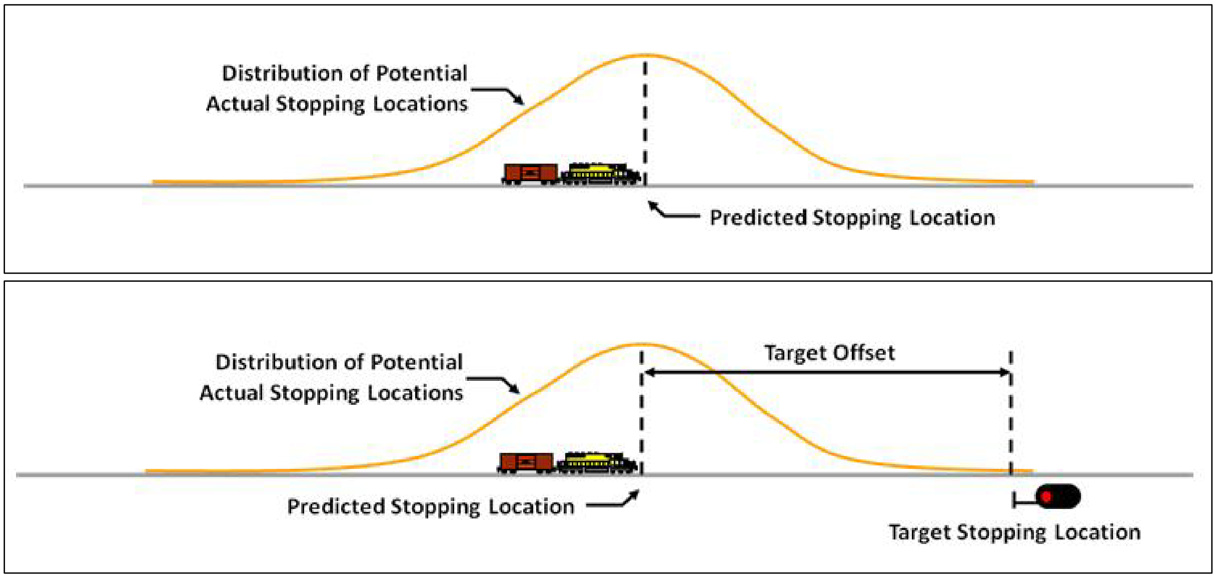
U.S. Department of
Transportation

**Federal Railroad
Administration**

Evaluation of PTC Braking Enforcement Algorithms for Passenger and Commuter Trains

Office of Research,
Development
and Technology
Washington, DC 20590



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13. ABSTRACT (Maximum 200 words)

Software algorithms used in Positive Train Control (PTC) systems designed to predict passenger train stopping distance and enforce a penalty brake application must be evaluated to verify their performance, which can be challenging due to variations in operational and equipment characteristics. The Federal Railroad Administration contracted Transportation Technology Center, Inc. to evaluate several PTC braking enforcement algorithms used in passenger and commuter train operations by implementing a previously established Monte Carlo simulation methodology supported by limited and focused field testing.

Additionally, as PTC braking enforcement algorithms have been shown to be overly conservative, which can lead to operational inefficiencies by interfering with normal train operations, the project also included development of a framework to investigate approaches to improving these algorithms and reducing the associated operational inefficiencies, as was done with freight braking algorithms in previous projects. As part of this task, a baseline algorithm was developed, which can be altered to realize operational improvements while still maintaining safety standards in forthcoming projects.

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METRIC/ENGLISH CONVERSION FACTORS

ENGLISH TO METRIC

LENGTH (APPROXIMATE)

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

AREA (APPROXIMATE)

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

MASS - WEIGHT (APPROXIMATE)

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

VOLUME (APPROXIMATE)

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

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

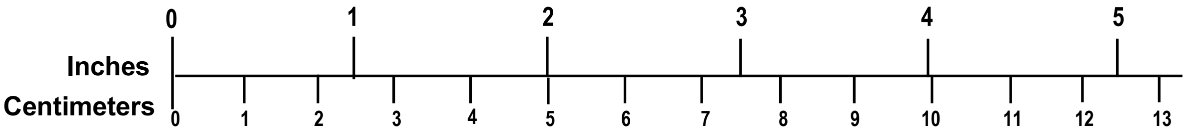
VOLUME (APPROXIMATE)

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 CONVERSIO

°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

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Executive Summary

Predictive enforcement of authority limits and other stop targets using a penalty air brake application is the means by which Positive Train Control (PTC) systems achieve enhanced safety. Predictive penalty brake enforcement is conceived as the final opportunity to stop a train safely in situations where the train crew failed to act to do so. Evaluating software algorithms designed to predict the stopping distance of trains and enforce a penalty application can be challenging, due to variations in operational and equipment characteristics. The Federal Railroad Administration (FRA) has sponsored many research programs in which Transportation Technology Center, Inc. (TTCI) worked with the FRA and industry to establish a methodology for quantifying the safety and operational performance of PTC braking enforcement algorithms using a combination of simulation and field testing. In this project, spanning from August 2014 through February 2019, TTCI implemented this methodology to evaluate two PTC braking enforcement algorithms used in passenger and commuter train operations. The results of this evaluation showed that, for the operations and equipment evaluated, the algorithms used in the Interoperable Electronic Train Management System (I-ETMS) had a probability of stopping the train short of the target of 99.78 percent for the commuter algorithm and 99.95 percent for the passenger algorithm. The algorithm used in the Advanced Civil Speed Enforcement System (ACSES) had a probability of stopping the train short of the target of 99.90 percent for the Type B train type. All these exceeded the previously established target of stopping the train short of the target with a probability of 99.5 percent or greater.

Additionally, predictive braking enforcement algorithms used in production PTC systems have shown to be overly conservative to ensure the train will stop short of the given target. However, this led to operational inefficiencies by enforcing trains to a stop prematurely or unnecessarily, interfering with the normal operation of the train, which can lead to reduced line capacity. To investigate approaches to improving PTC enforcement algorithms and reduce the associated operational inefficiencies, the project also included an effort to develop a framework and test applications that can be used to identify, develop, simulate, and test concepts for improving the accuracy of the stopping distance prediction and improving the operational performance of the systems utilizing these algorithms.

The first objective of the project was the evaluation of the braking enforcement algorithms used in the two most common North American passenger/commuter PTC systems: I-ETMS and ACSES. The methodology developed under this project can be used by the industry to verify that the braking enforcement algorithms meet established safety and operational efficiency objectives. The Monte Carlo simulation process was adopted from similar evaluations of the freight braking enforcement algorithms. The 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 that is used to validate the results achieved from the simulation modeling process.

The second objective of the project was to develop a braking enforcement test application that can be used to identify, simulate, and test improvements to PTC braking algorithms. This enforcement algorithm test application was used to establish a baseline on which enhancements can be made to prove their effectiveness in improving the performance of the PTC braking algorithms. Identification, development, simulation, and testing of potential enhancements will be conducted in a follow-on project.

TTCI developed the Passenger Train Braking Performance Model (PTBPM) in a multi-year effort to simulate braking performance of passenger equipment. In the PTC braking algorithm simulation test methodology, the PTBPM 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, wherein 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.

TTCI researchers collected field test data from five participating railroads; they modeled and validated equipment from the field tests within the PTBPM. They focused field testing on the most common grades, speeds, and equipment that each railroad would use.

TTCI developed a baseline braking enforcement test application to be used in the research and development of methods for improving the safety and performance of PTC braking enforcement algorithms in two ways:

1. As a point of reference to measure improvements against
2. As a starting point for development of test software for evaluating the logic for potential enhancements to the braking algorithm

Once researchers developed the baseline braking enforcement algorithm, they implemented the logic in a test software application that could interface the test environment. They evaluated the algorithm using the simulation test methodology described above to develop the reference data for comparison against future developments. Along with the baseline enforcement algorithm, a target offset for passenger equipment was created. The target offset function was intended to be used within the baseline algorithm to stop trains before the stopping target. The target offset function will be integrated in the baseline algorithm in a follow-on project.

1. Introduction

Positive Train Control (PTC) is a North American rail industry initiative of high interest because a Federal mandate requires its implementation on a large portion of the U.S. rail network. Class I freight railroads have completed extensive testing and simulations of the predictive braking enforcement function of the PTC system they are deploying. Passenger and commuter agencies require the same rigorous testing and simulation for the braking algorithm used in their PTC deployment. Freight train operations are, for the most part, similar between various railroads and regions of the U.S. due to interchange between participating railroads and car owners. Without this type of interchange, commuter and passenger train operations differ from agency to agency, and even similar car types are operated in different manners. To address these differences, the Federal Railroad Administration (FRA) supported a research project, contracted to Transportation Technology Center, Inc. (TTCI), to evaluate PTC braking enforcement algorithm performance and develop a practical methodology for demonstrating it using passenger trains.

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, 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 conceived as the final opportunity to safely prevent a violation, only when the locomotive crew has failed to take adequate action to do so.

The braking enforcement function of the system is critical in ensuring that trains comply with movement authorities and speed limits. There are several parameters that can affect the braking distance of a 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 can be described by a statistical distribution of potential stopping locations about the predicted stopping location, as Figure 1 illustrates.

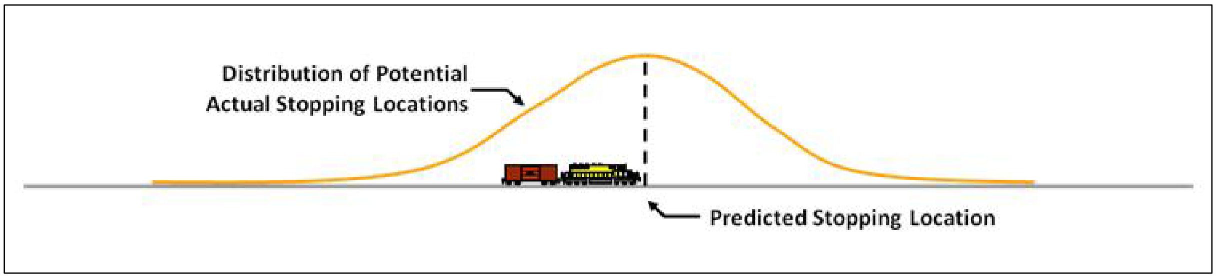


Figure 1. Illustration of Potential Difference between Predicted and Actual Train Stopping Location

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, such as 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.

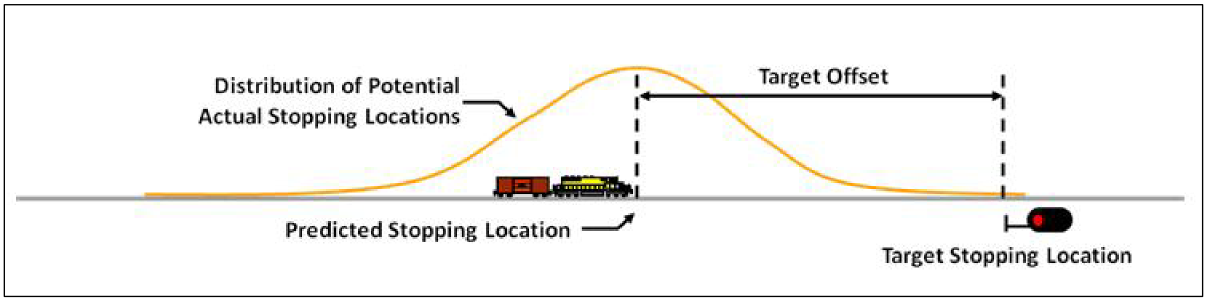


Figure 2. Use of a Target Offset to Compensate for Uncertainty in Stopping Distance Prediction

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 inefficient operational conditions. The target offset for these algorithms can be large, to the point where the braking enforcement algorithm will issue warnings of penalty brake applications in advance of where the locomotive engineer would normally start applying the brakes in accordance with good train handling. In some cases, the algorithm enforces the train to a stop unnecessarily, forcing train crews to operate 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 [1] established a metric to be used in evaluating the safety performance of PTC braking algorithms, specifically that the algorithm be demonstrated to stop the train short of the target stopping location with a 99.5 percent probability and 99 percent confidence level. Additionally, a methodology for evaluating the performance of the PTC braking enforcement algorithms used in North American freight train operations was developed and implemented. Based on this research effort, a similar methodology was conceived and documented for evaluating the performance of the PTC braking enforcement algorithms used in passenger and commuter train operations and a Passenger Train Braking Performance Model (PTBPM) was developed to support the methodology. This project expanded on this prior research by implementing the methods developed for evaluation of PTC braking enforcement algorithms for passenger and commuter train operations and creating the framework for developing and evaluating potential enhancements to these algorithms.

1.2 Objectives

The project included two major objectives. The first was to evaluate existing passenger and commuter PTC braking enforcement algorithms. To achieve this main objective, supporting objectives were to:

(1) Implement the tools to execute the simulation methodology for passenger and commuter trains, which included developing a Passenger/commuter Test Controller/Logger (P-TCL) to execute the Monte Carlo simulation methodology and interface with the existing PTBPM and PTC braking enforcement algorithms.

(2) Work with PTC system suppliers to implement and evaluate the performance of the resulting braking enforcement algorithm using the established methodology.

The second major objective was to develop and baseline the performance for a test application to be used as a framework for identifying and evaluating potential enhancements to PTC braking enforcement algorithms for passenger and commuter train operations in future projects.

1.3 Overall Approach

The project was organized according to the two major objectives listed above.

The first was the evaluation of existing PTC braking enforcement algorithms with the objective of demonstrating the safety and performance characteristics to provide data to support documentation of the safety case for the PTC systems.

The scope of this effort included the following major tasks:

1. Development of the P-TCL program to enable execution of batch simulations using the Monte Carlo method
2. Integration of the P-TCL program with the PTBPM and with the existing braking algorithms
3. Development of an implementation of the Advanced Civil Speed Enforcement System (ACSES) algorithm suitable for use within the simulation environment
4. Development of a simulation matrix, using operational information gathered from participating passenger and commuter railroads
5. Development and validation of PTBPM models of passenger and commuter equipment, using detailed equipment data and field test data provided by the participating railroads
6. Execution of the simulations and analysis of results to verify passenger and commuter train braking enforcement algorithm safety and performance characteristics

In addition to the evaluation of current industry braking enforcement algorithms, TTCI developed a baseline enforcement algorithm test application that can be used to develop and evaluate future enhancements to the existing enforcement braking methodologies. The major tasks of this work are outlined below:

- Develop baseline enforcement algorithm test application.
- Evaluate baseline enforcement algorithm safety and performance characteristics using the Monte Carlo process and the simulation matrix established.
- Refine assumptions and logic in baseline algorithm, including revised target offset function related to statistical regression of simulation tests.

1.4 Organization of the Report

This report is organized into sections defined by the various tasks of the project. Section 2 describes the overall evaluation approach, the simulation matrix, development of the passenger and commuter equipment models, and results of the validation of the models, using field test data. Section 3 presents the results of the evaluation of the Interoperable Electronic Train Management System (I-ETMS) braking enforcement algorithm. Section 4 shows the results of the evaluation of the ACSES enforcement algorithm. Section 5 describes the development of a target offset function for use in braking enforcement algorithms for passenger equipment. Section 6 describes the algorithm used as the base algorithm for development, provides a summary of the performance characteristics of the base algorithm from both simulation and field tests, and identifies a number of modifications made to the base algorithm before proceeding with the development of new functions to improve the performance relating to issues identified during the evaluation of the base enforcement algorithm. Section 7 presents the final conclusions and recommends further work to be considered.

2. Enforcement Algorithm Evaluation Tools and Methodology

Research efforts associated with PTC braking enforcement algorithms for freight operations have demonstrated a successful methodology for evaluating algorithm safety and performance for a broad range of operations [1]. The methodology, which makes use of computer modeling, has proven to be a cost-effective and safe technique for demonstrating the accuracy and reliability of the algorithms. The same methodology can be applied to algorithms for passenger and commuter rail operations. However, the details of the methodology, including the operational scenarios to include and the variable parameters to consider, must be tailored for these types of operations. This section describes the approach to the methodology and the reasoning and background for the operational scenarios and variable parameters selected.

2.1 Overview of Enforcement Algorithm Evaluation Approach

The enforcement algorithm evaluation methodology combined computer simulation and field testing to achieve the objective of providing a high level of statistical confidence in the result. The purpose of the simulation component of the methodology is to statistically quantify the safety and performance characteristics 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 broad range of operational scenarios. A limited amount of field testing is then used to validate the simulation results using hardware inputs to the enforcement algorithm. This evaluation methodology provides the capability to evaluate the enforcement algorithm over a broad range of operating scenarios that could not be tested efficiently in the field.

2.2 Overview of Simulation Testing Process

The simulation testing component of the enforcement algorithm evaluation methodology used a set of computer software tools to employ a Monte Carlo simulation process, resulting in a set of output data that could be analyzed to identify the statistical probability and confidence that the algorithm would 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 passenger or commuter train and the interdependence of these parameters, a deterministic evaluation was not feasible, making the Monte Carlo simulation process the preferred method of evaluating the enforcement algorithm.

The simulations were organized into different test scenarios, as can be seen in Figure 3, consisting of a nominal consist, nominal track profile, initial speed, and target location. The different scenarios were meant to represent potential operating situations that the system may encounter. The simulation configurations were organized into batches to make the simulation process more efficient. For each simulation a consist was modeled approaching the target stopping location at a specified speed and the enforcement algorithm initiates the brake application to prevent a violation of the stop target. Each of the simulations resulted in a single stopping location, given the configuration and version of the enforcement algorithm being evaluated. These results were aggregated to define the distribution of possible stop locations. This data was analyzed to determine safety and performance characteristics.

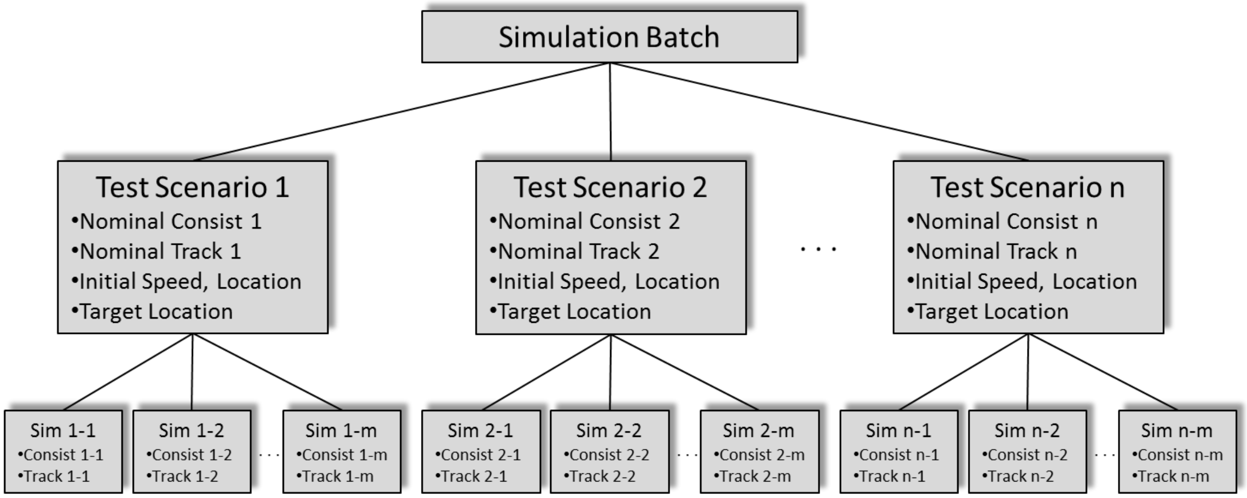


Figure 3. Organization of Simulations

In this methodology, the practical variability of the parameters that can have a significant effect on stopping distance of passenger and commuter trains was taken into consideration. These are listed and described in Section 2.2.2, Identification and Quantification of Variable Parameters.

2.2.1 Simulation Testing Tools

Figure 4 shows the three components needed for the simulation testing portion of the enforcement algorithm evaluation methodology:

- The Passenger Train Braking Performance Model (PTBPM), a longitudinal passenger train braking model. PTBPM includes a complete fluid dynamics model of the air brake system allowing for accurate modeling of a wide variety of air brake equipment, making it the ideal tool for performing braking enforcement algorithm testing.
- The Passenger Test Controller/Logger (P-TCL) is a software application that can generate the simulation inputs to the model from input provided by the user, run large batches of simulations using Monte Carlo simulation techniques, and log the required output.
- The enforcement algorithm under evaluation, implemented as a standalone software application incorporating a common interface to the simulation test components to receive train status and command brake enforcement applications.

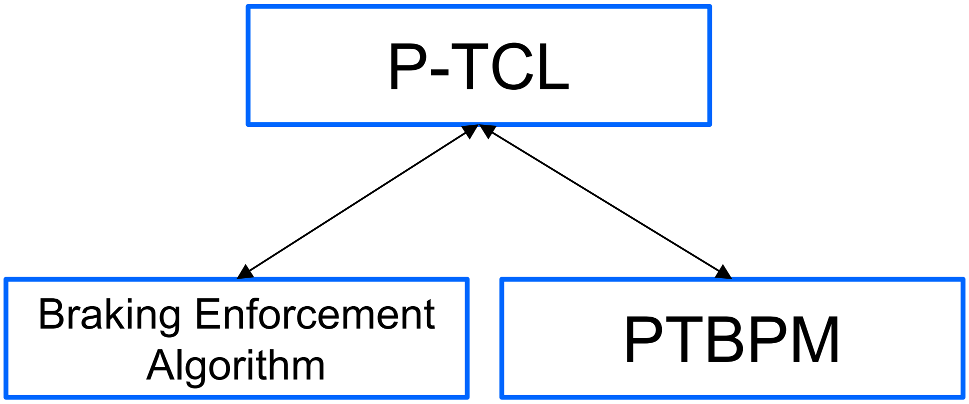


Figure 4. Simulation Testing Tools

Simulation Model

To model any braking enforcement scenario, a simulation program must be capable of the following:

- Accurately model the response of the train to given inputs.
- Model characters of individual components within each car of the consist and specific characteristics of the track.
- Report results in frequent periodical intervals.

To meet these needs for simulating passenger and commuter train types, the PTBPM was developed. The PTBPM, along with being a longitudinal train dynamics model, also includes an air brake model specifically for passenger and commuter vehicles. 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 allows the user to model essentially any currently used passenger or commuter rail car and arrange them into any train consist desired.

Passenger Test Controller and Logger

The PTBPM is capable of modeling one scenario at a time but to execute a substantial number of simulations simultaneously, faster than real time and in an efficient way, a program is needed to automatically manage PTBPM simulations and the interface to the enforcement algorithm being evaluated. TTCI created the P-TCL for this purpose. The P-TCL application performs the following three major functions:

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

In the P-TCL, a user can select the initial test parameters (initial speed, stopping location, etc.), distributions for varied parameters, and the number of simulations to run for each scenario. The user also can run many scenarios together in a batch. For each simulated second, the PTBPM reports train status data to the P-TCL, which is then passed along to the enforcement algorithm. When the enforcement algorithm predicts an impending target overrun, it sends a command to initiate a penalty brake enforcement to the P-TCL application, which executes the penalty in the PTBPM. Then P-TCL continues to advance the simulation until the train is stopped. The enforcement algorithm also can send a command to initiate an emergency brake enforcement which P-TCL then executes in the simulation model. Once the train has stopped, the simulation is complete, and the P-TCL software logs the output data in a database for post-process analysis.

Interface to Enforcement Algorithm

The enforcement algorithm evaluation methodology was designed so that it can be applied to evaluate any enforcement algorithm for any North American passenger or commuter PTC implementation. The devised simulation environment treated the enforcement algorithm as a black box that communicated with the simulation testing components over a specified communications interface. This interface specification was developed during the evaluation of the freight enforcement braking algorithm research project and was utilized in this effort. 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 C.

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 allowed for the enforcement algorithm to be implemented as an executable software application running on the same machine as the P-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.

2.2.2 Identification and Quantification of Variable Parameters

The Monte Carlo simulation technique employed in the enforcement algorithm evaluation methodology involved randomly assigning values to the various input parameters of the simulation model. These parameters were assigned for each simulation within each test scenario according to the practical variability of each parameter. This was achieved by defining the distribution of possible values for each parameter and using the P-TCL software to randomly assign values from these distributions.

The parameters varied were those that could have had a significant effect on the stopping distance of the consist being modeled. Evaluation of these parameters to determine their significance in varying through the Monte Carlo simulation method included discussions with experts in the air brake field, a literature review on train stopping distance calculations and air brake systems, and a review of parameters included in the PTBPM. In total, 26 parameters were evaluated, but only 11 were identified as having a significant effect on the stopping distance of passenger and commuter trains.

The variability of each parameter is described by one of the following different types of distributions:

- Continuous uniform (flat or rectangular) distribution, where all values within an interval are equally probable.

- Normal (Gaussian) distribution, where the shape and location is defined by a mean and standard deviation.
- Discrete distribution, where a number of discrete values are possible, each with a defined probability.
- 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.

Parameters Evaluated and Considered Significant

Table 1 shows the list of all the values varied in the simulations along with their distributions and minimum and maximum values. The minimum and maximum values in the normal distribution were used to describe the values that are ± three standard deviations (3σ) from the center value.

Table 1. Train and Environmental Parameters Varied during Monte Carlo Simulations

Parameter	Units	Distribution	Min	Max	Source
Atmospheric Pressure	psi/min	Right Normal (Gaussian)	10.2	14.7	Historical NOAA* weather data of U.S.
Ambient Air Temperature	°F	Normal (Gaussian)	21.7	86.5	Historical NOAA* weather data of U.S.
Brake Pipe Leakage Rate	psi/min	Right Normal (Gaussian)	0	5.35	Expert opinion
Error in Reported Track Grade	%	Uniform	-0.5%	0.5%	According to accuracy of grade data in track database
Position Error	ft	Normal (Gaussian)	-10.8	10.8	V-PTC Build 1A testing results
Speed Error	mph	Normal (Gaussian)	-0.48	0.48	V-PTC Build 1A testing results
Brake Unit COF Adjustment Factor		Normal (Gaussian)	0.80	1.2	Expert opinion
Brake Unit Effectiveness Ratio		Normal (Gaussian)	0.85	1.15	AAR standards
D.B. Effort Adjustment Factor		Normal (Gaussian)	0.85	1.2	Expert opinion
Head-End Brake Pipe Pressure Error	psi	Uniform	-0.5	0.5	Variability as specified by accuracy of Dynisco Model PT311JA pressure transducer
Rear-End Brake Pipe Pressure Error	psi	Uniform	-0.5	0.5	Accuracy of +/-3 psig per AAR Standard S-5701

Atmospheric 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. As stated in the related document "Development of an Operationally Efficient PTC Braking Enforcement Algorithm for Freight Trains" [2], NOAA data was used to create a variable distribution. The resulting distribution was a half-normal distribution with mean at 14.7 psi and standard deviation of 1.5, which used only the left, or lower, half of the full normal distribution.

Ambient Air Temperature

The ambient air temperature can significantly affect the flow of air in the air brake system. The NOAA historical weather data was used to quantify the variability in ambient temperature during a PTC enforcement scenario. The variability was 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 was developed from discussions with an expert in the field of air brake systems for passenger and commuter equipment. It is typical to have 1 psi/min or less leakage on a 6- to 10-car consist, but a consist cannot have leakage greater than 5 psi/min. Using 5 psi/min as the point three standard deviations above the mean results in a standard deviation value of 1.45 psi. The variability therefore is defined by a normal distribution with a mean of 1 psi/minute and a standard deviation of 1.45 psi/minute. The minimum leakage rate is limited to 0.1 psi/minute.

Error in Reported Track Grade

PTC systems typically use a track database (either kept onboard the locomotive, as in the case of I-ETMS, or transmitted to the locomotive through transponders, as in the case of ACSES) 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 accuracy of the stopping distance prediction. 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 1/10 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.

Position Error (Error in Reported Head-End Location)

As stated in the related document "Development of an Operationally Efficient PTC Braking Enforcement Algorithm for Freight Trains" [2], the accuracy of this system can be reasonably quantified using data reported in the Vital Positive Train Control (V-PTC) research project [3]. Using this data, the variability in the error in location is defined as a normal distribution with a mean of 0 and a standard deviation of 3.6 feet.

Speed Error

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 generally is 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 [3]. 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.

Brake Unit Coefficient of Friction (COF) Adjustment Factor (COF between Brake Shoe and Wheel or Brake Pad and Disc)

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. Similarly, the brake pad force is applied on either side of the brake disc and relies on the friction between the brake pad and the brake disc to retard the rotation of the axle to which the disc is fixed. As the friction changes, so does the ability to slow the car, making this a key parameter in determining train stopping performance. In the PTBPM, the coefficient of friction between the brake shoe and wheel or pad and disc is determined from the type of brake shoe or pad and the speed for each car individually. This value can be further modified by an adjustment factor that represents variations in the coefficient of friction from related factors such as weather, wheel temperature, and condition and composition of brake unit components. As stated in the related document "Development of an Operationally Efficient PTC Braking Enforcement Algorithm for Freight Trains" [2], a distribution of the percent change of coefficient of friction for a brake unit was based on AAR studies on the variation of the coefficient of friction between the brake shoe and the wheel [4, 5] along with discussions with experts in the field. This variability is defined by a normal distribution with a mean of 0 percent and a standard deviation of 6.67 percent. This variance is applied to both tread and disc brakes.

Brake Unit Effectiveness

The force provided by the brake shoe onto the tread or brake pad onto the disk on a given car is a result of the air pressure in the brake cylinder. The brake unit effectiveness ratio scales a given brake unit's nominal brake shoe or brake pad force and can be used to model wear or a variety of other factors that might affect the actual brake force applied by the brake unit. The potential variability of the brake unit force was quantified through expert opinion from suppliers and passenger railroads as well as limited measured data quantified for both tread and disc brake units. The variability is defined by a normal distribution with a mean of 0 percent and a standard deviation of 15 percent.

Dynamic Brake Effort Adjustment Factor

Dynamic braking effort is supplied by the locomotive or powered vehicle and provides another means by which trains can be slowed or stopped. The amount of dynamic brake effort varies by operational standards, types of locomotives/powered cars, and the speed of the train. The variability is defined by a normal distribution with a mean of 1 percent and a standard deviation of 20 percent.

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 piped 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 [6]. 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.

Parameters Evaluated and Not Considered Significant

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 26 parameters identified, 15 were determined to have such a slight effect that they were not included further in the process:

- Train weight and car load – All of the vehicles modeled in this effort were equipped with variable load devices. These devices maintain a constant brake rate regardless of the passenger load. The railroad technical advisory group decided that this parameter was not significant in this effort.
- Error in reported degree of track curvature – In I-ETMS, track curvature is determined by data in the track database, which includes track centerline survey data at intervals of approximately 25 to 30 feet. 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 110 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.
- 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 small, resulting in almost no appreciable added uncertainty in train stopping distance.
- Vehicle 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.
- Control valve and vent valve location – Due to shorter consist lengths and specifications for the locations of the valves for each car type, the variations in location will not have a significant effect on the time for the brakes to be activated and will be similar to the brake pipe length error.

- Truck curving resistance – Passenger equipment has a higher curving resistance compared to freight equipment, but the contribution of the potential variance in truck curving resistance to stopping distance still is small.
- Disc brake diameter – The variance in brake disc sizes is compensated for when building the brake units in PTBPM.
- Aerodynamic coefficient of drag, last vehicle drag area increase, and non-leading drag area increase – These drag effects can have a significant effect on energy consumption for passenger trains, but the contribution of the potential variance in aerodynamic resistance to stopping distance is still small.
- Wind speed and direction – This variable is considered when modeling aerodynamic coefficient of drag, last vehicle drag area increase, and non-leading drag area increase.
- Vehicle orientation – In passenger trains the vehicle orientation does not have an impact.
- Bearing base resistance – This variable will be covered by varying inputs for a Davis resistance equation bearing resistance coefficient. Additionally, the variation of this parameter will be small and the effect on stopping distance will be negligible.
- Wheel-rail coefficient of friction change from contaminants per axle – It was determined from expert opinion and *Technical Digest* [7] that the wheel-rail COF would not change significantly between axles as a passenger train passes over a contaminant. Most contaminants identified had an effect that lasted longer than the length of an entire freight consist containing more than 89 loaded cars. Shorter and lighter consists would have less of a chance to pick up the contaminants and have a changing wheel-rail COF between axles. Therefore, this parameter will not be varied.

2.3 Simulation Test Matrix

The simulation test matrix was made up of two parts: the consists and the operational conditions, including track grade, speed, and braking application types.

2.3.1 Consists

Simulation testing was performed using a range of consists based on historical revenue service train consists operated by a given railroad. The consists shown in the following sections were based on currently available information from the railroads that participated in this effort and may be altered or expanded as new information is collected from additional railroads. Consists were broken down into the two logical groups: commuter and passenger.

Commuter trains are defined as trains running within a city or from a suburban area to an urban area. They run with frequent stops and loads vary widely. These are broken down into two operational groups:

- Electric Multiple Unit (EMU)/Diesel Multiple Unit (DMU) Operations
- Push/Pull Operations

Push/Pull operations were evaluated in this project, while operations with EMU/DMU equipment is planned to be evaluated in a future project. Table 2 shows the Push/Pull consists. Short consists were three cars and long consists five to six cars. A variety of locomotives were included in the consist matrix and added variability due to different braking characteristics. Each consist included one or two cab cars at the opposite end from the locomotive; this was indicated as typical by commuter railroads.

Table 2. Push/Pull Operations Consists

#	Powered Vehicles	Trailing (unpowered) Vehicles	Cab Cars
1	1 EMD F125	3 Bombardier Single Level	1 Rotem Bi-level
2	1 EMD F125	6 Bombardier Single Level	1 Rotem Bi-level
3	1 EMD F125	3 Rotem Bi-level	1 Rotem Bi-level
4	1 EMD F125	6 Rotem Bi-level	1 Rotem Bi-level
5	1 EMD F59PHI	3 Bombardier Single Level	1 Rotem Bi-level
6	1 EMD F59PHI	3 Bombardier Single Level	1 Rotem Bi-level
7	1 EMD F59PHI	3 Rotem Bi-level	1 Rotem Bi-level
8	1 EMD F59PHI	6 Rotem Bi-level	1 Rotem Bi-level
9	1 MP36PH-3C	3 Bombardier Single Level	1 Rotem Bi-level
10	1 MP36PH-3C	3 Bombardier Single Level	1 Rotem Bi-level
11	1 MP36PH-3C	3 Rotem Bi-level	1 Rotem Bi-level
12	1 MP36PH-3C	6 Rotem Bi-level	1 Rotem Bi-level
13	2 MP36PH-3C	11 Rotem Bi-level	1 Bombardier Bi-level
14	1 EMD F125	1 Bombardier Single Level	1 Rotem Bi-level
15	1 MP36PH-3C	1 Bombardier Single Level	1 Rotem Bi-level
16	2 MP36PH-3C	10 Rotem Bi-level	2 Rotem Bi-level
17	2 EMD F125	10 Rotem Bi-level	2 Rotem Bi-level
18	1 EMD F59PHI	6 Bombardier Bi-level	1 Bombardier Bi-level
19	1 EMD F59PHI	5 Bombardier Bi-level	2 Bombardier Bi-level
20	1 MP-40	6 Bombardier Bi-level	1 Bombardier Bi-level
21	1 MP-40	5 Bombardier Bi-level	2 Bombardier Bi-level
22	1 EMD F40PH	3 Bombardier Bi-level	1 Bombardier Bi-level
23	1 EMD F40PH	5 Bombardier Bi-level	1 Bombardier Bi-level
24	1 EMD F59PHI	3 Bombardier Bi-level	1 Bombardier Bi-level
25	1 EMD F59PHI	5 Bombardier Bi-level	1 Bombardier Bi-level
26	1 EDM AEM-7	5 JW-II Trailer	1 JW-II Cab Car
27	1 EDM AEM-7	6 JW-II Trailer	1 JW-II Cab Car
28	1 ABB ALP-44	5 SEPTA-Ii Trailer	1 JW-II Cab Car
29	1 ABB ALP-44	6 SEPTA-Ii Trailer	1 JW-II Cab Car

Passenger trains typically operate between cities, over longer distances, and with a wider variety of cars. The consists include up to three locomotives, in various configurations. They can be placed either in the head or rear of the train, and this was varied in the test matrix.

Table 3. Passenger Consists

#	**Locomotive Hauled Consists**	
	Powered Vehicles	**Trailing (unpowered) Vehicles**
30	1 EMD F59PH	2 Superliner I
31	3 EMD F59PH	14 Superliner I
32	1 P42DC	2 Superliner I
33	3 P42DC	14 Superliner I
34	1 EMD F59PH	1 Superliner I
35	1 P42DC	1 Superliner I
36	1 EMD F59PH	1 Amfleet
37	1 EMD F59PH	3 Amfleet
38	3 EMD F59PH	14 Amfleet
39	1 P42DC	1 Amfleet
40	1 P42DC	3 Amfleet
41	1 P42DC	14 Amfleet
42	1 Charger SC44	1 Amfleet
43	1 Charger SC44	3 Amfleet
44	3 Charger SC44	14 Amfleet

2.3.2 Operating Configurations

After the consists were built, the operating conditions were varied to create a distinct scenario for train speed, track grade, and braking type. The operating conditions were derived from the distribution of typical and boundary conditions that were determined using track charts and operational information provided by commuter and passenger railroads. The X's in Figure 5 and Figure 6 show the speed/grade combinations that were simulated. Simulations were conducted on flat, decline, and inclines grades.

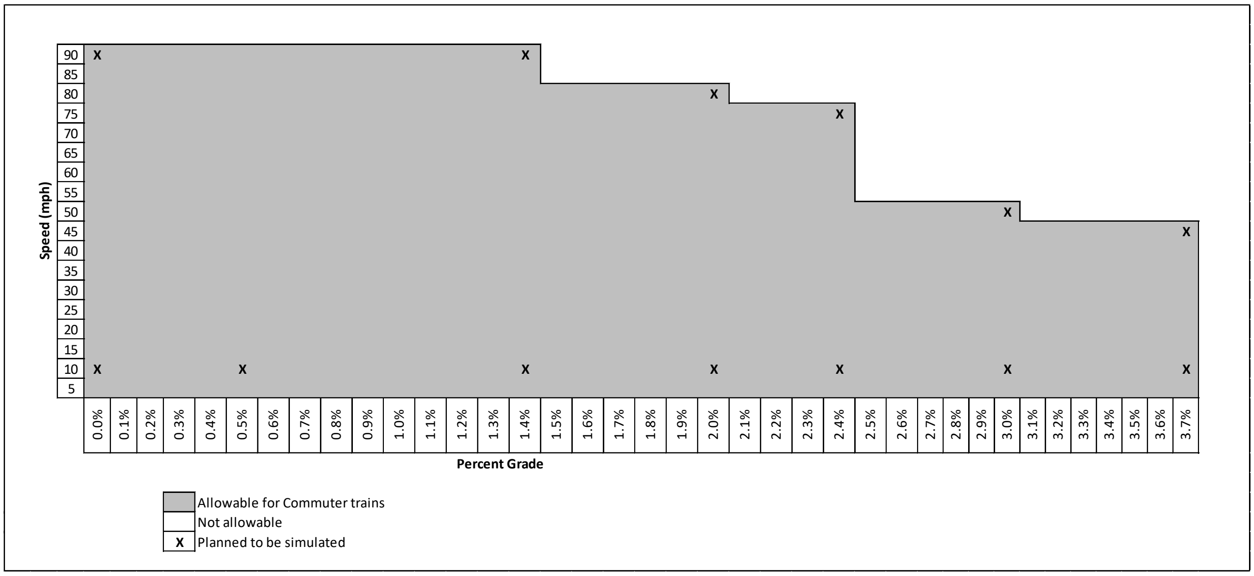


Figure 5. Boundary Operating Conditions for Commuter Simulations

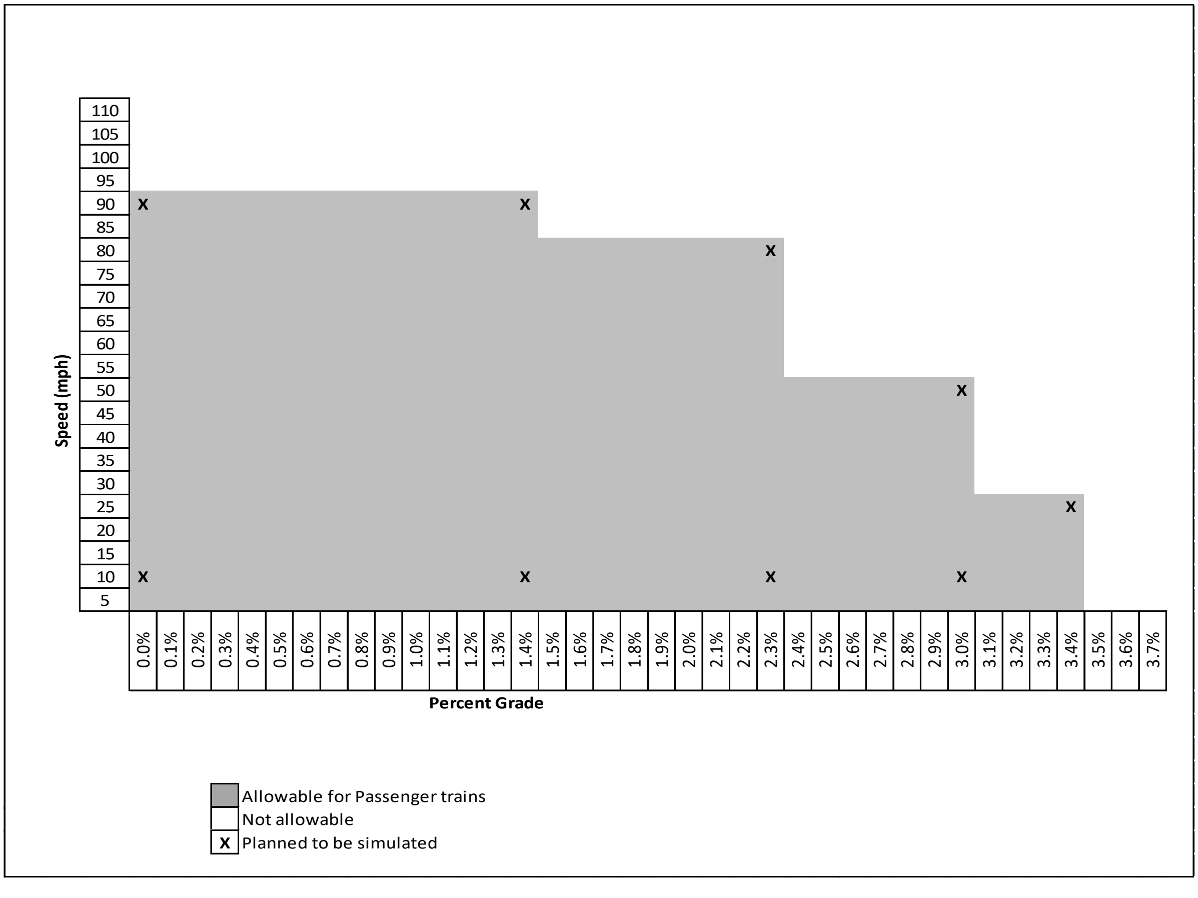


Figure 6. Boundary Operating Conditions for Passenger Simulations

Table 4 shows the simulated speeds for the various scenarios in the simulation matrix.

Table 4. Simulation Testing Speeds by Track Grade and Train Type

	Grade									
	Flat	**0.50%**	**1.40%**	**-1.40%**	**-2.00%**	**-2.30%**	**-2.40%**	**-3.00%**	**-3.40%**	**-3.70%**
Commuter	90, 10	10	90, 10	90, 10	80, 10		75, 10	50, 10		45,25,10
Passenger	90, 10		90, 10	90, 10		80, 10		50, 10	25	

Each of the above listed combinations of speed and grade also were simulated using combinations of different braking application types and braking algorithm configuration settings:

- Emergency Brake Backup – The backup can be turned on (TRUE) or be turned off (FALSE). If turned on, a predicted stopping distance using an emergency brake application will be calculated in addition to the stopping distance calculated based on a penalty brake application. If the enforcement algorithm determines that the train will still overrun a target after the penalty brake is applied it also will actuate an emergency brake application.
- Pneumatic/Blended – This determines if the locomotives in the consist used both dynamic and pneumatic braking throughout the simulation. The blended braking module in the model replicates the blended braking functionality found on many modern passenger/commuter locomotives.
- Commuter/Passenger – This is a setting used by the braking enforcement algorithms to determine the braking distance of the train based on specified brake rates and operational conditions.

2.4 Validation of Models Using Existing Field Test Data

Before the Monte Carlo simulation process was executed, the equipment used in the simulations was modeled and validated for accuracy. Field tests were modeled using the PTBPM and results were compared with the field test data.

The field testing component of the enforcement algorithm evaluation methodology was 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

The field test data received from the participating railroads consisted of multiple test runs for each scenario. When conducting the testing, the railroads attempted to maintain the same test conditions for each run within a scenario. Due to the dynamic nature of the test environment, there was some degree of variability in each scenario. Although most tests required the speed to be constant, it was not always possible and the speeds at enforcement could vary up to 10 miles per hour, which does have a significant result on the stopping distance. It was sometimes necessary to simulate multiple test runs of the same scenario to gain confidence that the model accurately represented the equipment used in the field test.

2.4.1 Overview of Field Testing Process

Participating railroads selected consists and test track locations with guidance from TTCI. TTCI communicated with the railroads to prevent overlap of testing specific combinations of track grades and equipment to provide better coverage of testing configurations. Multiple runs of each scenario were conducted to show consistency in the results. Most of the data provided was braking enforcement data, but some railroads provided stop distance testing data. The data was used to show the consistency in the stopping distance for each scenario tested.

Typically, the worst-case load condition was used during the field testing. For most cases this was the AW2 or AW3 load condition. The AW load conditions are described as follows:

- AW0 – Tare vehicle weight
- AW1 – AW0 plus fully seated load
- AW2 – AW1 plus standees at four passengers/m^2
- AW3 – AW1 plus standees at six passengers/m^2

The consists tested were either loaded with sandbags or additional cars with the brakes cut out were added to the consist to simulate passenger weight.

For stop distance tests, trains were allowed to reach a set speed before a full-service brake application was applied. The distance from the brake set to the final train stop position was measured.

2.4.2 Field Testing Comparison to Simulation Testing

Comparisons between the simulations and field testing were intended to verify that PTBPM would accurately model combinations of vehicles (powered and unpowered) and tracks. Information on the tracks was compiled from track charts (or other provided track information) provided by the testing railroad and models were created in PTBPM that included the grade and other relevant information. Consists also were modeled based on information provided by the railroad. Parameters such as brake rate, brake pipe length, types and locations of brake shoes and pads, powered vehicle types, dimensions, and weight were used to help accurately create the vehicle models.

Simulations were then run with the track and consist models based on the conditions of each field test. Once a simulated stopping distance was determined using the PTBPM, the following equation was used to determine the percent difference from the field test data:

$$\frac{(PTBPM - Field\ Test)}{Field\ Test} = \%\ Difference \tag{1}$$

In many cases, the values for vehicle parameters were provided by the railroad as a range of possible values for the vehicle type as opposed to measured exact values for each specific vehicle. This meant that the percent difference between the simulated result and field test result could be due to errors in the input values used. In these cases, the results were examined, and a judgement was made on which values may need to be adjusted to account for this variability. The models were then tuned by adjusting these parameters within the expected ranges in an attempt to reduce the percent difference to less that ±5 percent of the overall stopping distance.

2.4.2.1 Field Test Consists

Table 5 shows the consists used in the different railroad field tests. The vehicles are in the table in the same order as they were in each consist at the time of the brake testing.

Table 5. Field Testing Consists

#	Agency 1	Agency 2	Agency 3	Agency 4	Agency 5
1	Amerail Cab Car	MP-40	MP36	P42	EMD F59PHI
2	Budd Coach	MP-40	Hyundai Rotem Coach	P42	EMD F40
3	Budd Coach	Bombardier Cab Car	Bombardier Cab Car	Superliner I	Bombardier Cab Car
4	Amerail Coach	Bombardier Cab Car	Bombardier Cab Car	Superliner II	Bombardier Trailer
5	Amerail Cab Car	Bombardier Cab Car	Bombardier Cab Car	Superliner II	Bombardier Trailer
6	Budd Coach	Bombardier Cab Car	Bombardier Cab Car	Superliner II	Bombardier Trailer
7	EMD F40PHM-2	Bombardier Cab Car	Bombardier Cab Car	Superliner II	Bombardier Trailer
8	Budd Coach	Bombardier Cab Car	MP36	Superliner I	Bombardier Trailer
9	Amerail Coach	Bombardier Cab Car	Bombardier Cab Car	Superliner II	
10	Budd Coach		Bombardier Cab Car	Superliner I	
11	Budd Coach		Bombardier Cab Car	Superliner I	
12	Budd Coach		Bombardier Cab Car	Superliner I	
13	Budd Coach		Bombardier Cab Car	Superliner I	
14	Nippon Sharyo Cab Car		Hyundai Rotem Coach	Superliner I	
15	EMD F40PHM-2				

2.4.2.2 Analysis of Field Test Modeling Results

The following section shows the results of the comparison between each of the field tests and the simulations of those field tests after any tuning of parameters that were not precisely measured. Overall, there was good correlation between the field test data and the modeled stopping results for all the equipment modeled with most runs having a percent difference within ±5 percent.

Table 6 shows the results of the field test modeling for railroad 1. Field testing was conducted on either flat track or a constant -0.5 percent grade. Speeds ranged from 53.6 mph to 69 mph.

Table 6. Railroad 1 Field Test Modeling Results

Track Grade	Speed at Braking	Field Test Stopping Distance (ft.)	Simulation Stopping Distance (ft.)	Simulated to Measured delta (ft.)	Percent Difference
Mostly Flat, with -0.5% at the end	53.6	2726	2717	-9	-0.33%
	53.8	2756	2738	-18	-0.66%
	54.3	2717	2784	67	2.42%
	54.9	2682	2837	155	5.45%
	55.1	2696	2873	177	6.16%
	55.2	2792	2872	80	2.78%
	55.7	2783	2924	141	4.81%
	55.7	2830	2924	94	3.20%
	67.3	3822	3937	115	2.91%
	67.9	3750	3992	242	6.07%
	69	3967	4141	174	4.20%
-0.5%	64	3616	3682	66	1.81%
	64.6	3788	3743	-45	-1.21%
	64.7	3646	3753	107	2.86%
	64.7	3821	3753	-68	-1.81%
	65.4	3743	3823	80	2.10%
	65.8	3694	3864	170	4.40%
	66.4	3790	3926	136	3.46%
	66.7	3818	3957	139	3.51%
	67.2	4061	4008	-53	-1.31%
	67.4	3853	4029	176	4.38%
	67.5	3957	4040	83	2.05%
	67.8	3922	4071	149	3.66%

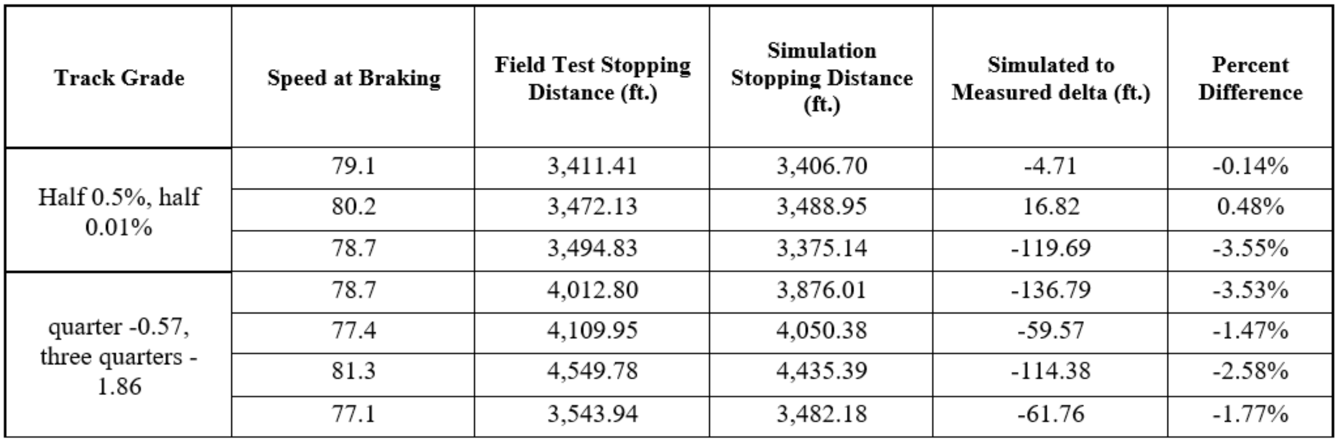
Table 7 shows the results of the field test modeling for Agency 2. Field testing was conducted on several different track grades: Flat track, track that varied from -0.08 percent to -0.67 percent, track that varied from 0.03 percent to 0.67 percent, -2.85 percent, and 2.85 percent. The speeds varied from 3.8 mph to 61.7 mph. Also, the brake application type included blended and pneumatic only.

Table 7. Railroad 2 Field Test Modeling Results

Track Grade	Brake Application Type	Speed at Braking	Field Test Stopping Distance (ft.)	Simulation Stopping Distance (ft.)	Simulated to Measured delta (ft.)	Percent Difference
-2.85%	Blended	30.8	689.02	754.78	69.78	9.54%
	Blended	31.1	729.24	767.19	42.19	5.20%
2.85%	Blended	34	568.12	530.54	-48.46	-6.61%
	Blended	34.8	581.53	543.97	-49.03	-6.46%
	Pneumatic	33.5	506.20	562.60	46.60	11.14%
	Pneumatic	36.4	600.11	643.06	31.06	7.16%
0.03% to 0.67%	Blended	60.5	1,698.51	1,700.74	9.74	0.13%
	Blended	61.7	1,835.99	1,757.54	-69.46	-4.27%
	Pneumatic	60.5	1,971.37	1,884.21	-78.79	-4.42%
	Pneumatic	61.1	1,933.29	1,911.88	-13.12	-1.11%
-0.08% to -0.67%	Blended	58	1,765.13	1,724.53	-33.47	-2.30%
	Blended	60.3	1,903.68	1,748.11	-147.89	-8.17%
	Pneumatic	55.5	1,726.00	1,629.06	-89.94	-5.62%
	Pneumatic	59.7	1,993.05	1,936.18	-48.82	-2.85%
Flat (0.0%)	Blended	58.6	1,586.00	1,637.32	51.32	3.24%
	Blended	60.3	1,776.29	1,717.06	-61.94	-3.33%
	Blended	60.3	1,785.27	1,727.53	-57.47	-3.23%
	Blended	61	1,990.33	2,028.78	38.78	1.93%
	Pneumatic	59.1	1,849.22	1,850.79	-1.21	0.08%
	Pneumatic	59.2	1,849.22	1,856.70	4.70	0.40%
	Pneumatic	60	1,958.09	1,826.13	-131.87	-6.74%
	Pneumatic	60.7	1,931.14	1,688.71	-242.29	-12.55%

Table 8 shows the results of the field test modeling for Agency 3. Field testing was conducted using two different track grades. The speeds at braking were near 80 mph.

Table 8. Railroad 3 Field Test Modeling Results



Track Grade	Speed at Braking	Field Test Stopping Distance (ft.)	Simulation Stopping Distance (ft.)	Simulated to Measured delta (ft.)	Percent Difference
Half 0.5%, half 0.01%	79.1	3,411.41	3,406.70	-4.71	-0.14%
	80.2	3,472.13	3,488.95	16.82	0.48%
	78.7	3,494.83	3,375.14	-119.69	-3.55%
quarter -0.57, three quarters -1.86	78.7	4,012.80	3,876.01	-136.79	-3.53%
	77.4	4,109.95	4,050.38	-59.57	-1.47%
	81.3	4,549.78	4,435.39	-114.38	-2.58%
	77.1	3,543.94	3,482.18	-61.76	-1.77%

Table 9 shows the results of the field test modeling for Agency 4. Field testing was conducted on track with a grade of 0.82 percent. The brake applications completed were 10 psi, 15 psi, and service. Also, the brake application type for all cases was blended.

Table 9. Railroad 4 Field Test Modeling Results

Track Grade	Speed at Braking	Field Test Stopping Distance (ft.)	Simulation Stopping Distance (ft.)	Simulated to Measured delta (ft.)	Percent Difference
-0.82%, 10 psi Application	70.63	10,445.39	10,324.84	120.55	-1.15%
-0.82%, 15 psi Application	69.25	5,341.04	5,380.35	39.31	0.74%
-0.82%, Full Service Application	70.86	3,908.51	3,964.09	55.58	1.42%

Table 10 shows the results of the field test modeling for Agency 5. Field testing was conducted on multiple track grades: flat track, ±1.10 percent, +2.10 percent, and steep downgrade. The speeds for the tests were either 90 mph, 30 mph, and 40 mph.

Table 10. Railroad 5 Field Test Modeling Results

Track Grade	Speed at Braking	Field Test Stopping Distance (ft.)	Simulation Stopping Distance (ft.)	Simulated to Measured delta (ft.)	Percent Difference
0%	90.5	5,296.22	4,995.14	-301.08	-6.03%
	91.4	5,337.52	5,085.27	-252.26	-4.96%
1.10%	86.8	3,866.00	3,750.42	-115.58	-3.08%
	84.7	3,333.09	3,584.52	251.43	7.01%
	83.9	3,352.51	3,522.35	169.84	4.82%
	86.7	3,649.82	3,742.35	92.53	2.47%
	91.3	4,457.43	4,350.16	-107.28	-2.47%
	89	4,219.98	4,152.59	-67.39	-1.62%
	89.6	3,872.18	3,977.85	105.67	2.66%
	89.5	4,300.01	4,195.36	-104.65	-2.49%
	90.9	4,428.21	4,316.04	-112.17	-2.60%
-1.10%	90.8	6,306.24	5,859.93	-446.32	-7.62%
	89.5	6,001.98	5,708.58	-293.40	-5.14%
	89.6	5,943.44	5,719.65	-223.79	-3.91%
	89.5	5,872.04	5,708.25	-163.79	-2.87%
	90.6	5,821.16	5,835.26	14.10	0.24%
	89.5	5,597.80	5,202.83	-394.97	-7.59%
2.10%	38.7	743.95	801.99	58.04	7.24%
	37.9	805.20	773.88	-31.32	-4.05%
	40.1	875.95	858.64	-17.31	-2.02%
	38.3	822.10	778.30	-43.80	-5.63%
Downgrade Steep Grade	34.5	1,243.44	1,184.24	-59.20	-5.00%
	33.5	1,167.41	1,250.00	82.59	6.61%
	31.6	1,158.96	1,138.46	-20.50	-1.80%
	35.3	1,330.56	1,324.75	-5.81	-0.44%

3. Simulation Analysis of I-ETMS Braking Enforcement Algorithm

The simulation matrix described in Section 2.3 was executed using the Monte Carlo simulation methodology for Wabtec's I-ETMS braking enforcement algorithm. The following subsections describe the evaluation of the I-ETMS enforcement algorithm including the exploratory data analysis, overall results, characterization of simulations that stopped past the target location, and characterization of simulations that stopped before the performance target.

3.1 Exploratory Data Analysis

To begin the analysis, a thorough exploratory data analysis (EDA) was performed. EDA is a method of using visual mediums (e.g., scatterplots, QQ-plots, etc.) to characterize the data being analyzed as well as undercover outliers, anomalies, and other underlying structures of the results data. The main objective of EDA is to ensure that the dataset is complete and that there are no anomalies in the data which would be caused by errors in processing of the simulation and therefore would not reflect a realistic result of the train enforcement application simulations.

Among others, the following measures of performance were analyzed:

- Penalty application speed difference – The difference between the target simulation speed at penalty enforcement and actual simulation speed at the enforcement location. This value is controlled by P-TCL's cruise control functionality, which will increase throttle or brake application to keep the consist at a constant speed up to the point of PTC penalty brake enforcement.
- Stopping location relative to target – The difference between the final stopping location and the target stopping location. Negative values indicate that a train has stopped short of the target and positive values indicate that a train has stopped past the target.

EDA of the enforcement speeds determined that simulations with a penalty application speed difference outside of ±20 mph would be excluded. In certain cases, there is variation between the target speed and the actual simulated speed at the point of enforcement due to (a) the use of pneumatic brakes on steep downgrades and (b) not having enough tractive effort to maintain the speed on steep upgrades. Figure 7 shows the Quantile-Quantile plot (QQ-plot) of all Penalty application speed differences for each simulation. The QQ plots allow data to be plotted according to their quantiles and compared with those of a theoretical distribution (e.g., normal or exponential) to determine if the data aligns to its expected position within the continuous distribution. In this case the plots are being used to view the spread of the data, especially at the tails. Overall, the model's cruise control performed acceptably, despite having some outliers. The following describes the amount of data for some select differences between the target enforcement speed and actual enforcement speed:

- 96.97 percent of simulations were within ±10 mph of the target simulation speed.
- 89.85 percent of simulations were within ±5 mph.

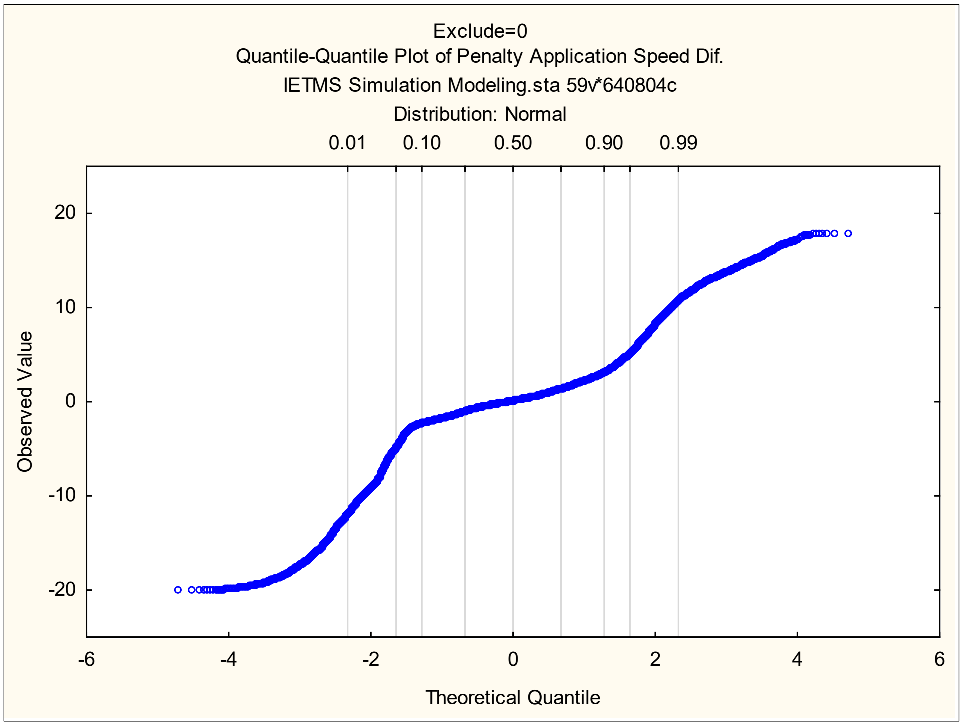


Figure 7. QQ-Plot of Penalty Application Speed Difference for I-ETMS Simulations

Figure 8 shows the overall spread of data in a scatter plot of stopping location relative to target versus penalty application speed difference. The graph also shows that simulations with a penalty application speed difference greater than ±5 mph did not overrun and did not negatively bias the final results.

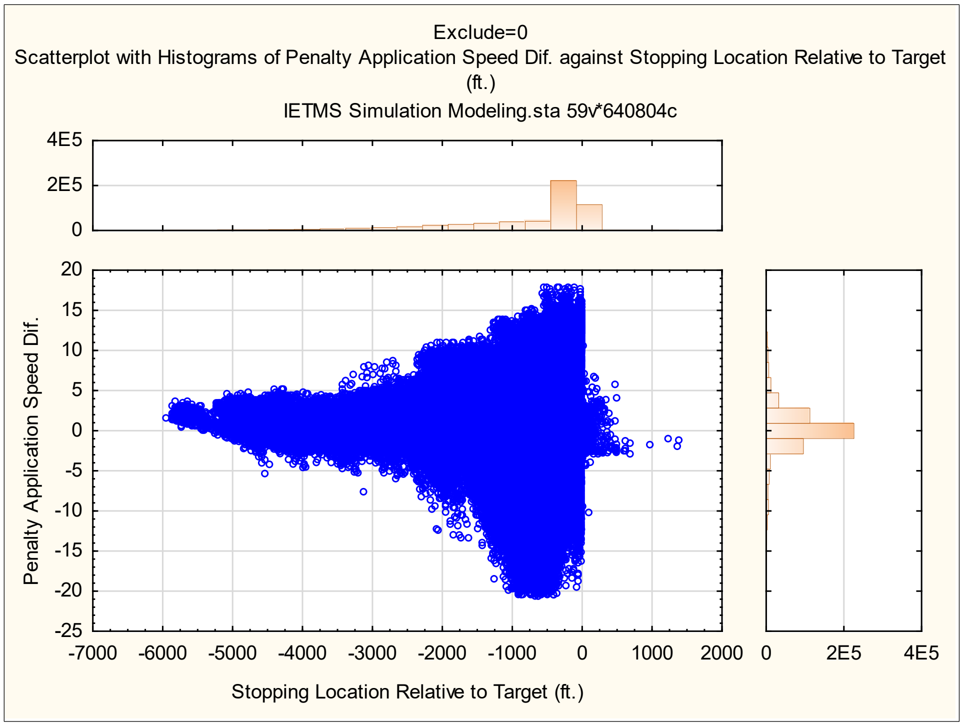


Figure 8. Scatterplot of Stopping Location Relative to Target vs. Penalty Application Speed Difference

3.2 Overall Summary

After the data was investigated for reliability and to understand the underlying characteristics, results were generated. Table 11 shows the overall results of the simulation testing separated by train type. The two main statistics presented are:

- Probability of Stopping Short of Target: The probability that a given train, under the given operating conditions, will stop short of the given stopping target following a PTC enforcement.
- Probability of Stopping Short of Performance Limit (Undershoot): The probability that a given train, under the given operating conditions will stop short of the target by > 500 feet for speeds < 30 mph and > 1,200 feet for speeds ≥ 30 mph, following a PTC enforcement.

Table 11. Overall Enforcement Algorithm Simulation Test Results

Train Type	Probability of Stopping Short of Target	Probability of Stopping Short of Performance Limit
Commuter	99.78%	12.90%
Passenger	99.95%	33.56%

The probability of stopping short of the target, as shown in Table 11, was 99.78 percent and 99.95 percent for the commuter and passenger algorithm settings respectively, considering the equipment and operational conditions modeled. These values met the previously established safety objective of being able to stop short of the target with a probability of ≥ 99.5 percent. The probability of stopping short of the performance limit was shown to be 12.9 percent, and 33.56 percent for the two algorithm settings.

Table 12 shows a further breakdown of the probability of stopping short – this time separated by emergency brake backup setting and brake application type. All the different configurations met the established safety objective of being able to stop short of the target with a probability of ≥ 99.5 percent. Those configurations that had a higher probability of stopping short of the target were more conservative and had a higher probability of stopping short of the performance limit. The probability of stopping short of the performance limit was more conservative in the configuration where blended braking was used and less conservative for the configuration where pneumatic braking was used.

Table 12. Overall Simulation Test Results by Brake Application Type

Train Type	Emergency Brake Backup Setting	Brake Application Type	Probability of Stopping Short of Target	Probability of Stopping Short of Performance Limit
Commuter	Disabled	Blended	99.83%	16.90%
		Pneumatic Only	99.77%	16.21%
	Enabled	Blended	99.88%	9.88%
		Pneumatic Only	99.62%	8.27%
Passenger	Disabled	Blended	99.96%	37.02%
		Pneumatic Only	99.91%	35.49%
	Enabled	Blended	99.97%	32.06%
		Pneumatic Only	99.97%	29.68%

Table 13 through Table 20 show further results broken down by stopping configuration, target speed at enforcement, and grade. Also included in the tables is an additional measure of performance:

- Enforcement Location Relative to Target (Mean): This is the mean difference between the target stopping location and the enforcement location in each simulation.

Table 13 shows results for the blended braking simulations. A positive maximum stopping location relative to the target means there were overruns for some of the simulations run at the speed and grade indicated.

Table 13. Commuter, Emergency Brake Backup Disabled, Blended Braking Results

Target Speed at Braking	Grade	Stopping Location Relative to Target (ft.)			Enforcement Location Relative to Target (ft.)
		Mean	Minimum	Maximum	Mean
10	0.0f	-119.8	-199.7	46.0	-228.8
	0.5i	-111.4	-148.6	-75.8	-204.5
	1.5d	-129.8	-288.8	2.3	-251.7
	1.5i	-93.0	-129.6	-56.8	-177.4
	2.4d	-130.3	-303.0	-0.1	-259.6
	2d	-140.2	-277.9	-17.6	-267.7
	3.7d	-245.2	-485.4	-0.1	-394.1
	3d	-111.4	-317.7	0.0	-248.4
25	3.7d	-341.3	-1,122.4	114.2	-978.2
45	3.7d	-1,059.9	-2,391.3	196.6	-2,669.3
50	2d	-574.9	-830.6	-375.4	-2,603.3
	3d	-584.1	-1,971.8	281.5	-2,389.8
75	2.4d	-1,089.9	-3,164.0	1,232.8	-4,581.9
80	2.4d	-1,247.7	-2,936.6	468.9	-5,764.4
	2d	-1,259.3	-3,231.7	977.9	-5,013.0
90	0.0f	-1,004.1	-2,504.9	167.4	-4,943.5
	1.5d	-1,427.9	-3,534.4	628.5	-5,904.7
	1.5i	-700.9	-1,918.8	137.2	-3,691.9

Table 14. Commuter, Emergency Brake Backup Disabled, Pneumatic Only Braking Results

Target Speed at Braking	Grade	Stopping Location Relative to Target (ft.)			Enforcement Location Relative to Target (ft.)
		Mean	Minimum	Maximum	Mean
10	0.0f	-118.8	-193.0	46.0	-227.8
	0.5i	-111.5	-155.4	-75.8	-204.7
	1.5d	-129.4	-280.8	9.4	-243.8
	1.5i	-93.4	-135.0	-58.2	-177.6
	2.4d	-136.8	-312.4	-1.2	-267.0
	2d	-144.2	-308.6	-29.0	-270.3
	3.7d	-240.0	-494.8	0.0	-396.0
	3d	-119.7	-363.2	-0.1	-259.1
25	3.7d	-329.6	-1,119.6	294.8	-1,006.0
45	3.7d	-951.9	-2,259.5	494.2	-2,619.1
50	2d	-471.6	-727.3	-172.5	-2,556.1
	3d	-515.8	-1,971.1	214.4	-2,457.0
75	2.4d	-954.6	-3,046.7	1,362.9	-4,603.0
80	2.4d	-742.4	-2,794.9	367.5	-5,772.4
	2d	-1,108.4	-3,251.9	1,389.1	-4,971.6
90	0.0f	-1,003.9	-2,487.9	278.8	-4,944.0
	1.5d	-1,383.8	-3,466.0	493.5	-5,943.1
	1.5i	-770.1	-1,918.8	0.0	-3,764.8

Table 15. Commuter, Emergency Brake Backup Enabled, Blended Braking Results

Target Speed at Braking	Grade	Stopping Location Relative to Target (ft.)			Enforcement Location Relative to Target (ft.)
		Mean	Minimum	Maximum	Mean
10	0.0f	-88.4	-149.0	-0.4	-198.5
	0.5i	-83.6	-129.2	-33.7	-177.4
	1.5d	-104.5	-253.0	-0.1	-227.2
	1.5i	-69.2	-101.9	-26.2	-153.8
	2.4d	-100.3	-284.4	-0.1	-230.3
	2d	-107.0	-251.9	-0.7	-235.1
	3.7d	-157.7	-379.8	-0.1	-305.3
	3d	-85.1	-289.3	0.0	-218.7
25	3.7d	-210.2	-896.4	2.0	-787.3
45	3.7d	-689.2	-1807.2	0.0	-2,219.1
50	2d	-185.7	-359.1	-38.8	-2,244.6
	3d	-449.6	-1,652.2	0.0	-2,117.1
75	2.4d	-691.2	-2,584.6	347.2	-4,066.2
80	2.4d	-827.5	-2,437.8	332.2	-5,225.6
	2d	-778.3	-2,673.3	394.5	-4,472.7
90	0.0f	-666.5	-1,960.0	133.2	-4,571.8
	1.5d	-975.9	-2,890.8	339.1	-5,358.8
	1.5i	-485.1	-1,532.6	71.2	-3,437.7

Table 16. Commuter, Emergency Brake Backup Enabled, Pneumatic Only Braking Results

Target Speed at Braking	Grade	Stopping Location Relative to Target (ft.)			Enforcement Location Relative to Target (ft.)
		Mean	Minimum	Maximum	Mean
10	0.0f	-88.7	-150.0	0.0	-200.7
	0.5i	-83.7	-126.7	-33.7	-177.6
	1.5d	-86.0	-227.6	-0.3	-200.4
	1.5i	-68.8	-106.1	-28.0	-153.9
	2.4d	-106.6	-274.9	-0.4	-236.5
	2d	-110.2	-247.0	-3.7	-236.9
	3.7d	-163.3	-400.9	0.0	-312.1
	3d	-94.8	-295.7	0.0	-228.9
25	3.7d	-220.2	-884.6	90.9	-827.9
45	3.7d	-672.6	-1,742.6	0.0	-2,259.0
50	2d	-127.2	-310.3	-23.2	-2,226.8
	3d	-398.2	-1,639.6	490.5	-2,149.1
75	2.4d	-593.2	-2,550.6	500.8	-4,133.6
80	2.4d	-486.6	-2,304.2	178.2	-5,195.2
	2d	-701.6	-2,540.9	689.5	-4,521.8
90	0.0f	-661.5	-1,960.0	79.3	-4,579.8
	1.5d	-773.8	-2,769.7	625.8	-5,364.5
	1.5i	-460.7	-1,532.6	119.0	-3,486.3

Table 17. Passenger, Emergency Brake Backup Disabled, Blended Braking Results

Target Speed at Braking	Grade	Stopping Location Relative to Target (ft.)			Enforcement Location Relative to Target (ft.)
		Mean	Minimum	Maximum	Mean
10	0.0f	-122.6	-204.9	28.9	-231.1
	0.5i	-115.1	-158.8	-74.2	-208.0
	1.5d	-140.9	-329.5	5.7	-262.0
	1.5i	-92.8	-171.6	-46.2	-177.9
	2.4d	-154.0	-340.5	-0.4	-282.8
	2d	-168.1	-318.6	-31.2	-295.4
	3.7d	-321.6	-624.5	-0.1	-480.9
	3d	-154.5	-478.4	0.0	-296.0
25	3.7d	-473.0	-1,715.1	0.0	-1,138.1
45	3.7d	-2,118.2	-3,500.1	-34.3	-3,792.5
50	2d	-1,344.3	-1,760.2	-890.6	-3,251.8
	3d	-1,464.7	-3,036.7	303.3	-3,313.9
75	2.4d	-2,912.8	-5,113.3	-259.0	-6,366.0
80	2.4d	-3,079.7	-4,445.3	-283.7	-7,597.8
	2d	-3,290.2	-5,280.2	-74.0	-7,035.9
90	0.0f	-2,087.8	-3,770.0	-11.9	-5,990.5
	1.5d	-3,363.4	-5,954.0	-747.5	-7,889.6
	1.5i	-1,322.8	-2,881.9	-4.1	-4,425.6

Table 18. Passenger, Emergency Brake Backup Disabled, Pneumatic Only Braking Results

Target Speed at Braking	Grade	Stopping Location Relative to Target (ft.)			Enforcement Location Relative to Target (ft.)
		Mean	Minimum	Maximum	Mean
10	0.0f	-125.2	-204.9	28.9	-232.5
	0.5i	-115.0	-158.8	-76.9	-208.1
	1.5d	-133.5	-303.1	-2.1	-247.6
	1.5i	-94.5	-129.6	-56.9	-180.4
	2.4d	-162.5	-352.9	4.1	-292.4
	2d	-173.5	-323.3	-41.1	-299.5
	3.7d	-341.3	-661.0	-0.1	-505.3
	3d	-164.9	-583.4	-0.1	-305.2
25	3.7d	-496.0	-1,735.9	467.3	-1,182.6
45	3.7d	-2,042.1	-3,488.2	-2.6	-3,810.8
50	2d	-1,241.8	-1,701.8	-804.4	-3,209.0
	3d	-1,317.2	-3,041.7	499.2	-3,306.6
75	2.4d	-2,699.8	-5,084.1	-14.6	-6,315.5
80	2.4d	-2,510.7	-4,331.3	417.3	-7,399.3
	2d	-3,066.2	-5,169.4	-9.6	-6,936.4
90	0.0f	-2,101.8	-3,747.0	-4.7	-6,009.0
	1.5d	-3,108.8	-5,865.0	258.4	-7,820.7
	1.5i	-1,397.2	-2,881.9	-1.0	-4,485.3

Table 19. Passenger, Emergency Brake Backup Enabled, Blended Braking Results

Target Speed at Braking	Grade	Stopping Location Relative to Target (ft.)			Enforcement Location Relative to Target (ft.)
		Mean	Minimum	Maximum	Mean
10	0.0f	-95.3	-162.6	62.9	-203.0
	0.5i	-87.1	-133.0	-39.6	-180.9
	1.5d	-112.1	-250.1	2.3	-232.6
	1.5i	-70.3	-101.9	-28.5	-155.4
	2.4d	-123.3	-303.0	-0.9	-254.8
	2d	-123.2	-288.2	-6.7	-248.2
	3.7d	-231.9	-484.2	0.0	-385.3
	3d	-116.7	-380.7	0.0	-262.0
25	3.7d	-351.9	-1,386.3	0.0	-967.9
45	3.7d	-1733.4	-3,164.1	-1.5	-3,393.6
50	2d	-957.5	-1,208.2	-734.7	-2,934.3
	3d	-1,171.5	-2,800.2	-0.8	-3,078.4
75	2.4d	-2,365.3	-4,685.4	-18.7	-5,949.3
80	2.4d	-2,626.4	-3,911.6	-176.0	-7,144.7
	2d	-2,643.2	-4,779.3	-27.3	-6,497.9
90	0.0f	-1,739.5	-3,343.2	-41.5	-5,654.5
	1.5d	-2,825.1	-5,159.3	-568.0	-7,353.9
	1.5i	-1,054.6	-2,473.4	-54.2	-4,138.1

Table 20. Passenger, Emergency Brake Backup Enabled, Pneumatic Only Braking Results

Target Speed at Braking	Grade	Stopping Location Relative to Target (ft.)			Enforcement Location Relative to Target (ft.)
		Mean	Minimum	Maximum	Mean
10	0.0f	-94.7	-162.6	62.9	-203.4
	0.5i	-87.3	-133.0	-39.6	-181.0
	1.5d	-104.5	-240.2	19.5	-217.6
	1.5i	-67.6	-125.4	-4.1	-151.3
	2.4d	-135.2	-312.4	-0.6	-264.7
	2d	-138.7	-285.0	-22.5	-265.2
	3.7d	-247.3	-528.1	-0.1	-404.1
	3d	-136.8	-533.0	0.0	-276.5
25	3.7d	-362.9	-1,484.2	0.0	-1,003.1
45	3.7d	-1,695.3	-3,195.1	-0.2	-3,448.0
50	2d	-867.3	-1,129.5	-557.4	-2,894.9
	3d	-1,114.5	-2,805.3	-0.1	-3,051.2
75	2.4d	-2,284.3	-4,695.8	-0.9	-5,910.3
80	2.4d	-1,981.3	-3,660.2	-1.0	-7,014.6
	2d	-2,585.7	-4,649.9	-2.0	-6,457.8
90	0.0f	-1,726.5	-3,343.2	-32.3	-5,645.6
	1.5d	-2,571.3	-5,159.6	-0.3	-7,291.2
	1.5i	-1,025.3	-2,473.4	-55.9	-4,123.9

3.3 Characterization of Overruns

In total there were 736 individual simulations that overran the target stopping position out of the 538,600 simulations run. The results of the Monte Carlo simulations showed that 610 of the overruns occurred with the commuter train type and 126 occurred with the passenger train type. Shown in Table 21, the configuration that had most of the overruns was the commuter train type with the emergency brake backup setting enabled and pneumatic friction braking only. This configuration accounted for 40.5 percent (247 out of 610) of the commuter simulations that overran the target position. The results of the simulations showed that 44.94 percent (111 out of 247) of these simulations were run with one consist (Consist 44), which was a longer train consisting of 3 locomotives and 14 cars. This consists represented a train operating in revenue service but not typically run during normal operations.

Table 21. Count of Simulations that Overran the Target Position

EA Train Type	Emergency Brake Backup Setting	Brake Application Type	Count
Commuter	Off	Blended	122
		Friction	157
	On	Blended	84
		Friction	247
Passenger	Off	Blended	24
		Friction	59
	On	Blended	22
		Friction	21

Table 22 shows the top 80 percent of simulations that overran the target position. Most of the overruns occur on downhill grades. Consist 13 on flat track at 10 mph represented about 12 percent (88) of the overruns. This consist contained 2 locomotives, 11 vehicles, and 1 cab car. The next 238 simulations (lines 2 through 5 in Table 22 all included the aforementioned Consist 44). The majority (169 out of 238) of these overruns occurred when the emergency brake backup was enabled. More overruns were expected with the emergency brake backup enabled due to the algorithm being more aggressive because of the ability to actuate an emergency enforcement if needed.

Table 22. Breakdown Table of Top 80 percent of Simulations that Overran the Target Position

Consist	Target Speed at Braking	Grade	Count	Percent	Average Stopping Location Relative to Target (ft.)
13	10	0.0f	88	11.96%	22.7
44	80	2.4d	66	8.97%	142.3
44	50	3d	63	8.56%	116.6
44	90	1.5d	63	8.56%	47.0
44	25	3.7d	46	6.25%	32.2
42	50	3d	37	5.03%	167.2
43	80	2.4d	29	3.94%	142.7
25	75	2.4d	28	3.80%	225.8
38	50	3d	23	3.13%	85.0
43	90	0.0f	21	2.85%	83.5
23	75	2.4d	21	2.85%	161.4
43	90	1.5d	19	2.58%	37.1
25	80	2d	18	2.45%	302.7
42	25	3.7d	17	2.31%	174.0
13	10	1.5d	17	2.31%	4.2
24	75	2.4d	14	1.90%	163.7
42	90	0.0f	13	1.77%	105.1
24	90	1.5d	13	1.77%	298.9

3.4 Characterization of Undershoots

In total, in 124,452 out of 538,600 individual simulations the train stopped short of the performance limit. The established criteria for a simulation to be considered an "undershoot" or to have stopped short of the performance limit was as follows:

- Probability of stopping short of performance limit (undershoot): The probability that a given train, under the given operating conditions will stop short of the target by > 500 feet for speeds < 30 mph and > 1,200 feet for speeds ≥ 30 mph, following a PTC enforcement.

Table 23 shows a summary count of all simulations in which the train stopped short of the performance target. There were more simulations under the passenger train type as compared to the commuter – 89,292 compared to 35,160. This was most likely due to the more conservative nature of the passenger train type based on the assumed brake rate. Within each train type the emergency brake backup disabled setting was more conservative.

Table 23. Count of Simulations that Undershot the Performance Target

EA Train Type	Emergency Brake Backup Setting	Brake Application Type	Count
Commuter (35,160)	Disabled (23,004)	Blended	11,861
		Friction	11,143
	Enabled (12,156)	Blended	6,777
		Friction	5,379
Passenger (89,292)	Disabled (48,208)	Blended	24,037
		Friction	24,171
	Enabled (41,084)	Blended	21,579
		Friction	19,505

Table 24 shows a breakdown by EA train type, speed, and grade. The most conservative configurations by count and minimum (smallest stopping position relative to target position) were the higher speed and greater downgrade tracks. Note that not a single simulation under 30 mph (the 500-foot undershoot limit) resulted in an undershoot.

Table 24. Breakdown Table of Undershoot Simulations by EA Train Type, Speed, and Grade

EA Train Type	Target Speed at Braking	Grade	Count	Mean	Minimum
Commuter	45	3.7d	4,177	-1,490.8	-2,391.3
	50	3d	2,534	-1,398.1	-1,971.8
	75	2.4d	4,270	-1,638.4	-3,164.0
	80	2.4d	2,107	-1,539.1	-2,936.6
	80	2d	5,308	-1,807.2	-3,251.9
	90	0.0f	4,940	-1,543.0	-2,504.9
	90	1.5d	9,220	-1,801.7	-3,534.4
	90	1.5i	2,604	-1,348.4	-1,918.8
Passenger	45	3.7d	9,374	-2,081.2	-3,500.1
	50	2d	165	-1,307.1	-1,760.2
	50	3d	9,695	-1,672.8	-3,041.7
	75	2.4d	11,239	-2,839.8	-5,113.3
	80	2.4d	6,746	-2,573.6	-4,445.3
	80	2d	12,050	-3,152.6	-5,280.2
	90	0.0f	15,019	-2,010.6	-3,770.0
	90	1.5d	15,424	-3,017.8	-5,954.0
	90	1.5i	9,580	-1,640.1	-2,881.9

4. Simulation Analysis of ACSES Braking Enforcement Algorithm

The simulation matrix described in Section 2.3 was executed using the Monte Carlo simulation methodology for the ACSES braking enforcement algorithm. The following sub-sections describe the definition and evaluation of the ACSES enforcement algorithm, including the development of a software implementation of the algorithm, the exploratory data analysis, overall results, characterization of simulations that stopped past the target location, and characterization of simulations that stopped short of the performance target.

4.1 Development of ACSES Software Application

The ACSES braking enforcement algorithm is embedded in the onboard locomotive hardware. The Monte Carlo simulation environment developed for this effort requires a software application that can interface with P-TCL and run faster than real time. It was necessary to develop a software application implementation of the ACSES braking enforcement algorithm to conduct simulations using the Monte Carlo simulation methodology with the ACSES braking algorithm. TTCI developed the application as described in Appendix D.

4.2 Exploratory Data Analysis

EDA of the enforcement speeds determined that simulations with a penalty application speed difference outside of ±20 mph would be excluded. In this case no simulations needed to be excluded. In certain cases, there is variation between the target enforcement speed and the simulated speed at the point of enforcement, due to (a) the use of pneumatic brakes on steep downgrades and (b) not having enough tractive effort to maintain the speed on steep upgrades. Figure 9 shows the QQ-plot of all penalty application speed differences for each simulation. Overall the model's cruise control performed acceptably, despite having some outliers. The following describe the amount of data for some select differences between the target enforcement speed and actual enforcement speed:

- 98.14 percent of simulations were within ±10 mph of the target simulation speed.
- 87.24 percent of simulations were within ±5 mph.

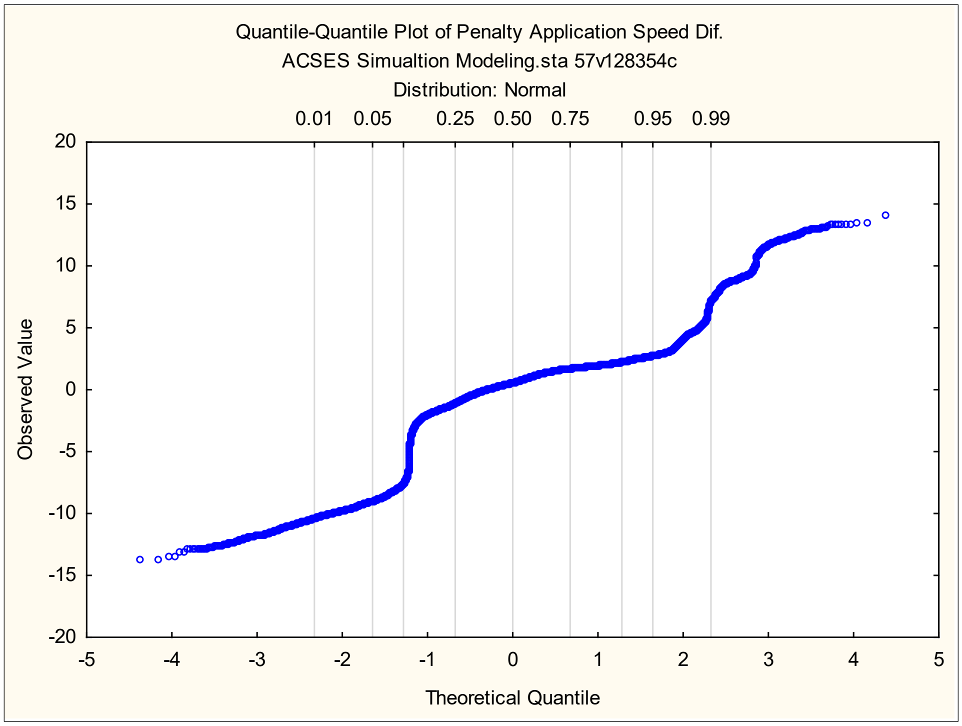


Figure 9. QQ-plot of Penalty Application Speed Difference for ACSES Simulations

Figure 10 shows the overall spread of data in a scatter plot of stopping location relative to target versus penalty application speed difference. The graph shows that simulations with a penalty application speed difference greater than ±5 mph did not overrun and did not negatively bias the final results. The group of simulations that stopped about 30,000 feet short of the target location were all simulations run at 45 mph down a 3.7 percent grade. The large group centered around 10,000 feet short of the target location were a mix of the following speed and grade combinations:

- 25 mph, -3.7 percent
- 75 mph, -2.4 percent
- 50 and 80 mph, -3.0 percent
- 80 mph, -2.0 percent
- 90 mph, -1.5 percent

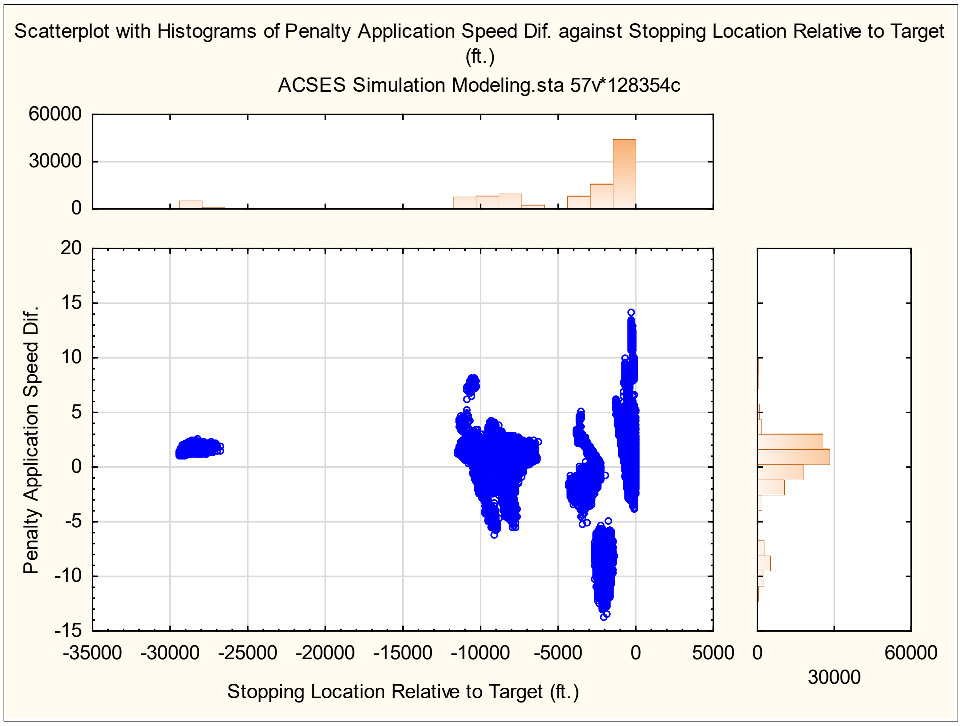


Figure 10. Scatterplot of Stopping Location Relative to Target vs. Penalty Application Speed Difference

4.3 Overall Summary

After the data was investigated for reliability and to understand the underlying characteristics, results were generated. Table 25 shows the overall results of the simulation testing. The two main statistics presented are:

- Probability of Stopping Short of Target: The probability that a given train, under the given operating conditions, will stop short of the given stopping target following a PTC enforcement.
- Probability of Stopping Short of Performance Limit (undershoot): The probability that a given train, under the given operating conditions will stop short of the target by > 500 feet for speeds < 30 mph and > 1,200 feet for speeds ≥ 30 mph, following a PTC enforcement.

Table 25. Overall Enforcement Algorithm Simulation Test Results

Train Type	Probability of Stopping Short of Target	Probability of Stopping Short of Performance Limit
B	99.90%	63.00%

The probability of stopping short of the target, as shown in Table 25, was 99.90 percent for the train type B algorithm setting. This value met the previously established safety objective of being able to stop short of the target with a probability of ≥ 99.5 percent. The probability of stopping short of the performance limit was conservative at 63.00 percent.

Table 26 and Table 27 show further results broken down by stopping configuration, target speed at enforcement, and grade. Also included in the tables is an additional measure of performance:

- Enforcement Location Relative to Target (Mean): This is the mean difference between the target stopping location and the enforcement location in each simulation.

Table 26. ACSES Blended Braking Results

Target Speed at Braking	Grade	Stopping Location Relative to Target (ft.)			Enforcement Location Relative to Target (ft.)
		Mean	Minimum	Maximum	Mean
10	0.0f	-81.3	-289.6	-8.9	-206.3
10	0.5i	-69.1	-188.7	-15.9	-186.3
10	1.5d	-211.4	-409.4	-107.3	-343.2
10	1.5i	-41.4	-126.0	23.9	-138.8
10	2.4d	-405.6	-760.0	-193.2	-541.5
10	2d	-296.7	-670.7	-128.5	-423.2
10	3.7d	-2,921.6	-3,709.4	-2,234.0	-3,083.4
10	3d	-705.4	-1,271.3	-390.6	-846.5
25	3.7d	-11,049.7	-11,456.1	-9,266.4	-11,817.6
45	3.7d	-28,702.0	-29,405.0	-27,471.3	-30,806.8
50	3d	-9,010.9	-9,736.8	-7,985.3	-11,151.2
75	2.4d	-9,779.8	-11,143.1	-7,721.7	-13,857.2
80	2d	-8,140.1	-9,169.4	-6,236.5	-12,406.0
90	0.0f	-3,278.1	-4,295.1	-2,002.5	-7,342.6
90	1.5d	-7,450.4	-8,369.6	-6,327.0	-12,431.7
90	1.5i	-2,036.2	-2,636.3	-1,409.4	-5,025.5

Table 27. ACSES Pneumatic Only Braking Results

Target Speed at Braking	Grade	Stopping Location Relative to Target (ft.)			Enforcement Location Relative to Target (ft.)
		Mean	Minimum	Maximum	Mean
10	0.0f	-81.4	-289.6	-8.9	-206.3
10	0.5i	-69.0	-192.5	-22.8	-185.9
10	1.5d	-218.9	-472.5	-89.8	-347.1
10	1.5i	-41.4	-117.3	25.5	-138.3
10	2.4d	-413.7	-817.0	-193.2	-548.2
10	2d	-316.8	-706.8	-125.3	-449.5
10	3.7d	-3,140.5	-3,864.5	-2,317.6	-3,309.0
10	3d	-720.6	-1,313.3	-395.0	-861.1
25	3.7d	-11,042.4	-11,456.1	-9,283.3	-11,825.6
45	3.7d	-28,481.3	-29,405.0	-26,751.8	-30,819.7
50	3d	-8,748.1	-10,852.9	-7,541.4	-10,908.0
75	2.4d	-9,599.7	-11,409.9	-7,721.7	-13,810.1
80	2d	-8,045.0	-9,229.3	-6,236.5	-12,432.7
90	0.0f	-3,278.1	-4,295.1	-2,002.5	-7,342.3
90	1.5d	-7,468.3	-8,369.6	-6,326.4	-12,428.4
90	1.5i	-2,036.3	-2,635.5	-1,409.4	-5,021.7

4.4 Characterization of Overruns

In total, in 95 out of 99,400 individual simulations the trains overran the target stopping position. Table 28 shows details of the overruns separated by brake application type, speed, and grade. The overruns all occurred at 10 mph on the 1.5 percent incline grade with the maximum distance past the target position at 25.5 feet.

Table 28. Count of Simulations that Overran the Target Position

				Stopping Location Relative to Target (ft.)		
Brake Application Type	Target Speed at Braking	Grade	Count	Mean	Minimum	Maximum
Blended	10	1.5i	49	6.1	0.1	23.9
Pneumatic Only	10	1.5i	46	6.7	0.0	25.5

4.5 Characterization of Undershoots

In total, in 62,596 of 99,400 individual simulations the train stopped short of the performance limit out. The established criteria for a simulation to be considered an "undershoot" or to have stopped short of the performance limit is as follows:

- Probability of stopping short of performance limit (undershoot): The probability that a given train, under the given operating conditions will stop short of the target by > 500 feet for speeds < 30 mph and > 1,200 feet for speeds ≥ 30 mph, following a PTC enforcement.

Table 29 shows a summary count of all simulations that undershot the performance target. The algorithm performed conservative across most speed and grade combinations with notably lower counts (i.e., less conservative) at 10 mph, 2.0 percent downgrade, and 2.4 percent downgrade.

Table 29. Count of Simulations that Undershot the Performance Target

Brake Application Type	Target Speed at Braking	Grade	Count
Pneumatic Only	10	2.4d	754
		2d	186
		3.7d	3073
		3d	2844
	25	3.7d	3548
	45	3.7d	3079
	50	3d	3080
	75	2.4d	2530
	80	2d	2640
	90	0.0f	3077
		1.5d	1756
		1.5i	5600
Blended	10	2.4d	576
		2d	156
		3.7d	2633
		3d	2649
	25	3.7d	3105
	45	3.7d	2640
	50	3d	3075
	75	2.4d	2524
	80	2d	2631
	90	0.0f	3080
		1.5d	1760
		1.5i	5600

5. Baseline Passenger and Commuter PTC Braking Enforcement Algorithm Definition and Simulation Analysis

The baseline passenger and commuter enforcement algorithm is planned to be used in the research and development of methods for improving the safety and performance of PTC braking enforcement algorithms for passenger and commuter operations in two ways:

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 enhancement to the braking algorithm

Once the baseline enforcement algorithm was developed, the logic was implemented in a test software application that could interface the simulation environment. The algorithm was evaluated using the simulation test methodology described in Section 2.2 to develop reference data for comparison against future developments. The baseline algorithm logic and assumptions were then reviewed, and issues were identified to be resolved before proceeding with the research and development of enhancements to the braking algorithm.

The following section is split into two parts. The first part describes the baseline algorithm and why it is used. The second part shows the results of the baseline algorithm evaluation.

5.1 Development of Phase I Algorithm

The requirements for selecting a base braking enforcement algorithm were that the enforcement algorithm must be nonproprietary so that the logic could be accessed for implementation in the test software and must 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 the one designed and implemented by TTCI as part of previous work completed for the freight base case algorithm [8]. The algorithm logic is described in Appendix B.

The braking enforcement algorithm estimated 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 was made using a numerical integration method from a force-acceleration model of the train. In this method, the forces acting on the train were estimated at each time step following the penalty brake application, which were then used to estimate the acceleration of the train. The acceleration was used to predict the velocity and position of the train for the next time step. The process was repeated until the predicted velocity of the train was zero, and then the predicted stopping distance was determined. The stopping distance was 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 was beyond the authority limit of the train, a penalty brake application was 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 North American Joint Positive Train Control (NAJPTC) 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 allow for easier implementation of the functions to be developed as part of future efforts to investigate potential enhancements to the algorithm logic. Modifications to the interface to the evaluation test environment also were made to allow for more simulations to be run in a shorter period of time than in the previous project.

The target offset function included in the baseline enforcement algorithm for freight operations was developed based on the potential variation from the mean stopping distance prediction for the types of trains and operational conditions expected during freight operations. As this target offset function did not consider passenger and commuter operations, it was removed from the version simulated during this project. An effort was conducted to develop a target offset function more suited to passenger and commuter trains and operational characteristics, following the evaluation of the baseline algorithm. That effort is described in further detail in Section 6.

5.2 Baseline Enforcement Algorithm Evaluation

The simulation testing methodology described in Section 2 was performed on the baseline enforcement algorithm.

5.2.1 Overall Summary

After the data was investigated for reliability and to understand the underlying characteristics, results were generated. Table 30 shows the overall results of the simulation testing separated by train type and brake application type. In the case of the baseline algorithm the train types were separated into two groups based on the equipment brake rate: above 1.7 mph/s and below 1.7 mph/s. The two main statistics presented are:

- Probability of Stopping Short of Target: The probability that a given train, under the given operating conditions, will stop short of the given stopping target following a PTC enforcement.
- Probability of Stopping Short of Performance Limit (undershoot): The probability that a given train, under the given operating conditions will stop short of the target by > 500 feet for speeds < 30 mph and > 1,200 feet for speeds ≥ 30 mph, following a PTC enforcement.

Table 30. Overall Enforcement Algorithm Simulation Test Results

Train Type	Brake Application Type	Probability of Stopping Short of Target	Probability of Stopping Short of Performance Limit
Brake Rate < 1.7	Blended	79.34%	0.02%
	Friction	77.90%	0.00%
Brake Rate >= 1.7	Blended	81.94%	0.00%
	Friction	78.90%	0.07%

The probability of stopping short of the target as shown in Table 30 ranged from 77.90 to 81.94 percent for the different train types and brake application types. These values did not meet the previously established safety objective of being able to stop short of the target with a probability of ≥ 99.5 percent. This was because this version of the algorithm did not include a target offset function and therefore represents the accuracy of the braking prediction alone, without adjusting for the variations in braking distance to achieve the safety objective, which would normally be accounted for by the target offset. The probability of stopping short of the performance limit was very low, ranging from 0 to 0.07 percent.

Tables 29 through Table 32 show results further broken down by brake rate grouping, target speed at enforcement, and grade. Also included in the tables is an additional measure of performance:

- Enforcement Location Relative to Target (mean): This is the mean difference between the target stopping location and the enforcement location in each simulation.

Table 31 shows results for train types with brake rate less than 1.7 mph/s using blended braking. Most overruns can be seen in the higher speed runs by observing the positive numbers in the maximum column for stopping location relative to target.

Table 31. Baseline Algorithm, Brake Rate < 1.7, Blended Braking Results

Target Speed at Braking	Grade	Stopping Location Relative to Target (ft.)			Enforcement Location Relative to Target (ft.)
		Mean	Minimum	Maximum	Mean
10	0.0f	-66.1	-100.0	0.0	-180.2
	0.5i	-64.5	-100.0	0.0	-169.7
	1.5d	-62.3	-99.8	-0.1	-189.7
	1.5i	-36.9	-100.0	0.0	-133.5
	2.4d	-55.1	-100.0	-0.1	-197.7
	2d	-55.7	-99.9	0.0	-190.4
	3.7d	-57.4	-99.9	0.0	-257.2
	3d	-55.1	-99.9	-0.2	-221.3
25	3.7d	-49.5	-100.0	0.0	-779.8
45	3.7d	-46.2	-100.0	664.1	-1,919.4
50	2d	-52.9	-99.3	-0.8	-2,189.7
	3d	-52.7	-1,932.7	323.2	-2,081.3
75	2.4d	534.8	-99.9	2,004.9	-3,483.0
80	2.4d	597.5	-98.8	2,031.4	-3,686.3
	2d	587.8	-99.3	1,854.9	-3,648.0
90	0.0f	229.7	-100.0	1,213.4	-4,138.1
	1.5d	948.0	-100.0	2,386.7	-4,035.0
	1.5i	-48.9	-100.0	-0.1	-2,625.4

Table 32. Baseline Algorithm, Brake Rate < 1.7, Pneumatic Only Braking Results

Target Speed at Braking	Grade	Stopping Location Relative to Target (ft.)			Enforcement Location Relative to Target (ft.)
		Mean	Minimum	Maximum	Mean
10	0.0f	-66.0	-100.0	-0.1	-179.8
	0.5i	-64.6	-100.0	0.0	-169.8
	1.5d	-59.2	-100.0	149.8	-182.9
	1.5i	-37.0	-100.0	0.0	-133.5
	2.4d	-51.4	-100.0	-0.1	-193.6
	2d	-60.7	-100.0	0.0	-188.7
	3.7d	-57.7	-99.9	0.0	-247.0
	3d	-52.1	-99.9	0.0	-218.3
25	3.7d	-48.8	-100.0	0.0	-778.1
45	3.7d	-31.1	-100.0	1,737.5	-2,056.2
50	2d	-50.3	-100.0	-2.0	-2,255.7
	3d	-39.3	-100.0	974.1	-2,181.5
75	2.4d	758.6	-99.9	2,566.5	-3,482.6
80	2.4d	544.6	-99.0	1,986.6	-3,685.0
	2d	842.2	-98.2	2,309.7	-3,667.4
90	0.0f	229.9	-100.0	1,213.4	-4,137.8
	1.5d	1,090.8	-100.0	3,080.7	-4,030.8
	1.5i	-43.5	-100.0	1,390.9	-2,619.6

Table 33. Baseline Algorithm, Brake Rate >=1.7, Blended Braking Results

Target Speed at Braking	Grade	Stopping Location Relative to Target (ft.)			Enforcement Location Relative to Target (ft.)
		Mean	Minimum	Maximum	Mean
10	0.0f	-62.5	-100.0	0.0	-177.3
10	0.5i	-60.1	-100.0	0.0	-164.4
10	1.5d	-64.6	-99.7	0.0	-185.9
10	1.5i	-37.7	-100.0	0.0	-135.9
10	2.4d	-56.4	-100.0	-0.1	-191.8
10	2d	-54.4	-99.9	-0.4	-197.1
10	3.7d	-60.8	-99.9	0.0	-272.7
10	3d	-54.9	-99.9	-0.2	-216.1
25	3.7d	-49.4	-100.0	0.0	-693.6
45	3.7d	-49.1	-100.0	0.0	-1,719.3
50	2d	-53.8	-99.3	-0.8	-2,191.2
50	3d	-49.9	-100.0	-0.1	-1,914.6
75	2.4d	206.2	-99.9	1,259.7	-3,469.7
80	2.4d	596.3	-98.8	1,910.2	-3,688.7
80	2d	266.6	-99.3	1,007.0	-3,659.4
90	0.0f	64.8	-100.0	8,53.6	-4,068.2
90	1.5d	669.0	-100.0	1,778.5	-4,022.5
90	1.5i	-48.9	-100.0	0.0	-2,603.6

Table 34. Baseline Algorithm, Brake Rate >=1.7, Pneumatic Only Braking Results

Target Speed at Braking	Grade	Stopping Location Relative to Target (ft.)			Enforcement Location Relative to Target (ft.)
		Mean	Minimum	Maximum	Mean
10	0.0f	-63.7	-100.0	-0.1	-176.0
10	0.5i	-60.5	-137.9	0.0	-166.0
10	1.5d	-67.3	-99.9	-0.1	-183.8
10	1.5i	-37.6	-100.0	0.0	-134.9
10	2.4d	-71.1	-265.6	0.0	-221.7
10	2d	-57.1	-231.9	0.0	-200.0
10	3.7d	-57.6	-99.9	0.0	-277.8
10	3d	-52.7	-99.9	-0.1	-216.1
25	3.7d	-133.4	-603.5	-0.1	-812.0
45	3.7d	-46.8	-100.0	570.8	-1,831.5
50	2d	-49.0	-100.0	-0.9	-2,253.3
50	3d	-49.2	-100.0	62.4	-2,018.9
75	2.4d	392.1	-2,382.0	2,002.6	-3,485.7
80	2.4d	544.6	-99.0	1,986.6	-3,684.1
80	2d	509.6	-97.1	1,594.6	-3,654.4
90	0.0f	57.8	-100.0	852.9	-3,996.3
90	1.5d	930.4	-100.0	2,224.5	-3,909.0
90	1.5i	-48.7	-99.9	-0.1	-2,599.3

5.2.2 Characterization of Overruns

In total, 35,796 of 173,463 individual simulations overran the target stopping position. The count of simulations which stopped past the target location was relatively equal between the various consists, enforcement algorithm train type, and brake application type. Table 35 shows the count of overruns by target speed and grade. The 90 mph, 1.5 percent decline; 80 mph, 2 percent decline; and 75 mph, 2.4 percent decline cases accounted for 79.37 percent of the simulations that stopped past the target location.

Table 35. Count of Simulations that Overran the Target Position

Target Speed at Braking	Grade	Count	Percent
10	1.5d	110	0.31%
45	3.7d	213	0.60%
50	3d	164	0.46%
75	2.4d	6,729	18.80%
80	2.4d	1,569	4.38%
80	2d	8,303	23.20%
90	0.0f	5,309	14.84%
90	1.5d	13,373	37.37%
90	1.5i	14	0.04%

5.2.3 Characterization of Undershoots

In total, in 35 of 173,463 individual simulations the train stopped short of the performance limit. The established criteria for a simulation to be considered an "undershoot" or to have stopped short of the performance limit is as follows:

- Probability of stopping short of performance limit (undershoot): The probability that a given train, under the given operating conditions will stop short of the target by > 500 feet for speeds < 30 mph and > 1,200 feet for speeds ≥ 30 mph, following a PTC enforcement.

Table 36 shows a summary count of all simulations that undershot the performance target. About two-thirds of the undershoot simulations came from the 25 mph, 3.7 percent downgrade simulations.

Table 36. Count of Simulations that Undershot the Performance Target

					Stopping Location Relative to Target (ft.)	
EA Train Type	**Brake Application Type**	**Target Speed at Braking**	**Grade**	**Count**	**Minimum**	**Maximum**
Brake Rate < 1.7	Blended	50	3d	8	-1,932.68	-1,571.69
Brake Rate >= 1.7	Friction	75	2.4d	7	-2,382.05	-2,107.37
Brake Rate >= 1.7	Friction	25	3.7d	20	-581.52	-500.01

6. Development of a Target Offset Function for Passenger and Commuter Operations

The target offset function of the PTC braking enforcement algorithm accounts for potential variability in the stopping distance of the train for the particular conditions (e.g., speed, train type, track grade, etc.) and adjusts the braking prediction accordingly to achieve the specified probability of stopping short of the target. Because the algorithm on which the baseline was based had a target offset function developed specifically for freight operations, it could not be effectively used for an algorithm designed for passenger and commuter operations. This section describes the effort to develop a target offset function suitable for use in algorithms designed for these types of operations.

To compute a target offset that represents the variability of the stopping distance for passenger and commuter trains, a range of scenarios were selected for use in a Monte Carlo simulation method. The Monte Carlo simulation method was used to quantify the variability of stopping distances for the scenarios while accounting for the variability of factors that affect stopping distance (e.g., brake pipe leakage, brake unit effectiveness, etc.). After Monte Carlo simulations were performed, statistical analysis was used to determine the target offset necessary to meet the safety objective probability limit of 99.5 percent for each specific scenario. Calculated target offset results were then combined using multi-variable regression techniques to generate a function that estimates the target offset for any scenario.

To be successful, it was necessary for the matrix of simulation scenarios to cover a range of train types, consist lengths, train speeds, and track grades. The same consists used when evaluating the enforcement algorithms were used but were placed into scenarios with a wider range of speeds and grades at smaller granularities. Table 37 shows the grades and speeds used. Each grade was matched with each speed. Some combinations were outside of those that might be possible in revenue service (e.g., 4 percent decline and 90 mph) but still needed to be considered to establish the complete range of the function. In total, the number of simulation scenarios was 3,016 and at least 100 simulations were run for each scenario with Monte Carlo variance of the parameters discussed in Section 2.2.2.

Table 37. List of Speeds and Grades Used in Combination for Target Offset Simulations

Starting Speed (mph)	Grade
10	Flat
15	0.5% Incline
20	1.5% Incline
30	3% Incline
40	4% Incline
45	0.5% Decline
60	1.5% Decline
90	3% Decline
-	4% Decline

From the stopping distance simulation data generated using the Monte Carlo method, the target offset for each scenario was computed based on the Winsorized mean of the distribution and the 99.5 percent quantile, as follows:

$$Target\ Offset = 99.5\%\ Quantile - Winsorized\ Mean \tag{2}$$

Direct computation of the 99.5 percent quantile for each scenario was not possible due to the small sample size of only 100 for each scenario. To estimate quantiles beyond the limit of the observed data set, the peaks-over-threshold (POT) method was used. Each scenario's 10 percent tail data was fit to an appropriate distribution and then expanded via Monte Carlo simulation using the EasyFit software package.

The process of the POT method considers the top 10 percent of the upper tail of each scenario's distribution (10 data points out of 100). These points are fit to an appropriate distribution and are expanded using that distribution to simulate 5,000 sample points using Monte Carlo expansion. The expansion allowed the desired quantile value to be calculated directly; the 95 percent quantile of the expanded data was calculated. The 95 percent quantile of the expanded data is equivalent to the 99.5 percent quantile of the original scenario distribution.

The Winsorized mean was used in the calculation of target offset to reduce the effect of the tail values on the full distribution and provides a better estimate of the mean based on the main body of data. The mean was Winsorized at 5 percent. Winsorizing is achieved by ordering the stopping distance result values from smallest to largest and by replacing the top and bottom x percent (in this case 5 percent) of tail data with the nearest adjacent value.

Next, the calculated target offset values for each scenario were combined and regression analysis techniques were applied to find a regression model that could predict the target offset for any scenario. Regression is used to determine the statistical relationship between the independent variables (predictors or contributors) in predicting a dependent (response) variable. The independent variables used initially were speed, grade, number of axles, consist weight in tons, number of cars in consist, and number of locomotives in consist. These were selected based on what inputs can currently be used for the existing enforcement algorithms. The selected independent variables were trimmed down to only include speed, grade, number of axles, and consist weight in tons through the regression process, which determined that they were the significant contributors in predicting target offset. The process of significant contributor selection included several intermediate analysis steps to check the value of each variable and to see if the model improved without variables that might be found as insignificant. Also, redundant factors that complicated the model without improving predication accuracy were removed in this process. For example, the number of axles was found to be redundant with consist weight in tons, but weight was found to be a stronger predicting variable. Also included in the intermediate analysis steps were attempts to separate or group the data, the result of which improved regression prediction accuracy at the price of including more functions. It was found that separating the groups based on grade and approximate brake rate gave the best results. A supplemental set of simulations was completed to estimate the brake rate of each consist.

The optimum regression equation was fit to the data using the least squares method through the Datafit software package. Table 38 shows the equations for target offset (TO) for each grouping. Each is a function of train velocity, v, the equivalent constant grade over the predicted stopping distance, g, the consist weight in tons, W_{TRAIN}, and the total axles in the consist, A_{TRAIN}.

Table 38. Target Offset Functions by Grouped by Grade and Brake Rate

Grade	Brake Rate	Target Offset Function
Less than -1.5	Between 1.2 and 1.7	$TO = e^{0.0288v - 0.52g - 0.106A_{TRAIN} + 0.005W_{TRAIN} + 2.911}$
Less than -1.5	Greater than 1.7	$TO = 8.726v - 76.004g - 4.502A_{TRAIN} - 0.175W_{TRAIN} - 110.773$
Between -1.5 and 0	Between 1.2 and 1.7	$TO = e^{0.027v - 0.077g - 0.012A_{TRAIN} + 0.0004W_{TRAIN} + 4.054}$
Between -1.5 and 0	Greater than 1.7	$TO = e^{0.026v + 0.05g + 0.007A_{TRAIN} - 0.0009W_{TRAIN} + 4.184}$
Between 0 and 1.5	Between 1.2 and 1.7	$TO = e^{0.026v - 0.084g - 0.0004A_{TRAIN} - 0.0001W_{TRAIN} + 4.03}$
Between 0 and 1.5	Greater than 1.7	$TO = 4.697v + 0.73g + 1.48A_{TRAIN} - 0.104W_{TRAIN} - 14.108$
Greater than 1.5	Between 1.2 and 1.7	$TO = 4.129v - 4.541g + 1.064A_{TRAIN} - 0.079W_{TRAIN} + 12.025$
Greater than 1.5	Greater than 1.7	$TO = 3.54v + 2.681g + 2.389A_{TRAIN} - 0.079W_{TRAIN} - 41.736$

The use of this target offset function resulted in a target offset that was more closely related to the specific characteristics of the scenario at the time the stopping distance prediction was made, due to the function taking the brake rate into consideration. The target offset function was also designed to produce a result that would give a high confidence in achieving the 0.995 probability of stopping short of the target without additional unnecessary conservatism.

7. Conclusion

As the primary objective of the project, the I-ETMS and ACSES enforcement algorithms were evaluated using passenger and commuter equipment and operational scenarios. Both algorithms were shown to meet the safety objective of having a probability of stopping short of the target of higher than 99.5 percent.

Table 39 shows the combined overall results of the I-ETMS and ACSES enforcement algorithms. The commuter train type used by the I-ETMS algorithm had more overruns when compared to the passenger train type. Most overruns for either train type occurred during higher speed and steeper downhill scenarios. While these scenarios are not outside of the operational envelope, they are less often encountered than many of the other operational conditions considered. While the passenger train type resulted in a lower probability of target overrun, it also was more conservative, having a probability of stopping short of the performance limit that was more than double the commuter train type.

The ACSES algorithm only overran the target during 10 mph, 1.5 degree inclines. The magnitude of the overruns were small, with none passing the target by more than 26 feet. ACSES was much more conservative, with 63 percent of simulations resulting in the train stopping short of the performance limit.

Table 39. I-ETMS and ACSES Overall Simulations Results

Enforcement Algorithm	Train Type	Probability of Stopping Short of Target	Probability of Stopping Short of Performance Limit
I-ETMS	Commuter	99.78%	12.90%
	Passenger	99.95%	33.56%
ACSES	B	99.90%	63.00%

A baseline enforcement algorithm for passenger and commuter trains also was created and evaluated during this project, to be used as a foundation for developing and evaluating potential algorithm improvements and to establish a baseline performance level for comparing against the performance of algorithms with these improvements included. The evaluation of the baseline enforcement algorithm showed that it was unsuccessful in meeting the safety objective established but did not include a target offset function. However, following the evaluation, a target offset function for passenger and commuter operations was developed with the objective of being included in the baseline algorithm in future evaluations to achieve the safety objective. Future recommended efforts in this area include implementation of the target offset function in the baseline algorithm, reevaluation of the baseline performance with the target offset function included, expansion of the simulation matrix to include more participating passenger and commuter railroads, identification of potential improvements to passenger and commuter algorithms, implementation of identified improvements in the braking algorithm test application, and evaluation of the effectiveness of the identified improvements through comparison against the baseline performance level. Through these efforts, it is expected that the safety and performance characteristics of PTC braking algorithms for passenger and commuter operations can continue to achieve the safety objectives of the system while minimizing the potential impact on operations.

8. References

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Appendix A.
Detailed Breakdown Results of I-ETMS Algorithm

Table 40. Agency 1 Results: Commuter, Emergency Brake Backup Disabled, and Blended Braking

Target Speed at Braking	Grade	Stopping Location Relative to Target (ft.)			Enforcement Location Relative to Target (ft.)
		Mean	Minimum	Maximum	Mean
10	0.0f	-124.98	-191.27	45.96	-228.42
	0.5i	-110.00	-148.26	-75.81	-204.39
	1.5d	-130.78	-263.59	2.27	-250.76
	1.5i	-92.61	-129.63	-60.56	-178.85
	2.4d	-150.58	-302.99	-8.26	-293.58
	2d	-123.21	-267.43	-20.12	-257.83
	3.7d	-214.55	-414.16	-4.88	-387.38
	3d	-121.80	-317.71	-0.03	-277.40
25	3.7d	-502.46	-1,122.41	-0.31	-1,238.35
45	3.7d	-1,031.38	-2,391.34	-0.13	-2,727.87
50	2d	-574.87	-830.62	-375.45	-2,603.32
	3d	-838.12	-1,971.77	-0.18	-2,447.66
75	2.4d	-1,190.60	-3,163.98	202.27	-4,422.05
80	2d	-1,487.69	-3,231.72	-4.59	-4,824.92
90	0.0f	-1,304.70	-2,504.94	-15.76	-4,883.94
	1.5d	-1,709.67	-3,534.42	-1.93	-5,733.82
	1.5i	-996.31	-1,918.85	-49.14	-3,962.84

Table 41 shows similar results to Table 42 in that there were no overruns of the target and there were similar stopping distances and enforcement locations.

Table 41. Agency 1 Results: Commuter, Emergency Brake Backup Disabled, and Pneumatic Only Braking

Target Speed at Braking	Grade	Stopping Location Relative to Target (ft.)			Enforcement Location Relative to Target (ft.)
		Mean	Minimum	Maximum	Mean
	0.0f	-123.91	-191.27	45.96	-229.16
	0.5i	-110.00	-148.26	-75.81	-204.38
	1.5d	-109.55	-235.93	9.36	-218.51
	1.5i	-92.72	-129.63	-60.56	-178.90
	2.4d	-161.50	-312.41	-22.01	-309.37
	2d	-123.39	-248.88	-40.62	-258.40
	3.7d	-232.96	-435.88	-4.62	-411.84
	3d	-128.90	-363.18	-0.39	-287.20
25	3.7d	-484.86	-1,119.59	-0.11	-1,234.19
45	3.7d	-909.43	-2,259.47	12.27	-2,702.26
50	2d	-471.57	-727.30	-172.51	-2,556.14
	3d	-764.04	-1,971.05	23.08	-2,444.67
75	2.4d	-946.16	-3,046.67	15.73	-4,301.76
80	2d	-1,248.82	-3,251.88	-0.08	-4,671.04
90	0.0f	-1,308.83	-2,487.94	-0.36	-4,885.60
	1.5d	-1,502.40	-3,465.96	-0.21	-5,643.75
	1.5i	-996.10	-1,918.85	-49.14	-3,963.01

Table 42. Agency 1 Results: Commuter, Emergency Brake Backup Enabled, and Blended Braking

Target Speed at Braking	Grade	Stopping Location Relative to Target (ft.)			Enforcement Location Relative to Target (ft.)
		Mean	Minimum	Maximum	Mean
10	0.0f	-92.81	-148.97	-0.36	-197.97
10	0.5i	-81.61	-126.66	-33.68	-176.46
10	1.5d	-100.56	-239.86	-0.39	-220.24
10	1.5i	-67.16	-99.83	-26.17	-152.42
10	2.4d	-113.37	-256.01	-0.09	-254.30
10	2d	-88.15	-216.15	-12.72	-221.92
10	3.7d	-136.22	-318.83	-1.04	-300.86
10	3d	-93.09	-254.93	-0.10	-243.72
25	3.7d	-317.95	-896.41	-0.11	-1,017.47
45	3.7d	-677.44	-1,807.18	-0.07	-2,258.48
50	2d	-185.70	-359.07	-38.84	-2,244.57
50	3d	-653.28	-1,652.17	-0.20	-2,180.98
75	2.4d	-777.06	-2,584.64	-0.11	-3,904.95
80	2d	-1,071.33	-2,673.26	-0.28	-4,328.51
90	0.0f	-888.45	-1,959.95	46.94	-4,466.67
90	1.5d	-1,170.34	-2,890.79	-0.59	-5,152.02
90	1.5i	-682.00	-1,532.62	-1.99	-3,604.80

Table 43. Agency 1 Results: Commuter, Emergency Brake Backup Enabled, and Pneumatic Only Braking

Target Speed at Braking	Grade	Stopping Location Relative to Target (ft.)			Enforcement Location Relative to Target (ft.)
		Mean	Minimum	Maximum	Mean
10	0.0f	-92.94	-150.03	-0.36	-198.06
10	0.5i	-81.66	-126.66	-33.68	-176.47
10	1.5d	-80.12	-206.03	-0.61	-187.86
10	1.5i	-67.13	-99.83	-28.01	-152.39
10	2.4d	-121.54	-269.90	-1.87	-267.37
10	2d	-88.10	-214.35	-3.74	-222.10
10	3.7d	-150.91	-334.66	-1.37	-320.21
10	3d	-99.68	-295.73	-0.19	-253.84
25	3.7d	-318.51	-884.58	-0.07	-1,027.06
45	3.7d	-650.28	-1,742.59	0.00	-2,278.68
50	2d	-127.20	-310.32	-23.16	-2,226.84
50	3d	-611.72	-1,639.61	-0.05	-2,183.88
75	2.4d	-599.82	-2,550.59	81.56	-3,832.38
80	2d	-931.81	-2,540.88	-0.05	-4,243.45
90	0.0f	-888.02	-1,959.95	-0.48	-4,466.66
90	1.5d	-1,053.91	-2,769.69	164.26	-5,113.78
90	1.5i	-681.92	-1,532.62	-1.99	-3,604.72

Table 44. Agency 1 Results: Passenger, Emergency Brake Backup Disabled, and Blended Braking

Target Speed at Braking	Grade	Stopping Location Relative to Target (ft.)			Enforcement Location Relative to Target (ft.)
		Mean	Minimum	Maximum	Mean
10	0.0f	-129.99	-194.67	28.94	-235.03
10	0.5i	-113.41	-158.82	-76.88	-207.77
10	1.5d	-152.35	-292.32	-14.10	-272.83
10	1.5i	-94.48	-129.63	-60.56	-180.78
10	2.4d	-192.45	-340.51	-28.93	-336.79
10	2d	-156.34	-294.74	-46.36	-292.19
10	3.7d	-317.47	-620.94	-15.02	-500.96
10	3d	-174.01	-478.39	-0.05	-332.51
25	3.7d	-935.18	-1,715.08	-293.26	-1,682.52
45	3.7d	-2,316.29	-3,500.12	-1,247.15	-4,060.61
50	2d	-1,344.33	-1,760.25	-890.62	-3,251.77
50	3d	-1,836.58	-3,036.66	-42.08	-3,473.48
75	2.4d	-3,033.10	-5,113.35	-527.97	-6,168.29
80	2d	-3,562.84	-5,280.24	-1,923.91	-6,955.73
90	0.0f	-2,531.46	-3,769.98	-1,171.55	-6,069.82
90	1.5d	-3,951.43	-5,954.03	-1,690.51	-7,967.35
90	1.5i	-1,809.21	-2,881.93	-842.91	-4,868.91

Table 45. Agency 1 Results: Passenger, Emergency Brake Backup Disabled, and Pneumatic Only Braking

Target Speed at Braking	Grade	Stopping Location Relative to Target (ft.)			Enforcement Location Relative to Target (ft.)
		Mean	Minimum	Maximum	Mean
10	0.0f	-130.78	-194.67	28.94	-233.93
10	0.5i	-113.47	-158.82	-76.88	-207.77
10	1.5d	-132.12	-256.64	-2.47	-241.94
10	1.5i	-94.42	-129.63	-60.56	-180.69
10	2.4d	-207.51	-352.87	-35.48	-357.01
10	2d	-157.68	-283.52	-62.58	-293.63
10	3.7d	-344.29	-660.95	-9.10	-534.41
10	3d	-185.51	-583.39	-0.18	-347.28
25	3.7d	-919.66	-1,735.86	-282.38	-1,682.01
45	3.7d	-2,188.96	-3,488.19	-660.20	-4,048.12
50	2d	-1,241.81	-1,701.76	-804.39	-3,209.04
50	3d	-1,750.78	-3,041.70	-1.47	-3,469.93
75	2.4d	-2,794.74	-5,084.15	-20.65	-6,097.69
80	2d	-3,278.83	-5,169.39	-1,133.93	-6,774.83
90	0.0f	-2,530.73	-3,746.96	-1,117.86	-6,069.56
90	1.5d	-3,706.13	-5,865.02	-1,213.86	-7,837.11
90	1.5i	-1,816.02	-2,881.93	-842.91	-4,840.19

Table 46. Agency 1 Results: Passenger, Emergency Brake Backup Enabled, and Blended Braking

Target Speed at Braking	Grade	Stopping Location Relative to Target (ft.)			Enforcement Location Relative to Target (ft.)
		Mean	Minimum	Maximum	Mean
10	0.0f	-97.63	-156.84	62.93	-203.11
10	0.5i	-85.29	-132.96	-39.64	-180.04
10	1.5d	-120.91	-250.07	2.27	-241.00
10	1.5i	-68.58	-99.16	-28.47	-154.03
10	2.4d	-152.29	-302.99	-5.13	-294.76
10	2d	-118.55	-267.43	-30.08	-253.37
10	3.7d	-212.99	-431.88	-15.02	-385.48
10	3d	-139.27	-380.72	-0.35	-295.79
25	3.7d	-701.04	-1,386.32	-156.85	-1,443.90
45	3.7d	-1,896.58	-3,164.15	-662.05	-3,639.03
50	2d	-957.48	-1,208.24	-734.71	-2,934.26
50	3d	-1,595.91	-2,800.19	-19.11	-3,228.99
75	2.4d	-2,622.83	-4,685.45	-184.26	-5,783.38
80	2d	-3,051.82	-4,779.26	-1,465.52	-6,430.55
90	0.0f	-2,120.97	-3,343.24	-886.93	-5,673.72
90	1.5d	-3,352.66	-5,159.26	-1,202.16	-7,370.74
90	1.5i	-1,480.43	-2,473.44	-665.11	-4,500.27

Table 47. Agency 1 Results: Passenger, Emergency Brake Backup Enabled, and Pneumatic Only Braking

Target Speed at Braking	Grade	Stopping Location Relative to Target (ft.)			Enforcement Location Relative to Target (ft.)
		Mean	Minimum	Maximum	Mean
10	0.0f	-98.01	-156.84	62.93	-203.18
10	0.5i	-85.26	-132.96	-39.64	-180.02
10	1.5d	-100.45	-235.93	19.54	-209.07
10	1.5i	-68.84	-99.16	-30.23	-153.94
10	2.4d	-165.19	-312.41	-0.55	-312.93
10	2d	-120.06	-248.88	-31.79	-255.18
10	3.7d	-241.90	-475.15	-9.10	-421.86
10	3d	-150.99	-532.96	-0.89	-310.47
25	3.7d	-701.57	-1,484.20	-74.36	-1,459.72
45	3.7d	-1,812.82	-3,195.08	-220.41	-3,666.23
50	2d	-867.29	-1,129.47	-557.41	-2,894.87
50	3d	-1,527.09	-2,805.30	-0.06	-3,242.02
75	2.4d	-2,386.87	-4,695.82	-13.48	-5,708.35
80	2d	-2,797.86	-4,649.89	-782.13	-6,273.48
90	0.0f	-2,120.96	-3,343.24	-886.93	-5,673.72
90	1.5d	-3,129.32	-5,159.57	-842.90	-7,258.97
90	1.5i	-1,478.87	-2,473.44	-665.11	-4,501.31

Agency 2

Table 48. Agency 2 Results: Commuter, Emergency Brake Backup Disabled, and Blended Braking

Target Speed at Braking	Grade	Stopping Location Relative to Target (ft.)			Enforcement Location Relative to Target (ft.)
		Mean	Minimum	Maximum	Mean
10	0.0f	-146.11	-199.67	-115.48	-244.72
10	0.5i	-121.96	-148.63	-93.25	-210.49
10	1.5d	-170.83	-265.50	-79.99	-272.16
10	1.5i	-97.59	-127.14	-71.23	-169.58
10	2.4d	-138.83	-267.10	-65.60	-219.86
10	2d	-188.65	-273.57	-82.59	-298.41
10	3.7d	-327.88	-437.57	-132.98	-448.12
10	3d	-178.31	-301.07	-80.57	-268.06
25	3.7d	-529.51	-1,024.21	-52.13	-1,018.25
45	3.7d	-1,450.91	-1,762.76	-751.07	-2,906.11
50	3d	-946.55	-1,430.12	-382.02	-2,460.46
75	2.4d	-1,493.47	-2,318.18	-868.57	-4,555.41
80	2d	-1,624.04	-2,392.23	-1,008.01	-5,391.27
90	0.0f	-1,458.22	-1,716.10	-1,204.35	-4,908.79
90	1.5d	-1,808.75	-2,613.09	-1,219.80	-5,836.84
90	1.5i	-1,142.31	-1,374.23	-761.33	-4,048.99

Table 49. Agency 2 Results: Commuter, Emergency Brake Backup Disabled, and Pneumatic Only Braking

Target Speed at Braking	Grade	Stopping Location Relative to Target (ft.)			Enforcement Location Relative to Target (ft.)
		Mean	Minimum	Maximum	Mean
10	0.0f	-144.06	-192.99	-112.97	-240.17
10	0.5i	-122.76	-155.45	-92.45	-211.71
10	1.5d	-139.38	-247.99	-74.27	-231.50
10	1.5i	-97.33	-134.98	-72.62	-169.45
10	2.4d	-141.45	-281.95	-67.26	-224.20
10	2d	-194.39	-287.19	-79.81	-297.78
10	3.7d	-321.49	-450.58	-108.94	-440.19
10	3d	-185.72	-306.79	-85.04	-278.13
25	3.7d	-542.32	-1,010.69	-80.51	-1,024.29
45	3.7d	-1,425.29	-1,807.24	-817.15	-2,869.14
50	3d	-982.58	-1,501.95	-526.22	-2,495.45
75	2.4d	-1,550.39	-2,177.39	-1,015.28	-4,624.89
80	2d	-1,583.84	-2,134.63	-1,009.02	-5,218.13
90	0.0f	-1,462.88	-1,725.87	-1,210.28	-4,916.40
90	1.5d	-1,848.98	-2,583.45	-1,268.69	-5,825.41
90	1.5i	-1,154.86	-1,385.34	-929.69	-4,069.18

Table 50. Agency 2 Results: Commuter, Emergency Brake Backup Enabled, and Blended Braking

Target Speed at Braking	Grade	Stopping Location Relative to Target (ft.)			Enforcement Location Relative to Target (ft.)
		Mean	Minimum	Maximum	Mean
10	0.0f	-106.21	-139.06	-79.24	-202.43
10	0.5i	-92.19	-121.86	-61.12	-182.44
10	1.5d	-126.55	-216.80	-65.71	-226.22
10	1.5i	-68.25	-89.02	-45.10	-139.19
10	2.4d	-111.99	-218.59	-50.32	-194.79
10	2d	-156.06	-248.25	-56.04	-271.17
10	3.7d	-233.81	-330.96	-95.97	-348.36
10	3d	-149.97	-270.27	-54.49	-243.33
25	3.7d	-361.22	-742.61	-1.26	-833.93
45	3.7d	-998.53	-1,293.76	-375.93	-2,454.70
50	3d	-701.29	-1,144.01	-162.57	-2,240.09
75	2.4d	-1,013.32	-1,840.02	-353.70	-4,104.29
80	2d	-908.04	-1,678.20	-417.93	-4,701.67
90	0.0f	-965.94	-1,241.00	-675.55	-4,425.63
90	1.5d	-1,131.49	-1,975.68	-551.73	-5,137.95
90	1.5i	-770.62	-992.55	-534.60	-3,639.78

Table 51. Agency 2 Results: Commuter, Emergency Brake Backup Enabled, and Pneumatic Only Braking

Target Speed at Braking	Grade	Stopping Location Relative to Target (ft.)			Enforcement Location Relative to Target (ft.)
		Mean	Minimum	Maximum	Mean
10	0.0f	-106.32	-141.04	-79.24	-202.50
10	0.5i	-92.14	-121.86	-61.12	-182.41
10	1.5d	-105.69	-198.01	-47.12	-199.46
10	1.5i	-68.19	-89.02	-42.97	-139.12
10	2.4d	-116.18	-238.71	-49.68	-201.60
10	2d	-155.18	-242.00	-53.60	-260.93
10	3.7d	-227.99	-311.44	-74.70	-338.94
10	3d	-158.29	-274.62	-56.57	-255.28
25	3.7d	-362.11	-764.13	-0.18	-827.51
45	3.7d	-966.44	-1,300.29	-400.42	-2,392.88
50	3d	-728.57	-1,102.16	-285.62	-2,268.90
75	2.4d	-1,066.56	-1,619.55	-506.10	-4,173.15
80	2d	-991.69	-1,601.44	-439.53	-4,620.71
90	0.0f	-965.94	-1,241.00	-675.55	-4,425.63
90	1.5d	-1,162.16	-1,824.86	-598.16	-5,140.15
90	1.5i	-770.57	-992.55	-532.33	-3,639.78

Table 52. Agency 2 Results: Passenger, Emergency Brake Backup Disabled, and Blended Braking

Target Speed at Braking	Grade	Stopping Location Relative to Target (ft.)			Enforcement Location Relative to Target (ft.)
		Mean	Minimum	Maximum	Mean
10	0.0f	-150.65	-204.90	-118.26	-246.78
10	0.5i	-126.18	-158.29	-92.45	-214.93
10	1.5d	-192.62	-286.22	-107.92	-293.93
10	1.5i	-99.24	-127.33	-72.62	-171.43
10	2.4d	-163.07	-302.93	-91.67	-243.01
10	2d	-212.44	-297.99	-102.84	-318.27
10	3.7d	-450.16	-624.49	-160.52	-575.05
10	3d	-209.41	-346.47	-94.23	-295.82
25	3.7d	-815.68	-1,543.36	-270.21	-1,304.56
45	3.7d	-2,715.21	-3,435.24	-1,774.95	-4,102.67
50	3d	-1,853.16	-2,459.11	-1,501.84	-3,299.50
75	2.4d	-3,492.27	-4,403.76	-2,862.05	-6,485.29
80	2d	-4,116.07	-4,735.89	-3,467.44	-7,669.28
90	0.0f	-2,775.74	-3,087.45	-2,501.77	-6,210.30
90	1.5d	-4,092.74	-4,844.43	-3,481.02	-8,105.72
90	1.5i	-2,058.18	-2,311.22	-1,785.37	-5,120.09

Table 53. Agency 2 Results: Passenger, Emergency Brake Backup Disabled, and Pneumatic Only Braking

Target Speed at Braking	Grade	Stopping Location Relative to Target (ft.)			Enforcement Location Relative to Target (ft.)
		Mean	Minimum	Maximum	Mean
10	0.0f	-150.66	-204.90	-118.26	-246.72
10	0.5i	-126.18	-158.29	-92.45	-214.93
10	1.5d	-157.68	-270.70	-90.08	-248.20
10	1.5i	-99.23	-127.33	-72.62	-171.49
10	2.4d	-162.96	-300.50	-86.81	-243.68
10	2d	-220.76	-312.20	-93.97	-322.57
10	3.7d	-448.57	-598.35	-146.99	-573.63
10	3d	-217.47	-357.07	-103.66	-305.68
25	3.7d	-829.58	-1,617.42	-319.25	-1,313.94
45	3.7d	-2,776.00	-3,408.24	-1,931.31	-4,170.20
50	3d	-1,880.77	-2,441.57	-1,521.71	-3,312.82
75	2.4d	-3,449.47	-4,516.86	-2,898.95	-6,399.47
80	2d	-4,169.47	-4,604.22	-3,384.22	-7,704.67
90	0.0f	-2,775.74	-3,087.45	-2,501.77	-6,210.30
90	1.5d	-4,085.63	-4,708.51	-3,357.60	-8,037.62
90	1.5i	-2,058.23	-2,311.22	-1,785.37	-5,120.43

Table 54. Agency 2 Results: Passenger, Emergency Brake Backup Enabled, and Blended Braking

Target Speed at Braking	Grade	Stopping Location Relative to Target (ft.)			Enforcement Location Relative to Target (ft.)
		Mean	Minimum	Maximum	Mean
10	0.0f	-113.38	-162.64	-85.77	-209.62
10	0.5i	-96.06	-126.18	-67.47	-186.19
10	1.5d	-148.68	-235.04	-75.32	-249.05
10	1.5i	-70.41	-93.36	-42.97	-141.33
10	2.4d	-132.79	-265.97	-65.60	-214.18
10	2d	-179.98	-273.57	-69.85	-291.18
10	3.7d	-335.94	-474.89	-132.98	-456.67
10	3d	-181.30	-311.22	-80.57	-270.71
25	3.7d	-654.21	-1,327.70	-95.38	-1,141.58
45	3.7d	-2,365.04	-2,958.11	-1,378.57	-3,783.91
50	3d	-1,587.11	-2,207.82	-1,192.45	-3,046.91
75	2.4d	-2,949.23	-3,926.13	-2,306.73	-5,941.65
80	2d	-3,556.55	-4,117.39	-3,025.76	-7,180.37
90	0.0f	-2,302.88	-2,591.51	-2,069.80	-5,744.64
90	1.5d	-3,451.62	-4,132.16	-2,894.98	-7,472.84
90	1.5i	-1,662.80	-1,939.15	-1,400.96	-4,663.99

Table 55. Agency 2 Results: Passenger, Emergency Brake Backup Enabled, and Pneumatic Only Braking

Target Speed at Braking	Grade	Stopping Location Relative to Target (ft.)			Enforcement Location Relative to Target (ft.)
		Mean	Minimum	Maximum	Mean
10	0.0f	-113.45	-162.64	-85.77	-209.65
10	0.5i	-96.14	-126.18	-67.47	-186.24
10	1.5d	-123.00	-227.73	-62.07	-215.72
10	1.5i	-70.34	-93.36	-45.10	-141.32
10	2.4d	-136.65	-265.18	-62.50	-219.99
10	2d	-184.96	-264.14	-68.70	-288.93
10	3.7d	-333.47	-462.95	-108.94	-453.03
10	3d	-189.35	-316.57	-85.04	-281.72
25	3.7d	-666.67	-1,312.64	-124.47	-1,148.40
45	3.7d	-2,400.25	-2,857.80	-1,545.99	-3,824.75
50	3d	-1,624.37	-2,186.49	-1,226.34	-3,073.91
75	2.4d	-2,986.23	-4,041.95	-2,366.00	-5,961.03
80	2d	-3,541.72	-3,901.68	-3,112.28	-7,121.37
90	0.0f	-2,302.88	-2,591.51	-2,069.80	-5,744.64
90	1.5d	-3,451.78	-4,041.70	-2,679.04	-7,416.50
90	1.5i	-1,662.82	-1,939.15	-1,400.96	-4,663.68

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Table 56. Agency 3 Results: Commuter, Emergency Brake Backup Disabled, and Blended Braking

Target Speed at Braking	Grade	Stopping Location Relative to Target (ft.)			Enforcement Location Relative to Target (ft.)
		Mean	**Minimum**	**Maximum**	**Mean**
10	0.0f	-118.80	-163.22	-91.22	-226.61
10	0.5i	-100.28	-119.62	-79.05	-195.89
10	1.5d	-42.49	-166.00	-0.07	-181.09
10	1.5i	-85.78	-112.58	-58.23	-169.05
10	2.4d	-98.00	-243.57	-19.24	-269.77
10	2d	-63.90	-177.49	-17.63	-169.38
10	3.7d	-39.99	-317.83	-0.05	-174.09
10	3d	-73.59	-265.13	-1.27	-279.61
25	3.7d	-31.45	-257.41	-0.14	-666.01
45	3.7d	-300.69	-1,456.52	196.59	-2,297.88
50	3d	-117.34	-919.07	-0.03	-2,500.20
75	2.4d	-343.36	-2,008.37	1,232.84	-4,648.52
80	2d	-342.41	-2,164.26	977.95	-4,889.71
90	0.0f	-313.30	-1,305.92	-0.05	-4,889.43
90	1.5d	-366.71	-2,120.81	628.50	-5,705.39
90	1.5i	-313.53	-810.74	119.00	-3,368.97

Table 57. Agency 3 Results: Commuter, Emergency Brake Backup Disabled, and Pneumatic Only Braking

Target Speed at Braking	Grade	Stopping Location Relative to Target (ft.)			Enforcement Location Relative to Target (ft.)
		Mean	Minimum	Maximum	Mean
10	0.0f	-118.83	-163.22	-90.21	-226.51
10	0.5i	-100.32	-119.62	-79.05	-195.92
10	1.5d	-49.35	-170.00	-0.13	-187.98
10	1.5i	-86.18	-112.58	-58.23	-168.86
10	2.4d	-113.17	-260.15	-40.87	-271.21
10	2d	-73.69	-178.11	-29.00	-169.61
10	3.7d	-46.81	-308.67	-0.05	-183.37
10	3d	-91.56	-266.37	-0.36	-276.49
25	3.7d	-33.42	-170.70	-0.06	-664.56
45	3.7d	-259.95	-1,416.44	494.23	-2,420.93
50	3d	-94.09	-980.25	214.38	-2,640.33
75	2.4d	-257.75	-1,684.09	1,362.86	-4,865.63
80	2d	-257.26	-2,018.87	1,389.08	-5,081.62
90	0.0f	-313.30	-1,305.92	-0.05	-4,889.43
90	1.5d	-316.77	-1,949.62	493.53	-5,776.06

Table 58. Agency 3 Results: Commuter, Emergency Brake Backup Enabled, and Blended Braking

Target Speed at Braking	Grade	Stopping Location Relative to Target (ft.)			Enforcement Location Relative to Target (ft.)
		Mean	Minimum	Maximum	Mean
10	0.0f	-90.05	-132.81	-59.25	-197.57
10	0.5i	-75.85	-101.41	-55.21	-172.68
10	1.5d	-26.10	-138.40	-0.14	-166.57
10	1.5i	-61.08	-85.82	-37.17	-143.49
10	2.4d	-64.82	-208.88	-1.59	-231.33
10	2d	-38.49	-144.20	-0.70	-141.02
10	3.7d	-22.21	-211.68	-0.05	-153.79
10	3d	-45.61	-227.93	-0.32	-240.80
25	3.7d	-12.37	-254.17	-0.02	-533.07
45	3.7d	-211.40	-1,158.42	0.00	-1,896.60
50	3d	-71.68	-751.49	-0.04	-1,994.84
75	2.4d	-236.12	-1,506.57	347.20	-4,094.29
80	2d	-216.90	-1,769.88	394.51	-4,411.42
90	0.0f	-165.93	-877.16	-0.02	-4,604.91
90	1.5d	-264.01	-1,683.51	56.31	-5,183.27
90	1.5i	-142.77	-669.24	71.20	-3,134.35

Table 59. Agency 3 Results: Commuter, Emergency Brake Backup Enabled, and Pneumatic Only Braking

Target Speed at Braking	Grade	Stopping Location Relative to Target (ft.)			Enforcement Location Relative to Target (ft.)
		Mean	Minimum	Maximum	Mean
10	0.0f	-90.20	-132.81	-60.17	-197.69
10	0.5i	-75.81	-101.41	-55.21	-172.65
10	1.5d	-31.10	-149.43	-0.32	-169.05
10	1.5i	-61.34	-85.82	-37.17	-143.73
10	2.4d	-79.22	-222.18	-13.80	-233.42
10	2d	-50.06	-152.42	-4.26	-144.14
10	3.7d	-29.84	-236.79	0.00	-164.09
10	3d	-58.49	-244.06	-0.39	-237.91
25	3.7d	-12.57	-200.92	-0.01	-561.31
45	3.7d	-183.15	-1,071.04	-0.06	-2,014.62
50	3d	-55.47	-812.25	-0.02	-2,175.58
75	2.4d	-169.46	-1,326.89	500.78	-4,328.99
80	2d	-161.90	-1,353.64	689.50	-4,655.86
90	0.0f	-165.94	-877.16	-0.02	-4,604.91
90	1.5d	-193.56	-1,378.70	625.82	-5,317.81
90	1.5i	-204.45	-810.74	119.00	-3,272.70

Table 60. Agency 3 Results: Passenger, Emergency Brake Backup Disabled, and Blended Braking

Target Speed at Braking	Grade	Stopping Location Relative to Target (ft.)			Enforcement Location Relative to Target (ft.)
		Mean	Minimum	Maximum	Mean
10	0.0f	-124.90	-161.33	-96.14	-235.27
10	0.5i	-104.27	-138.65	-74.15	-199.64
10	1.5d	-57.89	-189.09	5.67	-201.66
10	1.5i	-88.56	-119.40	-63.69	-172.24
10	2.4d	-133.87	-257.37	-48.14	-308.73
10	2d	-87.43	-206.51	-31.19	-196.68
10	3.7d	-66.18	-419.40	-0.13	-202.34
10	3d	-121.88	-283.95	-1.24	-329.89
25	3.7d	-81.66	-570.40	-0.01	-722.39
45	3.7d	-968.94	-2,701.67	-34.33	-3,127.63
50	3d	-957.39	-1,777.42	-161.32	-3,524.37
75	2.4d	-2,043.15	-4,083.03	-258.97	-6,461.46
80	2d	-2,091.97	-3,868.03	-73.98	-6,706.69
90	0.0f	-1,531.56	-2,422.73	-911.90	-6,066.74
90	1.5d	-2,329.47	-4,101.20	-747.52	-7,593.60
90	1.5i	-941.14	-1,556.22	-568.75	-4,067.26

Table 61. Agency 3 Results: Passenger, Emergency Brake Backup Disabled, and Pneumatic Only Braking

Target Speed at Braking	Grade	Stopping Location Relative to Target (ft.)			Enforcement Location Relative to Target (ft.)
		Mean	Minimum	Maximum	Mean
10	0.0f	-124.68	-163.22	-94.61	-232.42
10	0.5i	-104.24	-133.84	-79.05	-199.67
10	1.5d	-74.05	-191.04	-2.08	-211.48
10	1.5i	-87.66	-112.58	-58.23	-170.38
10	2.4d	-153.47	-283.10	-66.00	-314.85
10	2d	-94.45	-195.78	-41.06	-192.31
10	3.7d	-76.38	-445.95	-0.06	-216.03
10	3d	-143.05	-306.22	-1.09	-331.51
25	3.7d	-89.67	-379.76	-0.21	-719.32
45	3.7d	-805.69	-2,675.75	-2.62	-3,147.58
50	3d	-735.47	-1,688.69	-1.10	-3,470.37
75	2.4d	-1,713.67	-3,762.29	-14.59	-6,422.35
80	2d	-1,779.60	-3,784.33	-9.58	-6,633.98
90	0.0f	-1,528.93	-2,457.05	-874.52	-6,069.08
90	1.5d	-1,967.80	-3,932.08	-209.98	-7,388.60
90	1.5i	-927.88	-1,575.27	-568.75	-4,084.85

Table 62. Agency 3 Results: Passenger, Emergency Brake Backup Enabled, and Blended Braking

Target Speed at Braking	Grade	Stopping Location Relative to Target (ft.)			Enforcement Location Relative to Target (ft.)
		Mean	Minimum	Maximum	Mean
10	0.0f	-96.36	-135.30	-73.13	-204.00
10	0.5i	-78.87	-101.41	-55.21	-175.55
10	1.5d	-41.59	-166.00	-0.04	-182.34
10	1.5i	-62.52	-85.82	-39.25	-144.91
10	2.4d	-99.53	-250.36	-14.00	-272.48
10	2d	-59.51	-197.51	-6.71	-165.73
10	3.7d	-40.16	-317.83	-0.01	-174.76
10	3d	-75.88	-265.73	-0.04	-293.68
25	3.7d	-39.11	-525.85	-0.05	-575.63
45	3.7d	-636.83	-2,342.48	-1.54	-2,695.93
50	3d	-670.45	-1,491.43	-5.55	-3,201.39
75	2.4d	-1,607.19	-3,518.43	-18.70	-6,024.51
80	2d	-1,633.47	-3,664.07	-27.33	-6,227.50
90	0.0f	-1,174.20	-2,171.07	-510.60	-5,725.59
90	1.5d	-1,832.53	-3,703.07	-568.02	-7,066.67
90	1.5i	-709.34	-1,289.07	-347.86	-3,809.09

Table 63. Agency 3 Results: Passenger, Emergency Brake Backup Enabled, and Pneumatic Only Braking

Target Speed at Braking	Grade	Stopping Location Relative to Target (ft.)			Enforcement Location Relative to Target (ft.)
		Mean	Minimum	Maximum	Mean
10	0.0f	-96.52	-135.30	-66.44	-203.92
10	0.5i	-78.91	-101.41	-55.21	-175.58
10	1.5d	-52.34	-170.00	-0.32	-189.62
10	1.5i	-62.42	-85.82	-39.25	-144.75
10	2.4d	-117.35	-262.84	-40.87	-275.50
10	2d	-69.16	-178.11	-22.52	-164.72
10	3.7d	-51.88	-322.70	-0.07	-187.68
10	3d	-104.38	-285.89	-0.04	-290.36
25	3.7d	-47.20	-586.80	-0.05	-604.59
45	3.7d	-547.57	-2,284.45	-0.21	-2,768.08
50	3d	-501.78	-1,471.14	-1.17	-3,195.97
75	2.4d	-1,321.35	-3,341.22	-0.86	-6,000.88
80	2d	-1,381.93	-3,335.93	-2.04	-6,226.43
90	0.0f	-1,174.20	-2,171.07	-510.60	-5,725.91
90	1.5d	-1,508.22	-3,507.36	-0.26	-6,928.89
90	1.5i	-709.65	-1,289.07	-347.86	-3,808.34

Agency 4

Table 64. Agency 4 Results: Commuter, Emergency Brake Backup Disabled, and Blended Braking

Target Speed at Braking	Grade	Stopping Location Relative to Target (ft.)			Enforcement Location Relative to Target (ft.)
		Mean	Minimum	Maximum	Mean
10	0.0f	-131.58	-160.96	-97.60	-227.16
10	0.5i	-116.57	-148.07	-89.53	-207.56
10	1.5d	-194.56	-281.01	-89.99	-315.23
10	1.5i	-96.70	-125.31	-67.76	-178.56
10	2.4d	-168.85	-290.25	-82.88	-267.83
10	2d	-234.59	-277.89	-138.05	-374.25
10	3.7d	-386.73	-485.35	-198.62	-529.73
10	3d	-156.10	-246.23	-74.19	-257.06
25	3.7d	-544.27	-832.93	-344.93	-968.64
45	3.7d	-1,174.94	-1,793.47	-703.22	-2,451.65
50	3d	-831.95	-1,483.71	-551.98	-2,249.73
75	2.4d	-1,860.48	-2,424.48	-1,172.56	-4,993.38
80	2d	-1,973.72	-2,438.50	-1,444.48	-5,490.53
90	0.0f	-1,389.32	-1,743.10	-954.59	-4,885.68
90	1.5d	-2105.96	-2,643.46	-1,488.69	-6,156.41
90	1.5i	-907.09	-1,349.74	-439.90	-3,505.51

Table 65. Agency 4 Results: Commuter, Emergency Brake Backup Disabled, and Pneumatic Only Braking

Target Speed at Braking	Grade	Stopping Location Relative to Target (ft.)			Enforcement Location Relative to Target (ft.)
		Mean	Minimum	Maximum	Mean
10	0.0f	-131.69	-160.96	-97.60	-227.19
10	0.5i	-116.58	-148.07	-89.53	-207.56
10	1.5d	-197.13	-280.80	-100.34	-314.98
10	1.5i	-96.52	-125.31	-67.76	-178.34
10	2.4d	-200.13	-306.37	-103.00	-308.21
10	2d	-245.11	-308.62	-188.43	-389.78
10	3.7d	-372.33	-494.84	-2.15	-510.23
10	3d	-144.91	-249.36	-87.84	-221.98
25	3.7d	-622.91	-965.99	-370.72	-1,069.08
45	3.7d	-1,130.01	-1,831.44	-616.35	-2,458.28
50	3d	-869.88	-1,436.56	-410.56	-2,340.23
75	2.4d	-1,782.55	-2,432.61	-957.36	-5,031.91
80	2d	-1,863.00	-2,471.37	-977.73	-5,481.22
90	0.0f	-1,389.32	-1,743.10	-954.59	-4,885.68
90	1.5d	-2,098.13	-2,643.46	-1,044.90	-6,150.98
90	1.5i	-936.18	-1,349.74	-473.48	-3,602.07

Table 66. Agency 4 Results: Commuter, Emergency Brake Backup Enabled, and Blended Braking

Target Speed at Braking	Grade	Stopping Location Relative to Target (ft.)			Enforcement Location Relative to Target (ft.)
		Mean	Minimum	Maximum	Mean
10	0.0f	-99.13	-131.45	-61.79	-198.03
10	0.5i	-89.06	-129.20	-61.49	-180.16
10	1.5d	-159.35	-238.10	-74.04	-282.11
10	1.5i	-71.57	-101.90	-44.35	-152.56
10	2.4d	-141.90	-284.44	-41.78	-243.61
10	2d	-198.92	-251.88	-98.97	-343.69
10	3.7d	-284.89	-379.82	-122.70	-426.15
10	3d	-116.19	-289.35	-54.62	-215.42
25	3.7d	-410.52	-742.39	-167.17	-846.90
45	3.7d	-896.19	-1,441.37	-188.36	-2,178.22
50	3d	-606.63	-1,325.46	-66.79	-2,039.44
75	2.4d	-1,344.24	-1,905.26	-449.26	-4,475.75
80	2d	-1,371.42	-1,972.03	-653.13	-4,893.43
90	0.0f	-968.99	-1,322.91	-551.17	-4,451.32
90	1.5d	-1,467.95	-2,117.33	-755.76	-5,523.16
90	1.5i	-661.37	-1046.96	-300.65	-3,316.11

Table 67. Agency 4 Results: Commuter, Emergency Brake Backup Enabled, and Pneumatic Only Braking

Target Speed at Braking	Grade	Stopping Location Relative to Target (ft.)			Enforcement Location Relative to Target (ft.)
		Mean	Minimum	Maximum	Mean
10	0.0f	-99.58	-131.22	-62.19	-200.73
10	0.5i	-90.01	-123.10	-66.07	-181.12
10	1.5d	-159.72	-227.60	-81.95	-279.89
10	1.5i	-71.60	-101.90	-46.37	-152.76
10	2.4d	-167.71	-274.91	-75.88	-279.41
10	2d	-207.85	-247.02	-132.27	-358.49
10	3.7d	-270.87	-400.88	-92.51	-404.83
10	3d	-127.15	-270.27	-63.93	-210.67
25	3.7d	-487.10	-803.12	-195.02	-951.94
45	3.7d	-940.35	-1,472.42	-270.67	-2,305.50
50	3d	-672.79	-1,296.12	-44.18	-2,170.01
75	2.4d	-1,260.14	-1,990.26	-523.02	-4,537.07
80	2d	-1,283.89	-1,915.70	-449.61	-4,923.83
90	0.0f	-966.59	-1,369.50	-496.94	-4,446.68
90	1.5d	-1,444.89	-2,035.94	-628.40	-5,536.28
90	1.5i	-706.84	-977.29	-396.74	-3,580.05

Table 68. Agency 4 Results: Passenger, Emergency Brake Backup Disabled, and Blended Braking

Target Speed at Braking	Grade	Stopping Location Relative to Target (ft.)			Enforcement Location Relative to Target (ft.)
		Mean	Minimum	Maximum	Mean
10	0.0f	-138.53	-181.29	-97.50	-240.66
10	0.5i	-120.17	-154.50	-86.48	-210.42
10	1.5d	-210.26	-282.89	-105.33	-329.24
10	1.5i	-98.53	-126.90	-68.45	-180.48
10	2.4d	-188.79	-332.19	-87.50	-285.43
10	2d	-253.51	-318.56	-122.48	-387.67
10	3.7d	-463.52	-591.87	-193.86	-601.43
10	3d	-214.32	-331.27	-105.07	-328.08
25	3.7d	-778.60	-1,267.32	-522.28	-1,202.67
45	3.7d	-2,029.05	-3,017.34	-1,515.88	-3,279.63
50	3d	-1,925.82	-2,628.63	-1,466.05	-3,441.99
75	2.4d	-3,682.47	-4,523.23	-2,899.98	-6,697.26
80	2d	-3,945.27	-4,371.15	-3,425.18	-7,312.87
90	0.0f	-2,539.29	-2,958.78	-1,981.16	-5,980.34
90	1.5d	-4,090.43	-4,712.73	-3,384.83	-8,074.77
90	1.5i	-1,775.14	-2,230.34	-1,388.67	-4,744.97

Table 69. Agency 4 Results: Passenger, Emergency Brake Backup Disabled, and Pneumatic Only Braking

Target Speed at Braking	Grade	Stopping Location Relative to Target (ft.)			Enforcement Location Relative to Target (ft.)
		Mean	Minimum	Maximum	Mean
10	0.0f	-136.52	-175.83	-100.27	-232.01
10	0.5i	-119.68	-148.07	-89.53	-210.54
10	1.5d	-212.69	-284.92	-113.08	-329.18
10	1.5i	-98.56	-125.31	-68.45	-180.54
10	2.4d	-220.48	-328.80	-106.05	-325.21
10	2d	-268.29	-323.27	-145.77	-408.14
10	3.7d	-488.89	-632.74	-184.09	-631.06
10	3d	-202.54	-329.67	-104.81	-292.86
25	3.7d	-845.31	-1,317.68	-564.08	-1,270.24
45	3.7d	-2,069.50	-3,064.78	-1,454.82	-3,346.45
50	3d	-1,863.22	-2,684.87	-1,378.57	-3,360.36
75	2.4d	-3,623.09	-4,460.09	-2,665.72	-6,724.23
80	2d	-3,845.71	-4,367.77	-3,157.94	-7,297.79
90	0.0f	-2,546.97	-2,929.49	-2,120.14	-6,016.80
90	1.5d	-4,087.72	-4,713.00	-3,384.83	-8,079.11
90	1.5i	-1,775.01	-2,228.11	-1,388.67	-4,745.61

Table 70. Agency 4 Results: Passenger, Emergency Brake Backup Enabled, and Blended Braking

Target Speed at Braking	Grade	Stopping Location Relative to Target (ft.)			Enforcement Location Relative to Target (ft.)
		Mean	Minimum	Maximum	Mean
10	0.0f	-105.63	-148.41	-79.79	-202.84
10	0.5i	-92.28	-121.89	-66.45	-183.62
10	1.5d	-174.14	-237.92	-89.03	-295.67
10	1.5i	-73.22	-101.90	-46.37	-154.12
10	2.4d	-161.19	-298.36	-59.79	-260.70
10	2d	-223.20	-288.16	-88.12	-364.13
10	3.7d	-381.76	-484.19	-154.07	-524.24
10	3d	-157.42	-288.94	-69.88	-261.14
25	3.7d	-610.83	-990.51	-357.62	-1,032.89
45	3.7d	-1,669.16	-2,492.83	-1,186.48	-2,905.10
50	3d	-1,579.18	-2,131.08	-1,197.91	-3,048.44
75	2.4d	-3,223.71	-4,049.88	-2,284.71	-6,269.72
80	2d	-3,431.92	-3,912.31	-2,867.97	-6,845.14
90	0.0f	-2,152.08	-2,569.05	-1,714.48	-5,627.31
90	1.5d	-3,505.73	-4,128.83	-2,809.74	-7,512.74
90	1.5i	-1,468.18	-1,831.14	-1,139.72	-4,409.70

Table 71. Agency 4 Results: Passenger, Emergency Brake Backup Enabled, and Pneumatic Only Braking

Target Speed at Braking	Grade	Stopping Location Relative to Target (ft.)			Enforcement Location Relative to Target (ft.)
		Mean	Minimum	Maximum	Mean
10	0.0f	-106.91	-137.37	-76.70	-209.57
10	0.5i	-93.68	-124.84	-64.22	-184.48
10	1.5d	-176.52	-240.20	-97.30	-295.62
10	1.5i	-73.12	-101.90	-44.55	-154.31
10	2.4d	-189.42	-306.67	-81.33	-298.88
10	2d	-234.48	-284.98	-186.84	-380.93
10	3.7d	-376.15	-528.05	-132.05	-515.05
10	3d	-146.80	-263.59	-80.80	-225.54
25	3.7d	-686.94	-1,031.96	-390.95	-1,125.37
45	3.7d	-1,756.17	-2,605.96	-1,151.51	-3,041.68
50	3d	-1,555.51	-2,147.63	-1,118.44	-3,019.19
75	2.4d	-3,183.69	-3,928.01	-2,443.00	-6,334.22
80	2d	-3,347.83	-3,887.30	-2,756.54	-6,855.77
90	0.0f	-2147.75	-2,552.94	-1,562.72	-5,596.80
90	1.5d	-3,494.81	-4,128.53	-2,809.74	-7,509.61
90	1.5i	-1,467.95	-1,831.14	-1,139.72	-4,409.38

Agency 5

Table 72. Agency 5 Results: Commuter, Emergency Brake Backup Disabled, and Blended Braking

Target Speed at Braking	Grade	Stopping Location Relative to Target (ft.)			Enforcement Location Relative to Target (ft.)
		Mean	Minimum	Maximum	Mean
10	0.0f	-101.31	-172.74	-1.58	-226.13
10	1.5d	-101.19	-288.84	-12.07	-230.19
10	1.5i	-92.26	-123.82	-56.76	-180.93
10	2.4d	-108.22	-257.77	-0.07	-238.56
10	3d	-82.78	-276.16	-0.09	-207.56
25	3.7d	-53.00	-685.90	114.17	-759.15
50	3d	-326.56	-1,728.84	281.45	-2,329.01
80	2.4d	-1,247.71	-2,936.58	468.86	-5,764.43
90	0.0f	-701.86	-1,827.93	167.40	-5,034.61
90	1.5d	-883.63	-2,442.68	9.77	-6,046.47
90	1.5i	-485.54	-1,243.29	137.16	-3,612.84

Table 73. Agency 5 Results: Commuter, Emergency Brake Backup Disabled, and Pneumatic Only Braking

Target Speed at Braking	Grade	Stopping Location Relative to Target (ft.)			Enforcement Location Relative to Target (ft.)
		Mean	Minimum	Maximum	Mean
10	0.0f	-104.45	-172.52	-16.18	-223.95
10	1.5d	-102.68	-241.74	-7.28	-226.63
10	1.5i	-92.25	-122.45	-59.79	-180.86
10	2.4d	-103.31	-251.83	-1.17	-232.45
10	3d	-96.66	-270.58	-0.05	-236.46
25	3.7d	-69.55	-668.40	294.83	-830.85
50	3d	-195.48	-1,431.94	119.38	-2,439.88
80	2.4d	-742.44	-2,794.90	367.49	-5,772.35
90	0.0f	-698.64	-1,859.94	278.78	-5,032.02
90	1.5d	-612.13	-2,479.63	16.79	-6,199.50
90	1.5i	-465.67	-1,257.30	-0.04	-3,640.15

Table 74. Agency 5 Results: Commuter, Emergency Brake Backup Enabled, and Blended Braking

Target Speed at Braking	Grade	Stopping Location Relative to Target (ft.)			Enforcement Location Relative to Target (ft.)
		Mean	Minimum	Maximum	Mean
10	0.0f	-77.33	-140.84	-0.75	-198.36
10	1.5d	-76.12	-253.00	-2.03	-203.35
10	1.5i	-70.79	-101.13	-40.98	-159.44
10	2.4d	-84.19	-224.11	-0.31	-218.21
10	3d	-63.15	-213.71	-0.02	-185.54
25	3.7d	-26.62	-426.53	2.04	-568.84
50	3d	-271.36	-1,486.22	-0.15	-2,083.54
80	2.4d	-827.53	-2,437.82	332.23	-5,225.59
90	0.0f	-455.60	-1,642.79	133.17	-4,719.11
90	1.5d	-490.49	-1,749.57	339.10	-5,556.42
90	1.5i	-329.67	-1,070.52	-0.06	-3,421.77

Table 75. Agency 5 Results: Commuter, Emergency Brake Backup Enabled, and Pneumatic Only Braking

Target Speed at Braking	Grade	Stopping Location Relative to Target (ft.) Mean			Enforcement Location Relative to Target (ft.)
		Mean	Minimum	Maximum	Mean
10	0.0f	-77.04	-147.64	0.00	-203.22
10	1.5d	-79.40	-204.35	-0.31	-198.34
10	1.5i	-70.73	-106.12	-34.29	-159.34
10	2.4d	-81.48	-226.33	-0.38	-210.70
10	3d	-74.69	-223.63	-0.01	-202.66
25	3.7d	-30.65	-450.01	90.89	-644.39
50	3d	-145.37	-1,341.12	490.54	-2074.86
80	2.4d	-486.63	-2,304.23	178.20	-5,195.16
90	0.0f	-444.91	-1,593.54	79.28	-4,740.09
90	1.5d	-328.19	-2,032.95	145.01	-5,658.95
90	1.5i	-322.63	-1,085.34	0.00	-3,441.51

Table 76. Agency 5 Results: Passenger, Emergency Brake Backup Disabled, and Blended Braking

Target Speed at Braking	Grade	Stopping Location Relative to Target (ft.)			Enforcement Location Relative to Target (ft.)
		Mean	Minimum	Maximum	Mean
10	0.0f	-105.02	-170.41	-23.18	-220.39
10	1.5d	-118.40	-329.47	-18.83	-239.36
10	1.5i	-90.33	-171.64	-46.19	-177.86
10	2.4d	-118.35	-278.24	-0.42	-246.17
10	3d	-115.58	-365.36	-0.01	-246.75
25	3.7d	-129.86	-1,117.22	-0.10	-829.16
50	3d	-1,050.18	-2,216.34	303.32	-3,088.74
80	2.4d	-3,079.71	-4,445.26	-283.68	-7,597.76
90	0.0f	-1,561.81	-2,432.35	-11.87	-5,849.35
90	1.5d	-2,595.72	-3,520.86	-1230.69	-7,772.94
90	1.5i	-888.27	-1,587.08	-4.06	-4,043.83

Table 77. Agency 5 Results: Passenger, Emergency Brake Backup Disabled, and Pneumatic Only Braking

Target Speed at Braking	Grade	Stopping Location Relative to Target (ft.)			Enforcement Location Relative to Target (ft.)
		Mean	Minimum	Maximum	Mean
10	0.0f	-106.21	-176.79	-10.39	-226.68
10	1.5d	-120.66	-303.13	-30.55	-238.57
10	1.5i	-94.14	-116.72	-56.88	-183.90
10	2.4d	-121.29	-257.47	4.10	-249.59
10	3d	-129.00	-404.09	-0.07	-264.77
25	3.7d	-147.67	-1,139.98	467.30	-892.28
50	3d	-800.28	-2,084.79	499.16	-3,105.25
80	2.4d	-2,510.69	-4,331.30	417.34	-7,399.28
90	0.0f	-1,584.39	-2,516.31	-4.74	-5,884.63
90	1.5d	-2,197.01	-3,963.88	258.35	-7,790.81
90	1.5i	-899.06	-1,587.08	-0.99	-4,061.42

Table 78. Agency 5 Results: Passenger, Emergency Brake Backup Enabled, and Blended Braking

Target Speed at Braking	Grade	Stopping Location Relative to Target (ft.)			Enforcement Location Relative to Target (ft.)
		Mean	Minimum	Maximum	Mean
10	0.0f	-85.45	-161.14	-0.51	-200.87
10	1.5d	-93.36	-246.93	-5.63	-213.86
10	1.5i	-72.03	-98.34	-40.98	-160.80
10	2.4d	-97.14	-249.17	-0.90	-222.37
10	3d	-88.26	-286.91	-0.01	-215.69
25	3.7d	-60.08	-221.93	-0.70	-674.21
50	3d	-861.99	-1,990.65	-0.76	-2,904.31
80	2.4d	-2,626.44	-3,911.59	-176.01	-7,144.66
90	0.0f	-1,299.42	-2,274.68	-41.54	-5,602.02
90	1.5d	-2,151.21	-3,107.11	-610.77	-7,339.64
90	1.5i	-718.52	-1,436.81	-54.21	-3,869.57

Table 79. Agency 5 Results: Passenger, Emergency Brake Backup Enabled, and Pneumatic Only Braking

Target Speed at Braking	Grade	Stopping Location Relative to Target (ft.)			Enforcement Location Relative to Target (ft.)
		Mean	Minimum	Maximum	Mean
10	0.0f	-83.71	-154.95	-1.52	-200.27
10	1.5d	-96.23	-219.86	-5.80	-210.93
10	1.5i	-66.42	-125.44	-4.06	-152.07
10	2.4d	-99.05	-259.41	-0.80	-225.91
10	3d	-117.29	-357.87	-0.04	-256.39
25	3.7d	-74.85	-841.01	-0.03	-727.13
50	3d	-677.05	-1,806.69	-0.09	-2,854.24
80	2.4d	-1,981.34	-3,660.20	-1.03	-7,014.55
90	0.0f	-1,277.91	-2,144.22	-32.33	-5,587.82
90	1.5d	-1,753.33	-3,024.91	-3.42	-7,331.90
90	1.5i	-708.09	-1,353.03	-55.86	-3,877.73

Appendix B.
Passenger Predictive Braking Enforcement Algorithm Definition Document

Passenger Predictive Braking Enforcement Algorithm Definition Document

Version 0.1 (DRAFT)

November 18, 2015

Prepared by:

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

Revision History

Date	**Revision**	**Description**
9/21/2015	0.1	Initial Draft

1. Introduction

1.1 Purpose

The purpose of this document is to fully define and describe the logic flow and mathematical equations for a predictive braking enforcement algorithm intended for implementation in a Positive Train Control (PTC) system.

1.2 Scope

This document is intended as a comprehensive description of the predictive braking enforcement algorithm defined within. It is not intended as a detailed software requirements specification. It includes a definition of the logic flow and mathematical equations required to develop a functional implementation.

The predictive braking enforcement algorithm described within this document is intended for use in PTC systems for passenger trains. Considerations for freight trains are not included.

The definition of the algorithm contains background on the source of the logic and equations to provide context but is not intended to provide a complete background on the development of the algorithm.

Information and data pertaining to safety validation of the algorithm is not included in this document, although the intent of the program under which this algorithm was developed is to provide a separate report on the testing and validation of the logic included in this document.

No attempt has been made within this document to consider software implementation techniques, particularly as related to implementation in a safety critical application.

1.3 Intended Audience

This document is intended for developers of Positive Train Control (PTC) onboard systems and software considering predictive braking and enforcement algorithm options for inclusion in their system.

1.4 Applicable Documents

The following documents are applicable in that they are either referenced in the algorithm description document or provide useful background information:

- Braking and Prediction Algorithm Definition for the NAJPTC IDOT Project, Rev C.
- Hay, William W. (1982). *Railroad Engineering, Second Edition*. John Wiley & Sons, Inc.

1.5 Definitions and Acronyms

1.5.1 Definitions

The following terms are used in the document:

- Bail – The act of venting the locomotive brake cylinder pressure generated by the application of the automatic brake to atmosphere.
- Brake cylinder – A reservoir that is supplied with compressed air during an air brake application to control a piston connected to the brake shoes through the brake rigging. The amount of pressure in the brake cylinder determines the amount of force applied by the brake shoes.
- Brake pipe – A pipe that runs the length of the train and is used both to supply compressed air to the brake system on each car and to transmit air brake signals to the control valves on each car via changes to the pressure of the air within the pipe.
- Brake pipe propagation time – The time it takes for an air brake application signal to propagate throughout the length of the train and apply brakes on all cars in the train.
- Brake rate – The deceleration rate provided by the vehicle in miles per hour per second.
- Braking profile – The location/speed curve that describes the response of the train to either a penalty or emergency brake application, given the current conditions.
- Control valve – An air valve on each car that responds to changes in brake pipe pressure by directing air between the brake pipe, emergency reservoir, and brake cylinder.
- Degree of curvature – The central angle turned over a 100 foot chord length, expressed in degrees.
- Dynamic brake – A form of locomotive braking, where the leads of the traction motors are reversed (effectively turning them into generators), providing resistance to the rotating wheels and dissipating the energy generated as heat through a resistor bank.
- Emergency air brake application – A rapid reduction of the brake pipe pressure to atmospheric pressure. An emergency brake application results in higher brake force.
- Equalization – The point at which the brake pipe pressure equalizes with the brake cylinder pressure.
- Movement authority – Authorization given to the train crew by a dispatcher or control operator allowing the train to occupy track limits.
- Onboard computer – The PTC computer onboard the locomotive responsible for collecting train status and target information and applying the penalty brake.
- 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.
- Percent grade – The ratio of the change in track elevation over a specified distance, expressed as a percent.
- 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.

- 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 train movement authority or speed limit violation. Also described as "enforcement algorithm" or simply "algorithm."
- Service air brake application – A reduction of the brake pipe pressure at a service rate.
- Speed limit – The maximum allowed speed for a train over a particular section of track.
- 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.
- Target offset – A distance that is added to the stopping distance prediction to ensure that the train will stop short of the target with the required confidence, given potential inaccuracies in the prediction calculation.

1.5.2 Acronyms

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

- BCP – Brake Cylinder Pressure
- BPP – Brake Pipe Pressure
- IDOT – Illinois Department of Transportation
- NAJPTC – North American Joint Positive Train Control
- OBC – Onboard Computer
- PTC – Positive Train Control

2. Algorithm Overview

The enforcement algorithm described within this document is based on the version developed for the North American Joint Positive Train Control (NAJPTC) program. While other enforcement algorithms have been developed since this algorithm was originally released, the original NAJPTC version serves as a good industry base case and is available in the public domain. The algorithm described within this document seeks to improve on the performance of the NAJPTC algorithm and contains many revisions to the logic, while keeping many of the methods and concepts from the original version.

The primary objective of the predictive braking enforcement algorithm is to enforce PTC train movement authority and speed limits by initiating a penalty air brake application to stop the train from violating any such limit if the train crew fails to take action to prevent the violation, but to be transparent to the train crew when the train is handled properly to prevent the violation. The enforcement algorithm seeks to achieve these objectives by periodically predicting the stopping distance of the train, adding a target offset to the prediction, comparing this result against any authority or speed limits, and initiating a penalty air brake application as necessary.

The stopping distance prediction is performed by employing a simplified longitudinal train energy model to predict the braking profile of the train. The prediction assumes a penalty application is initiated at the time the prediction is made, using a combination of fixed (e.g., consist make-up) and dynamic (e.g., brake pipe pressure) data available to the onboard system. The stopping distance prediction is designed to result in a nominal prediction, which is then adjusted to meet the safety requirements of the system via the calculation of a target offset.

The target offset is a safety buffer added to the stopping location prediction to ensure the train will stop short of the target with a certain probability. Figure B1 illustrates this concept by showing a distribution of stopping locations representing the potential variability in stopping location relative to a target for a given scenario. This variability arises from the potential inaccuracies in the prediction attributed to a number of assumptions and unknowns in the prediction calculation. The nominal prediction is located at the mean of this distribution, meaning that, if no target offset were used, the likelihood that the train would overshoot the target would be 50 percent. As the figure illustrates, the target offset adjusts the target relative to the distribution, so that the likelihood of an overshoot is significantly reduced.

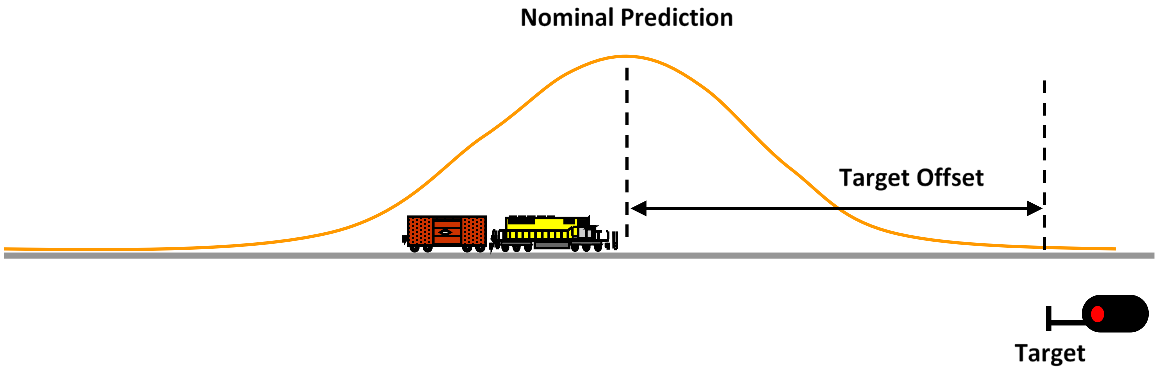


Figure B1. Illustration of Target Offset

The target offset is based on a regression of the results of a Monte Carlo sensitivity analysis of freight train stopping distance. The target offset function adjusts the stopping location prediction to provide a statistically significant probability of the train stopping short of the target 99.5 percent of the time.

This section defines the functions, equations, and logic flow of the predictive braking enforcement algorithm. This section will include sufficient detail for developing a working implementation of the algorithm for use in a functional PTC system. The overall architecture of the algorithm is designed to be modular to allow for additional functions to be added or modules to be replaced relatively quickly without affecting other functions or modules within the algorithm. Therefore, the descriptions within this section are organized into a series of functional modules.

2.1 Initialization

This section describes the functions necessary for initialization of the algorithm. The primary objective of these functions is to set all of the fixed data used by the enforcement algorithm. Although the term initialization is used, these functions are designed to be used to modify these data items at any point, not just when the algorithm is started. For example, if the PTC implementation allows for modification of the consist after the train is en route, the *Update Consist Data* function would be used to update the consist information appropriately.

2.1.1 Update Consist Data

This function is used to initialize, update, or modify the consist data that is used by the enforcement algorithm. The consist data provided to the enforcement algorithm includes:

- Number of locomotives
- For each locomotive:
    - Locomotive position in train (push/pull)
    - Locomotive weight in tons

  - Locomotive status, either Run or Isolate
  - Locomotive length in feet
  - Number of axles
- Total trailing weight in tons
- Total number of loaded cars
- Total number of empty cars
- Total train length, including locomotives
- Total number of axles for tailing cars
- Total train brake shoe force (optional input)

2.1.1.1 Derive Nominal Brake Force Curve

The nominal brake force curve is used to estimate of the retarding force applied to the wheels by the brake shoes based on the #16 line pressure out of the control valve.

The following items are assumed since there is no input for them into the current braking algorithm:

- Min. service brake pipe pressure reduction is 5–7 psi.
- Brake rate cannot be higher than 2 mph/s or lower than 0 mph/s.
- Brake rate in an emergency cannot be higher than 2.65 mph/s or lower than 0 mph/s.

To determine the nominal brake force curve, the full service brake force must be calculated. The following equation calculates the nominal full service brake force for the train.

$$Full\ Serv\ F_{B\ nom} = \frac{BR_{fs} * W_t * 1.467}{32.17}$$

Where:

BR_{fs} – Full service brake rate (assumed to be 2 mph/s)

W_t – Weight of the train

It is also assumed that the service limiting valve setting is 60 psi.

Once the full service nominal brake force is calculated it is then divided by the full service limiting valve setting to give the slope of the nominal brake force curve.

$$M = \frac{Full\ Serv\ F_{B\ nom}}{60}$$

This slope along with the #16 line pressure will be used to calculate the brake force of the train. For a normal service brake application the brake force of the train will be limited by the service limiting valve setting. For an emergency brake application the brake force will be limited based on the emergency brake rate of the train. This emergency brake rate BR_{EM} is assumed to be 2.65 mph/s.

$$Max\ Emergency\ F_{B\ limit} = \frac{BR_{EM} * W_t * 1.467}{32.17}$$

2.1.2 Update Track Data

This function is used to initialize or update the track data required, which includes:

- Elevation or percent grade and location reference for each grade change
- Track centerline coordinates at frequent intervals for use in determining heading and degree of track curvature.

2.2 Main Process

This section describes the primary high-level functions of the enforcement algorithm that make up the main processing loop. Figure B2 illustrates the flow of the functions within this process. Each of these functions are described generally in this section and described in more detail in subsequent sections, where appropriate.

The main process is to be repeated periodically, as required by the overall PTC system design. Each iteration of the main process will result in a decision on whether a penalty or emergency brake application is necessary to prevent a movement authority or speed limit violation. A frequency of 1 Hz is considered typical.

2.2.1 Update Targets

This function is used to define locations where the train must be at or below a given speed, including movement authorities (zero speed targets) and speed restrictions (non-zero speed targets). The function accepts target data from the onboard system and assigns or removes targets from the target data store, as necessary. Each target contains two data items:

- Target Location – Location of the target as referenced to the track database
- Target Speed – Speed limit at the target in miles per hour (mph)

When the algorithm completes the brake profile prediction, these targets are used to determine if a penalty brake application is necessary.

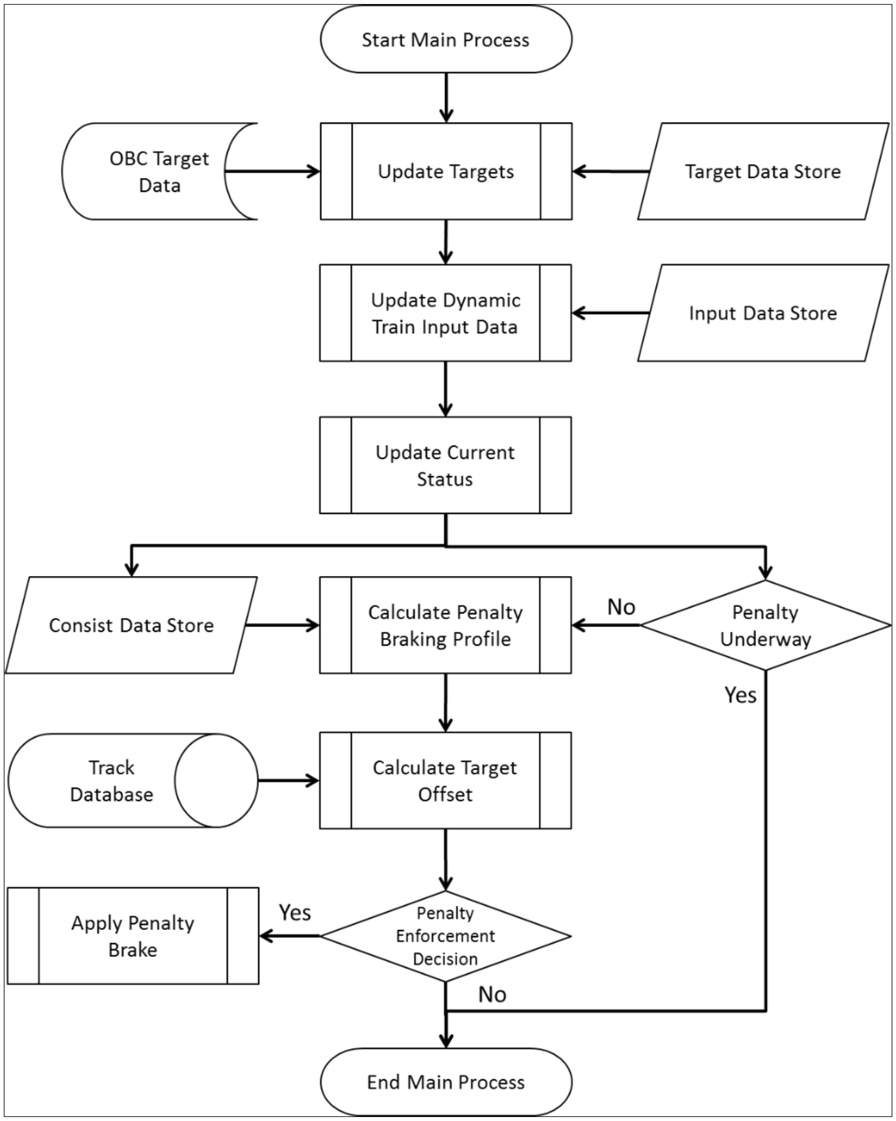


Figure B2. Main Process Flow Diagram

2.2.2 Update Dynamic Train Input Data

During each iteration of the main process, this function collects train status information from the onboard system for use elsewhere in the algorithm. The following data items are assigned in this function:

- Location – Current location of the lead locomotive as referenced to the track database
- Speed – Current speed of the lead locomotive in mph
- Head-end Brake Pipe Pressure – Current BPP at the lead locomotive in psi
- Direction – Current setting of the reverser handle on the lead locomotive; generally, forward or reverse

- Throttle Notch – Current integer notch setting of the throttle handle on the lead locomotive (not currently used)
- Dynamic Brake Setup Status – Current setting of the dynamic brake setup status bit (Boolean)

2.2.3 Update Current Status

This function updates the algorithm on the current status of the train based on train input data from the onboard system, consist data, and track data from the track database. The current status serves as the initial data point in the braking profile prediction. Specifically, the current state of the air brake system is determined, the average track grade and curvature under the train is determined, forces acting on the train are calculated, and the locomotive dynamic braking force acting on the train, if any, is estimated.

2.2.4 Penalty Brake Enforcement Prediction

If the predictive braking enforcement algorithm has not yet enforced a penalty air brake application, the algorithm determines if a penalty air brake application is necessary to avoid violating any of the currently established targets. This comprises three processes: *Calculate Penalty Braking Profile, Calculate Target Offset* and the *Penalty Enforcement Decision*.

2.2.4.1 Calculate Penalty Braking Profile

This function calculates the braking profile of the train by assuming a penalty brake application is made at the time of the calculation, given the current status of the train, the consist data, and the track data from the track database. This calculation represents a nominal prediction of stopping distance without any conservative assumptions, which are accounted for in the target offset function.

2.2.4.2 Calculate Target Offset

This function calculates the target offset, based on the consist data, the current status of the train, and the track data over the section of track covered by the braking profile. The target offset calculation was not included in the baseline algorithm.

2.2.4.3 Penalty Enforcement Decision

This function is used to determine if a penalty brake enforcement is necessary, given the previously calculated braking profile and target offset. All currently active targets are evaluated to determine if a violation is predicted. Multiple targets and combinations of zero speed and non-zero speed targets may need to be evaluated.

For zero speed targets, the predicted zero speed location of the train, according to the braking profile, is added to the calculated target offset and compared against the zero speed target location. If the sum of the predicted zero speed location and the target offset is greater than the target location, a penalty brake application is initiated.

2.3 Update Air Brake System Status

The objective of this function is to determine the current state of the air brake system, including the brake pipe pressure, #16 line pressure, and total brake force. This function is used to update the actual air brake system status every iteration through the main processing loop, as well as update the predicted air brake system status for each time step during the penalty braking profile prediction.

Ultimately, the total brake force calculated from this process is used by the enforcement algorithm to determine the amount of brake retarding force acting on the train at any given time. However, because of the complexity of the air brake system, there are a number of intermediate values that must be calculated and stored in order to accurately model the brake force.

The air brake system is controlled by adjusting the amount of pressure in the brake pipe. The control valves, located on each car, respond to changes in brake pipe pressure by allowing air to flow between the various reservoirs on the car. When brake pipe pressure is reduced, the control valve(s) on each car allows air to flow to the brake cylinder(s) on that car, which applies the brakes. When the brake cylinder pressure reaches the brake pipe pressure, the system is lapped, and the control valve prevents any more air from flowing between the reservoirs, holding the brake cylinder pressure and the brake application constant. When brake pipe pressure is increased, the control valve(s) on each car allows air to vent the brake cylinder pressure to the atmosphere to release the brakes.

The air brake model employed in the *Update Air Brake System Status* function evaluates the brake pipe pressure to determine the status of the brake system, which is then used to determine the pressures in each vehicle’s #16 line, and then resulting brake force. The *Update Air Brake System Status* function flow is illustrated in Figure B3.

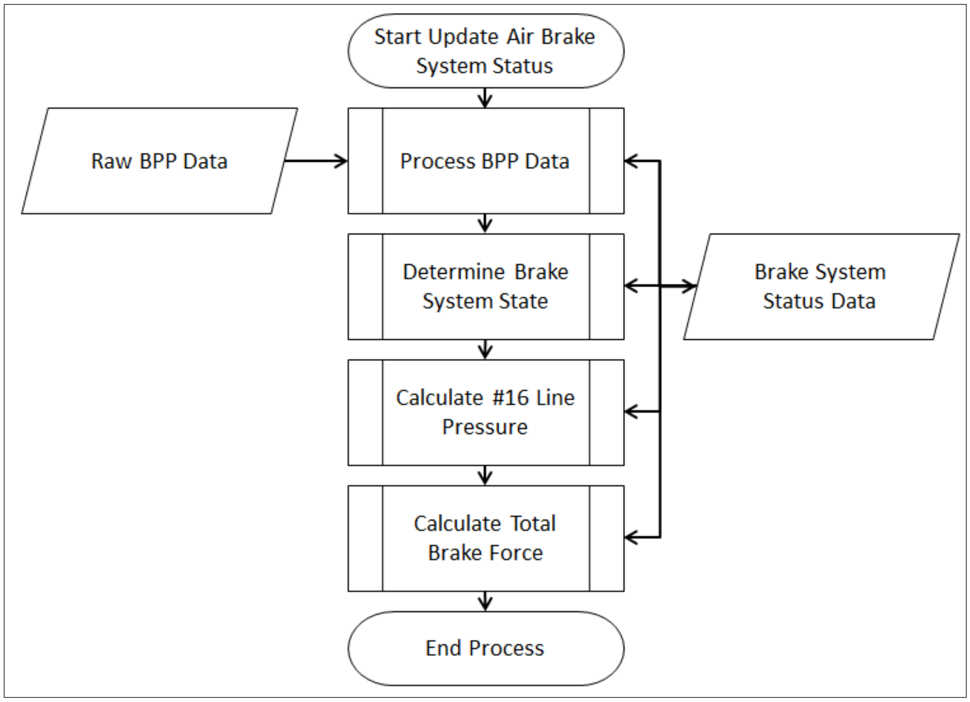


Figure B3. Update Air Brake System Status Flow Diagram

The function has four primary processes which are described in detail in the following subsections:

- *Process Brake Pipe Pressure Data* – Filters the raw brake pipe pressure data to determine the brake pipe pressures, and brake pipe pressure reduction (if any).
- *Determine Brake System State* – Determines whether the brake system is fully charged, releasing, applying service, applying emergency, or holding, based on the brake pipe data and the brake system data from the previous time step.
- *Calculate #16 Line Pressure* – Determines the #16 line pressure based on the current brake state, the difference in brake pipe pressure since the last time step, and assumed release and application rates. #16 line pressure is used to determine the brake rate for the train.
- *Calculate Total Brake Force* – Determines the total brake force for the train based on the train brake rate and weight of the train.

Because the air brake system status is dependent on previous status data, each of these processes produces data that is saved for the next time step.

The model of the air brake system described in the following subsections includes a number of parameters, defined below. Each of these is initialized at the time the system is started, and the initialization values are defined in the following parameter descriptions.

- Brake system state – One of five states that identify the behavior of the brake system. Initialized to emergency.

- Brake pipe pressure (BPP) parameters:
    - Brake pipe pressure at its highest setting (psi), BPP_{SET}. This is the highest brake pipe pressure that is reached by the head end of the train. If $BPP_{CUR} > BPP_{SET}$ then $BPP_{SET} = BPP_{CUR}$. Initialized to fully charged psi.
    - Current brake pipe pressure (psi), BPP_{CUR}. The brake pipe pressure at the head end of the train, as determined from filtering the data reported to the enforcement algorithm from the onboard computer. Initialized to 0 psi.
    - Previous brake pipe pressure (psi), BPP_{PREV}. The brake pipe pressure from the previous time step. Initialized to 0 psi.
    - Brake pipe pressure delta (psi), BPP_{Δ}. The change of the brake pipe pressure from the previous time step (BPP_{CUR}-BPP_{PREV}). Initialized to $BPP_{PRE} = BPP_{SET}$.
    - Hold brake pipe pressure (psi), BPP_{HOLD}. Reference value for determining brake system state changes. Initialized to 0 psi.
- #16 line pressure (psi), #16Line. The pressure in the line going from the brake control valve to the brake cylinders. Initialized to 0 psi.
- Application rate, App_{Rate}. The rate in which brake pipe pressure is vented to the #16 line during a brake application operation. The rate is assumed to be 2.5 psi/s.
- Release rate, REL_{Rate}. The rate in which brake pipe pressure is vented out of the #16 line during a brake release operation. The rate is assumed to be 3.7 psi/s.
- Full service reduction. The full amount of brake pipe pressure reduction that can occur during a non-emergency brake application. The reduction is assumed to be 24 psi.
- Slope for nominal brake force curve calculated in section 3.1.1.1.
- Maximum emergency brake force limit calculated in section 3.1.1.1.

2.3.1 Process Brake Pipe Pressure Data

This function uses the raw front brake pipe pressure received from PTBPM to determine whether a brake application or release is underway. This function is used both in updating the real-time status of the brake system, where the input is provided by the onboard system, and when calculating the brake profile, where the input is calculated and provided as an input to the function. In the latter case the processing of the raw data is not necessary but does not negatively affect the prediction. Performing the filtering in either case reduces the complexity of the overall process. Figure B4 illustrates the flow of the process.

The first function within this process computes the head end brake pipe pressure, BPP_{CUR}, by averaging the raw head end BPP data from the onboard system for the most recent sample with the previous two samples.

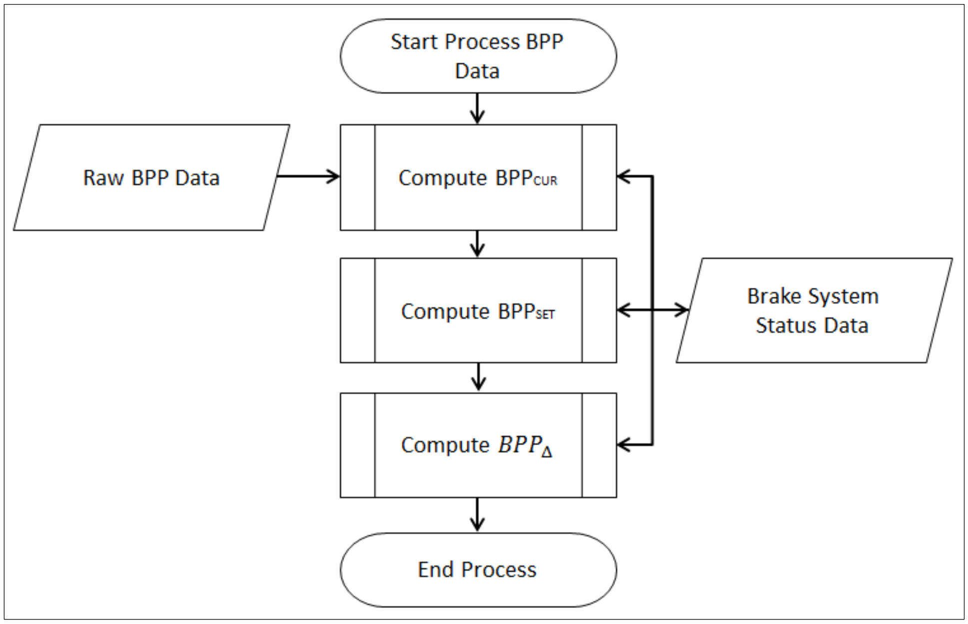


Figure B4. Process BPP Data Flow Diagram

The next function changes the highest brake pipe pressure, BPP_{SET}, to be equal to the current brake pipe pressure, BPP_{CUR}, if it has become higher using the following equation:

$$\text{If, } BPP_{CUR} > BPP_{SET}\text{, then } BPP_{SET} = BPP_{CUR}$$

The final function of this process determines the change in brake pipe pressure since the last time step, BPP_{Δ}, using the following equation:

$$BPP_{\Delta} = BPP_{CUR} - BPP_{PREV}$$

These values are used later in the update air brake system status function to identify changes in the brake system state, as described in the next section.

2.3.2 Determine Brake System State

The *Determine Brake System State* process uses the current brake pipe pressure and brake system status to identify changes in the brake system state. This data is used later to determine the #16 line pressure and, ultimately, braking force.

The process is a state machine that comprises the following five states:

- Fully charged – The brake pipe is charged and being held to its set point and the brakes are released.
- Applying service – A service brake pipe pressure reduction is underway, resulting in the control valves directing air to the brake cylinders on each car.
- Applying emergency – The brake pipe pressure is venting at a rapid rate.
- Holding service – The brake pipe pressure is being held steady at a level below the set point.

- Releasing – The brake pipe pressure is increasing, which results in the brake cylinder pressure venting to atmosphere.

Figure B5 shows a state diagram illustrating the potential state changes between the brake system states listed above. Each state contains its own set of events that will trigger a brake system state change that are reevaluated each time the function is executed. There are also a number of functions that are used in more than one brake system state. The following subsections describe the various brake system states and functions within the determine brake system state process.

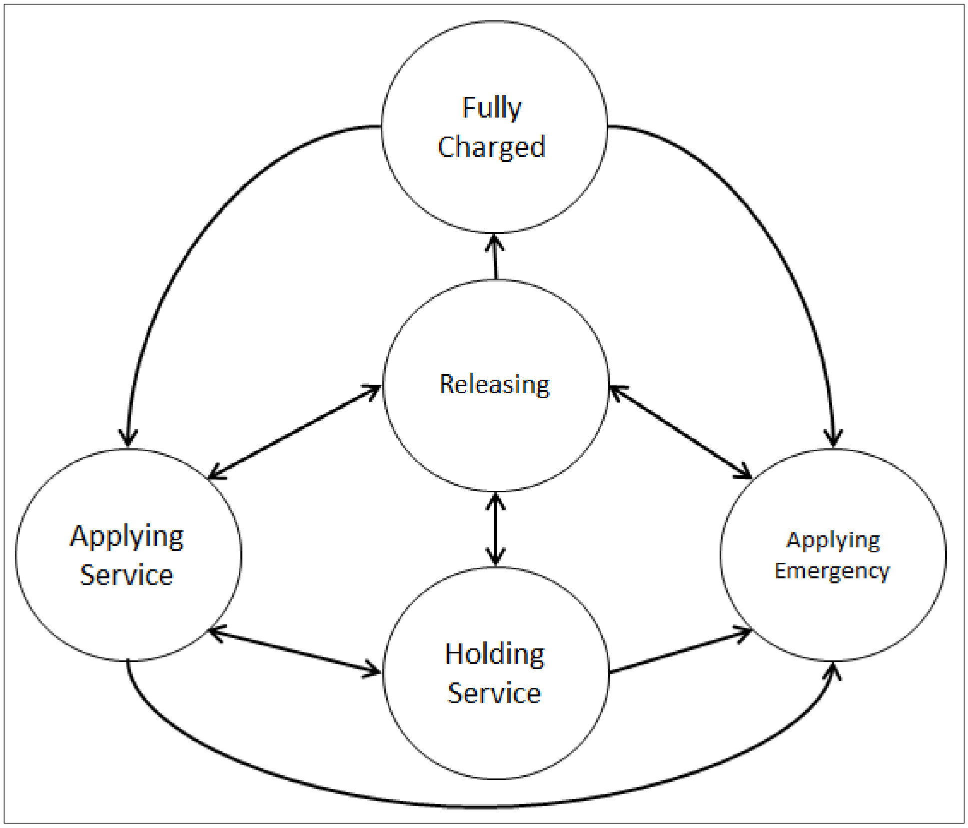


Figure B5. Brake System State Diagram

2.3.2.1 Fully Charged Brake System State

When the brake system is fully charged, the brake pipe pressure is at full pressure, and there is no pressure in the brake cylinders. From this state, a brake pipe pressure reduction will result in a brake application (service or emergency).

The flow diagram in Figure B6 shows the *Determine Brake System State* process when the brake system is in the fully charged state. As the diagram shows, when in the fully charged state, the brake system will transition to the applying emergency state if the rate of change of the brake pipe pressure, BPP_{Δ}, is less than -15 psi/second. The brake system state will transition to the applying service state if the rate of change of the brake pipe pressure, BPP_{Δ} is less than -15 psi/second or if BPP_{SET}-BPP_{CUR} is greater than 3 psi.

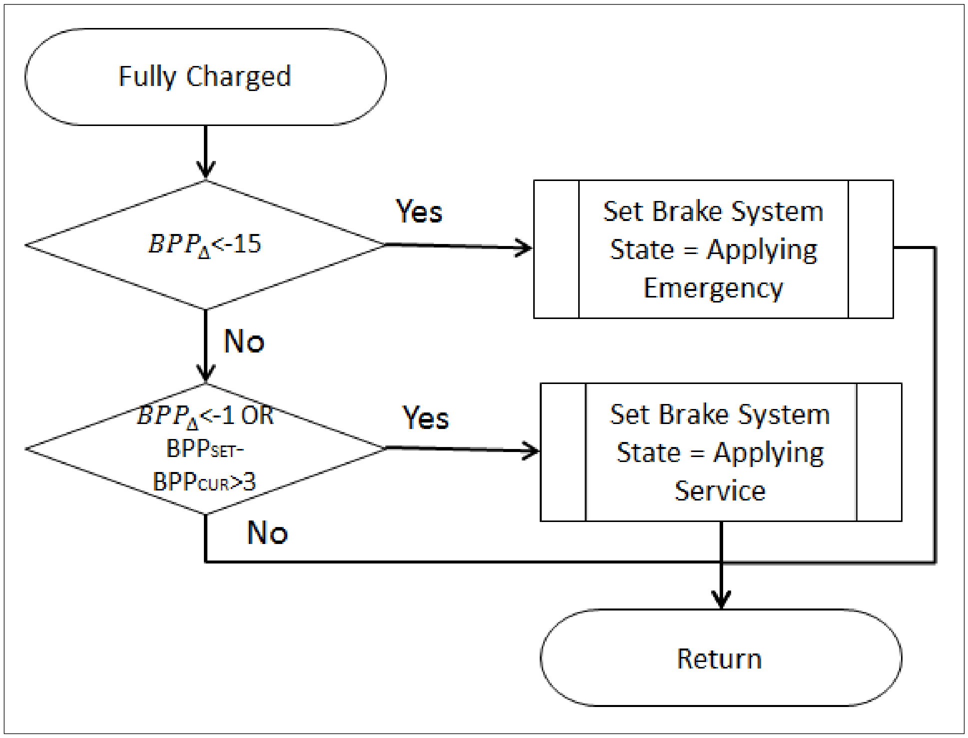


Figure B6. Fully Charged State Flow diagram

2.3.2.2 Applying Service Brake System State

As the state diagram in Figure B5 shows, the applying service state can transition to the applying emergency state, the releasing state, or the holding service state. The events that trigger these transitions are illustrated in Figure B7, which shows the flow diagram for the applying service state.

As Figure B7 shows, if the head end brake pipe pressure, BPP_{CUR}, has lowered, the hold pressure, BPP_{HOLD}, is set to this value. This hold pressure is used to determine a change in the direction of the brake pipe pressure. In this state the hold pressure is reset to the current brake pipe pressure, BPP_{CUR} , if it is lower than the hold. The hold pressure is then used in the state to determine if the brake state should transition or not.

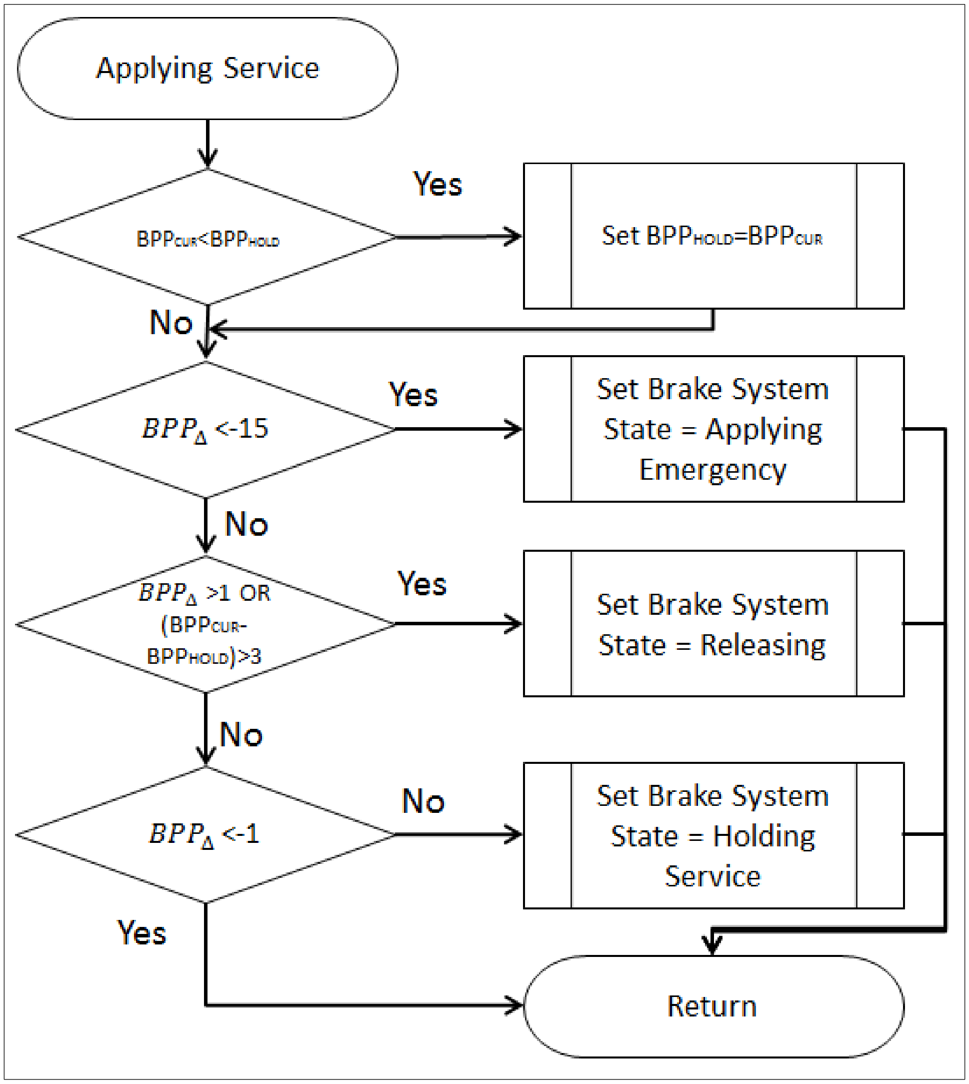


Figure B7. Applying Service State Flow Diagram

The brake system state will transition to the applying emergency state if the rate of change of the brake pipe pressure, BPP_{Δ}, is less than -15 psi/second. The brake system state will transition to the releasing state if the rate of change of the brake pipe pressure, BPP_{Δ} is greater than 1 psi/second or if BPP_{CUR}-BPP_{HOLD} is greater than 3 psi. The brake system state will transition to the holding service state if the rate of change of the brake pipe pressure, BPP_{Δ} is not less than 1 psi/second. If none of the conditions described above are met, the brake state will remain in the applying service state until the next time step.

2.3.2.3 Applying Emergency Brake System State

The process flow for the applying emergency brake state is very similar to that of the applying service brake state. Figure B8 shows the flow diagram for the applying emergency brake state. Similar to the applying service brake state function, this function begins by setting the hold pressure, BPP_{HOLD}, to the head end brake pipe pressure, BPP_{CUR}, when the head end brake pipe pressure has lowered. Also in this state, the hold pressure is reset to the current brake pipe pressure, BPP_{CUR} , if it is lower than the hold. The hold pressure is then used in the state to determine if the brake state should transition or not.

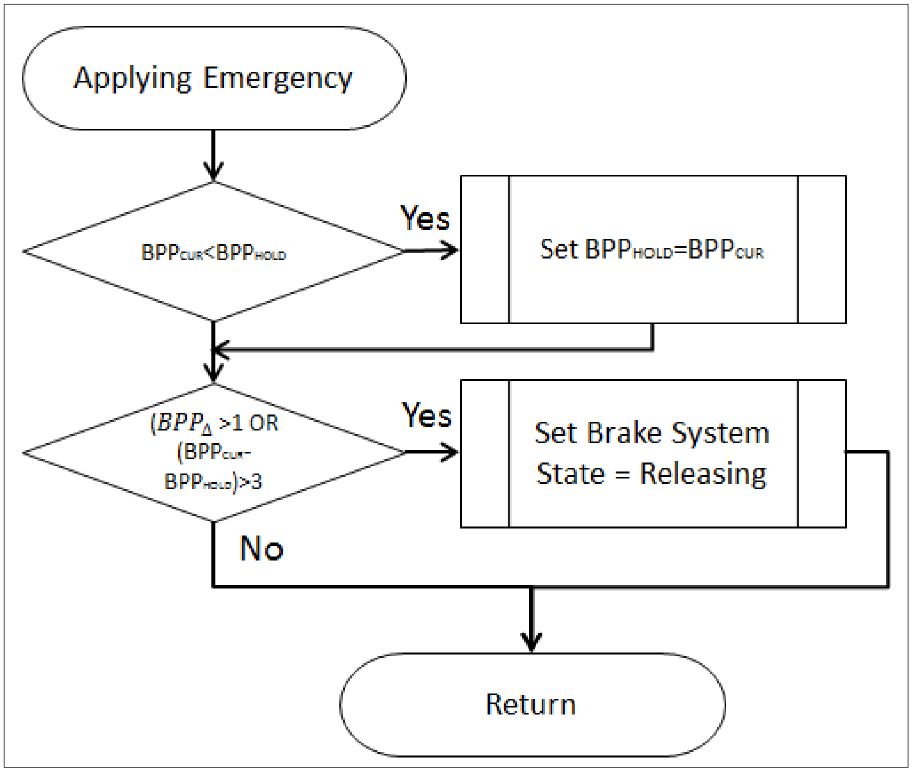


Figure B8. Applying Emergency State Flow Diagram

The brake system state will transition to the releasing state if the rate of change of the brake pipe pressure, BPP_{Δ} is greater than 1 psi/second or if BPP_{CUR}-BPP_{HOLD} is greater than 3 psi. If none of the conditions described above are satisfied, the brake state will remain in the applying emergency state until the next time step.

2.3.2.4 Holding Service Application Brake System State

If the brake system state is set to holding service application, the process flow depicted in Figure B9 is followed. The brake system state will transition to the applying emergency state if the rate of change of the brake pipe pressure, BPP_{Δ}, is less than -15 psi/second. The brake system state will transition to the releasing state if the rate of change of the brake pipe pressure, BPP_{Δ}, is greater than 1 psi/second or if BPP_{CUR}-BPP_{HOLD} is greater than 3 psi. The brake system state will transition to the applying service state if the rate of change of the brake pipe pressure, BPP_{Δ}, is less than -1 psi/second or if BPP_{HOLD}-BPP_{CUR} is greater than 3 psi. If neither a brake set nor a brake release is detected, the brake system will remain in the holding service application state.

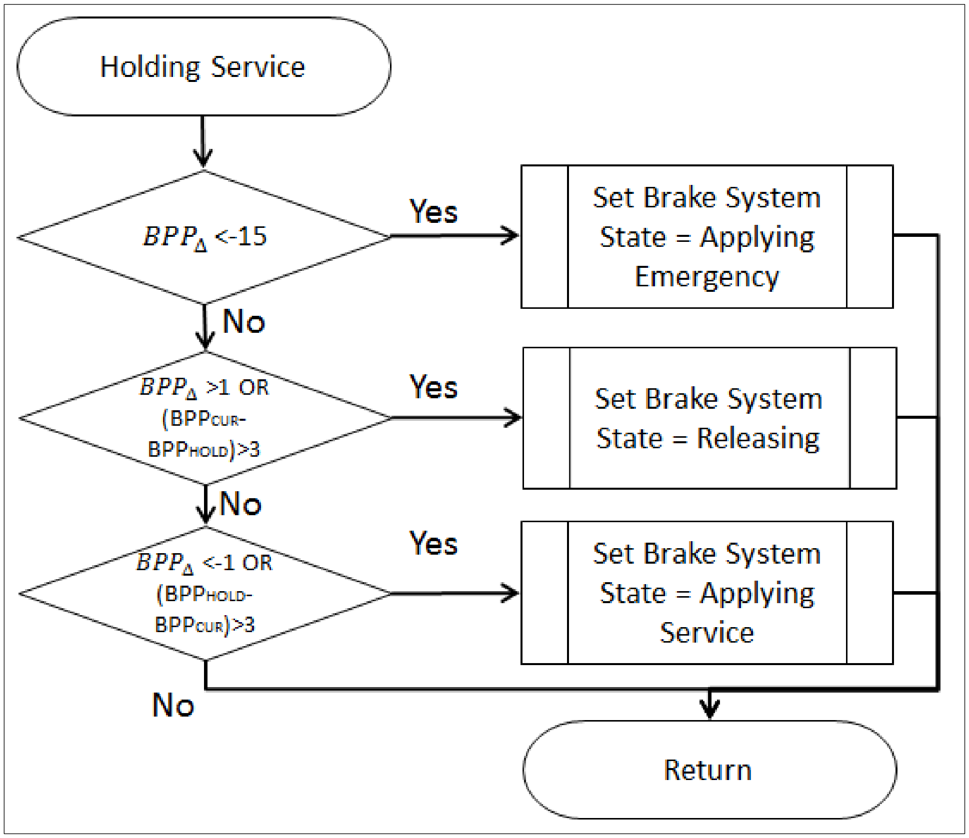


Figure B9. Holding Service Application State Flow Diagram

2.3.2.5 Releasing Brake System State

The process flow for the releasing brake system state is illustrated in Figure B10. In this state, the hold pressure is reset to the current brake pipe pressure, BPP_{CUR} , if it is higher than the hold. The hold pressure is then used in the state to determine if the brake state should transition or not.

The brake system state will transition to the fully charged state if BPP_{SET}-BPP_{CUR}=0 psi. The brake system state will transition in the applying emergency state if the rate of change of the brake pipe pressure, BPP_{Δ}, is less than -15 psi/second. The brake system state will transition to the applying service state if the rate of change of the brake pipe pressure, BPP_{Δ}, is less than -1 psi/second or if BPP_{HOLD}-BPP_{CUR} is greater than 3 psi. The brake system state will transition to the applying service state if the rate of change of the brake pipe pressure, BPP_{Δ}, is less than 1 psi/second. If none of these conditions are met, the brake state will remain in the releasing state for the next time step.

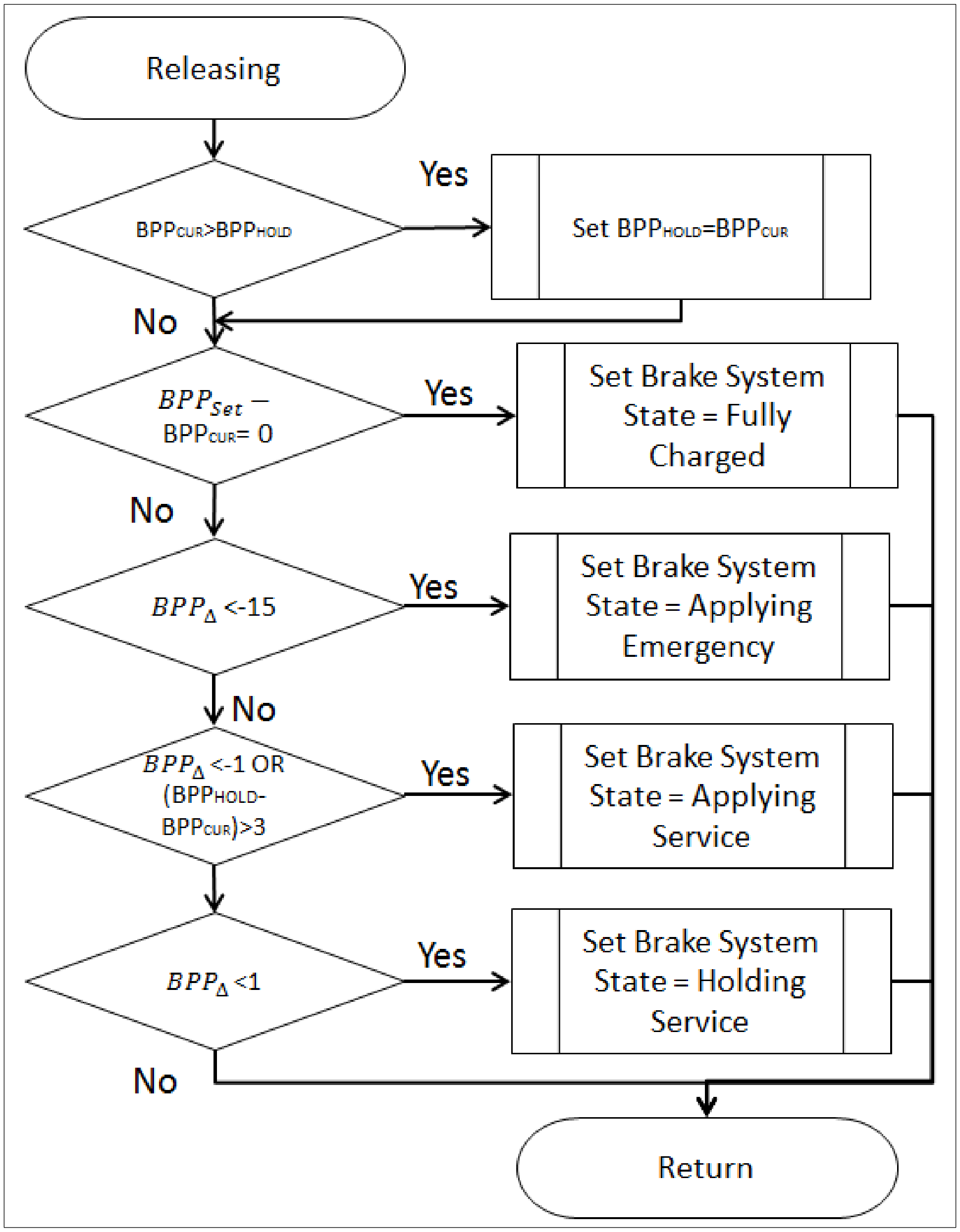


Figure B10. Releasing Brake State Flow Diagram

2.3.3 Calculate #16 Line Pressure

The *Calculate #16 Line Pressure* process determines the current average #16 line pressure, #16Line$_{CUR}$, for the train. The #16 line pressure is used later in the algorithm to determine the brake force for the train.

If the brake state is fully charged, the # 16 line pressure, #16Line$_{CUR}$, is set to 0 psi. If the brake state is holding service, then the control reference pressure will not change from the previous step. If the brake state is applying service or applying emergency, the control reference pressure is set according to the following equation:

$$\#16LINE_{CUR} = \#16LINE_{PREV} + |\mathrm{BPP}_{\Delta}| * APP_{RATE}$$

If the brake state is releasing, the control reference pressure is set according to the following equation:

$$\#16LINE_{CUR} = \#16LINE_{PREV} - |\mathrm{BPP}_{\Delta}| * REL_{RATE}$$

The #16 line pressure variable is capped based on the full service reduction and application rate. The following if statement is used to calculate the #16 line pressure during the applying service brake state:

$$\text{If } \#16LINE_{CUR} > APP_{RATE} * Full\ Service\ Reduction,$$
$$\text{then } \#16LINE_{CUR} = APP_{RATE} * Full\ Service\ Reduction$$

The #16 line pressure variable is only capped based on the available #16 line pressure during the applying emergency brake state.

2.4 Update Track Grade and Curvature

The purpose of the update track grade and curvature process is to determine the grade and curvature at the head end of the train to be used later in calculating the forces acting on the train. This function is used both to monitor the real-time track grade and curvature under the train and to provide track grade and curvature data for the braking profile prediction.

The process described here assumes that the weight of the train is uniformly distributed throughout the length of the train. A method for determining track grade and track curvature forces for a train with non-uniform distribution of weight along the train may be provided in later versions.

2.4.1 Update Track Grade

Track grade information is obtained using the location of the head end of the train and the track grade in the track database.

$$\%Grd_{CUR} = Grade\ Under\ End\ of\ Train$$

2.4.2 Update Track Curvature

The degree of track curvature is traditionally defined as the central angle turned over a 100-foot section of track. This definition is useful for determining train resistance due to track curvature. To calculate the resistance over the entire length of the train, the degree of curvature under the head end of the train is used, $\mathrm{Crv}_{\mathrm{CUR}}$.

$$|Crv_{CUR}| = Curvature\ Under\ Head\ of\ Train$$

2.5 Calculate Train Forces

The *Calculate Train Forces* process performs calculations to determine the net force acting on the train (without dynamic brake force, which is determined later), both in real time and during the braking profile prediction. The net force acting on the train at any given time can be modeled as the sum of the various independent forces acting on the train, as follows:

$$F_{NET} = \Sigma F = F_{LOC} + F_{GRD} + F_{CRV} + F_{RES} + F_{BRK}$$

Where F_{NET} is the net force acting on the train, F_{LOC} is the tractive force generated by the locomotives; F_{GRD} is the grade force; F_{CRV} is the curving resistance; F_{RES} is the net resistive forces acting on the train due to aerodynamic, wheel/rail, and bearing resistance; and F_{BRK} is the retarding force from the air brake system.

2.5.1 Calculate Locomotive Force

During a brake application, the tractive effort produced by the locomotives, F_{LOC}, is assumed to be zero.

2.5.2 Calculate Grade and Curving Forces

The grade force, F_{GRD}, is computed using the following equation:

$$F_{GRD} = 20 * W_{TRAIN} * \%Grd_{CUR}$$

Where W_{TRAIN} is the weight of the train in tons and $\%Grd_{CUR}$ is the grade under the train, as described in Section 3.4.1. The negative sign in the above equation serves to produce a positive force for a negative (downhill) grade, tending to accelerate the train, and a negative force for a positive (uphill) grade, tending to decelerate the train.

The curving force, F_{CRV}, is determined by from the following equation:

$$F_{CRV} = -0.8 * W_{TRAIN} * CRV_{CUR}$$

Where W_{TRAIN} is the weight of the train in tons and Crv_{CUR} is the degree of curvature under the head end of the train, as described in Section 3.4.2. The negative sign in this equation serves to produce a result that is always negative, tending to decelerate the train, regardless of the direction of the curve.

2.5.3 Calculate Resistive Force

The total train resistive force, F_{RES}, is the sum of the resistive forces acting on the locomotives and the resistive forces acting on the trailing cars. The resistive forces are calculated using a form of the modified Davis equation, which is used to calculate the resistance of a given rail vehicle:

$$R_u = 0.6 + \frac{20}{w} + 0.01V + \frac{KV^2}{wn}$$

Where R_u is the vehicle resistance in lbs/ton, w is the weight per axle in tons, n is the number of axles on the vehicle, V is the vehicle speed in mph, and K is the aerodynamic drag coefficient for the vehicle. Multiplying this equation by the weight of the vehicle in tons, W_{VEH}, gives the resistance in lbs/vehicle, R_{VEH}:

$$R_{VEH} = 0.6W_{VEH} + 20n + 0.01W_{VEH}V + KV^2$$

Multiplying this equation by the number of cars, N_{CARS}, and locomotives, N_{LOCS}, gives the resistance in lbs for the train:

$$R_{TRAIN} = 0.6W_{TRAIN} + 20n_{TOTAL} + 0.01W_{TRAIN}V + (K_{LOCOS}N_{LOCS} + K_{CARS}N_{CARS})V^2$$

Where W_{TRAIN} is the total weight of the train in tons, n_{TOTAL} is the total number of axles in the train, K_{LOCS} is the aerodynamic coefficient for locomotives, and K_{CARS} is the aerodynamic coefficient for trailing cars. The following aerodynamic coefficients for locomotives and trailing cars are assumed:

$$K = \begin{cases} 0.663 \; for \; locomotives \\ 0.464 \; for \; trailing \; cars \end{cases}$$

Substituting in the aerodynamic coefficients and introducing a negative sign to produce a negative result, tending to decelerate the train, results in the following equation for the resistive forces acting on the train:

$$F_{RES} = -(0.6W_{TRAIN} + 20n_{TOTAL} + 0.01W_{TRAIN}V + (0.663N_{LOCS} + 0.464N_{CARS})V^2)$$

2.5.4 Calculate Brake Force

The brake force, F_{BRK}, is the retarding force acting on the train due to the brakes being applied. It is calculated by using the current #16 line pressure and the nominal brake force curve.

$$F_{BRK} = M * \#16Line_{CUR}$$

Where

$$M = \frac{Full\ Serv\ F_{B\ nom}}{60}$$

For a service application the brake force is limited to the nominal full service brake force by not allowing the #16 line pressure exceed the full service limiting valve setting. For an emergency brake application, the brake force will be allowed to exceed the nominal full service brake force but will be limited to the maximum emergency brake force calculated in Section 3.1.1.1.

$$Max\ Emergency\ F_{B\ limit} = \frac{BR_{EM} * W_t * 1.467}{32.17}$$

Where
BR_{EM} – Full service brake rate (assumed to be 2.65 mph/s)

W_t – Weight of the train

2.6 Calculate Penalty Braking Profile

The *Calculate Penalty Braking Profile* process is responsible for computing the braking profile for the train, prior to any PTC air brake enforcement, by assuming a penalty brake application is initiated at the time of the calculation. The process is run once each time through the main process, as shown in Figure B2, and the result is used, along with the target offset, to determine if a penalty air brake enforcement is necessary. The *Calculate Penalty Braking Profile* process flow is shown in Figure B11.

The prediction of the brake profile is performed by employing a numerical integration process whereby the acceleration is determined based on the forces acting on the train and then integrated with respect to time to determine the velocity, which is again integrated with respect to time to determine the position at each time step. The value of the integration time step used in this process is considered an implementation issue, influenced by the required accuracy of the prediction and the processing capabilities of the system. However, the following should be taken into consideration when selecting an appropriate value:

- A sufficient number of time steps should be allowed between air brake state transitions to ensure an accurate prediction of auxiliary reservoir and brake cylinder pressures.
- The distance traveled in one time step should not include a large change in track grade.
- The change in both acceleration and velocity over a single time step should be kept to a minimum.

A value of 1 second is considered typical for the integration time step.

The process begins by calculating the current acceleration of the train, given the current force status, previously determined. The acceleration is calculated according to Newton's Second Law of Motion:

$$\sum F = ma$$

Where $\sum F$ is the sum of the forces acting on the train in lbs, m is the total mass of the train in slugs (equal to the total weight of the train in lbs divided by the acceleration due to gravity ~ 32.2 ft/s^2), and a is the instantaneous acceleration of the train in ft/s^2.

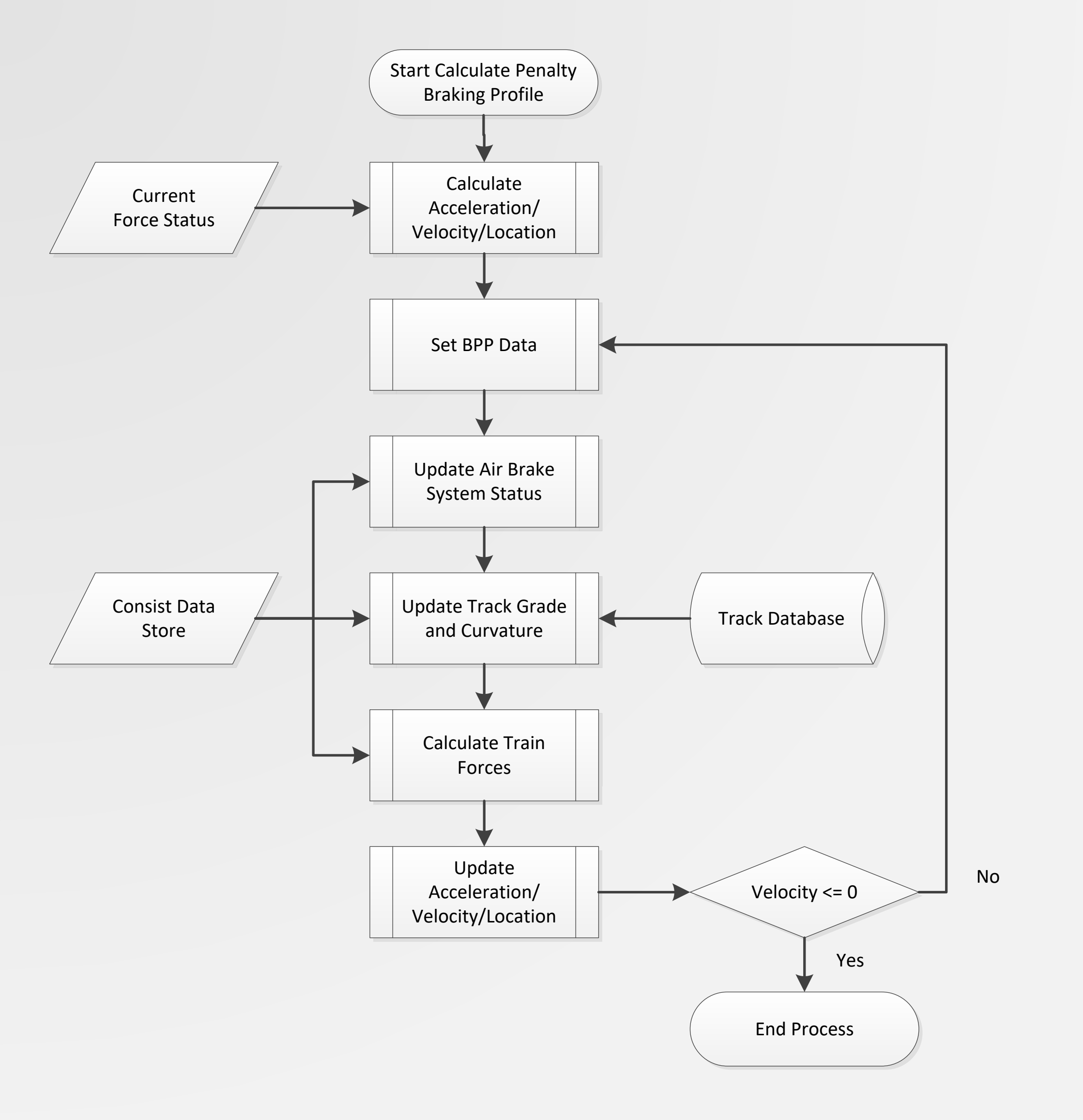


Figure B11. Calculate Penalty Braking Profile Flow Diagram

The predicted velocity in ft/s, v, over the integration time step, Δt, can then be determined, using the current velocity according to:

$$v = v_{PREV} + a\Delta t$$

The predicted location, x, can then be determined, using the current location according to:

$$x = x_{PREV} + v_{PREV}\Delta t + \frac{a}{2}\Delta t^2$$

Next, the predicted brake pipe pressure is set, based on the assumption that the penalty brake has been applied. The service rate of reduction of the brake pipe pressure is assumed to be 4 psi/second, meaning that the brake pipe pressure at the head end at any given time into the brake profile calculation can be determined according to:

$$BPP_{FRONT,t} = BPP_{FRONT,CUR} - 4.0t$$

Where $BPP_{FRONT,t}$ is the predicted head-end brake pipe pressure at the given number of seconds into the brake profile prediction, $BPP_{FRONT,CUR}$ is the actual current head end brake pipe pressure, and t is the number of seconds into the brake profile prediction.

This new predicted brake pipe pressure status is used in the air brake model to update all of the brake system parameters for the next predicted time step using the *Update Air Brake System Status* process defined in Section 3.3.

The grade and curvature data is then updated for the next predicted time step, based on the predicted location from the previous time step, using the *Update Track Grade and Curvature* process defined in Section 3.4.

The forces acting on the train at the next predicted time step are then calculated, based on the predicted values using the *Calculate Train Forces* process defined in Section 3.5. If the dynamic brake status is set to active, the dynamic brake force is added to the net force calculated from the *Calculate Train Forces* function, as described earlier in this section.

The forces acting on the train are used to recalculate the acceleration and this numerical integration process is repeated until the predicted velocity is less than or equal to zero.

2.7 Calculate Target Offset

The *Calculate Target Offset* function generates the buffer distance to offset the predicted stopping distance necessary to provide a high level of statistical confidence that the enforcement will result in the train stopping short of the target 99.5 percent of the time. The function is the result of a regression analysis on a large number of stopping distance simulations with Monte Carlo variation of the parameters that affect stopping distance for a variety of operating scenarios.

The target offset function calculates the target offset based on the following:

- Train type
- Train loading condition
- Power configuration (head end or distributed power)
- Current train speed, v, in mph
- Equivalent constant grade over the predicted stopping distance, g
- Trailing weight, W_{CARS}, in tons
- Total length, L_{TRAIN}, in feet
- Total number of axles on the train, n_{TOTAL}
- Number of empty, N_{EMPTY}, and loaded, N_{LOAD}, cars

Calculation of Target Offset TBD

Appendix C.
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^{TM}) software. The TCL software manages execution of the EA and TOES^{TM} 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^{TM} to EA via TCL at regular time intervals throughout the simulation and TCL initiates a penalty brake application in TOES^{TM} 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^{TM} – Train Operations and Energy Simulator
- TTCI – Transportation Technology Center, Inc.
- VM – Virtual Machine

1. Concept of Operations

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

1.1 Simulation Testing

This section describes the simulation test process and required interfaces. The simulation testing process flow is illustrated in Figure C1. 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 1 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.

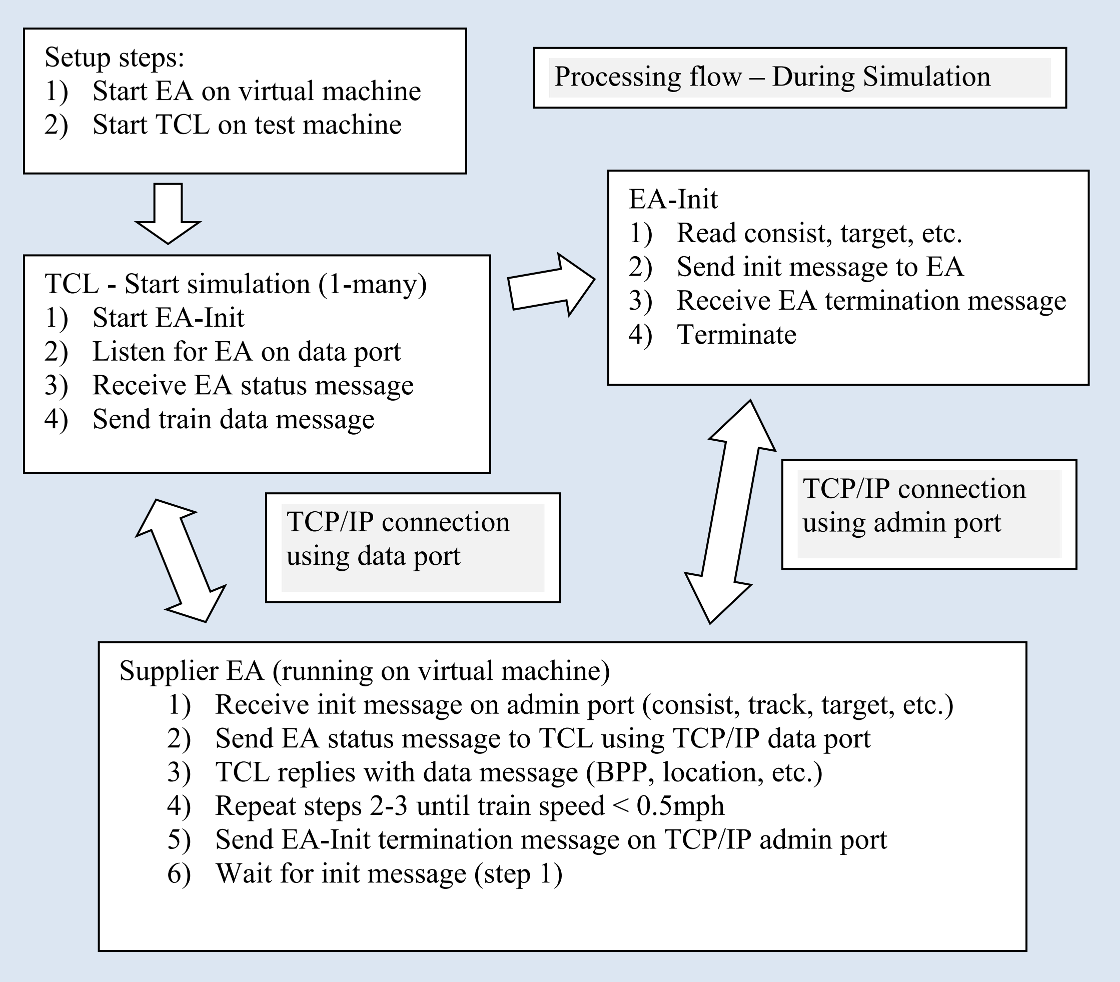


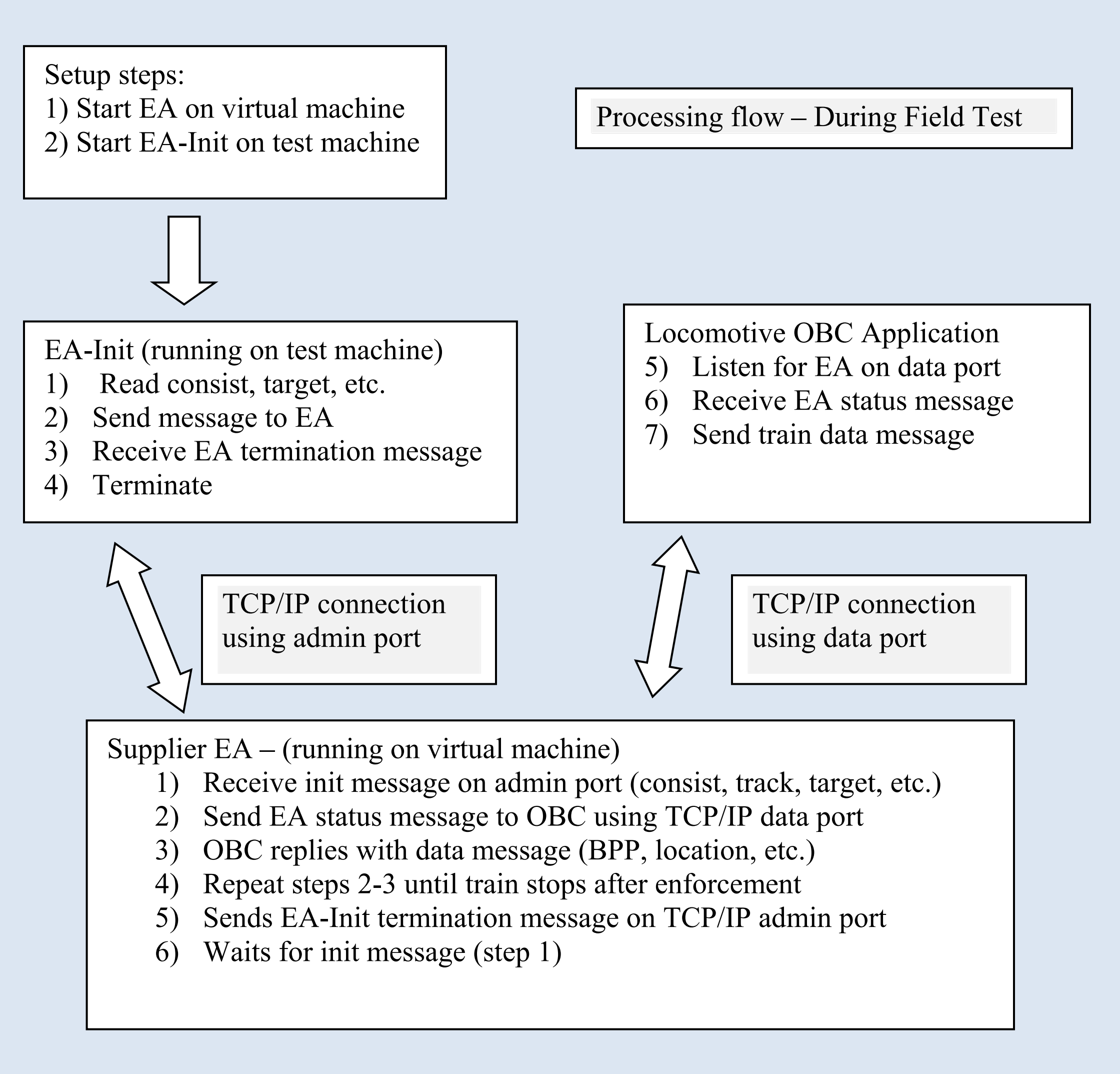
Figure C1. Simulation Test Process Flow

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.

1.2 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 C2. The primary difference is that during field testing, the EA software and the EA-Init application reside on a test computer 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).



Setup steps:
1) Start EA on virtual machine
2) Start EA-Init on test machine

EA-Init (running on test machine)
1) Read consist, target, etc.
2) Send message to EA
3) Receive EA termination message
4) Terminate

Locomotive OBC Application
5) Listen for EA on data port
6) Receive EA status message
7) Send train data message

Supplier EA – (running on virtual machine)
1) Receive init message on admin port (consist, track, target, etc.)
2) Send EA status message to OBC using TCP/IP data port
3) OBC replies with data message (BPP, location, etc.)
4) Repeat steps 2-3 until train stops after enforcement
5) Sends EA-Init termination message on TCP/IP admin port
6) Waits for init message (step 1)

Figure C2. Field Test Process Flow

1.3 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 its EA software. Specific track sections for each individual test will be identified in the initialization message using an agreed-upon identifier.

1.4 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
- As a software executable that can run on the test machines
- 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 a 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.

1.4.1 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).

2. Interface Specifications

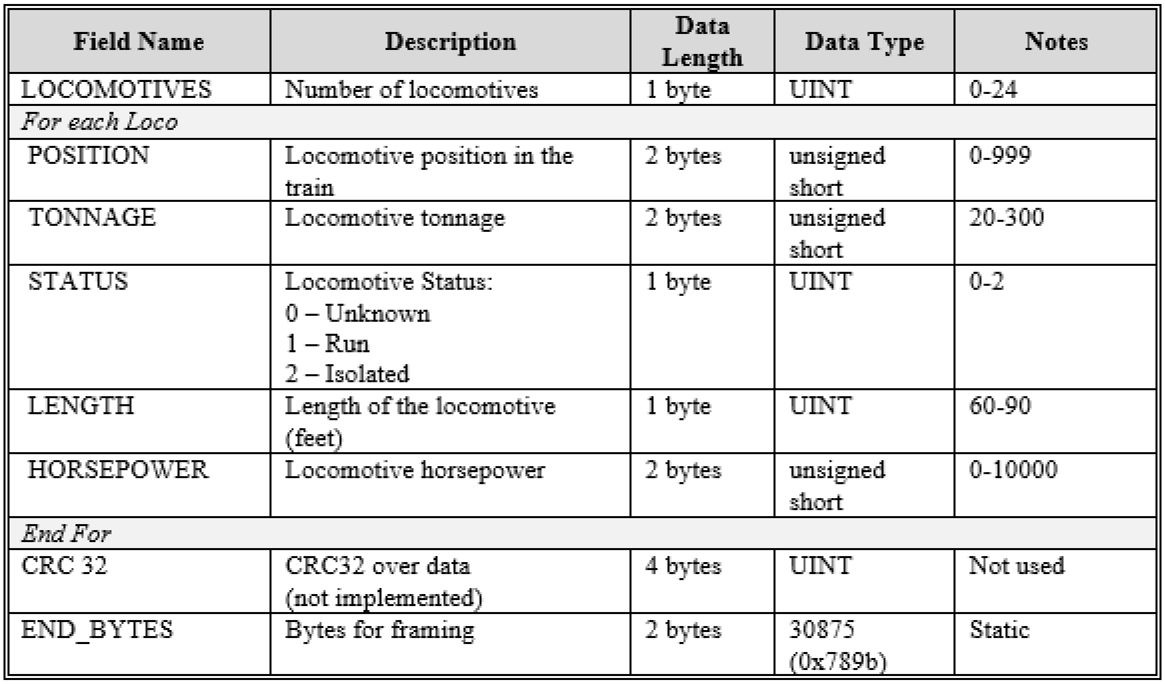
This section specifies the format for the various messages used in the enforcement algorithm evaluation processes described in the previous section.

2.1 Initialization Message Specification

Table B80 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 B80 - 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	Track file number	2 bytes	unsigned short	None
TARGET_LOCATION	Target stopping location (footage)	4 bytes	unsigned integer	None
TARGET_SPEED	Target speed (mph)	1 byte	unsigned integer	None
START_LOCATION	Initial starting track location (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 (lbs) (optional) – not including locomotives	4 bytes	unsigned integer	0-2000000



Field Name	Description	Data Length	Data Type	Notes
LOCOMOTIVES	Number of locomotives	1 byte	UINT	0-24
For each Loco				
POSITION	Locomotive position in the train	2 bytes	unsigned short	0-999
TONNAGE	Locomotive tonnage	2 bytes	unsigned short	20-300
STATUS	Locomotive Status: 0 – Unknown 1 – Run 2 – Isolated	1 byte	UINT	0-2
LENGTH	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.

2.2 Train Data Message Specification

Table B81 specifies the format for the train data message 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 B81. Train Data Message

Field Name	Description	Data Length	Data Type	Notes
START_BYTES	Bytes for Framing	2 bytes	21930 (0x55aa)	Static

Field Name	Description	Data Length	Data Type	Notes
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 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

2.3 EA Status Message Specification

Table B82 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 B81. 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

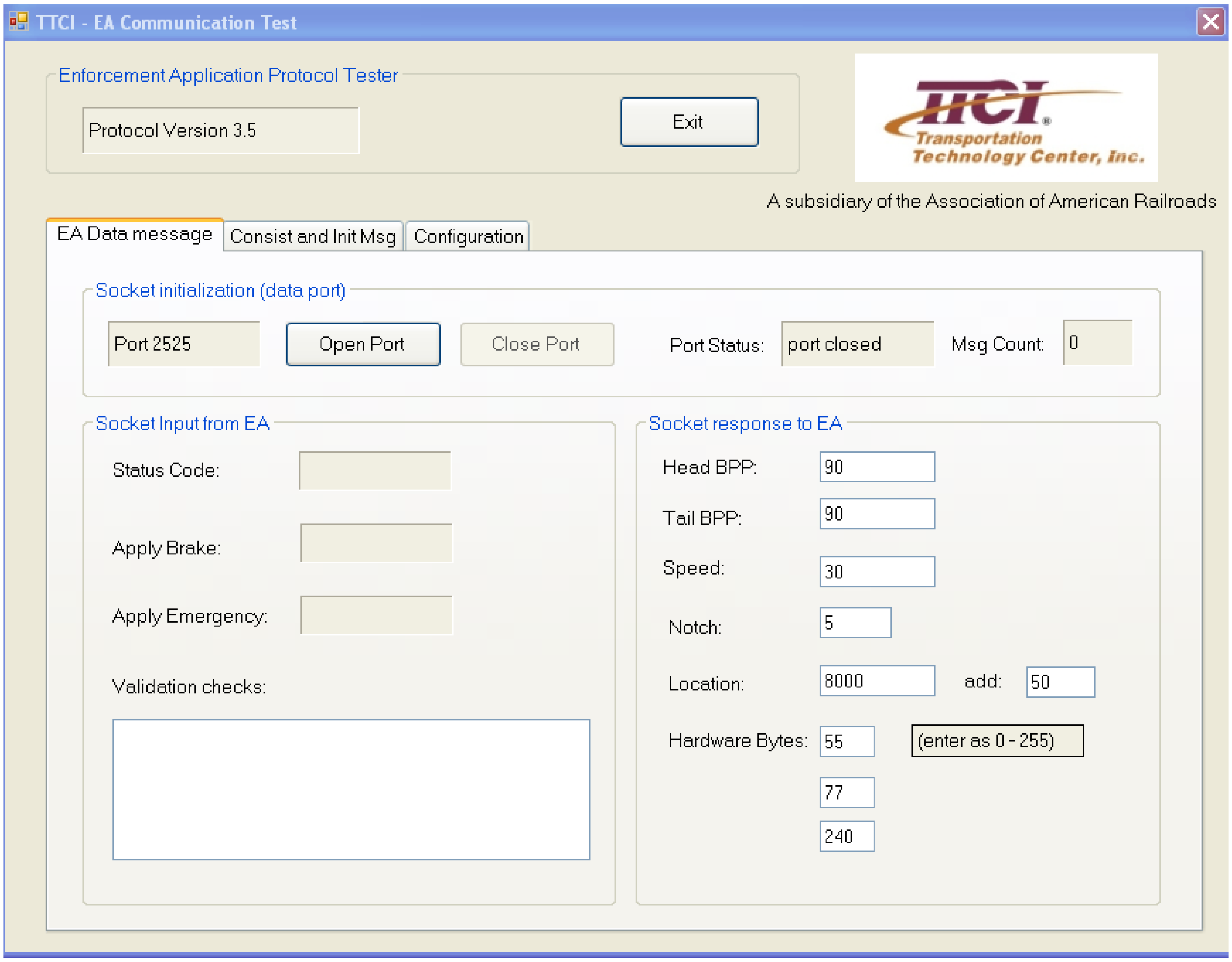
Appendix CA – Protocol Test Application

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.



Protocol Version 3.5

Port 2525

Port Status: port closed

Msg Count: 0

Status Code:

Apply Brake:

Apply Emergency:

Validation checks:

Head BPP: 90

Tail BPP: 90

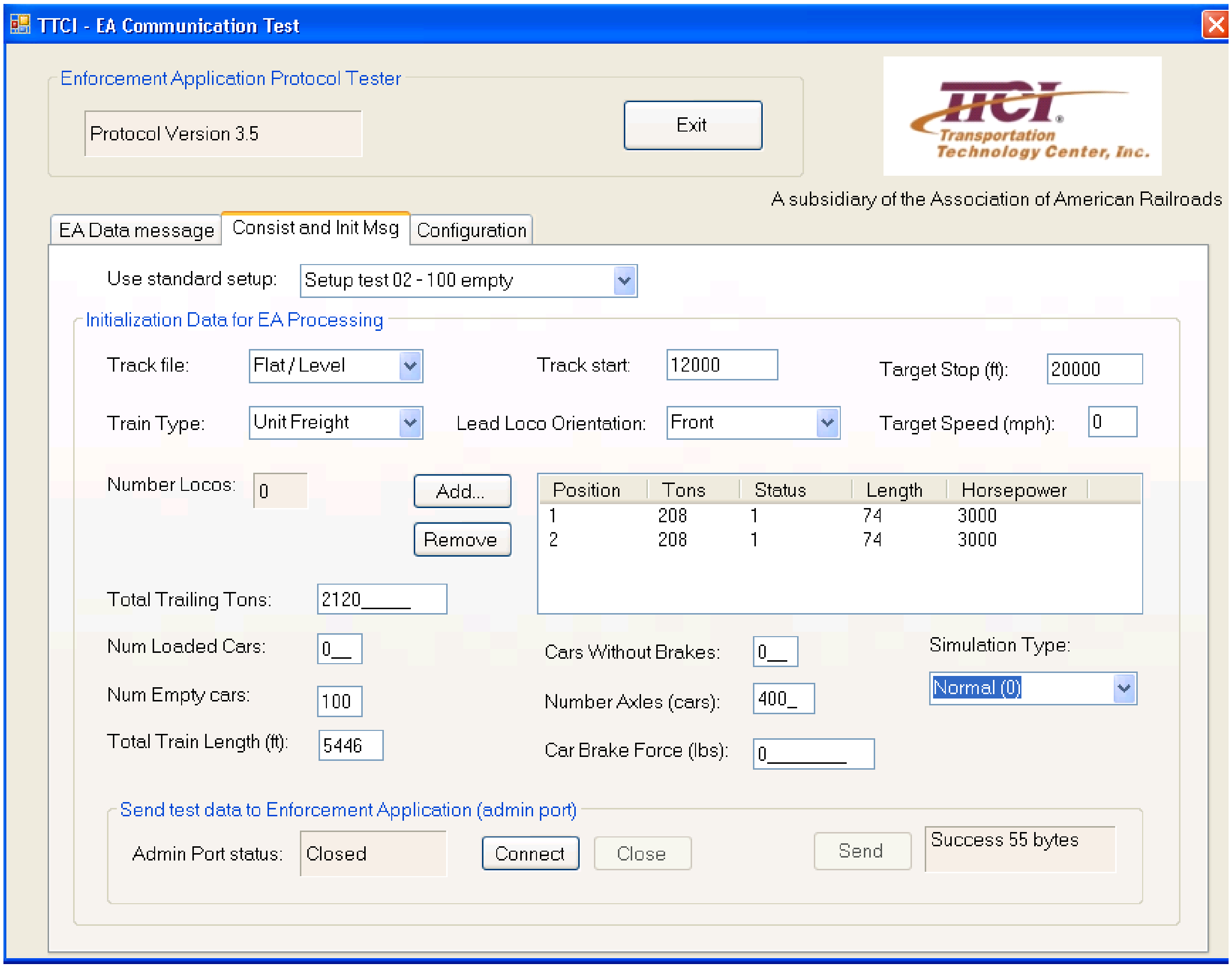
Speed: 30

Notch: 5

Location: 8000 add: 50

Hardware Bytes: 55 (enter as 0 - 255)
77
240

Figure C3 - EA Protocol Test Application – Data Message Tab



Protocol Version 3.5

Use standard setup: Setup test 02 - 100 empty

Track file: Flat / Level

Track start: 12000

Target Stop (ft): 20000

Train Type: Unit Freight

Lead Loco Orientation: Front

Target Speed (mph): 0

Number Locos: 0

Position	Tons	Status	Length	Horsepower
1	208	1	74	3000
2	208	1	74	3000

Total Trailing Tons: 2120_____

Num Loaded Cars: 0__

Cars Without Brakes: 0__

Simulation Type: Normal (0)

Num Empty cars: 100

Number Axles (cars): 400_

Total Train Length (ft): 5446

Car Brake Force (lbs): 0________

Admin Port status: Closed

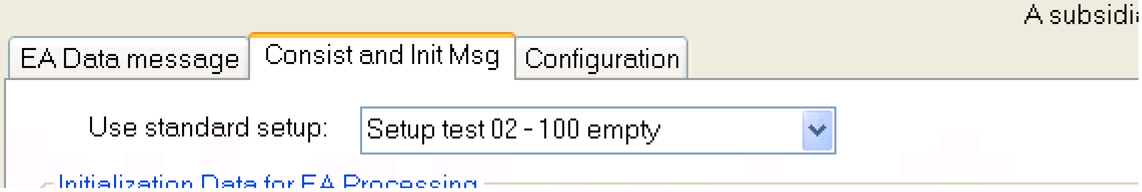
Success 55 bytes

Figure C4 – EA Protocol Test Application – Initialization Message Tab

Appendix CB. Installation and Setup Testing

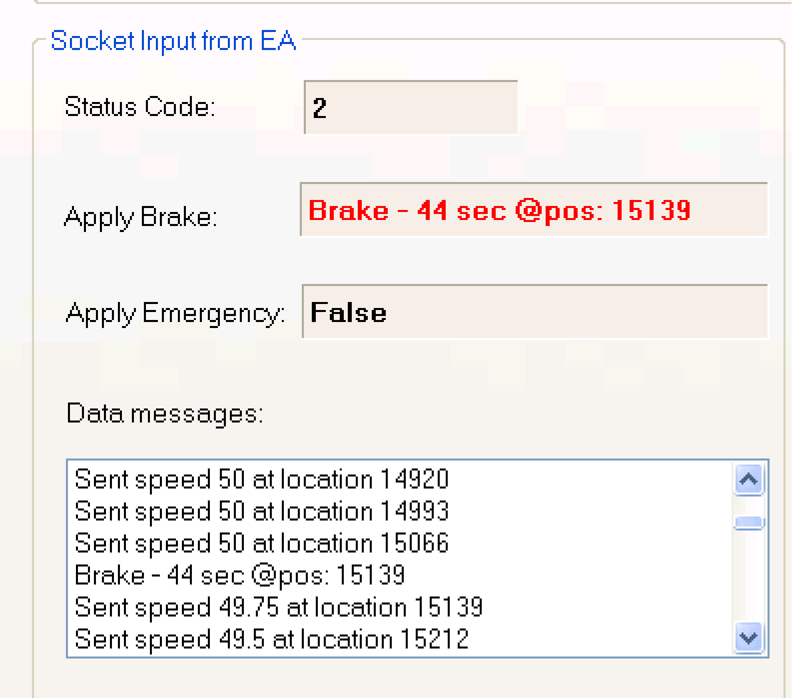
This section describes how the protocol test application is used to validate the machine setup and to ensure that the EA software is installed and configured properly. The process is described as follows:

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.



Use standard setup: Setup test 02 - 100 empty

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.



Status Code: 2

Apply Brake: Brake - 44 sec @pos: 15139

Apply Emergency: False

Data messages:

```
Sent speed 50 at location 14920
Sent speed 50 at location 14993
Sent speed 50 at location 15066
Brake - 44 sec @pos: 15139
Sent speed 49.75 at location 15139
Sent speed 49.5 at location 15212
```

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.

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 D.
ACSES Enforcement Algorithm Definition Document

Revision History

Date	Revision	Description
9/21/2015	0.1	Initial Draft

Table of Contents

1. Introduction

1.1 Purpose

The purpose of this document is to fully define and describe the logic flow and mathematical equations for the ACSES predictive braking enforcement algorithm.

1.2 Scope

This document is intended as a comprehensive description of the predictive braking enforcement algorithm defined within. It is not intended as a detailed software requirements specification. It includes a definition of the logic flow and mathematical equations required to develop a functional implementation.

The predictive braking enforcement algorithm described within this document is intended for use in PTC systems for passenger trains. Considerations for freight trains are not included.

The definition of the algorithm contains background on the source of the logic and equations to provide context but is not intended to provide a complete background on the development of the algorithm.

Information and data pertaining to safety validation of the algorithm is not included in this document, although the intent of the program under which this algorithm was developed is to provide a separate report on the testing and validation of the logic included in this document.

No attempt has been made within this document to consider software implementation techniques, particularly as related to implementation in a safety-critical application.

1.3 Intended Audience

This document is intended for developers of Positive Train Control (PTC) onboard systems and software considering predictive braking and enforcement algorithm options for inclusion in their system.

1.4 Applicable Documents

The following documents are applicable in that they are either referenced in the algorithm description document or provide useful background information:

- Braking and Prediction Algorithm Definition for the NAJPTC IDOT Project, Rev C.
- Hay, William W. (1982). *Railroad Engineering, Second Edition*. John Wiley & Sons, Inc.

1.5 Definitions and Acronyms

1.5.1 Definitions

The following terms are used in the document:

- Braking profile – The location/speed curve that describes the response of the train to either a penalty or emergency brake application, given the current conditions.

- Degree of curvature – The central angle turned over a 100-foot chord length, expressed in degrees.
- 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.
- Percent grade – The ratio of the change in track elevation over a specified distance, expressed as a percent.
- 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 train movement authority or speed limit violation. Also described as "enforcement algorithm" or simply "algorithm."
- Service air brake application – A reduction of the brake pipe pressure at a service rate
- Speed limit – The maximum allowed speed for a train over a particular section of track.
- 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.

1.5.2 Acronyms

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

- IDOT – Illinois Department of Transportation
- NAJPTC – North American Joint Positive Train Control
- PTC – Positive Train Control

2. Algorithm Overview

The enforcement algorithm described within this document is based on the version developed for the North American Joint Positive Train Control (NAJPTC) program. While other enforcement algorithms have been developed since this algorithm was originally released, the original NAJPTC version serves as a good industry base case and is available in the public domain. The algorithm described within this document seeks to improve on the performance of the NAJPTC algorithm and contains many revisions to the logic, while keeping many of the methods and concepts from the original version.

The primary objective of the predictive braking enforcement algorithm is to enforce PTC train movement authority and speed limits by initiating a penalty air brake application to stop the train from violating any such limit if the train crew fails to take action to prevent the violation, but to be transparent to the train crew when the train is handled properly to prevent the violation. The enforcement algorithm seeks to achieve these objectives by periodically predicting the stopping distance of the train, adding a target offset to the prediction, comparing this result against any authority or speed limits, and initiating a penalty air brake application as necessary.

The stopping distance prediction is performed by employing a braking curve approach to predict the braking profile of the train. The prediction assumes a penalty application is initiated at the time the prediction is made, using a combination train type and a grade correction factor.

3. Detailed Algorithm Definition

This section defines the functions, equations, and logic flow of the ACSES braking enforcement algorithm. This section will include sufficient detail for developing a working implementation of the algorithm for use in a functional PTC system.

3.1 Initialization

This section describes the functions necessary for initialization of the algorithm. The primary objective of these functions is to set all of the fixed data used by the enforcement algorithm. Although the term initialization is used, these functions are designed to be used to modify these data items at any point, not just when the algorithm is started. For example, if the PTC implementation allows for modification of the consist after the train is in route, the *Update Consist Data* function would be used to update the consist information appropriately.

3.1.1 Initialize Train Type

This function is used to initialize the train type that is used by the ACSES enforcement algorithm. The train type descriptions are listed below:

Table D82. ACSES Train Types

Type	Max Speed	Consist	Restrictions
A	110 mph	Future high speed train; consist TBD	
B1	110 mph	Maximum of 2 P-40 or P-42 locomotives with not less than 2 nor more than 14 Amfleet/Horizon	No non-passenger carrying or Superliner cars
B2	110 mph	Maximum of 1 P-40 or P-42 locomotive with 14 cars or less with no more than 1 non-passenger carrying car for each Amfleet/Horizon car in the consist	No more than 2 of the non-passenger carrying cars may be MHC cars (Series 1400–1569); no Superliner cars
B3	110 mph	Maximum of 1 P-40 or P-42 locomotive, 14 cars or less with no more than 2 RoadRailer vans for each Amfleet/Horizon car	No MHC cars, baggage cars or Superliner cars
C1	90 mph	Maximum of 2 P-40 or P-42 locomotives and 14 cars or less with a minimum of e Amfleet, Horizon, or Superliner cars	Maximum of 11 non-passenger carrying cars
C2	90 mph	Maximum of 3 P-40 or P-42 locomotives, 15 to 30 cars with a minimum of 7 Amfleet/Horizon or 9 Superliner cars	Not more than 1 baggage car. No MHC cars. Remaining cars may be Express cars, including RoadRailers.
D	90 mph	All trains that do not qualify as Types A, B, or C	

3.1.2 *Update Track Data*

This function is used to initialize or update the track data required, which includes:

- Elevation or percent grade and location reference for each grade change

3.2 Main Process

This section describes the primary high-level functions of the enforcement algorithm that make up the main processing loop. Figure D1 illustrates the flow of the functions within this process. Each of these functions are described generally in this section and described in more detail in subsequent sections, where appropriate.

The main process is to be repeated periodically, as required by the overall PTC system design. Each iteration of the main process will result in a decision on whether a penalty or emergency brake application is necessary to prevent a movement authority or speed limit violation. A frequency of 1 Hz is considered typical.

3.2.1 *Update Targets*

This function is used to define locations where the train must be at or below a given speed, including movement authorities (zero speed targets) and speed restrictions (non-zero speed targets). The function accepts target data from the onboard system and assigns or removes targets from the target data store, as necessary. Each target contains two data items:

- Target Location – Location of the target as referenced to the track database
- Target Speed – Speed limit at the target in mph

When the algorithm completes the brake profile prediction, these targets are used to determine if a penalty brake application is necessary.

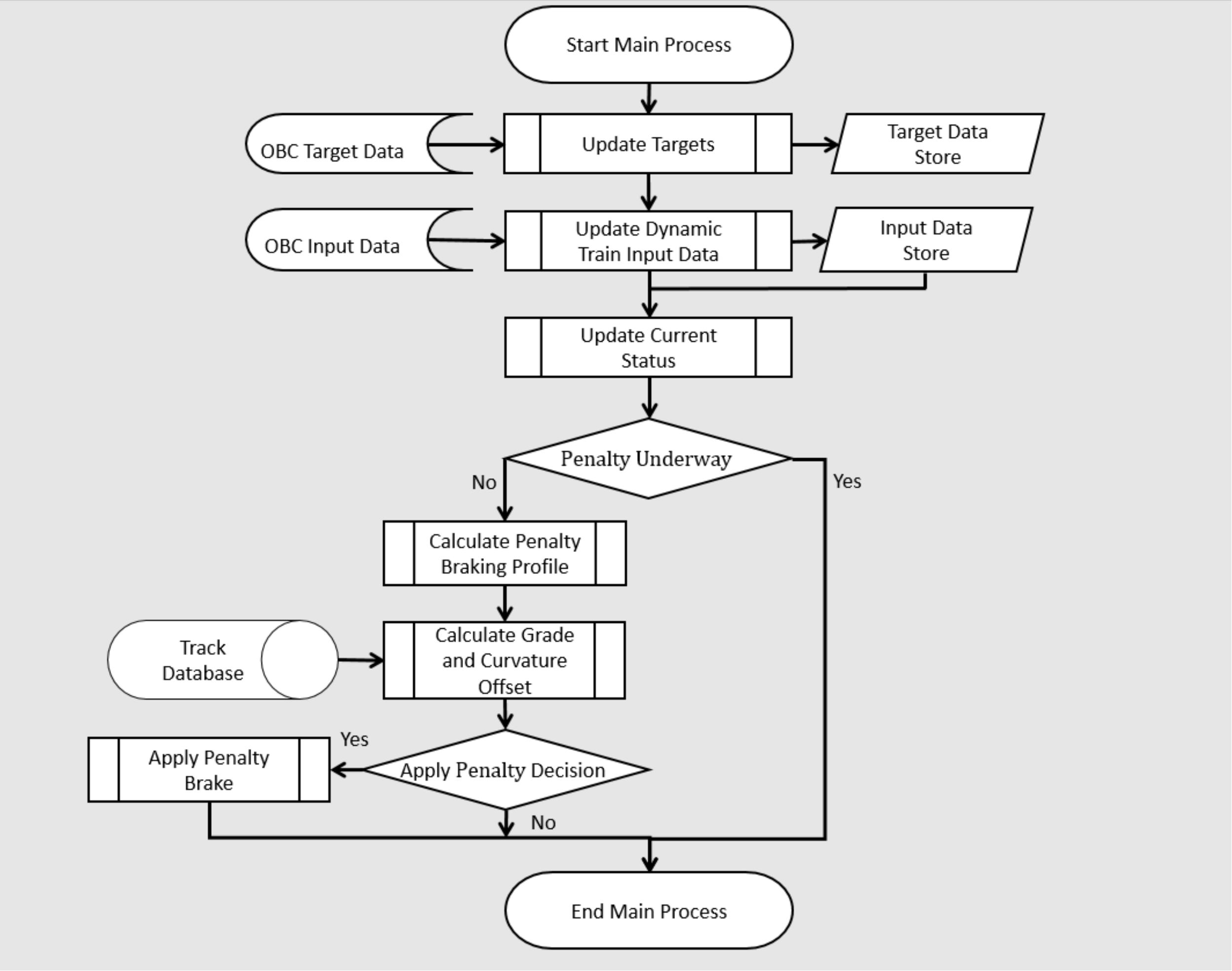


Figure D1. Main Process Flow Diagram

3.2.2 Update Dynamic Train Input Data

During each iteration of the main process, this function collects train status information from the onboard system for use elsewhere in the algorithm. The following data items are assigned in this function:

- Location – current location of the lead locomotive as referenced to the track database
- Speed – current speed of the lead locomotive in miles per hour (mph)

3.2.3 Update Current Status

This function updates the algorithm on the current status of the train based on train input data from the onboard system, consist data, and track data from the track database. The current status serves as the initial data point in the braking profile prediction.

3.2.4 Penalty Brake Enforcement Prediction

If the predictive braking enforcement algorithm has not yet enforced a penalty air brake application, the algorithm determines if a penalty air brake application is necessary to avoid violating any of the currently established targets. This comprises two processes: *Calculate Penalty Braking Profile,* and the *Penalty Enforcement Decision*.

Calculate Penalty Braking Profile

This function calculates the braking profile of the train by assuming a penalty brake application is made at the time of the calculation, given the current status of the train, the train type, and the track data from the track database. This calculation represents a nominal prediction of stopping distance. The *Calculate Penalty Braking Profile* function is described in detail in Section 3.4.

Penalty Enforcement Decision

This function is used to determine if a penalty brake enforcement is necessary, given the previously calculated braking profile. All currently active targets are evaluated to determine if a violation is predicted. Multiple targets and combinations of zero speed and non-zero speed targets may need to be evaluated.

For zero speed targets, the predicted zero speed location of the train, according to the braking profile, is compared against the zero speed target location. If the predicted zero speed location is greater than the target location, a penalty brake application is initiated.

For non-zero speed targets, the predicted location of the train at the target speed is compared against the target location. If the predicted location at the target speed is greater than the target location, a penalty brake application is initiated.

3.3 Calculate Penalty Braking Profile

The Calculate Penalty Braking Profile process is responsible for computing the braking profile for the train, prior to any PTC air brake enforcement, by assuming a penalty brake application is initiated at the time of the calculation. The process is run once each time through the main process, as shown in Figure D1, and the result is used to determine if a penalty air brake enforcement is necessary. The Calculate Penalty Braking Profile process flow is shown in Figure D2.

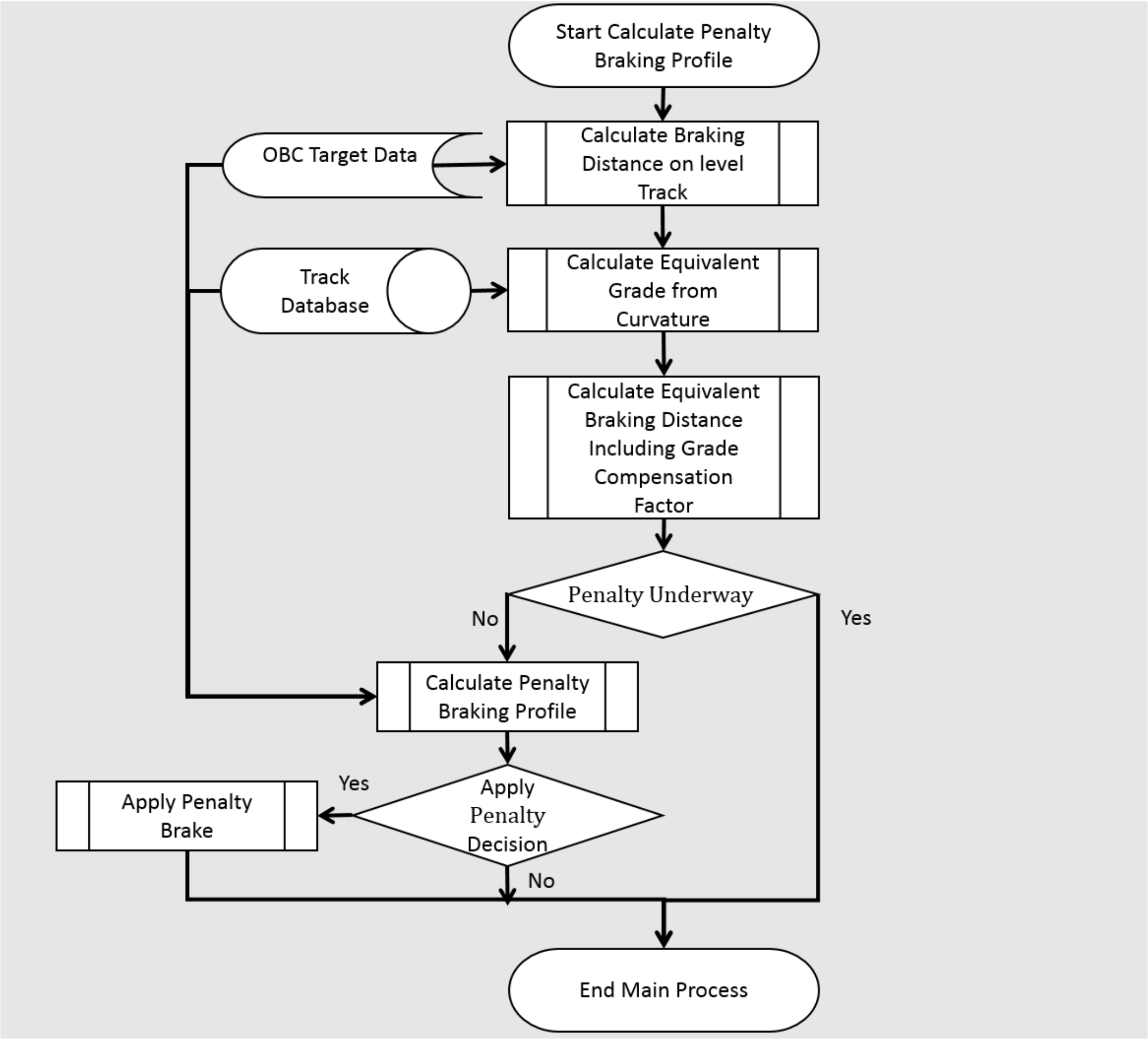


Figure D2 - Calculate Penalty Braking Profile Flow Diagram

The prediction of the brake profile is performed by employing the equations listed in the following table. Each passenger train type has a defined braking distance equation for braking to a stop and for predicting speed reduction distance.

Table D83. Braking Prediction Calculations

Train Type	Stop Distance Calculation	Speed Reduction Calculation
A	TBD	TBD
B	$D_0 = 0.8333*V_i^2+11.73*V_i$	$D_0 = 0.75*V_i^2+11.73*V_i - 0.75*V_f^2$
C	$D_0 = 0.8333*Vi2+26.25*Vi$	$D_0= 0.75*V_i^2+23.63*V_i - 0.75*V_f^2$
D	$D_0 = 0.8333*Vi2+31.25*Vi$	$D_0 = 0.75*V_i^2+28.13*V_i - 0.75*V_f^2$

The Stop Distance Calculation is the distance to stop in feet on level tangent track with a 25% safety factor and 8 seconds of “free running” time. V_I is the initial speed in mph. For types C and D additional brake pipe set-up time has been included. The Speed Reduction Calculation is the distance in feet to reduce speed from an initial speed V_I in mph to a final speed V_F in mph with a 12.5% safety factor.

3.4 Calculate Grade and Curvature Offset

Each of the equations defined in Table D84 is for level tangent track. The effects of grade and track curvature can be incorporated into a final answer for predicted stopping distance by using the grade compensation factors defined in this section. Since there is a numerical “closed loop” involved in this calculation, (i.e., The stopping distance can’t be known until the average grade is known but the average grade can’t be determined until the stopping distance is known.) An approximation procedure is used to provide accuracy of the final distance well within the safety margins provided by the assumptions on the equations themselves. The distance resulting from the above equations is first computed to determine the stopping (reduction) profile. The effective average grade, including curvature effects, over this distance can then be calculated. This effective average grade is then used in the grade compensation factor.

3.4.1 Calculate Equivalent Grade from Curvature

When the train or a portion of the train is moving over a curved section of track, there is an additional resistance force opposing movement. This force arises from the additional friction associated with forcing the train around curved track. The curvature effects can be modeled effectively by converting the curving force to an equivalent grade force. This can be done by using the following equation:

$$G_c = .05 * C$$

Where:

G_C is the equivalent grade percentage due to the curvature.

C is the average curvature of the track, during the penalty braking profile calculated in Table 2 above. This value is entered in as degrees of curvature and is value is always positive. This value is calculated by determining the penalty braking distance from the equations in Table 2 and referencing the track charts to determine the average curvature over this distance.

3.4.2 Calculate Equivalent Braking Distance Including Grade Compensation Factor

Once the equivalent grade from curvature has been calculated the grade compensation factor can be calculated using the following formula.

$$= \begin{cases} \dfrac{6}{G_a + G_c + 6} * D_o, For\ up\ grades \\ \dfrac{4}{G_a + G_c + 4} * D_o, For\ down\ grades \\ \dfrac{4}{G_c + 4} * D_o, For\ flat\ track \end{cases}$$

Where:

De is the equated braking distance compensating for grade and curvature.

G_C is the equivalent grade percentage due to the curvature.

D_0 is the level tangent track value for distance resulting from application of the appropriate equation from Table D84.

G_a is the effective average track grade in percent. This value is calculated by determining the penalty braking distance from the equations in Table D84 and referencing the track charts to determine the average grade over this distance. Note that prediction implies that these trains cannot stop on a down grade of 4 percent or greater