement algorithm software once the train has received a penalty application.
- Emergency enforcement location. The location in footage relative to a specific point on the track will be measured by the LCU and recorded by the enforcement algorithm software once the train has received an emergency application.
- Stopping location. The location in footage relative to a specific point on the track will be measured by the LCU and recorded by the enforcement algorithm software once the train has come to a stop.
- Stopping location relative to the target. The difference in footage between the stopping location and the target location will be calculated in post-processing.
- Stopping distance. The difference in footage between the point of penalty brake application and stopping location will be calculated in post-processing.

4.7 Data Collection Schematics

None.

5.0 Instrumentation Identification

5.1 On-Board Instrumentation List

The on-board instrumentation includes:

- Locomotive control unit (LCU)

- Laptop computer containing enforcement algorithm software
- Locomotive brake pipe pressure transducer
- GPS antennas
- Penalty brake valve
- Emergency brake valve
- Two test cars with brake pipe pressure transducers spaced throughout the train:
  - 10-car train: at the 10th car
  - 40-car train: at the 10th and 40th car
  - 90-car train: at the 40th and 90th car
- Two test cars with brake cylinder pressure transducers spaced throughout the train:
  - 10-car train: at the 10th car
  - 40-car train: at the 10th and 40th car
  - 90-car train: at the 40th and 90th car
- Two unmanned data acquisition computers (UDAC)

5.2 Wayside Instrumentation List

None.

5.3 Special Instrumentation List

A hand-operated tribometer will be used for recording rail adhesion coefficients at test locations around the RTT.

6.0 Photography and Video

6.1 Photography Requirements

None.

6.2 Video Requirements

None.

7.0 Transportation Technology Center, Inc. Requirements

7.1 Facility Requirements

None.

7.2 Track Requirements

The enforcement algorithm will be tested at various locations, as per Table 1, around the 13.5 mile Railroad Test Track (RTT) at the Transportation Technology Center (TTC). Other tracks may be needed for switching and storage of test cars.

7.3 Labor/Personnel Requirements

The following personnel will be required to setup, perform, and analyze the results from the tests planned:

- Test engineer(s): The test engineer(s) will be responsible for organizing and managing the test activities, including providing test plans, procedures, and data sheets to test personnel, and ensuring test activities can be performed in a safe manner. It will also be the responsibility of the test engineer(s) to oversee setup of the instrumentation, running the enforcement algorithm software, and recording or ensuring necessary data is recorded. Post test, the test engineer(s) will analyze the data collected for use in other tests and future developments of the enforcement algorithm.
- Test controller: The test controller will be in charge of the actual tests and all movements of the test consist. This includes ensuring all safety rules, test plans, and other instructions are followed by all test personnel. The test controller will be the point of communication between the test engineers and the locomotive engineer and any other test personnel. The test controller will coordinate all train moves with the proper personnel in the Operations Control Center (OCC), and ensure safe test conditions at all times. Finally, the test controller will keep a detailed log of the test activities.
- Locomotive engineer: The locomotive engineer will execute train moves as necessary for test setup, switching, and test functions.
- Instrumentation engineer(s): The instrumentation engineer(s) will work closely with the test engineer(s) to set up all test instrumentation, and ensure the proper operation of the instrumentation and data collection system during testing.

7.4 Equipment Requirements

The following equipment will be required for the field tests:

- Four locomotives, including at least one of the three locomotives equipped with the necessary LCU used for enforcement algorithm testing
- 85-90 loaded test cars from the Facility for Accelerated Service Testing (FAST) train

7.5 Material Requirements

None.

7.6 Special Requirements

None.

8.0 Restoration and/or Dismantling

8.1 Facility Restoration

None.

8.2 Track Restoration

None.

8.3 Equipment Disposition

None.

8.4 Material Disposition

None.

8.5 Special Equipment Disposition

None.

9.0 Data Requirements

9.1 Data Types

The following data will be collected during this field test:

- Locomotive location
- Locomotive speed
- Locomotive brake pipe pressure
- Locomotive notch
- Dynamic Brake Voltage
- Dynamic Brake Setup Status
- Train brake pipe pressure at three locations throughout the train (test cars)
- Train brake cylinder pressure at three locations throughout the train (test cars)
- Specific test consist makeup

9.2 Recording Techniques

Locomotive location, speed, brake pipe pressure, dynamic brake data, and locomotive notch will be collected once per second by the locomotive control unit (LCU). Train brake pipe pressure and brake cylinder pressure from three of the test cars will be collected at 256 Hz using an unmanned data acquisition computer (UDAC).

9.3 Data Analysis

The data collected will be used to evaluate the performance of the enforcement algorithm. For each test, the data collected will be reprocessed using the TTCI enforcement algorithm test application. The results will be compared against the safety and performance objectives for each test scenario, and used to validate the results of simulation testing that will support the evaluation of the algorithm against these objectives.

The actual brake pipe and brake cylinder data, stop distance and stop time will also be compared to the prediction data from the enforcement algorithm to determine the accuracy of the prediction and identify any flaws in the algorithm logic that need to be investigated.

9.4 Reports

Documentation of the field test will be included in a final report for the project.

10.0 Safety

TTCI has a very successful safety record. Strict operating and safety rules will be followed during the work described in this proposal.

A pre-test meeting will be held before any physical work is started. Safety and quality issues will be addressed at this meeting.

A safety and job briefing will be held prior to start of testing each day, with subsequent job briefings throughout the day if required by a change in the work plan.

11.0 Work Schedule

The field testing will occur during the week of April 18, 2011.

12.0 Quality Assurance

TTCI is committed to providing products and/or services that meet and/or exceed the customers' specified contractual and project requirements. TTCI recognizes that in order to provide and maintain a consistently high quality in the work it undertakes, an effective Quality Management System is necessary so as to ensure that proper communication, work control and accountable records are generated for all work undertaken.

It is the policy, therefore, of TTCI to control and conduct its business of consultancy and test services in the railway transportation arena by means of a formalized system of modern quality management that conforms to the requirements of ISO 9001–2000. Through the QMS, TTCI is able to ensure that our products and services meet or exceed our customers' expectations.

In order to ensure our entire organization supports the quality process, TTCI sponsors an employee led Quality Resource Team (QRT). The mission of the QRT is to "To promote customer satisfaction by providing effective training, education, and communication tools for Team TTCI." The QRT works directly with TTCI's marketing team to identify customer satisfaction issues and help resolve them. The QRT also provides period refresher training to TTCI employees in science of Continuous Quality Improvement, Customer Satisfaction, and the implementation of problem solving tools.

13.0 Support Specialties

N/A

Task Order 242: Development of a PTC Enforcement Algorithm for Freight Trains

Enforcement Testing with Manifest Freight Equipment

Field Test Implementation Plan

November 2011

Approval:____

Jared Withers, COTM **Date**

Presented By:

Transportation Technology Center, Inc.

A Subsidiary of the **Association of American Railroads**

55500 D.O.T. Road

P.O. Box 11130

Pueblo, Colorado, USA 81001

1.0 Project Title

Development of an Implementation-Ready Enforcement Braking Algorithm for Freight Trains

2.0 Introduction

The objective of this test is to evaluate the performance of a developmental PTC braking enforcement algorithm with modifications designed specifically for use on manifest freight equipment. The potential safety and performance benefits of the modified algorithm have been demonstrated through field testing comparisons with the base algorithm using unit train equipment. This test is designed to demonstrate similar safety and performance levels using manifest freight equipment. This document describes the field test plan for this evaluation.

Positive Train Control (PTC) is an emerging train control technology intended to enhance safety and possibly improve train performance and plant capacity. The underlying concept of the technology is that movement authorities are transmitted digitally to the controlling locomotive of each train. The locomotive tracks the train's location with respect to its authority and speed limits and the train's stopping ability based on known and assumed train parameters and current status, and automatically applies brakes to prevent the train from violating any limit in the event of human failure. Enforcement braking is an event of last recourse when the locomotive engineer has failed to take adequate action.

The primary objective of this research program is to identify and test methods for improving enforcement algorithm performance. As such, a number of modifications to a base case enforcement algorithm have been investigated and tested as part of this program. The process began with a review of, and modifications to, the base logic of the algorithm, followed by the addition of a number of new, developmental functions. The algorithm was exclusively designed for, and tested on, unit train equipment.

As part of the third phase of work under this task order, modifications to the algorithm have now been designed and implemented for expanding the scope of the algorithm to manifest freight train equipment. These modifications include changes to some of the underlying assumptions, as well as a change to the target offset function, which provides the enforcement algorithm with the specified safety assurance.

2.1 Key Personnel

Customer Contact, <u>Ruben Pena, Assistant Director, Business Acquisition / DC</u>

Telephone: 719-584-0543

Fax: 719-584-0770

Email: ruben_pena@ttci.aar.com

Program Manager, <u>Dingqing Li, Scientist and Chief Government Programs</u>

Telephone: 719-584-0740

Fax: 719-584-0791

Email: dingqing_li@ttci.aar.com

Project Manager, Joe Brosseau, Senior Engineer II

Telephone: 719-584-7128

Fax: 719-584-0771

Email: joe_brosseau@ttci.aar.com

2.2 Responsibilities

The project manager for this project is Joe Brosseau. He is responsible for ensuring that the test is completed on time, within budget, and will ensure all deliverables meet or exceed FRA requirements. He will also be responsible for ensuring that the test is executed according to the test plan, that all data is collected properly, and that the test is completed safely.

2.3 Documentation

The results of this test will be documented within the final report for this project.

3.0 Preparation

In preparation for field testing of the enforcement algorithm, the following tasks will be completed:

- Test locomotive setup/checkout. This includes the installation of a PTC locomotive control unit (LCU). The LCU will be capable of interfacing with the TTCI enforcement algorithm test application operating on a separate test machine. The TTCI enforcement algorithm test application will be used as an enforcement algorithm and for data collection purposes.
- Enforcement algorithm software setup/checkout. This includes testing of the enforcement algorithm software in a simulation environment to determine that the algorithm will operate as expected.
- Test consist setup. This includes acquiring the manifest freight cars to be used in the test consist and installing the appropriate test instrumentation. It also includes documentation of reporting marks, car type, dimensions, brake system information (including brake rigging type, number of brake cylinders, control valve type, approximate brake cylinder piston travel, and approximate brake pipe length), and coupler/draft gear types for each car in the test consist. Finally, it includes documenting the scaled weight of each car in the test consist.
- Tribometer readings will be taken before and after testing to document track conditions.

4.0 Implementation

4.1 Constraints

None.

4.2 Operation Sequence

4.2.1 Track Testing

The field test configuration is shown in Figure 1. The lead locomotive of the test consist will house a Locomotive Control Unit (LCU) and a standard laptop PC. The LCU will be used as interface to the locomotive's brake and computer systems. The laptop PC will contain the TTCI enforcement algorithm test application.

The enforcement algorithm will collect 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 will be collected by the enforcement algorithm application, in real time as the test is run, and used to enforce penalty and emergency brake applications, as necessary, to avoid a target overrun. The enforcement algorithm test application will also be used to record the data throughout each test for use in determining when the brakes were applied, where the train stopped, etc.

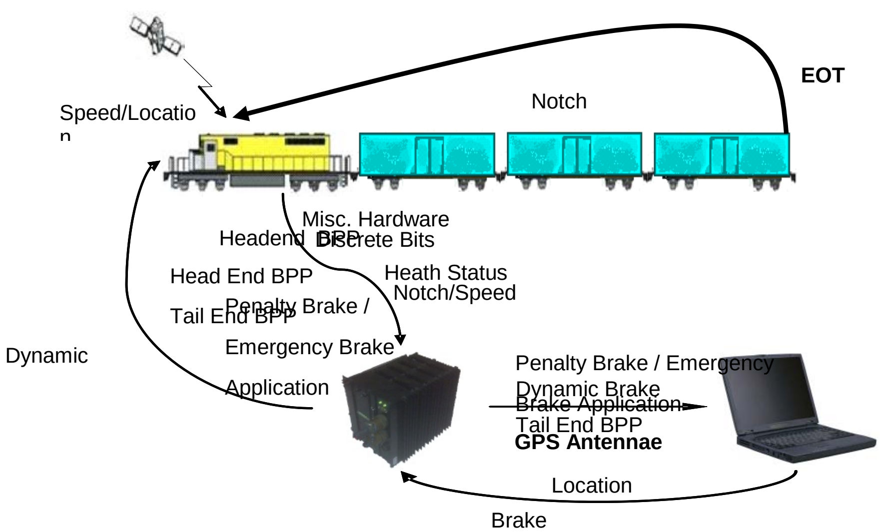


Figure 1 –Test Configuration

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

- Consist – The field tests will use a test consist made up of a combination of empty manifest freight cars from the Union Pacific Railroad (UPRR) and loaded hopper/gondola cars from the Facility for Accelerated Service Testing (FAST). The length of the consist is specified for each test scenario as one of the following:
  - Long – 90 to 100 cars (based on availability of cars)
  - Medium – 40 cars
  - Short – 10 cars
- 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.
  - EBB-Safety – Test to ensure that the emergency brake backup routine stops the train short of the target when penalty braking is insufficient to do so. This situation is forced by having some locomotives continue to apply tractive effort after penalty braking is invoked.

The specific test cases are listed in Table 1. Tests will be run multiple times to evaluate repeatability, up to three tests per test case. Each test case will be performed using the base case algorithm as well as the developmental algorithm.

For the EBB-Safety test case, the emergency brake back-up function of the enforcement algorithm will be evaluated. For this test case, the train will be artificially forced to overrun the target by a small margin following the penalty enforcement to evaluate whether the emergency brake back-up function enforces an emergency brake application to stop the train short of the target. This is achieved by maintaining the throttle on the locomotives following the penalty brake application.

Table 1 –Test Scenarios

Test Case	Consist	Track	Speed	Brake State	Type of Test	Target	Number of Runs
1	Long	Flat	10	Fully Charged	Safety	R24	3
2	Long	Flat	10	Fully Charged	Performance	R24	2
3	Long	Flat	30	Fully Charged	Safety	R24	3
4	Long	Flat	60	Fully Charged	Safety	R24	2
5	Long	Decline	30	Fully Charged	Safety	R14	3
6	Long	Decline	30	Applied	Safety	R14	2
7	Long	Decline	30	Fully Charged	Performance	R14	2
8	Long	Decline	10	Fully	Safety	R14	2

				Charged			
9	Long	Incline	30	Fully Charged	Safety	R48	2
10	Long	Crest	30	Fully Charged	Safety	R69	2
11	Long	Flat	30	Fully Charged	EBB -safety	R24	3
12	Med	Flat	30	Fully Charged	Safety	R24	2
13	Med	Decline	60	Fully Charged	Safety	R14	2
14	Med	Decline	60	Fully Charged	Performance	R14	2
15	Short	Flat	30	Fully Charged	Safety	R24	3
16	Short	Flat	30	Fully Charged	Performance	R24	2
17	Short	Decline	30	Fully Charged	Safety	R14	3

For each test, the train will be moved to the starting position appropriate for the specific test case. The train will then be accelerated to the specified test speed and proceed 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.

For the safety tests, when the enforcement algorithm determines that a penalty brake application is necessary, the LCU will apply the penalty brake. When this occurs, the locomotive engineer will bail off the locomotive brakes. If the locomotive is in dynamic brake at the time the penalty is applied, the locomotive engineer will maintain the setting of the dynamic brake throughout the stop. If the locomotive is in throttle at the time the penalty is applied, the locomotive engineer will move the throttle to idle. In the case of the emergency brake backup test, the locomotives will maintain the throttle setting until the emergency brake is applied.

For the performance tests, the locomotive crew will stop the train prior to the target using normal train handling procedures. The enforcement algorithm may or may not enforce a penalty brake application in these test cases.

Once the train has stopped, the absolute stopping location will be recorded and the location relative to the target will be measured and recorded before resetting the train for the next test run.

4.2.2 Validation Testing

N/A

4.2.3 Endurance Testing

N/A

4.2.4 Safety Margin Tests

N/A

4.3 Operation Locations

The stop tests will occur at various locations, as per Table 1, around the Railroad Test Track (RTT), located at the Transportation Technology Center (TTC) in Pueblo, CO.

4.4 Special Support

N/A

4.5 Instrumentation Types

See section 5.0.

4.6 Measurement Definitions

The following measurements will be taken during the field test for each test run:

- Penalty enforcement location. The location in footage relative to a specific point on the track will be measured by the LCU and recorded by the enforcement algorithm software once the train has received a penalty application.
- Emergency enforcement location. If the emergency brake is enforced, the location in footage relative to a specific point on the track will be measured by the LCU and recorded by the enforcement algorithm software once the train has received the emergency application.
- Stopping location. The location in footage relative to a specific point on the track will be measured by the LCU and recorded by the enforcement algorithm software once the train has come to a stop.
- Stopping location relative to the target. The difference in footage between the stopping location and the target location will be calculated in post-processing.
- Stopping distance. The difference in footage between the point of penalty brake application and stopping location will be calculated in post-processing.

4.7 Data Collection Schematics

None.

5.0 Instrumentation Identification

5.1 On-Board Instrumentation List

The on-board instrumentation includes:

- Locomotive control unit (LCU)
- Laptop computer containing enforcement algorithm software
- Locomotive brake pipe pressure transducer
- GPS antennas
- Penalty brake valve

- Emergency brake valve
- Brake pipe pressure transducer located on the last car of the train
- Brake cylinder pressure transducer located on the last car of the train
- Unmanned data acquisition computer (UDAC) located on the last car of the train

5.2 Wayside Instrumentation List

None.

5.3 Special Instrumentation List

A hand-operated tribometer will be used for recording rail coefficient of friction at test locations around the RTT.

6.0 Photography and Video

6.1 Photography Requirements

None.

6.2 Video Requirements

None.

7.0 Transportation Technology Center, Inc. Requirements

7.1 Facility Requirements

None.

7.2 Track Requirements

The enforcement algorithm will be tested at various locations, as per Table 1, around the 13.5 mile Railroad Test Track (RTT) at the Transportation Technology Center (TTC). Other tracks may be needed for switching and storage of test cars.

7.3 Labor/Personnel Requirements

The following personnel will be required to setup, perform, and analyze the results from the tests planned:

- Test engineer(s): The test engineer(s) will be responsible for organizing and managing the test activities, including providing test plans, procedures, and data sheets to test personnel, and ensuring test activities can be performed in a safe manner. It will also be the responsibility of the test engineer(s) to oversee setup of the instrumentation, running the enforcement algorithm software, and recording or ensuring necessary data is recorded. Post test, the test engineer(s) will analyze the data collected for use in other tests and future developments of the enforcement algorithm.
- Test controller: The test controller will be in charge of the actual tests and all movements of the test consist. This includes ensuring all safety rules, test plans, and other instructions are followed by all test personnel. The test controller will be the point of

communication between the test engineers and the locomotive engineer and any other test personnel. The test controller will coordinate all train moves with the proper personnel in the Operations Control Center (OCC), and ensure safe test conditions at all times. Finally, the test controller will keep a detailed log of the test activities.

- Locomotive engineer: The locomotive engineer will execute train moves as necessary for test setup, switching, and test functions.
- Instrumentation engineer(s): The instrumentation engineer(s) will work closely with the test engineer(s) to set up all test instrumentation, and ensure the proper operation of the instrumentation and data collection system during testing.

7.4 Equipment Requirements

The following equipment will be required for the field tests:

- Four locomotives, including at least one of the three locomotives equipped with the necessary LCU used for enforcement algorithm testing
- Approximately 80 empty manifest freight cars (mix of car types) borrowed from the UPRR
- 20 loaded test cars from the Facility for Accelerated Service Testing (FAST) train

7.5 Material Requirements

None.

7.6 Special Requirements

None.

8.0 Restoration and/or Dismantling

8.1 Facility Restoration

None.

8.2 Track Restoration

None.

8.3 Equipment Disposition

None.

8.4 Material Disposition

None.

8.5 Special Equipment Disposition

None.

9.0 Data Requirements

9.1 Data Types

The following data will be collected during this field test:

- Locomotive location
- Locomotive speed
- Locomotive brake pipe pressure
- Locomotive notch
- Dynamic Brake Voltage
- Dynamic Brake Setup Status
- Train brake pipe pressure at last car in train
- Train brake cylinder pressure at last car in train
- Specific test consist makeup

9.2 Recording Techniques

Locomotive location, speed, brake pipe pressure, dynamic brake data, and locomotive notch will be collected once per second by the locomotive control unit (LCU). Train brake pipe pressure and brake cylinder pressure from the last test car will be collected at 256 Hz using an unmanned data acquisition computer (UDAC).

9.3 Data Analysis

The data collected will be used to evaluate the performance of the enforcement algorithm. The results of each test will be compared against the safety and performance objectives for the test scenario, and used to validate the results of simulation testing that will support the evaluation of the algorithm against these objectives.

The actual brake pipe and brake cylinder data, stop distance and stop time will also be compared to the prediction data from the enforcement algorithm to determine the accuracy of the prediction and identify any flaws in the algorithm logic that need to be investigated.

9.4 Reports

Documentation of the field test will be included in a final report for the project.

10.0 Safety

TTCI has a very successful safety record. Strict operating and safety rules will be followed during the work described in this proposal.

A pre-test meeting will be held before any physical work is started. Safety and quality issues will be addressed at this meeting.

A safety and job briefing will be held prior to start of testing each day, with subsequent job briefings throughout the day if required by a change in the work plan.

11.0 Work Schedule

The field testing is planned for the week of November 28, 2011. However, if the test cars are not available at this time, the testing will occur in December, 2011.

12.0 Quality Assurance

TTCI is committed to providing products and/or services that meet and/or exceed the customers' specified contractual and project requirements. TTCI recognizes that in order to provide and maintain a consistently high quality in the work it undertakes, an effective Quality Management System is necessary so as to ensure that proper communication, work control and accountable records are generated for all work undertaken.

It is the policy, therefore, of TTCI to control and conduct its business of consultancy and test services in the railway transportation arena by means of a formalized system of modern quality management that conforms to the requirements of ISO 9001–2000. Through the QMS, TTCI is able to ensure that our products and services meet or exceed our customers' expectations.

In order to ensure our entire organization supports the quality process, TTCI sponsors an employee led Quality Resource Team (QRT). The mission of the QRT is to "To promote customer satisfaction by providing effective training, education, and communication tools for Team TTCI." The QRT works directly with TTCI's marketing team to identify customer satisfaction issues and help resolve them. The QRT also provides period refresher training to TTCI employees in science of Continuous Quality Improvement, Customer Satisfaction, and the implementation of problem solving tools.

13.0 Support Specialties

N/A

Task Order 242: Development of a PTC Enforcement Algorithm for Freight Trains

Testing of Available Locomotive Data and Interfaces

Field Test Implementation Plan

November 2011

Approval:____

Jared Withers, COTM **Date**

Presented By:

Transportation Technology Center, Inc.

A Subsidiary of the **Association of American Railroads**

55500 D.O.T. Road

P.O. Box 11130

Pueblo, Colorado, USA 81001

1.0 Project Title

Development of an Implementation-Ready Enforcement Braking Algorithm for Freight Trains

2.0 Introduction

The objective of this test is to evaluate the data and interfaces available on various types of locomotives to determine their applicability to PTC enforcement algorithm stopping distance prediction.

Positive Train Control (PTC) is an emerging train control technology intended to enhance safety and possibly improve train performance and plant capacity. The underlying concept of the technology is that movement authorities are transmitted digitally to the controlling locomotive of each train. The locomotive tracks the train's location with respect to its authority and speed limits and the train's stopping ability based on known and assumed train parameters and current status, and automatically applies brakes to prevent the train from violating any limit in the event of human failure. Enforcement braking is an event of last recourse when the locomotive engineer has failed to take adequate action.

The primary objective of this research program is to identify and test methods for improving enforcement algorithm performance. As such, a number of modifications to a base case enforcement algorithm have been investigated and tested as part of this program.

Part of the third phase of work under this task order is a study of the data types and interfaces available on various types of locomotives. It is recognized that the enforcement algorithm may require certain data elements from the locomotive system, or that the performance of the enforcement algorithm may be improved with these data elements. It is also recognized that various types and vintages of locomotives are used in the industry, and that the enforcement algorithm may need to work on any or all of these types of locomotives.

The study has identified a number of data elements and interfaces that are universally available for all locomotives. These primarily consist of data and interfaces to the brake systems and data signals available on the 27-pin MU cable. Two data elements that are not generally required by, but may improve the performance of, the enforcement algorithm are tractive effort and dynamic brake effort. On newer locomotives, this data is potentially available from the locomotive computer, in various forms. The objective of this test is to collect this data and evaluate its potential use in PTC enforcement algorithms.

2.1 Key Personnel

Customer Contact, Ruben Pena, Assistant Director, Business Acquisition / DC

Telephone: 719-584-0543

Fax: 719-584-0770

Email: ruben_pena@ttci.aar.com

Program Manager, Dingqing Li, Scientist and Chief Government Programs

Telephone: 719-584-0740

Fax: 719-584-0791

Email: dingqing_li@ttci.aar.com

Project Manager, Joe Brosseau, Senior Engineer II

Telephone: 719-584-7128

Fax: 719-584-0771

Email: joe_brosseau@ttci.aar.com

2.2 Responsibilities

The project manager for this project is Joe Brosseau. He is responsible for ensuring that the test is completed on time, within budget, and will ensure all deliverables meet or exceed FRA requirements. He will also be responsible for ensuring that the test is executed according to the test plan, that all data is collected properly, and that the test is completed safely.

2.3 Documentation

The results of this test will be documented within the final report for this project.

3.0 Preparation

In preparation for field testing of the enforcement algorithm, the following tasks will be completed:

- Test locomotive setup/checkout. This task primarily consists of working with the locomotive manufacturer to setup the each test locomotive computer to collect the appropriate data elements.
- Test car setup. A test car will be equipped with an instrumented coupler to measure the force on the coupler at the rear end of the locomotive consist. This task includes installing the instrumented coupler, as well as setting up the data acquisition system to collect the coupler force data.

4.0 Implementation

4.1 Constraints

None.

4.2 Operation Sequence

4.2.1 Track Testing

The goal of the on-track testing will be to collect tractive effort and dynamic brake effort data from the test locomotives along with coupler force data from the trailing coupler of the locomotive consist. The data collected can then be analyzed in various ways to determine how it could potentially be used in enforcement algorithm stopping distance predictions.

The track testing will consist of two components. In the first component, data will be collected from the test locomotives during normal operations at the Facility for Accelerated Service

Testing (FAST). The FAST train consists of three locomotives (an EMD SD70MAC and two EMD SD70M) and 80 – 115 loaded hopper/gondola cars. The FAST train operates on a 2.7-mile loop known as the high tonnage loop (HTL). The data collected during this component of testing will be used to identify a general level of accuracy, given multiple locomotives, including various types, in a full train application over multiple hours of continuous operation, and other associated operating scenarios.

The second component will consist of collecting data under specific operating conditions with specific locomotives. In this component, AC and DC locomotives will be evaluated separately, in operating scenarios including continuous pulling up a grade (measuring tractive effort), and constant braking down a grade (measuring dynamic brake effort). This component of testing will be performed on the train dynamics track (TDT). The consist will include a single locomotive and 30 loaded cars from the FAST consist. The data collected during this component of testing will identify a general level of accuracy for a single locomotive in a specific operating scenario. This will help to identify a high level view of relative accuracy from locomotive to locomotive, as well as differences between AC and DC locomotives. Each test scenario will be run multiple times to provide repeatability data for comparison and to increase the overall data set.

The test scenarios are listed below in table 1, below.

Table 1 –Test Scenarios

Test Case	Locomotives	Consist	Track
1	All FAST Locomotives	Full FAST Consist	HTL
2	1 SD70M (DC)	30 FAST cars	TDT (incline)
3	1 SD70MAC (AC)	30 FAST cars	TDT (incline)
4	1 SD70M (DC)	30 FAST cars	TDT (decline)
5	1 SD70MAC (AC)	30 FAST cars	TDT (decline)

4.2.2 Validation Testing

N/A

4.2.3 Endurance Testing

N/A

4.2.4 Safety Margin Tests

N/A

4.3 Operation Locations

The testing will occur at the Transportation Technology Center (TTC) in Pueblo, CO. The first component will use the HTL, and the second component will use the TDT, as described in section 4.2.1.

4.4 Special Support

N/A

4.5 Instrumentation Types

See section 5.0.

4.6 Measurement Definitions

The following measurements will be taken during the field test for each test run:

- Tractive effort/dynamic brake effort. The computed pulling or braking force generated by each locomotive.
- Coupler force. The draft or buff force at the lead coupler of the car immediately adjacent to the locomotive consist.

4.7 Data Collection Schematics

None.

5.0 Instrumentation Identification

5.1 On-Board Instrumentation List

The on-board instrumentation includes:

- Onboard computer that computes tractive/dynamic brake effort on each locomotive
- Locomotive data acquisition system that collects tractive/dynamic brake effort data from the onboard computer
- Instrumented coupler that measures coupler force on the lead coupler of the car immediately adjacent to the locomotive consist
- Unmanned data acquisition computer (UDAC) located on the locomotive for collecting instrumented coupler data

5.2 Wayside Instrumentation List

None.

5.3 Special Instrumentation List

None.

6.0 Photography and Video

6.1 Photography Requirements

None.

6.2 Video Requirements

None.

7.0 Transportation Technology Center, Inc. Requirements

7.1 Facility Requirements

None.

7.2 Track Requirements

The testing will utilize the HTL and the TDT at the Transportation Technology Center (TTC). Other tracks may be needed for switching and turning the test consist.

7.3 Labor/Personnel Requirements

The following personnel will be required to setup, perform, and analyze the results from the tests planned:

- Test engineer(s): The test engineer(s) will be responsible for organizing and managing the test activities, including providing test plans, procedures, and data sheets to test personnel, and ensuring test activities can be performed in a safe manner. It will also be the responsibility of the test engineer(s) to oversee setup of the instrumentation, and recording or ensuring necessary data is recorded. Post test, the test engineer(s) will analyze the data collected.
- Test controller: The test controller will be in charge of the actual tests and all movements of the test consist. This includes ensuring all safety rules, test plans, and other instructions are followed by all test personnel. The test controller will be the point of communication between the test engineers and the locomotive engineer and any other test personnel. The test controller will coordinate all train moves with the proper personnel in the Operations Control Center (OCC), and ensure safe test conditions at all times. Finally, the test controller will keep a log of the test activities.
- Locomotive engineer: The locomotive engineer will execute train moves as necessary for test setup, switching, and test functions.
- Instrumentation engineer(s): The instrumentation engineer(s) will work closely with the test engineer(s) to set up test instrumentation, and ensure the proper operation of the instrumentation and data collection system during testing.

7.4 Equipment Requirements

The following equipment will be required for the field tests:

- FAST locomotives
- Loaded cars from the FAST train

7.5 Material Requirements

None.

7.6 Special Requirements

None.

8.0 Restoration and/or Dismantling

8.1 Facility Restoration

None.

8.2 Track Restoration

None.

8.3 Equipment Disposition

None.

8.4 Material Disposition

None.

8.5 Special Equipment Disposition

None.

9.0 Data Requirements

9.1 Data Types

The following data will be collected during this field test:

- Locomotive location
- Locomotive speed
- Locomotive notch
- Computed locomotive tractive effort
- Computed locomotive dynamic brake effort
- Coupler force at the lead coupler of the car adjacent to the locomotive consist

9.2 Recording Techniques

Locomotive location and speed will be determined using GPS and recorded by the UDAC at a frequency of 1 Hz. Coupler force data will also be recorded by the UDAC at a frequency of 100 Hz. Locomotive notch, tractive/dynamic brake effort, and other associated data will be recorded by the locomotive computer data acquisition system at a frequency of 10 Hz.

9.3 Data Analysis

The tractive/dynamic brake effort data will be analyzed against the coupler force data for each test scenario to provide an indication of the level of accuracy, and associated potential benefits to the stopping distance prediction, given the various test conditions. Comparisons will be made between operating with multiple units, as well as with each unit individually. Comparisons will also be made between the measurements on the AC locomotive and the DC locomotives. This will not be a comprehensive analysis, but rather a conceptual look at the capabilities that may be available.

9.4 Reports

Documentation of the field test will be included in a final report for the project.

10.0 Safety

TTCI has a very successful safety record. Strict operating and safety rules will be followed during the work described in this proposal.

A pre-test meeting will be held before any physical work is started. Safety and quality issues will be addressed at this meeting.

A safety and job briefing will be held prior to start of testing each day, with subsequent job briefings throughout the day if required by a change in the work plan.

11.0 Work Schedule

The field testing is planned for the weeks of November 21, 2011 and November 28, 2011. Scheduling of other test activities may alter the exact test dates.

12.0 Quality Assurance

TTCI is committed to providing products and/or services that meet and/or exceed the customers' specified contractual and project requirements. TTCI recognizes that in order to provide and maintain a consistently high quality in the work it undertakes, an effective Quality Management System is necessary so as to ensure that proper communication, work control and accountable records are generated for all work undertaken.

It is the policy, therefore, of TTCI to control and conduct its business of consultancy and test services in the railway transportation arena by means of a formalized system of modern quality management that conforms to the requirements of ISO 9001–2000. Through the QMS, TTCI is able to ensure that our products and services meet or exceed our customers' expectations.

In order to ensure our entire organization supports the quality process, TTCI sponsors an employee led Quality Resource Team (QRT). The mission of the QRT is to "To promote customer satisfaction by providing effective training, education, and communication tools for Team TTCI." The QRT works directly with TTCI's marketing team to identify customer satisfaction issues and help resolve them. The QRT also provides period refresher training to TTCI employees in science of Continuous Quality Improvement, Customer Satisfaction, and the implementation of problem solving tools.

13.0 Support Specialties

N/A

Appendix F.
Developmental Enforcement Algorithm Definition Document

Appendix G.
Detailed Simulation Results from Evaluation of Base Enforcement Algorithm

Appendix H.
Detailed Simulation Results from Evaluation of Phase 1 Developmental Enforcement Algorithm

Appendix I.
Detailed Simulation Results from Evaluation of Phase 2 Developmental Enforcement Algorithm

Appendix J.
Detailed Simulation Results from Evaluation of Phase 3 Developmental Enforcement Algorithm

Appendix K.
Detailed Simulation Results from Evaluation of Wabtec Enforcement Algorithm with Brake Force Provided

Appendix L.
Detailed Simulation Results from Evaluation of Wabtec Enforcement Algorithm with Assumed Brake Force

Abbreviations and Acronyms

AAR	Association of American Railroads
AC	Alternating current
ALD	Automatic location detector
BNSF	BNSF Railway
CBTC	Communications-based Train Control
CSX	CSX Transportation
CTC	Centralized Traffic Control
DC	Direct current
EDA	exploratory data analysis
EMD	Electro-Motive Diesel Inc.
ETMS	Electronic Train Management System
FAST	Facility for Accelerated Service Testing
FRA	Federal Railroad Administration
GPD	Generalized Pareto distribution
GPS	Global Positioning System
GRL	gross rail load
HTL	High Tonnage Loop
IDOT	Illinois Department of Transportation
I-ETMS®	Interoperable Electronic Train Management System (I-ETMS® is a registered trademark of Wabtec
IP	Internet protocol
IR&D	internal research and development
LDS	location determination system
LMC	Lockheed Martin Corporation
MU	multiple-unit
NAJPTC	North American Joint Positive Train Control
NOAA	National Oceanic and Atmospheric Administration
NS	Norfolk Southern Corporation
PTC	Positive Train Control
RTT	Railroad Test Track
SIL	safety integrity level

TCL	test controller/logger
TDT	transmission control protocol
TE	tractive effort
THR	Tolerable Hazard Rate
TIP	Test Implementation Plan
TOES™	Train Operations and Energy Simulator (TOES is a trademark of TTCI)
TTC	Transportation Technology Center (the site)
TTCI	Transportation Technology Center, Inc. (the company)
UMLER	Universal Machine Language Equipment Register
UPRR	Union Pacific Railroad
V-PTC	Vital-Positive Train Control
WILD	wheel impact load detector
Wabtec	Wabtec Railway Electronics