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I-ETMS™ Positive Train Control Passenger Braking Algorithm Enhancement – Phase II

DOT/FRA/ORD-23/36

Final Report | September 2023

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14. ABSTRACT
The Federal Railroad Administration (FRA) funded Transportation Technology Center, Inc. (TTCI) to examine the performance benefits of four potential modifications to the current methodology used for passenger braking enforcement algorithms (EA) in the Interoperable Electronic Train Management System (I-ETMS™) Positive Train Control (PTC). Additionally, researchers developed a methodology for simulating PTC braking algorithm performance for Electric Multiple Unit/Diesel Multiple Unit consists. This process does not rely on brake pipe pressure changes and requires different information to be provided to the EA and simulation program. Finally, the project included field testing to demonstrate the modifications to the EA reflected operational data. Due to the global pandemic, equipment was limited and testing was conducted using available cars and locomotives. The testing was conducted using the baseline, Total Approach Management, tuned train type, and specified consist algorithms. An analysis of the test results showed that the enhancements could be used to improve the EA performance for certain scenarios.

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Positive Train Control, PTC, braking, braking algorithm enhancements, field testing, Electric Multiple Unit, EMU, Diesel Multiple Unit, DMU, enforcement algorithm, enforcement algorithms, EA

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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

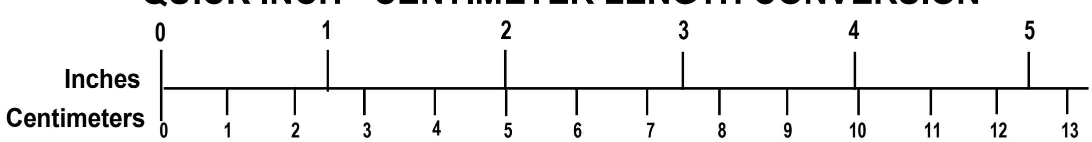
VOLUME (APPROXIMATE)

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)

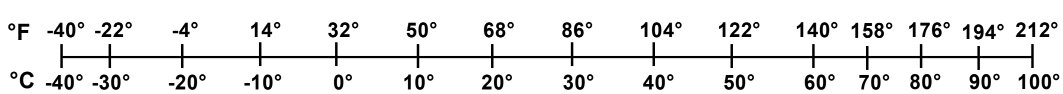
TEMPERATURE (EXACT)

[(9/5) y + 32] °C = x °F

QUICK INCH - CENTIMETER LENGTH CONVERSION



QUICK FAHRENHEIT - CELSIUS TEMPERATURE CONVERSIO



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

Updated 6/17/98

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Executive Summary

From May 2018 to November 2021, the Federal Railroad Administration sponsored Transportation Technology Center, Inc. to examine the performance benefits of four potential modifications to the current methodology used for passenger braking enforcement algorithms (EA) in Interoperable Electronic Train Management System (I-ETMS™) Positive Train Control (PTC) applications and found that all four showed improvements compared to the baseline. Algorithms were designed so that 99.5 percent of all passenger trains stop before the target, which can impact the efficiency of some consists and vehicles. This work took place at the Transportation Technology Center. Improving the performance of the EA without sacrificing safety will allow agencies to operate more efficiently. The four methods examined were: Target Approach Management (TAM), specified consist length trains, tuned train types, and adaptive braking.

TAM is a functional concept that allows consists to approach a target at slower speeds without experiencing an unnecessary PTC brake enforcement application. During this project, the research team developed a TAM process; concurrently Wabtec Corporation also created their own process and released it as a function of their I-ETMS algorithm. Examining both TAM processes showed that implementing the TAM enhancement would improve performance by allowing consists to get closer to a target location without negatively impacting the probability of overrunning the target. The TAM enhancement improved overall probability of overrunning the target to less than 0.1 percent. With this improvement, the EA meets the overall safety goal of being able to stop short of the target with a probability equal to or greater than 99.9 percent.

The specified consist makeup enhancement relies on the observation that short trains behave differently compared to longer trains. A higher ratio of locomotives to cars creates lower available braking force and leads to an increase in overruns for shorter trains. Modifying the algorithm to calculate a ratio for brake rates based on the number of locomotives and cars reduced the occurrence of overruns with only a minor impact to operational efficiency. The specified consist length enhancement increased the overall probability of stopping significantly short of the target by 16.58 percent.

The tuned train type enhancement relies on each passenger and commuter agency setting their equipment to meet specific brake rates and operational metrics in their captive fleets. Regression analysis of the data provided brake rates and target offsets for each of the four agencies modeled. Analysis for the tuned train type enhancement compares only to baseline results for the four agencies modeled, which had an overall probability of 98.18 percent to stop short of the target and a 23.51 percent probability to stop short of the performance limit. The tuned train type enhancement increased the overall probability of stopping short of the target by 1.78 percent. With this enhancement, the EA meets the overall safety goal of being able to stop short of the target with a probability equal to or greater than 99.5 percent. The tuned train type enhancement did increase the overall probability of stopping short of the performance limit by 8.95 percent. When the results were broken down by agency, it demonstrated that improvements were made in both safety and performance for three out of the four case studies.

Using an adaptive algorithm allows the EA to determine the brake forces more accurately for a specific consist. Brake rates from prior brake applications are used to predict the brake rate during a PTC braking enforcement. However, there are many factors that can affect braking

performance, thus a more detailed risk analysis would be required before an adaptive algorithm could be implemented. The analysis for this project showed a potential increase in safety. The adaptive braking enhancement increased the overall probability of stopping short of the target by 1.23 percent.

Additionally, the project included development of a methodology for simulating PTC braking algorithm performance for Electric Multiple Unit (EMU)/Diesel Multiple Unit (DMU) consists. EMU and DMU equipment operate by relaying electronic signals to the brakes and rarely include a brake pipe. This process does not rely on brake pipe pressure changes and requires different information to be provided to the EA and simulation program.

Finally, the project included field testing to demonstrate the modifications to the EA reflected operational data. Due to the global pandemic, equipment was limited, and testing was conducted using available cars and locomotives. The testing was conducted using the baseline, TAM, tuned train type, and specified consist algorithms. Analysis of the test results showed that the enhancements could be used to improve the EA performance for certain scenarios.

1. Introduction

Positive Train Control (PTC) is a technology designed to increase safety. The Interoperable Electronic Train Management System (I-ETMS™) PTC braking algorithms are intended to stop 99.5 percent of trains at or before the target, which means that, while poor performing trains will stop before the target, the more efficient trains may stop a significant distance short of the target, impacting operational efficiency. The Federal Railroad Administration (FRA) sponsored Transportation Technology Center, Inc. (TTCI) to investigate possible improvements to PTC braking algorithms that could be expected to bring about increased operational efficiency, while maintaining safety performance.

1.1 Background

PTC functions to enforce the operational limits of each train through application of the automatic penalty brake in the event the train is predicted to violate either its movement authority or speed limits. In current PTC implementations, a software algorithm is implemented on board the locomotive to predict the stopping location of the train, based on known and assumed characteristics of the train and current conditions. During PTC testing and analysis of enforcement algorithm (EA) performance, it has been observed that these algorithms can be overly conservative with the potential to sacrifice operational performance to meet the required safety objectives associated with the system. This is a concern for commuter railroads with tight schedules operating on busy tracks, e.g., during rush hour. For the PTC system to be effective, the EA must be capable of meeting the safety requirements of the system while minimizing interference with normal railroad operations.

Based on these initial findings, an industrywide effort with FRA funding was initiated to explore opportunities to reduce the negative operational impact of PTC braking EAs. As part of this effort, researchers developed a methodology to analyze the characteristics of the EA using Monte Carlo simulation techniques validated with field testing. Techniques for improving EA performance for freight operations were developed and implemented using a test implementation of a base case EA and these techniques were analyzed using the methodology developed. This initial effort achieved significant improvements in EAs designed for freight train operations, though the team recognized that the same types of issues would need to be investigated for passenger and commuter train operations.

In the first phase, the research team expanded the methodology developed for freight rail equipment and operations, researched PTC passenger and commuter equipment and operational characteristics, built models of the equipment and consists for a variety of U.S. passenger and commuter operations, developed a Monte Carlo simulation matrix covering these operations, integrated current passenger and commuter PTC braking algorithms into the Monte Carlo simulation environment, and evaluated these algorithms to demonstrate their performance characteristics. These results can be used to identify where potential improvements could be made to further enhance PTC capabilities to support effective implementation of the technology.

1.2 Objectives

The primary objective of the project was to identify, develop, simulate, and test methods to improve predictive braking EAs for passenger and commuter trains in an I-ETMS PTC system design. Other components of this main objective were to:

- Modify the Passenger Train Braking Performance Model (PTBPM) so that it is capable of modeling Electric Multiple Unit (EMU) equipment.
- Perform PTC braking algorithm simulations of the Interoperable Electronic Train Management System (I-ETMS)[1] and identify potential areas of improvement.
- Modify the passenger/commuter train EA test application and conduct testing to establish a baseline against which to compare potential improvements.
- Use input provided by representatives from intercity passenger and commuter agencies, as well as feedback from FRA, to develop and implement the highest priority techniques identified in the test application.
- Support passenger and commuter agencies by providing data and analysis to support their PTC safety analyses.

1.3 Overall Approach

The first task of this project was to modify the simulation environment to support braking algorithm simulations for scenarios involving EMU and DMU equipment. The research team worked with the participating passenger/commuter railroads to determine the differences between their EMUs and regular passenger locomotives, coaches, and cab cars. Researchers identified several differences in the control and braking systems. Due to the operational aspects of EMU/DMU equipment, the interface between the EA and the PTC braking algorithm simulation environment required changes. The Interface Control Document (ICD) was updated to include the changes needed. The authors implemented the changes to the interface in the modeling software, so that EMU/DMU can be simulated by PTC braking algorithm software that supports the new interface.

The research team analyzed the safety and performance of the current I-ETMS algorithm by using the simulation matrix defined in the previous project and reviewing the results of the simulations to improve operational efficiency. The research team developed a list of potential improvements, and the project's advisory group (AG) chose the top four highest priority enhancements to be implemented.

Because the I-ETMS EA is a proprietary algorithm, TTCI developed a test application with a baseline version of a braking algorithm to be used to analyze the relative improvement of potential enhancements. The baseline algorithm was established by performing simulations and analyzing the results to determine the probability of stopping short of a target and the probability of stopping short of the performance objective.

Initial suggested improvements were based upon the previous work done for freight railroads, as well as input from AG members. In addition, the AG assigned priority to enhancements based upon their expected effect upon operational efficiency. The following four were the determined to be the most interesting with the best chance of improving operations: (1) Target Approach Management (TAM), (2) specified consist calculations, (3) tuned train types, and (4) an adaptive algorithm. TAM is currently in use by freight trains, but no analysis using passenger equipment had been completed before this project. Each enhancement required changes to the baseline

[1] Trademark Wabtec Corporation

algorithm to implement the desired functionality. All the enhancements were tested individually so that the relative improvement to the baseline could be accurately quantified.

The EA was then modified, with the enhancements chosen by the AG, to compare the results and show the relative improvement in braking algorithm performance if these modifications were implemented. The end result of the simulation testing would allow for passenger and commuter railroads to prioritize the enhancements that they feel would be of the highest benefit to overall operations if implemented in the current PTC systems operation in the field.

1.4 Organization of the Report

This report is organized as follows: Section 2 describes the software changes required for EMU/DMU integration. Section 3 describes the baseline EA. Section 4 provides the baseline simulation results. Section 5 describes the enhancements and the results from the simulations of the algorithm using those enhancements. Section 6 details the field testing. Appendix A provides the baseline for the braking EA. Appendix B contains the interface control document.

2. Braking Simulation Software Changes for EMU/DMU Integration

The braking and propulsion systems on EMU equipment differ from those found on other passenger/commuter vehicles and onboard PTC systems that have been modified to account for these differences. The modifications to the modeling software used to simulate PTC braking enforcements were needed to pass the expected data to the PTC EA and run PTC braking algorithm performance simulations.

The research team investigated the various types of EMUs to determine what modifications would be required. Through this study, they determined that there are many differences between the various types of EMUs used in the industry. The existing PTC onboard systems were modified specifically for each EMU type. To accommodate the various implementations, TTCI worked with one PTC vendor to develop a method for simulating all EMUs that did not require significant development and expansion of the interface between the PTC braking algorithm software and the simulation environment. With this method, the simulation environment sends the brake demand as a percentage of the maximum total braking force, and tractive effort as a percentage of the maximum tractive effort. The EA software uses this value in its calculations to determine if a brake enforcement is needed to prevent overrun of an upcoming stop target.

PTBPM, the Passenger Test Controller Logger (P-TCL), and the communication software application required modifications to implement these changes. The initialization message was modified to include the type of EMU being simulated. P-TCL also was modified to send the brake force as a percentage of the maximum brake force that can be generated by the EMU consist. In Equation 1, this was calculated by summing the brake force produced by each EMU/DMU in the consist and dividing the total by the sum of the maximum brake force for each EMU/DMU unit. The resulting value is multiplied by 100 to convert it to a percentage. The maximum brake force is a constant value for each EMU type and will be used by both the EA and the PTC braking algorithm simulation software.

$$\text{EMU\_Brake\_Percent} = \frac{\sum Current\ EMU\ brake\ force}{\sum Maximum\ EMU\ brake\ force} x\ 100 \tag{1}$$

P-TCL was also modified to send the current tractive force being generated by the EMU consist as a percentage of the maximum tractive force that can be generated by the EMU consist. Equation 2 calculated this by summing the tractive effort produced by each EMU/DMU in the consist and then dividing the total by the sum of the maximum tractive effort for each EMU/DMU unit. The resulting value is multiplied by 100 to convert it to a percentage. The maximum tractive force is a constant value for each EMU type and will be used by both the EA and the PTC braking algorithm simulation software.

$$\text{EMU\_Tractive\_Percent} = \frac{\sum Current\ EMU\ \text{tractive effort}}{\sum Maximum\ EMU\ tractive\ effort} x\ 100 \tag{2}$$

3. Baseline Enforcement Algorithm

The I-ETMS EA is proprietary content, therefore the team developed a test application with a baseline version of a braking algorithm to be used to analyze the relative improvement of potential enhancements. The baseline algorithm was established by performing simulations and analyzing the results to determine the probability of stopping short of a target and the probability of stopping short of the performance objective. Appendix A describes the baseline braking EA.

3.1 Baseline Simulation Matrix

To provide a baseline for comparing the performance of the potential enhancements, the EA test application was evaluated using a simulation matrix including operational models from four commuter/passenger railroads. Using previously validated equipment models, normal operational speeds, and typical track grades aided in the development of the simulation batches. The simulation matrix described in Table 1 and Table 2 was used to evaluate all of the algorithms except for TAM (i.e., baseline, specified consist, adaptive, and Tuned Train).

Table 1. Consists Used for Baseline, Specified Consist, Adaptive, and Tuned Train Simulation Matrix

No.	Powered Vehicles (Qty.)	Trailing (Unpowered) Vehicles (Qty.)	Cab Cars (Qty.)
1	EMD F59PH (1)	Superliner I (2)	N/A
2	EMD F59PH (3)	Superliner I (14)	N/A
3	P42DC (1)	Superliner I (2)	N/A
4	P42DC (3)	Superliner I (14)	N/A
5	EMD F59PH (1)	Superliner I (1)	N/A
6	P42DC (1)	Superliner I (1)	N/A
7	EMD F59PH (1)	Amfleet (1)	N/A
8	EMD F59PH (1)	Amfleet (3)	N/A
9	EMD F59PH (3)	Amfleet (14)	N/A
10	P42DC (1)	Amfleet (1)	N/A
11	P42DC (1)	Amfleet (3)	N/A
12	P42DC (1)	Amfleet (14)	N/A
13	Charger SC44 (1)	Amfleet (1)	N/A
14	Charger SC44 (1)	Amfleet (3)	N/A
15	Charger SC44 (3)	Amfleet (14)	N/A
16	EMD F40PH (1)	Bombardier Bi-level (3)	Bombardier Bi-level (1)
17	EMD F40PH (1)	Bombardier Bi-level (5)	Bombardier Bi-level (1)
18	EMD F59PHI (1)	Bombardier Bi-level (3)	Bombardier Bi-level (1)
19	EMD F59PHI (1)	Bombardier Bi-level (5)	Bombardier Bi-level (1)
20	EMD F59PHI (1)	Bombardier Bi-level (6)	Bombardier Bi-level (1)
21	EMD F59PHI (1)	Bombardier Bi-level (5)	Bombardier Bi-level (2)
22	MP-40 (1)	Bombardier Bi-level (6)	Bombardier Bi-level (1)
23	MP-40 (1)	Bombardier Bi-level (5)	Bombardier Bi-level (2)
24	EMD F125 (1)	Bombardier Single Level (3)	Rotem Bi-level (1)

No.	Powered Vehicles (Qty.)	Trailing (Unpowered) Vehicles (Qty.)	Cab Cars (Qty.)
25	EMD F125 (1)	Bombardier Single Level (5)	Rotem Bi-level (1)
26	EMD F125 (1)	Rotem Bi-level (3)	Rotem Bi-level (1)
27	EMD F125 (1)	Rotem Bi-level (5)	Rotem Bi-level (1)
28	EMD F59PHI (1)	Bombardier Single Level (3)	Rotem Bi-level (1)
29	EMD F59PHI (1)	Bombardier Single Level (5)	Rotem Bi-level (1)
30	EMD F59PHI (1)	Rotem Bi-level (3)	Rotem Bi-level (1)
31	EMD F59PHI (1)	Rotem Bi-level (5)	Rotem Bi-level (1)
32	MP36PH-3C (1)	Bombardier Single Level (3)	Rotem Bi-level (1)
33	MP36PH-3C (1)	Rotem Bi-level (5)	Rotem Bi-level (1)
34	MP36PH-3C (1)	Rotem Bi-level (3)	Rotem Bi-level (1)
35	MP36PH-3C (1)	Rotem Bi-level (5)	Rotem Bi-level (1)
36	EMD F125 (1)	Bombardier Single Level (1)	Rotem Bi-level (1)
37	MP36PH-3C (1)	Bombardier Single Level (1)	Rotem Bi-level (1)
38	MP36PH-3C (2)	Rotem Bi-level (10)	Rotem Bi-level (1)
39	EMD F125 (2)	Rotem Bi-level (10)	Rotem Bi-level (1)

Table 2. Speed Grade Combinations Used for Baseline, Specified Consist, Adaptive, and Tuned Train Simulation Matrix

Speed	Grade (%)
10 mph	0.0
10 mph	-1.5
10 mph	1.5
10 mph	-2.4
10 mph	-3
25 mph	-3.7
50 mph	-3
90 mph	0.0
90 mph	-1.5
90 mph	1.5

The EA test application used for this project was a PTC braking algorithm developed by the research team to provide a baseline to which relative improvements from potential enhancements could be compared. This was necessary to allow the potential modifications and enhancements to be evaluated without having to implement them in vendor proprietary software. For the initial baseline results algorithm, changes were made that included varying the target offset and brake rate calculations, which allowed the EA to approach similar overall results to similar EA software being used by the railroads.

3.2 Baseline Simulation Results

The analysis of the Monte Carlo baseline algorithm simulation results is intended to statistically quantify the safety and performance characteristics of the EA for each scenario simulated. The results are separated into four main sections of analysis: (1) Exploratory Data Analysis (EDA), (2) overall results, (3) analysis of overruns, and (4) analysis of undershoots.

3.2.1 Baseline Exploratory Data Analysis

First, researchers performed a thorough EDA. An EDA uses visual mediums (e.g., scatterplots, quantile-quantile (Q-Q) plots) to characterize the data being analyzed, as well as uncover outliers, anomalies, and other underlying structures of the results data. The main objective of the EDA is to ensure that the dataset is complete and that there are no data anomalies caused by simulation processing errors which, in turn, could reflect an unrealistic result of the train enforcement application tests.

Two of the performance measures analyzed were:

- Penalty application speed difference: The difference between the target speed and the actual speed at the enforcement location. The P-TCL's cruise control function controls the speed, and will adjust the throttle or brake application to keep the consist at a constant speed up to the point of the 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.

In certain cases, there is variation between the input speed and the actual speed at the point of enforcement. This variation is primarily due to (1) the use of pneumatic brakes on steep downgrades, and (2) insufficient tractive effort to maintain the speed on steep inclines. Figure 1 shows the Q-Q plot of all penalty application speed differences for each simulation. As can be seen, the cruise control of the model performed well, as exemplified by the fact that:

- 99.51 percent of simulations were within ±10 mph of the target simulation speed.
- 98.17 percent of simulations were within ±5 mph of the target simulation speed.

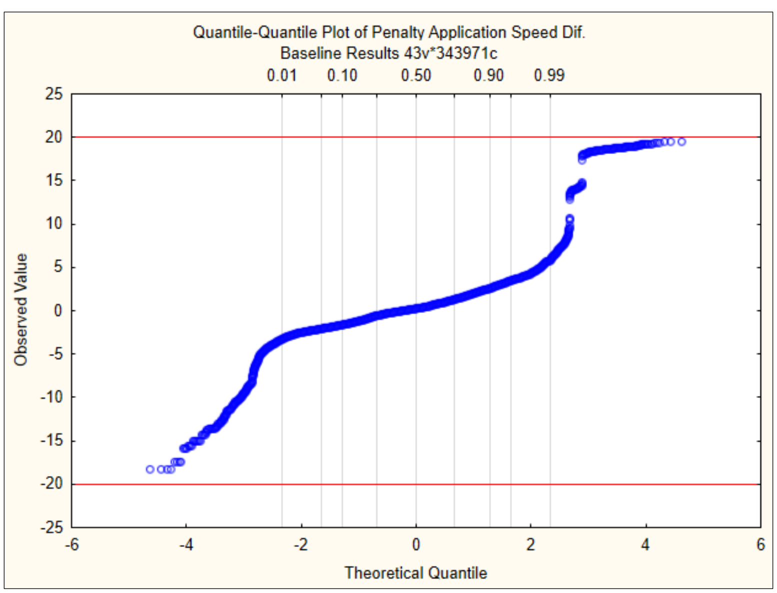

Figure 1. Baseline Q-Q Plot of Penalty Application Speed Differences for All Simulations

[Figure 2](#) shows the spread of data in a scatterplot of stopping location relative to target versus the penalty application speed difference. The figure shows that most of the data is centered on a penalty application speed difference of zero, and most simulations stop close to the target.

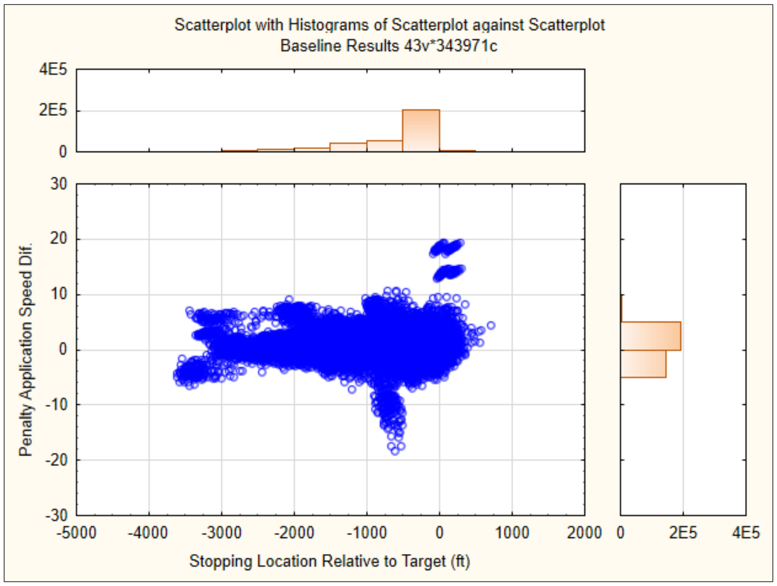

Figure 2. Baseline Scatterplot of Stopping Location Relative to Target vs. Penalty Application Speed Difference

3.2.2 Baseline Overall Results

After the data was investigated for reliability and the underlying characteristics were understood, the results were generated. Table 3 shows the overall results of the simulation testing by presenting two main statistics:

- 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 more than 500 feet for speeds less than 30 mph and more than 1,200 feet for speeds greater than or equal to 30 mph.

Table 3. Baseline Overall EA Simulation Test Results

Probability of Stopping Short of Target	Probability of Stopping Short of Performance Limit
97.90%	21.21%

As shown in Table 3, the probability of stopping short of the target is 97.90 percent. This does not meet the safety objective of being able to stop short of the target with a probability equal to or greater than 99.5 percent. This is due to the target offset function not being optimized in the baseline EA. Since the objective of developing the EA test application was to establish a baseline with which comparisons of potential enhancements could be made, failure of the EA test application to meet the safety objective does not diminish its effectiveness or preclude its use as a baseline. The probability of stopping short of the performance limit is 21.21 percent.

Table 4 shows the statistics for each emergency brake backup setting (i.e., enabled or disabled) and brake application type (i.e., blended or pneumatic only). The probability of stopping short of both the target and the performance limit was similar for each of the brake application types, but the probability of stopping short of the target was higher for scenarios where the emergency brake backup setting was enabled.

Table 4. Baseline Overall Simulation Test Results by Emergency Brake Backup Setting and 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
Passenger	Enabled	Blended	98.18%	23.51%
Passenger	Enabled	Pneumatic Only	98.11%	24.22%
Passenger	Disabled	Blended	96.50%	24.21%
Passenger	Disabled	Pneumatic Only	96.43%	24.07%
Commuter	Enabled	Blended	99.37%	18.54%
Commuter	Enabled	Pneumatic Only	98.76%	18.29%
Commuter	Disabled	Blended	98.06%	18.55%
Commuter	Disabled	Pneumatic Only	97.82%	18.29%

Table 5 through Table 8 show the detailed breakdown results for each of the four configurations with 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 scenario. Table 5 shows the results using the passenger train type with the emergency brake backup setting enabled. For some simulations, the train stopped past the target, i.e., the maximum stopping location relative to the target is greater than zero. Most groups have at least one simulation that stopped past the target with the maximum overrun being 174.3 feet for 90 mph on a 1.5 percent downgrade using pneumatic only braking.

Table 6 shows the results using the passenger train type with the emergency brake backup setting disabled. For some simulations, the train stopped past the target, i.e., the maximum stopping location relative to the target is greater than zero. All groups have at least one simulation that stopped past the target with the maximum overrun being 718.7 feet for 90 mph on a 1.5 percent downgrade using pneumatic only braking.

Table 7 shows the results using the commuter train type with the emergency brake backup setting enabled. For some simulations, the train stopped past the target, i.e., the maximum stopping location relative to the target is greater than zero. Some groups have at least one simulation that stopped past the target with the max overrun being 103.1 feet for 10 mph with 3.0 percent downgrade using pneumatic only braking.

Table 8 shows the results using the commuter train type with the emergency brake backup setting disabled. For some simulations, the train stopped past the target, i.e., the maximum stopping location relative to the target is greater than zero. Most groups have at least one simulation that stopped past the target with the max overrun being 438.1 feet for 90 mph with 1.5 percent downgrade using pneumatic only braking.

Table 5. Baseline Results Breakdown Passenger with Emergency Brake Backup Enabled

			Stopping Location Relative to Target (feet)			Enforcement Location Relative to Target (feet)
Brake Application Type	Target Speed at Braking	Grade	Mean	Minimum	Maximum	Mean
Blended	10 mph	0.0f	-53.0	-112.5	21.7	-159.7
		1.5d	-89.0	-363.0	53.5	-202.1
		1.5i	-41.8	-99.8	44.5	-133.1
		2.4d	-174.6	-630.7	33.3	-290.2
		3d	-172.3	-608.5	128.2	-308.1
	25 mph	3.7d	-597.0	-2,112.3	-45.1	-1,103.8
	50 mph	3d	-1,118.5	-3,361.3	-36.7	-2,587.3
	90 mph	0.0f	-1,048.5	-2,183.9	131.6	-4,277.8
		1.5d	-1,879.5	-3,615.0	-33.3	-5,500.8
		1.5i	-717.0	-1,536.1	29.6	-3,632.4
Pneumatic Only	10 mph	0.0f	-52.8	-109.3	27.9	-159.7
		1.5d	-91.5	-371.0	49.5	-202.8
		1.5i	-41.6	-99.8	44.5	-132.9
		2.4d	-155.2	-637.6	40.9	-267.7
		3d	-191.0	-608.5	128.2	-327.1
	25 mph	3.7d	-604.0	-2,101.9	-39.7	-1,115.2
	50 mph	3d	-1146.3	-3,314.0	49.7	-2,661.1
	90 mph	0.0f	-1049.2	-2,183.9	131.6	-4,279.0
		1.5d	-1,851.6	-3,571.4	174.3	-5,521.9
		1.5i	-718.6	-1,536.1	29.6	-3,636.4

Note: f = flat; d = decline/downgrade; i = incline.

Table 6. Baseline Results Breakdown Passenger with Emergency Brake Backup Disabled

			Stopping Location Relative to Target (feet)			Enforcement Location Relative to Target (feet)
Brake Application Type	Target Speed at Braking (mph)	Grade	Mean	Minimum	Maximum	Mean
Blended	10 mph	0.0f	-52.6	-112.5	31.6	-159.6
		1.5d	-88.8	-363.0	53.8	-202.1
		1.5i	-41.9	-99.8	44.5	-133.2
		2.4d	-146.4	-630.7	35.1	-261.5
		3d	-182.4	-550.2	305.7	-322.0
	25 mph	3.7d	-595.9	-2,112.3	81.8	-1,103.8
	50 mph	3d	-1,173.0	-3,361.3	119.0	-2,643.3
	90 mph	0.0f	-1,032.5	-2,183.9	493.0	-4,279.1
		1.5d	-1,872.0	-3,615.0	342.0	-5,498.3
		1.5i	-682.9	-1536.1	324.6	-3,632.0
Pneumatic Only	10 mph	0.0f	-52.5	-109.3	37.4	-159.6
		1.5d	-91.4	-370.0	49.8	-202.8
		1.5i	-41.6	-99.8	44.5	-132.9
		2.4d	-155.1	-637.6	42.2	-267.7
		3d	-201.5	-550.2	305.7	-340.0
	25 mph	3.7d	-596.2	-2,101.9	105.4	-1,106.7
	50 mph	3d	-1,144.0	-3,314.0	276.5	-2,661.1
	90 mph	0.0f	-1,032.5	-2,183.9	493.0	-4,279.1
		1.5d	-1,845.9	-3,571.4	718.7	-5,521.9
		1.5i	-684.0	-1,536.1	324.6	-3,636.4

Table 7. Baseline Results Breakdown Commuter with Emergency Brake Backup Enabled

			Stopping Location Relative to Target (feet)			Enforcement Location Relative to Target (feet)
Brake Application Type	Target Speed at Braking (mph)	Grade	Mean	Minimum	Maximum	Mean
Blended	10	0.0f	-79.7	-136.8	16.4	-186.7
		1.5d	-85.4	-182.3	41.0	-197.8
		1.5i	-69.7	-122.9	25.8	-161.1
		2.4d	-102.6	-253.0	22.6	-213.8
		3d	-118.4	-304.2	63.9	-275.8
	25	3.7d	-392.1	-725.5	-87.8	-889.2
	50	3d	-911.3	-1,564.8	-80.1	-2,376.9
	90	0.0f	-1,082.1	-2,144.4	-28.0	-4,304.6
		1.5d	-1,594.3	-2,901.5	-51.7	-5,224.4
		1.5i	-782.8	-1,559.2	-109.9	-3,698.9
Pneumatic Only	10	0.0f	-72.9	-136.8	27.9	-179.8
		1.5d	-87.9	-202.9	32.1	-198.0
		1.5i	-69.5	-122.9	25.8	-161.0
		2.4d	-103.8	-259.3	12.2	-212.0
		3d	-118.4	-297.8	103.1	-262.2
	25	3.7d	-393.4	-704.4	-48.7	-891.9
	50	3d	-887.6	-1,607.7	-52.8	-2,393.7
	90	0.0f	-1,081.9	-2,144.4	-28.0	-4,304.7
		1.5d	-1,569.1	-3,005.6	57.4	-5,240.1
		1.5i	-783.6	-1,559.2	-109.9	-3,702.5

Table 8. Baseline Results Breakdown Commuter with Emergency Brake Backup Disabled

			Stopping Location Relative to Target (feet)			Enforcement Location Relative to Target (feet)
Brake Application Type	Target Speed at Braking (mph)	Grade	Mean	Minimum	Maximum	Mean
Blended	10	0.0f	-79.5	-136.8	25.2	-186.7
		1.5d	-85.2	-182.3	41.7	-197.8
		1.5i	-69.6	-122.9	25.9	-161.1
		2.4d	-102.5	-253.0	24.0	-213.8
		3d	-108.8	-304.2	295.2	-275.8
	25	3.7d	-391.8	-725.5	-33.5	-889.2
	50	3d	-910.7	-1,564.8	-42.6	-2,376.8
	90	0.0f	-1,061.1	-2,144.4	197.8	-4,304.6
		1.5d	-1,593.9	-2,901.5	72.9	-5,224.4
		1.5i	-747.3	-1,559.2	362.4	-3,698.9
Pneumatic Only	10	0.0f	-79.4	-136.8	31.5	-186.7
		1.5d	-87.9	-202.9	36.8	-198.0
		1.5i	-69.7	-122.9	25.9	-161.1
		2.4d	-103.8	-259.3	12.8	-212.1
		3d	-112.0	-297.8	295.2	-279.2
	25	3.7d	-393.2	-704.4	5.7	-891.9
	50	3d	-886.6	-1,607.7	140.5	-2,393.7
	90	0.0f	-1,061.0	-2,144.4	197.8	-4,304.6
		1.5d	-1,565.6	-3,005.6	438.1	-5,240.2
		1.5i	-748.5	-1,559.2	362.4	-3702.5

3.2.3 Characterization of Overruns

In total, 7,209 simulations failed to stop short of the target location. Table 9 shows a breakdown of the simulations that stopped past the target location grouped by consist. Most of the overruns are from simulations using consists 38 and 39, which are larger, 14-vehicle consists.

Table 9. Baseline Overruns Breakdown by Consist

		Stopping Location Relative to Target (feet)		
Consist	**Count**	**Mean**	**Minimum**	**Maximum**
38	2,077	52.86	0.02	306.94
39	2,070	51.29	0.02	305.67
19	623	87.69	0.41	493.04
17	543	79.46	0.92	570.77
18	533	96.01	0.34	718.74
4	407	7.12	0.03	37.18
12	355	10.65	0.06	49.82
15	215	12.06	0.11	53.78
2	181	6.98	0.14	24.66
9	173	11.09	0.14	44.48
35	12	10.07	5.69	13.43
31	8	5.14	5.03	5.25
27	4	15.68	15.68	15.68
30	4	6.24	6.24	6.24
23	4	4.66	4.66	4.66

Table 10 shows a breakdown of the simulations that stopped past the target location grouped by speed and grade.

Table 10. Baseline Overruns Breakdown by Speed and Grade

			Stopping Location Relative to Target (feet)		
Target Speed at Braking (mph)	**Grade**	**Count**	**Mean**	**Minimum**	**Maximum**
10	3d	1,313	105.36	0.06	305.67
10	1.5i	1,120	9.41	0.05	44.48
90	1.5i	1,104	78.36	0.07	362.39
90	0.0f	975	84.01	0.22	493.04
10	0.0f	825	6.01	0.02	37.40
10	2.4d	792	6.87	0.02	42.21
10	1.5d	647	14.34	0.05	53.78
90	1.5d	315	104.80	0.34	718.74
50	3d	101	69.40	0.94	276.49
25	3.7d	17	36.77	3.47	105.44

3.2.4 Characterization of Undershoots

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 more than 500 feet for speeds less than 30 mph and more than 1,200 feet for speeds greater than or equal to 30 mph.

In total, 72,956 simulations stopped short of the performance limit. Table 11 shows a breakdown of undershoots by speed and grade. The brake application type, emergency brake backup setting, and consist were relatively equally represented within the undershoot simulations. Several of the undershoots occurred on the higher-speed simulations and/or on flat and downhill grades.

Table 11. Baseline Undershoot Breakdown by Speed and Grade

			Stopping Location Relative to Target (ft)		
Target Speed at Braking (mph)	**Grade**	**Count**	**Mean**	**Minimum**	**Maximum**
90	1.5d	24,788	-2,107.7	-3,615.0	-1,200.0
25	3.7d	15,527	-725.1	-2,112.3	-500.0
90	0.0f	14,682	-1,607.8	-2,183.9	-1,200.4
50	3d	12,664	-1,496.6	-3,361.3	-1,200.0
90	1.5i	4,378	-1295.9	-1,559.2	-1,200.0
10	3d	477	-546.2	-608.5	-500.1
10	2.4d	440	-617.5	-637.6	-595.7

4. Enhancements

Enhancements to the baseline algorithm were developed to evaluate the potential improvement in both the safety and operational efficiency. Table 1 and Table 2 in Section 3.1 define the simulation matrix for all the enhancements excluding TAM.

4.1 Enhancement 1 – Target Approach Management

The PTC braking algorithm is designed to enforce a penalty braking application based on the calculated braking curve of a train as it approaches a target. In some instances, the train needs to be allowed to approach a target much more closely than the braking algorithm will allow (e.g., when a switch point is near a passenger platform.) TAM utilizes a limited enforcement zone where only the emergency brake is applied by PTC. A TAM zone is determined by a configurable distance to a target and a configurable speed. In normal operation outside of a TAM zone, the PTC system will enforce according to the penalty braking profile and, once the penalty brake has been applied, will determine if the emergency brake needs to be applied by examining the emergency braking profile. When a train is within a TAM zone and below a configurable speed, the PTC system will only enforce according to the emergency braking profile, disregarding the penalty brake profile. Figure 3 shows the flow of the main process with the TAM function included.

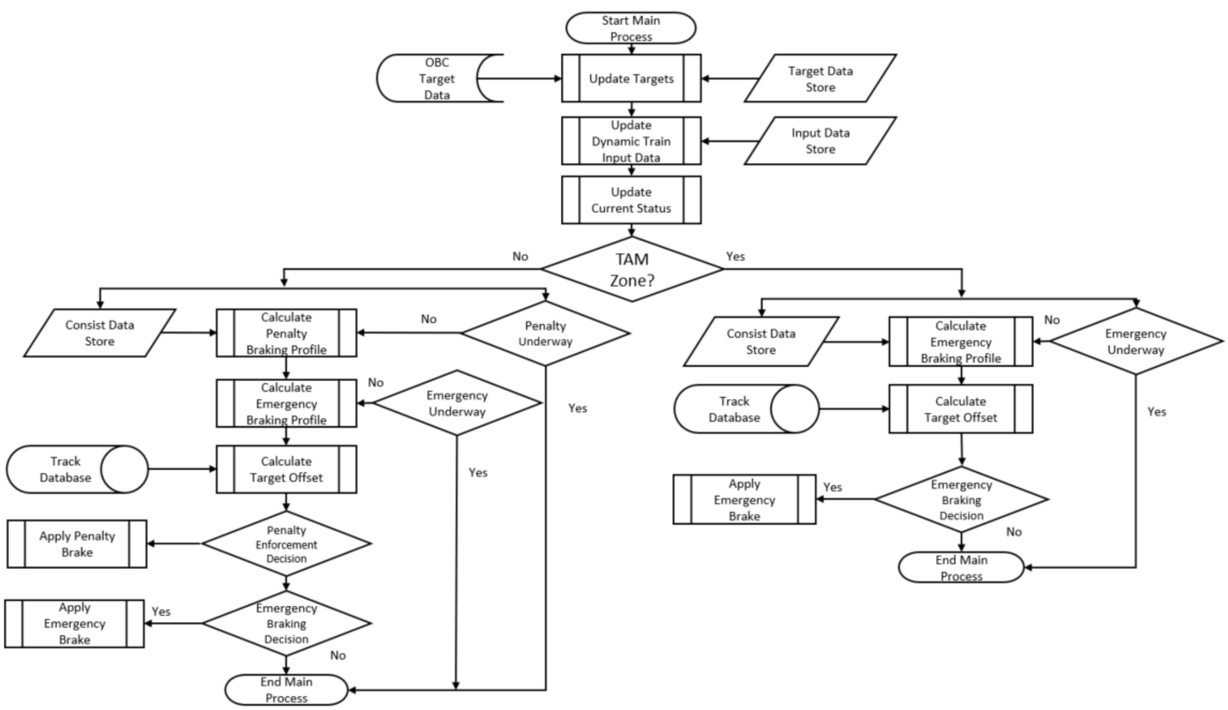

Figure 3. Target Approach Management Process Flow Diagram

4.1.1 TAM Simulation Matrix

One of the major objectives of the TAM algorithm analysis was to help the passenger and commuter railroads determine the configuration parameters to be used in revenue service. The two parameters studied were the TAM speed and TAM zone length. The TAM zone is the distance in front of the target in which the TAM functionality is enabled. The industry standard

TAM zone length is currently set to 1,000 feet. The TAM speed is the maximum speed that the train can travel in the TAM zone and receive a TAM enforcement. If the train is traveling above this speed, the normal penalty brake curve is used to determine if an enforcement is necessary. The current industry TAM speed is 10 mph. In this analysis, speeds of 5 and 10 mph were used along with TAM zone lengths of 500 and 1,000 feet. Table 12 lists the consists used for the TAM simulations. The speed and grade combinations listed in Table 13 were used.

The configurations used for the simulations were emergency brake backup setting enabled, using blended and pneumatic only brake application types.

Table 12. Consists Used for TAM Simulation Matrix

No.	Powered Vehicles (Qty.)	Trailing (unpowered) Vehicles (Qty.)	Cab Cars (Qty.)
1	EMD F59PH (1)	Superliner I (2)	
2	EMD F59PH (3)	Superliner I (14)	
3	P42DC (1)	Superliner I (2)	
4	P42DC (3)	Superliner I (14)	
5	EMD F59PH (1)	Superliner I (1)	
6	P42DC (1)	Superliner I (1)	
7	EMD F59PH (1)	Amfleet (1)	
8	EMD F59PH (1)	Amfleet (3)	
9	EMD F59PH (3)	Amfleet (14)	
10	P42DC (1)	Amfleet (1)	
11	P42DC (1)	Amfleet (3)	
12	P42DC (1)	Amfleet (14)	
13	Charger SC44 (1)	Amfleet (1)	
14	Charger SC44 (1)	Amfleet (3)	
15	Charger SC44 (3)	Amfleet (14)	
16	EMD F40PH (1)	Bombardier Bi-level (3)	Bombardier Bi-level (1)
17	EMD F40PH (1)	Bombardier Bi-level (5)	Bombardier Bi-level (1)
18	EMD F59PHI (1)	Bombardier Bi-level (3)	Bombardier Bi-level (1)
19	EMD F59PHI (1)	Bombardier Bi-level (5)	Bombardier Bi-level (1)
20	EMD F59PHI (1)	Bombardier Bi-level (6)	Bombardier Bi-level (1)
21	EMD F59PHI (1)	Bombardier Bi-level (5)	Bombardier Bi-level (2)
22	MP-40 (1)	Bombardier Bi-level (6)	Bombardier Bi-level (1)
23	MP-40 (1)	Bombardier Bi-level (5)	Bombardier Bi-level (2)
24	EMD F125 (1)	Bombardier Single Level (3)	Rotem Bi-level (1)
25	EMD F125 (1)	Bombardier Single Level (5)	Rotem Bi-level (1)
26	EMD F125 (1)	Rotem Bi-level (3)	Rotem Bi-level (1)
27	EMD F125 (1)	Rotem Bi-level (5)	Rotem Bi-level (1)
28	EMD F59PHI (1)	Bombardier Single Level (3)	Rotem Bi-level (1)
29	EMD F59PHI (1)	Bombardier Single Level (5)	Rotem Bi-level (1)
30	EMD F59PHI (1)	Rotem Bi-level (3)	Rotem Bi-level (1)
31	1 EMD F59PHI	Rotem Bi-level (5)	Rotem Bi-level (1)
32	1 MP36PH-3C	Bombardier Single Level (3)	Rotem Bi-level (1)
33	1 MP36PH-3C	Rotem Bi-level (5)	Rotem Bi-level (1)
34	1 MP36PH-3C	Rotem Bi-level (3)	Rotem Bi-level (1)

Table 13. Speed Grade Combinations Used in TAM Simulation Matrix

Speed (mph)	Grade (%)
5	0.0
5	-0.5
5	0.5
5	-1.0
5	1.0
10	0.0
10	-0.5
10	0.5
10	-1.0
10	1.0

TAM Simulation Exploratory Data Analysis

An analysis of the variation of speeds when the emergency brake application is initiated showed that there was no bias introduced to the stopping location due to that variation as shown in Figure 4. The left graph is for target approach of 500 feet while the right is for 1,000 feet.

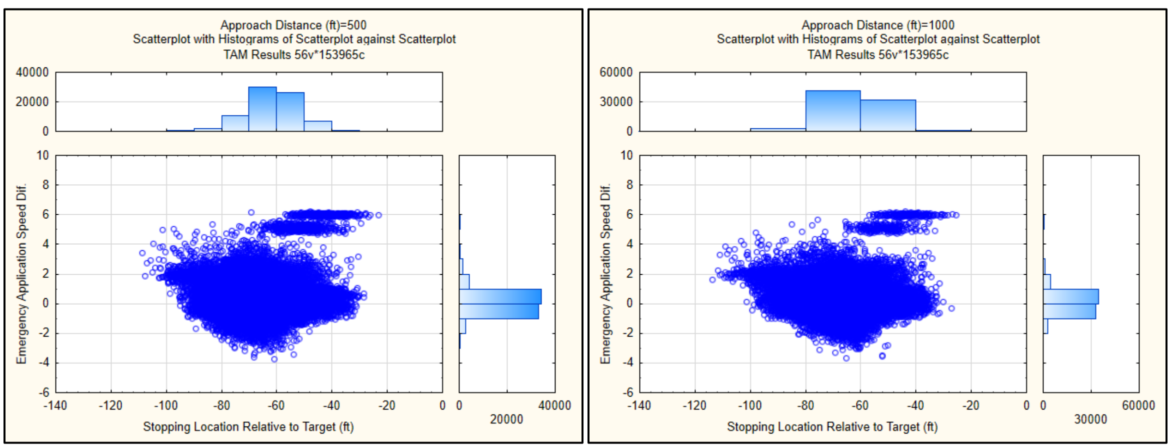

Figure 4. TAM Scatterplot of Stopping Location Relative to Target vs. Penalty Application Speed Difference

TAM Overall Results

Table 14 shows the probability of stopping short of the target and the probability of stopping short of performance limit for the TAM simulations. Given the initial lower speeds and shorter distance from the target, the AG determined that stopping 100 feet before the target was the maximum distance desired. Any simulations that stopped more than 100 feet before the target were designated as stopping short of the performance limit.

Table 14. TAM Overall Simulation Test Results by Emergency Brake Backup Setting and Brake Application Type

Approach Distance	Probability of Stopping Short of Target	Probability of Stopping Short of Performance Limit
500 feet	99.99%	0.03%
1,000 feet	99.99%	0.12%

As shown in Table 14, the probability of stopping short of the target is at least 99.99 percent for the two approach distances. This meets the previously established safety objective of being able to stop short of the target with a probability equal to or greater than 99.5 percent. The probability of stopping short of the performance limit is 0.03 and 0.12 percent for 500-and 1,000-foot approach distances, respectively.

Table 15 shows the statistics for each approach distance and brake application type (i.e., blended or pneumatic only). The probability of stopping short of both the target and the performance limit was similar for each of the brake application types, but the probability of stopping short of the performance limit was slightly higher when using the blended brake application type.

Table 15. TAM Overall Simulation Test Results by Emergency Brake Backup Setting and Brake Application Type

Approach Distance	Emergency Brake Backup Setting	Brake Application Type	Probability of Stopping Short of Target	Probability of Stopping Short of Performance Limit
500 feet	Enabled	Blended	99.99%	0.04%
500 feet	Enabled	Pneumatic Only	99.99%	0.02%
1,000 feet	Enabled	Blended	99.99%	0.18%
1,000 feet	Enabled	Pneumatic Only	99.99%	0.06%

Figure 5 shows the distribution of stopping distances for both the 500- and 1,000-foot TAM zones.

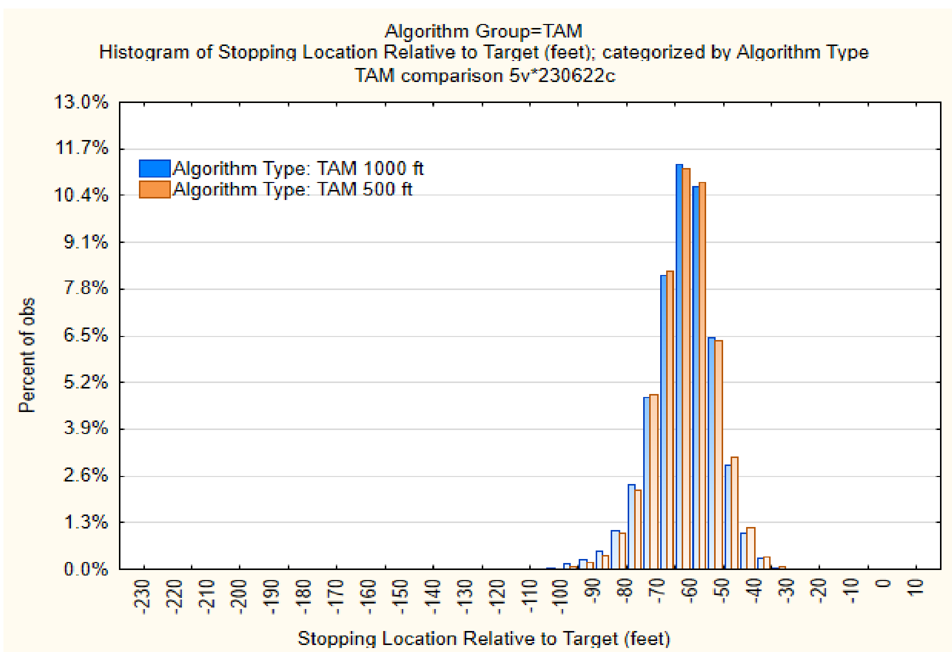

Figure 5. Histogram of Stopping Location Relative to Target for Both 500- and 1,000-foot Simulations

Table 16 through Table 19 show the results for each of the brake application types and approach distances. There were no TAM simulations that stopped past the target.

Table 16. TAM Results Breakdown Blended Brake Application Type—500-foot Approach Distance

		Stopping Location Relative to Target (feet)			Enforcement Location Relative to Target (feet)
Target Speed at Braking (mph)	Grade	Mean	Minimum	Maximum	Mean
5	0.0f	-58.9	-77.0	-40.8	-58.9
	0.5d	-63.1	-80.9	-44.9	-63.1
	0.5i	-57.6	-75.5	-30.3	-57.6
	1.0d	-66.5	-86.5	-46.2	-66.5
	1.0i	-54.4	-72.1	-23.2	-54.4
10	0.0f	-61.9	-86.5	-37.4	-61.9
	0.5d	-69.3	-99.2	-40.6	-69.3
	0.5i	-59.1	-88.1	-31.7	-59.1
	1.0d	-75.1	-108.7	-43.1	-75.1
	1.0i	-55.5	-82.1	-30.3	-55.5

Table 17. TAM Results Breakdown Pneumatic Only Brake Application Type—500-foot Approach Distance

		Stopping Location Relative to Target (feet)			Enforcement Location Relative to Target (feet)
Target Speed at Braking (mph)	Grade	Mean	Minimum	Maximum	Mean
5	0.0f	-58.5	-79.2	-37.9	-58.5
	0.5d	-62.3	-83.0	-44.1	-62.3
	0.5i	-57.7	-77.4	-33.0	-57.7
	1.0d	-65.9	-89.9	-47.5	-65.9
	1.0i	-54.5	-72.6	-26.7	-54.5
10	0.0f	-61.1	-86.2	-32.2	-61.1
	0.5d	-66.6	-93.6	-36.4	-66.6
	0.5i	-59.2	-83.2	-28.4	-59.2
	1.0d	-72.3	-102.3	-33.0	-72.3
	1.0i	-55.6	-79.1	-28.5	-55.6

Table 18. TAM Results Breakdown Blended Brake Application Type—1,000-foot Approach Distance

		Stopping Location Relative to Target (feet)			Enforcement Location Relative to Target (feet)
Target Speed at Braking (mph)	Grade	Mean	Minimum	Maximum	Mean
5	0.0f	-59.0	-77.3	-38.2	-59.0
	0.5d	-63.0	-83.0	-44.0	-63.0
	0.5i	-57.8	-77.3	-34.2	-57.8
	1.0d	-66.5	-245.7	-44.5	-66.5
	1.0i	-54.8	-73.7	-25.5	-54.8
10	0.0f	-62.9	-97.5	-32.9	-62.9
	0.5d	-69.4	-99.7	-40.7	-69.4
	0.5i	-59.9	-87.5	-32.3	-59.9
	1.0d	-75.4	-113.7	-46.0	-75.4
	1.0i	-56.3	-80.5	-27.2	-56.3

Table 19. TAM Results Breakdown Pneumatic Only Brake Application Type—1,000-foot Approach Distance

		Stopping Location Relative to Target (feet)			Enforcement Location Relative to Target (feet)
Target Speed at Braking (mph)	Grade	Mean	Minimum	Maximum	Mean
5	0.0f	-58.6	-76.4	-39.8	-58.6
	0.5d	-62.4	-83.0	-44.7	-62.4
	0.5i	-57.9	-77.3	-31.4	-57.9
	1.0d	-66.1	-251.2	-44.1	-66.1
	1.0i	-54.8	-73.7	-25.5	-54.8
10	0.0f	-62.0	-91.3	-32.7	-62.0
	0.5d	-67.1	-97.3	-35.9	-67.1
	0.5i	-59.9	-87.5	-32.3	-59.9
	1.0d	-73.3	-107.9	-37.9	-73.3
	1.0i	-56.3	-80.5	-27.2	-56.3

TAM Characterization of Undershoots

Based on a committee discussion, the established criteria for a simulation to be considered an undershoot, or to have stopped short of the performance limit, for a TAM simulation is as follows: The probability that a given train, under the given operating conditions, will stop short of the target by more than 100 feet.

In total, 122 simulations stopped short of the performance limit. Table 20 shows a breakdown of undershoots by approach distance, brake application type, speed, and grade. Several undershoots occurred when configured with a 1,000-foot approach distance, using blended braking, and operating on a 1.0 percent downgrade.

Table 20. TAM Undershoot Breakdown by Approach Distance, Brake Application Type, Speed, and Grade

					Stopping Location Relative to Target (feet)		
Approach Distance	Brake Application Type	Target Speed at Braking	Grade	Count	Mean	Minimum	Maximum
1,000 feet	Blended	10 mph	1.0d	68	-104.0	-113.70	-100.03
	Friction		1.0d	25	-102.8	-107.93	-100.04
500 feet	Blended	10 mph	1.0d	14	-103.9	-108.69	-100.25
	Friction		1.0d	7	-101.4	-102.30	-100.29
1,000 feet	Blended	5 mph	1.0d	5	-222.5	-245.68	-184.56
	Friction		1.0d	3	-211.1	-251.16	-157.66

4.1.2 Simulation of I-ETMS TAM Implementation

In parallel with the research work, one of the PTC providers developed and implemented TAM functionality in their enforcement braking algorithm (i.e., the I-ETMS enforcement braking algorithm). This algorithm is used in freight operations and is configured to allow TAM enforcements in the TAM zone of 1,000 feet and at speeds lower than 10 mph. The AG decided that a safety analysis of this algorithm using passenger and commuter train types was needed.

Figure 6 shows the distributions of results for the I-ETMS algorithm. The data has two modes: one centered at about -130 and the other at -90. This bi-modal distribution is due to the different speeds with the 5-mph runs being closer to the stopping target.

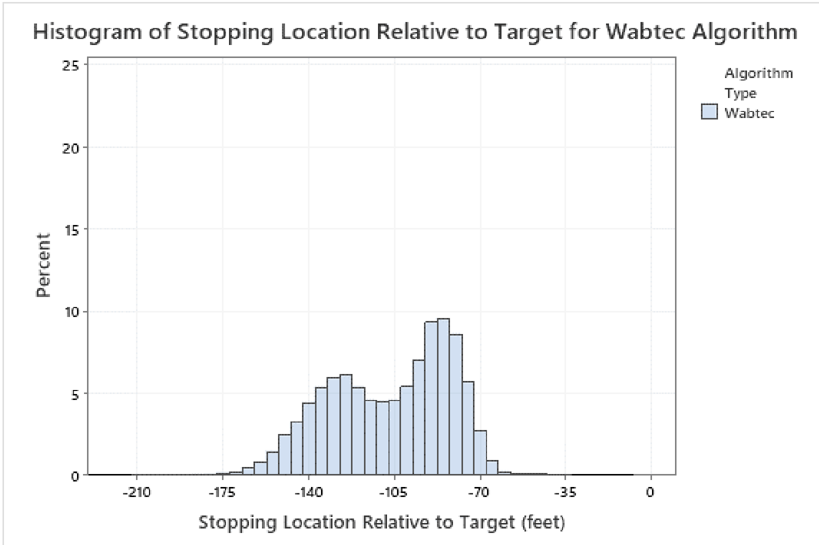

Figure 6. Histogram of Wabtec Stopping Location Relative to Target for Both 5- and 10-mph Simulations

I-ETMS TAM Exploratory Data Analysis

As shown in Figure 7, an analysis of the variation of the speeds when the emergency brake application is initiated showed that there was no bias introduced to the stopping location due to that variation.

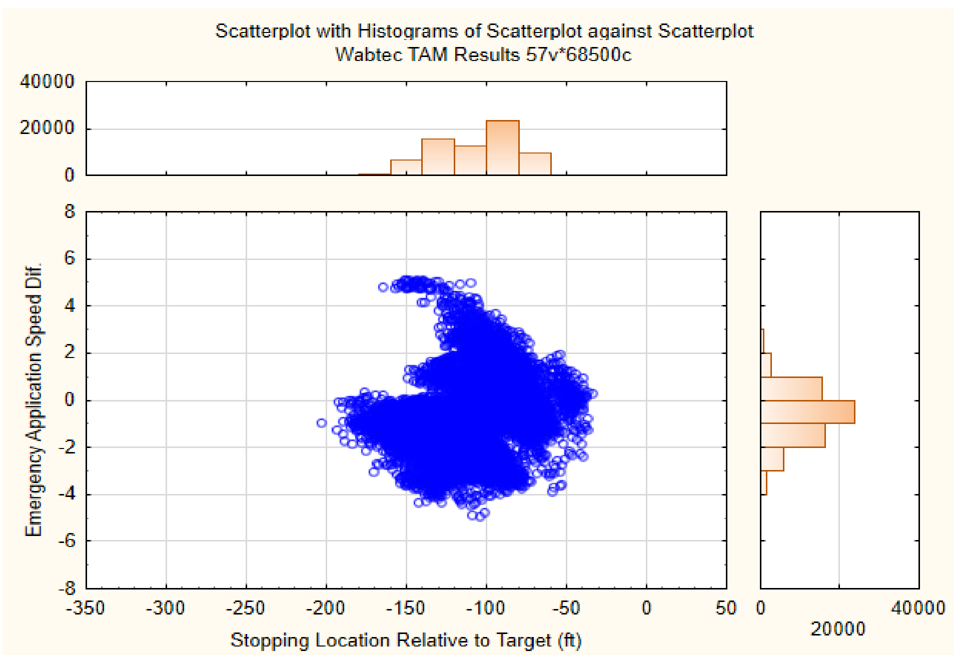

Figure 7. I-ETMS TAM Scatterplot of Stopping Location Relative to Target vs. Penalty Application Speed Difference

I-ETMS TAM Overall Results

Table 21 shows the probability of stopping short of the target and the probability of stopping short of the performance limit for the I-ETMS TAM simulations. Given the initial lower speeds and shorter distance from the target, the AG determined that stopping 100 feet before the target was the maximum distance desired. Any simulations that stopped more than 100 feet before the target were designated as stopping short of the performance limit.

Table 21. I-ETMS TAM Overall Simulation Test Results by Emergency Brake Backup Setting and Brake Application Type

Probability of Stopping Short of Target	Probability of Stopping Short of Performance Limit
99.99%	52.24%

As shown in Table 21, the probability of stopping short of the target is at least 99.99 percent for an approach distance of 1,000 feet. This meets the previously established safety objective of being able to stop short of the target with a probability equal to or greater than 99.5 percent. The probability of stopping short of the performance limit is 52.24 percent.

Table 22 shows the statistics for each brake application type (i.e., blended or pneumatic only) for an approach distance of 1,000 feet.

Table 22. I-ETMS TAM Overall Simulation Test Results by Emergency Brake Backup Setting and Brake Application Type

Emergency Brake Backup Setting	Brake Application Type	Probability of Stopping Short of Target	Probability of Stopping Short of Performance Limit
Enabled	Blended	99.99%	51.09%
Enabled	Pneumatic Only	99.99%	48.91%

Table 23 and Table 24 show the detailed breakdown results for each of the brake application types and approach speeds. There were no TAM simulations that stopped past the target.

Table 23. I-ETMS TAM Results Breakdown – Blended Brake Application Type

		Stopping Location Relative to Target (feet)			Enforcement Location Relative to Target (feet)
Target Speed at Braking (mph)	Grade	Mean	Minimum	Maximum	Mean
5	0.0f	-93.2	-170.0	-53.3	-117.2
	0.5d	-87.5	-137.9	-57.5	-111.6
	0.5i	-85.3	-113.8	-61.8	-108.9
	1.0d	-86.9	-275.2	-36.6	-109.1
	1.0i	-83.7	-112.6	-59.3	-107.4
10	0.0f	-140.1	-188.7	-87.8	-194.5
	0.5d	-124.8	-185.4	-80.1	-169.2
	0.5i	-130.4	-169.4	-94.7	-182.8
	1.0d	-123.7	-206.8	-67.2	-163.7
	1.0i	-122.4	-160.7	-89.5	-173.7

Table 24. I-ETMS TAM Results Breakdown – Pneumatic Only Brake Application Type

		Stopping Location Relative to Target (feet)			Enforcement Location Relative to Target (feet)
Target Speed at Braking (mph)	Grade	Mean	Minimum	Maximum	Mean
5	0.0f	-92.9	-166.9	-53.4	-117.6
	0.5d	-87.5	-138.2	-56.8	-113.7
	0.5i	-85.2	-113.8	-61.8	-108.7
	1.0d	-87.2	-282.0	-33.9	-112.8
	1.0i	-83.7	-112.6	-59.3	-107.4
10	0.0f	-139.5	-185.8	-87.0	-194.5
	0.5d	-120.0	-185.4	-66.5	-165.5
	0.5i	-130.4	-169.4	-94.7	-182.8
	1.0d	-111.1	-182.4	-72.3	-155.5
	1.0i	-122.4	-154.3	-89.5	-173.7

I-ETMS TAM Characterization of Undershoots

Based on committee discussion, the established criteria for a simulation to be considered an undershoot, or to have stopped short of the performance limit, for a TAM simulation is as follows: The probability that a given train, under the given operating conditions, will stop short of the target by more than 100 feet.

In total, 35,784 simulations stopped short of the performance limit. Table 25 shows a breakdown of undershoots by speed and grade. Several of the undershoots occurred at 10 mph. The undershoots were roughly balanced between brake application types.

Table 25. I-ETMS TAM Undershoot Breakdown by Speed, and Grade

			Stopping Location Relative to Target (feet)		
Target Speed at Braking (mph)	Grade	Count	Mean	Minimum	Maximum
10	0.5i	6,992	-130.4	-169.4	-100.5
10	0.0f	6,991	-139.8	-188.7	-102.6
10	1.0i	6,950	-122.6	-160.7	-100.0
10	0.5d	6,065	-126.8	-185.4	-100.0
10	1.0d	4,523	-124.8	-206.8	-100.0
5	1.0d	1,493	-113.0	-282.0	-100.0
5	0.5d	1,224	-108.7	-138.2	-100.0
5	0.0f	1,089	-117.3	-170.0	-100.0
5	0.5i	296	-103.1	-113.8	-100.0
5	1.0i	161	-102.9	-112.6	-100.0
	Total:	**35,784**			

4.2 Enhancement 2 – Specified Consist Makeup

The expected amount of braking force for short trains varies from that of long trains, due to the use of locomotive braking. Passenger locomotives do not supply as much brake force as the passenger coaches. The baseline algorithm does not account for this; therefore, it is more probable that short trains will stop beyond the target. To address this, a modification was made to the algorithm to adjust the brake rate according to the number of locomotives and cars in the consist using a weighted average. To determine the specified consist brake force curve, Equation 3 shows the calculation for the nominal full service brake force for the train.

$$Full\ Serv\ F_{B\ nom} = \frac{BR_{sc} * W_t * 2000 * 1.467}{32.17} \tag{3}$$

Where:

BR_{sc} – Specified Consist Brake Rate

W_t – Weight of the train in tons

Equation 3 uses the specified consist brake rate, as opposed to the full service brake rate of 2 mph/s used in the baseline algorithm. Equation 4 shows the calculation for the specified consist brake rate (BR_{sc}).

$$BR_{sc} = \frac{(1.2 * N_{Loco}) + (1.6 * N_{Car})}{N_{Loco} + N_{Car}} \tag{4}$$

Where:

N_{LOCO} – Number of Locomotives in Consist

N_{Car} – Number of Cars in Consist

It is also assumed that the service limiting valve setting is 60 psi for locomotives and cars.

Once the full service nominal brake force is calculated, it is divided by the full service limiting valve setting to give the slope of the nominal brake force curve (Equation 5).

$$M = \frac{Full\ Serv\ F_{B\ nom}}{60} \tag{5}$$

This slope, along with the #16 line pressure, is 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 2.2 mph/s (Equation 6).

$$F_{Emer} = \frac{BR_{scem} * W_t * 2000 * 1.467}{32.17} \tag{6}$$

Where:

BR_{scem} – Specified Consist Emergency Brake Rate

W_t – Weight of the train in tons

The Equation 6 uses the specified consist emergency brake rate, as opposed to the full service brake rate of 2.2 mph/s used in the baseline algorithm. Equation 7 shows the calculation of the specified consist emergency brake rate (BR_{scem}).

$$BR_{scem} = \frac{(1.5 * N_{Loco}) + (2.2 * N_{Car})}{N_{Loco} + N_{Car}} \quad (7)$$

Where:

N_{LOCO} – Number of Locomotives in Consist

N_{Car} – Number of Cars in Consist

It is also assumed that the emergency limiting valve setting is 90 psi for locomotives and 70 psi for cars.

4.2.1 Specified Consist Simulation Matrix

The simulations ran using the specified train enhancement that included all 39 consists, all 10 speed/grade combinations and all 8 configurations of enforcement algorithm type, the emergency brake backup setting, and brake enforcement type, as described in Section 3.

4.2.2 Specified Consist Results

The analysis of the Monte Carlo specified consist algorithm simulation results is intended to statistically quantify the safety and performance characteristics of the enforcement algorithm for each scenario simulated. The results are separated into four main sections of analysis: (1) EDA, (2) overall results, (3) analysis of overruns, and (4) analysis of undershoots.

Specified Consist Exploratory Data Analysis

Figure 8 shows the Q-Q plot of all penalty application speed differences for each simulation. As can be seen, the cruise control of the model performed well, as exemplified by the fact that:

- 99.99 percent of simulations were within ±10 mph of the target simulation speed.
- 98.95 percent of simulations were within ±5 mph of the target simulation speed.

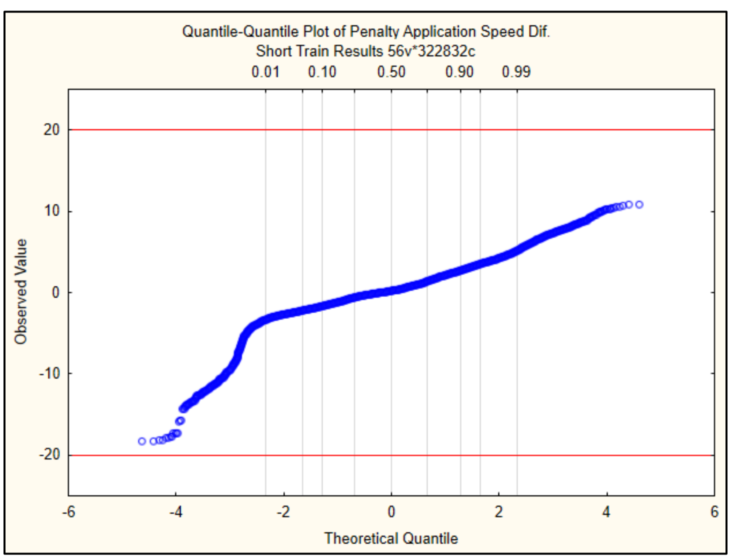

Figure 8. Specified Consist Q-Q Plot of Penalty Application Speed Differences for all Simulations

Figure 9 shows the overall spread of data in a scatterplot of the stopping location relative to the target versus the penalty application speed difference. The histogram shows that most of the data is centered on a penalty application speed difference of zero, and most simulations stop close to the target position.

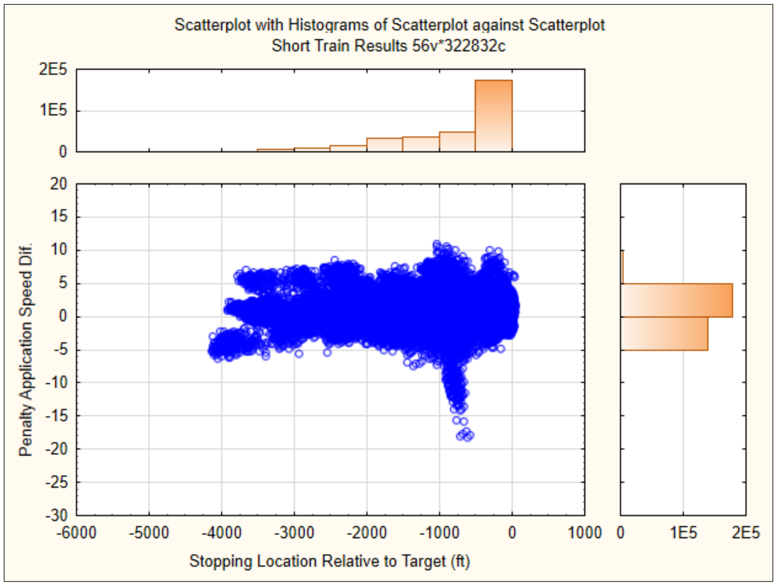

Figure 9. Specified Consist Scatterplot of Stopping Location Relative to Target vs. Penalty Application Speed Difference

Specified Consist Overall Results

Table 26 provides the results from data taken after it was investigated for reliability and the underlying characteristics were understood.

Table 26. Specified Consist Overall Simulation Test Results

Probability of Stopping Short of Target	Probability of Stopping Short of Performance Limit
99.68%	37.79%

As shown in Table 26, the probability of stopping short of the target is 99.68 percent. With this enhancement, the baseline was improved to meet the previously established safety objective of being able to stop short of the target with a probability equal to or greater than 99.5 percent. While the overall probably of stopping short of the target is 99.68 percent, the simulations run using the commuter train type and emergency brake backup disabled did not meet the safety objective. However, the results from the simulations of these configurations still showed an increased probability of stopping short of the target over the baseline results. The probability of stopping short of the performance limit is 33.79 percent.

Table 27 shows the statistics for each emergency brake backup setting (i.e., enabled or disabled) and brake application type (i.e., blended or pneumatic only). The probability of stopping short of both the target and the performance limit was similar for each of the brake application types, but the probability of stopping short of the performance limit was higher for scenarios using the passenger train type.

Table 27. Specified Consist Overall Simulation Test Results by Emergency Brake Backup Setting and 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
Passenger	Enabled	Blended	99.98%	40.11%
Passenger	Enabled	Pneumatic Only	99.99%	36.87%
Passenger	Disabled	Blended	99.93%	41.51%
Passenger	Disabled	Pneumatic Only	99.93%	41.14%
Commuter	Enabled	Blended	99.69%	27.75%
Commuter	Enabled	Pneumatic Only	99.67%	27.92%
Commuter	Disabled	Blended	98.08%	27.06%
Commuter	Disabled	Pneumatic Only	98.22%	28.10%

Table 28 through Table 31 show the results for each of the four configurations with an additional measure of performance: Enforcement location relative to target (mean), which is the mean difference between the target stopping location and the enforcement location in each scenario.

Table 28 shows the results from using the passenger train type with the emergency brake backup setting enabled. For some simulations, the train stopped past the target, i.e., the maximum stopping location relative to the target is greater than zero. There were overruns for simulations run at 10 mph on flat grade.

Table 28. Specified Consist Results Breakdown Passenger with Emergency Brake Backup Enabled

			Stopping Location Relative to Target (feet)			Enforcement Location Relative to Target (feet)
Brake Application Type	Target Speed at Braking (mph)	Grade	Mean	Minimum	Maximum	Mean
Blended	10	0.0f	-59.3	-102.5	16.0	-166.3
		1.5d	-94.0	-185.4	-24.2	-208.0
		1.5i	-46.4	-83.1	-1.3	-137.9
		2.4d	-255.7	-632.7	-131.2	-371.6
		3d	-347.5	-1,018.4	-194.4	-461.2
	25	3.7d	-1,052.7	-2,152.8	-678.7	-1,559.3
	50	3d	-1,947.2	-3,283.4	-1,063.2	-3,412.5
	90	0.0f	-1,481.5	-2,497.3	-261.4	-4,723.8
		1.5d	-2,326.4	-3,636.8	-596.1	-5,953.1
		1.5i	-1,025.2	-1,818.4	-181.2	-3,991.9
Pneumatic Only	10	0.0f	-62.8	-105.4	-4.9	-165.9
		1.5d	-95.1	-181.1	-17.5	-203.8
		1.5i	-46.4	-83.1	-1.3	-137.9
		2.4d	-243.3	-452.9	-144.0	-354.1
		3d	-325.9	-614.2	-189.3	-440.9
	25	3.7d	-939.8	-1,436.9	-676.6	-1,425.3
	50	3d	-1,894.3	-2,481.8	-943.8	-3,441.5
	90	0.0f	-1,540.5	-2,497.3	-261.4	-4,792.5
		1.5d	-2,357.5	-3,625.6	-432.9	-6,020.1
		1.5i	-1,026.8	-1,818.4	-181.2	-3,996.4

Table 29 shows results using the passenger train type with the emergency brake backup setting disabled. For some simulations, the train stopped past the target, i.e., the maximum stopping location relative to the target is greater than zero. There were overruns on simulations at 10 mph on flat and 1.5 percent incline, and 90 mph on 1.5 percent incline.

Table 29. Specified Consist Results Breakdown Passenger with Emergency Brake Backup Disabled

Brake Application Type	Target Speed at Braking (mph)	Grade	Stopping Location Relative to Target (feet) Mean	Stopping Location Relative to Target (feet) Minimum	Stopping Location Relative to Target (feet) Maximum	Enforcement Location Relative to Target (feet) Mean
Blended	10	0.0f	-63.7	-114.1	5.7	-170.8
		1.5d	-144.4	-415.3	-29.3	-259.4
		1.5i	-46.6	-83.7	19.6	-138.0
		2.4d	-257.2	-618.3	-111.0	-376.0
		3d	-346.1	-1,030.4	-189.1	-462.6
	25	3.7d	-1,049.5	-2,123.3	-650.5	-1,562.3
	50	3d	-1,902.8	-3,230.7	-1,127.4	-3,375.7
	90	0.0f	-1,503.5	-2,513.2	-289.2	-4,740.4
		1.5d	-2,883.7	-4,135.2	-774.3	-6,507.7
		1.5i	-984.8	-1,837.6	41.5	-3,953.7
Pneumatic Only	10	0.0f	-63.5	-110.5	11.8	-170.8
		1.5d	-147.0	-417.7	-34.9	-261.1
		1.5i	-46.6	-83.7	19.6	-138.0
		2.4d	-259.1	-703.7	-111.3	-374.3
		3d	-346.5	-1,082.7	-187.7	-461.8
	25	3.7d	-1,054.9	-2,188.3	-659.5	-1,571.3
	50	3d	-1,882.4	-3,189.5	-990.0	-3,399.8
	90	0.0f	-1,503.5	-2,513.2	-289.2	-4,740.4
		1.5d	-2,860.4	-4,029.6	-572.7	-6,531.7
		1.5i	-986.2	-1,837.6	41.5	-3,958.1

Table 30 shows the results while using the commuter train type with the emergency brake backup setting enabled. For some simulations, the train stopped past the target, i.e., the maximum stopping location relative to the target is greater than zero. Most 10 mph groups have at least one simulation that stopped past the target with the maximum overrun being 24.7 feet for 10 mph flat grade using pneumatic only braking.

Table 30. Specified Consist Results Breakdown Commuter with Emergency Brake Backup Enabled

			Stopping Location Relative to Target (feet)			Enforcement Location Relative to Target (feet)
Brake Application Type	Target Speed at Braking (mph)	Grade	Mean	Minimum	Maximum	Mean
Blended	10	0.0f	-79.9	-136.7	19.0	-187.0
		1.5d	-100.0	-208.6	-9.9	-213.7
		1.5i	-72.4	-129.6	12.2	-164.1
		2.4d	-115.6	-277.9	20.8	-233.4
		3d	-145.7	-344.1	18.5	-268.1
	25	3.7d	-543.5	-1,116.7	-92.7	-1,046.2
	50	3d	-1,278.8	-2,110.5	-258.7	-2,753.6
	90	0.0f	-1,281.1	-2,455.1	-93.9	-4,584.1
		1.5d	-2,062.2	-3,488.8	-200.6	-5,688.8
		1.5i	-1,006.8	-1,703.4	-143.7	-3,962.0
Pneumatic Only	10	0.0f	-79.8	-136.7	24.7	-187.0
		1.5d	-101.3	-201.6	-14.1	-211.9
		1.5i	-73.4	-129.6	12.2	-163.8
		2.4d	-115.5	-301.8	24.6	-228.4
		3d	-150.1	-349.0	12.7	-272.6
	25	3.7d	-543.9	-1,100.5	-95.4	-1,045.4
	50	3d	-1,252.1	-2,132.1	-124.4	-2,768.5
	90	0.0f	-1,335.9	-2,455.1	-93.9	-4,576.9
		1.5d	-2,064.9	-3,470.3	-78.3	-5,705.6
		1.5i	-1,024.2	-1,703.4	-143.7	-3,946.3

Table 31 shows the results while using the commuter train type with the emergency brake backup setting disabled. For some simulations, the train stopped past the target, i.e., the maximum stopping location relative to the target is greater than zero. Like the results shown in Table 30, most 10-mph groups have at least one simulation that stopped past the target, but there are also overruns for 90 mph on 1.5 percent incline.

Table 31. Specified Consist Results Breakdown Commuter with Emergency Brake Backup Disabled

			Stopping Location Relative to Target (feet)			Enforcement Location Relative to Target (feet)
Brake Application Type	Target Speed at Braking (mph)	Grade	Mean	Minimum	Maximum	Mean
Blended	10	0.0f	-84.1	-147.4	18.7	-191.3
		1.5d	-94.9	-202.9	37.6	-207.5
		1.5i	-72.3	-128.5	25.7	-163.9
		2.4d	-109.2	-294.3	51.3	-228.2
		3d	-136.4	-364.2	35.9	-260.7
	25	3.7d	-529.3	-1,139.8	-147.7	-1,040.7
	50	3d	-1,216.8	-2,058.9	-321.7	-2,697.9
	90	0.0f	-1,357.3	-2,513.2	-78.2	-4,597.4
		1.5d	-2,079.4	-3,666.6	-303.9	-5,711.1
		1.5i	-959.8	-1,769.9	41.5	-3,925.9
Pneumatic Only	10	0.0f	-88.3	-146.8	-18.9	-191.2
		1.5d	-99.2	-223.4	32.5	-205.9
		1.5i	-72.3	-128.5	25.7	-163.9
		2.4d	-109.9	-300.2	45.4	-224.1
		3d	-141.0	-406.1	43.5	-264.8
	25	3.7d	-531.0	-1,133.8	-132.8	-1,041.0
	50	3d	-1,195.4	-2,111.9	-221.6	-2,718.3
	90	0.0f	-1,424.5	-2,513.2	-78.2	-4,671.2
		1.5d	-2,054.1	-3,706.9	-129.9	-5,731.5
		1.5i	-960.4	-1,769.9	41.5	-3,929.3

Specified Consist Characterization of Overruns

In total, 1,030 simulations failed to stop before the target location. Table 32 shows the simulations that stopped past the target location grouped by consist. The most over runs were observed with consists 38 and 39, which are larger 14-vehicle consists.

Table 32. Baseline Overruns Breakdown by Consist

		Stopping Location Relative to Target (feet)		
Consist	Count	Mean	Minimum	Maximum
38	554	10.51	0.03	51.27
39	374	8.86	0.05	41.55
12	31	10.13	0.34	32.54
15	28	14.57	1.07	29.58
4	19	5.39	0.03	16.54
2	7	6.16	0.97	17.42
9	7	10.90	1.36	24.28
19	4	9.76	9.76	9.76
30	2	3.46	3.46	3.46
18	2	1.27	1.27	1.27
23	2	3.35	3.35	3.35
Total	**1,030**			

Table 33 shows a breakdown of the simulations that stopped past the target location grouped by speed and grade.

Table 33. Baseline Overruns Breakdown by Speed and Grade

			Stopping Location Relative to Target (feet)		
Target Speed at Braking (mph)	Grade	Count	Mean	Minimum	Maximum
10	2.4d	488	11.90	0.03	51.27
10	1.5i	256	5.26	0.03	25.70
10	3d	110	9.46	0.65	43.55
10	0.0f	83	6.70	0.03	24.69
10	1.5d	81	12.77	0.34	37.62
90	1.5i	12	29.27	9.76	41.55

Specified Consist Characterization of Undershoots

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 more than 500 feet for speeds less than 30 mph, and more than 1,200 feet for speeds greater than or equal to 30 mph.

In total, 109,098 simulations stopped short of the performance limit. Table 34 shows the undershoots by speed and grade. The brake application type, emergency brake backup setting, and consist had a relatively equal representation of undershoot simulations. Many of the undershoots occurred on the higher-speed simulations and/or on flat and downhill grades.

Table 34. Specified Consist Undershoot Breakdown by Speed and Grade

			Stopping Location Relative to Target (feet)		
Target Speed at Braking (mph)	Grade	Count	Mean	Minimum	Maximum
90	1.5d	28,923	-2521.2	-4,135.2	-1,200.3
25	3.7d	24,490	-911.9	-2,188.3	-500.0
50	3d	23,238	-1,831.4	-3,283.4	-1,200.0
90	0.0f	18,746	-1,828.9	-2,513.2	-1,200.4
90	1.5i	11,583	-1,437.8	-1,837.6	-1,200.2
10	3d	1,458	-675.2	-1,082.7	-500.1
10	2.4d	660	-579.6	-703.7	-544.7
	Total	**109,098**			

Specific Consist Comparison to Baseline

Table 35 shows the overall baseline results for probability of stopping short of the target compared to the specified consist enhancement results. Overall, the probability of stopping short of the target was greater with the specified consist enhancement than with the baseline. The largest differences in the probability of stopping short of the target were seen in simulations for the passenger train type with the emergency brake backup setting disabled; both showing over 3 percent improvement from the baseline.

Table 35. Comparison Table Specified Consist and Baseline—Probability of Stopping Short of Target

Train Type	EBB Setting	Brake App. Type	Probability of Stopping Short of Target: Baseline	Probability of Stopping Short of Target: Specified Consist	% Difference.
Passenger	Enabled	Blended	98.18%	99.98%	1.80%
		Pneumatic Only	98.11%	99.99%	1.88%
	Disabled	Blended	96.50%	99.93%	3.43%
		Pneumatic Only	96.43%	99.93%	3.50%
Commuter	Enabled	Blended	99.37%	99.69%	0.32%
		Pneumatic Only	98.76%	99.67%	0.91%
	Disabled	Blended	98.06%	98.08%	0.02%
		Pneumatic Only	97.82%	98.22%	0.40%
		Overall	**97.90%**	**99.68%**	**1.78%**

Table 36 shows the baseline results for the probability of stopping short of the performance limit compared to the specified consist enhancement results. The improvement in safety found in Table 35 shows a loss in operational efficiency with the probability of stopping short of the performance limit increasing by 13.91 percent.

Table 36. Comparison Table Specified Consist and Baseline—Probability of Stopping Short of Performance Limit

Train Type	EBB Setting	Brake App. Type	Probability of Stopping Short of Performance Limit: Baseline	Probability of Stopping Short of Performance Limit: Specified Consist	% Difference.
Passenger	Enabled	Blended	23.51%	40.11%	16.60%
		Pneumatic Only	24.22%	36.87%	12.65%
	Disabled	Blended	24.21%	41.51%	17.30%
		Pneumatic Only	24.07%	41.14%	17.07%
Commuter	Enabled	Blended	18.54%	27.75%	9.21%
		Pneumatic Only	18.29%	27.92%	9.63%
	Disabled	Blended	18.55%	27.06%	8.51%
		Pneumatic Only	18.29%	28.10%	9.81%
		Overall	**21.21%**	**37.79%**	**16.58%**

Table 37 compares the baseline and specified consist enhancement results, while comparing the consists that stopped beyond the target location. As seen in Section 3.2.3, the overruns from the larger consists of 38 and 39 still exist but were reduced. Smaller consists 17, 18, and 19, for which there were a larger number of overruns in the baseline, had their overrun counts reduced to almost zero with the short train enhancement. Further, the mean overrun distance was reduced for most cases.

Table 37. Comparison Table Short Train and Baseline Overruns by Consist

		Baseline Overruns				Specified Consist Overruns			
			Stopping Location Relative to Target (feet)				Stopping Location Relative to Target (feet)		
Consist	Vehicle Count	Count	Mean	Min.	Max.	Count	Mean	Min.	Max.
38	14	2,077	52.86	0.02	306.94	554	10.51	0.03	51.27
39	14	2,070	51.29	0.02	305.67	374	8.86	0.05	41.55
19	7	623	87.69	0.41	493.04	4	9.76	9.76	9.76
17	7	543	79.46	0.92	570.77	-	n/a	n/a	n/a
18	5	533	96.01	0.34	718.74	2	1.27	1.27	1.27
4	17	407	7.12	0.03	37.18	19	5.39	0.03	16.54
12	15	355	10.65	0.06	49.82	31	10.13	0.34	32.54
15	17	215	12.06	0.11	53.78	28	14.57	1.07	29.58
2	17	181	6.98	0.14	24.66	7	6.16	0.97	17.42
9	17	173	11.09	0.14	44.48	7	10.90	1.36	24.28
35	7	12	10.07	5.69	13.43	-	n/a	n/a	n/a
31	7	8	5.14	5.03	5.25	-	n/a	n/a	n/a
27	7	4	15.68	15.68	15.68	-	n/a	n/a	n/a
30	5	4	6.24	6.24	6.24	2	3.46	3.46	3.46
23	8	4	4.66	4.66	4.66	2	3.35	3.35	3.35
Total		**7,209**				**1,030**			

4.3 Enhancement 3 – Tuned Train Type

In the baseline algorithm, the settings for passenger and commuter brake rates are based on data gathered through previous field testing conducted by the railroads. Brake rate is a measure of the rate at which the train is decelerating, in mph/s. Because of interchange in freight operations, PTC braking algorithms for freight trains must consider the braking performance of all car types in interchange service. In contrast, many passenger and commuter railroads operate with a captive fleet, and each may have their own specified braking rates. Using the same brake rate for all passenger and commuter operations is not the most efficient method, particularly for railroads that utilize a brake rate that is greater than the average across the industry. Several agencies use the same type of vehicles, but by modifying components, such as the relay valve, the brake rate can be tuned to match the other vehicles in their fleet.

The tuned train type enhancement development focused on performing a regression analysis of the baseline results, categorized by the operations of each individual agency, which was used to develop individual brake rates and target offsets for each agency.

4.3.1 Algorithm by Agency

The tuned train types enhancement uses a braking algorithm designed for each individual rail agency. The braking algorithms were designed by using data from enforcement braking tests gathered for four different agencies and optimizing the algorithm for each agency's equipment. DataFit regression software was used to explore the best equation to fit for each agency. The software included several different regression equations beyond standard linear equations.

The analysis focused on four aspects: (1) speed in miles per hour, (2) grade percentage of track, (3) number of axles, and (4) total tonnage of the consist. These aspects were used to calculate a more specialized brake rate and target offset for the braking algorithm to use for each agency. To evaluate the enhancement concept, only four agencies were used in the research as part of this project, but the same type of analysis could be performed to develop customized target offset functions for any agency utilizing a PTC braking algorithm. These agencies were selected because they provided the research team with the vehicle and field test data needed to perform this detailed analysis.

For all functions that follow:

- X1 = Speed in mph
- X2 = grade percentage where negative numbers are downhill and positive numbers are uphill
- X3 = Number of Axles
- X4 = Tonnage
- Y = Target Offset
- BRfs = Full Service Brake Rate in mph/s
- BRem = Emergency Brake Rate in mph/s

Agency 1

Equation 8 shows the function to calculate the target offset for Agency 1.

$$Y = e^{\alpha * x1 + \beta * x2 + \gamma * x3 + \delta * x4 + \varepsilon} \tag{8}$$

Where:

α = 0.0280429731394022

β = -0.228464681274874

γ = -0.074040772470914

δ = 0.00319639713648062

ε = 3.87505662647437

BRfs = 1.57

BRem = 2.16

Agency 2

Equation 9 shows the function to calculate the target offset for Agency 2.

$$Y = (\alpha * x1^{\beta} * \gamma^{x2}) + \delta \tag{9}$$

Where:

α = 0.959463181735283

β = 1.35621616591324

γ = 0.905517355434843

δ =31.805

BRfs = 1.82

BRem = 2.5

Note: Use the added constant δ only for runs of 10 mph or lower. Do not use the constant δ for any other speeds.

Agency 3

Equation 10 shows the function to calculate the target offset for Agency 3 for speed less than 50 mph.

$$Y = \alpha * x1^{\beta} * \gamma^{x2} + \delta \tag{10}$$

Where:

α = 0.64947330309372

β = 1.50741442323668

γ = 0.800517777110579

δ = 40.653 for speeds 0 to 15

δ = 0 for speeds greater than 15 and less than 50 mph

BRfs = 1.71

BRem = 2.48

Note: Use this function for runs of 0 to 49 mph only. Use the added constant δ for runs of 15 mph or lower only. The constant δ is zero for speeds between 15 mph and 49 mph.

Equation 11 shows the function to calculate target offset for speeds of 50 mph or greater.

$$Y = \alpha * x1^{\beta} * \gamma^{x2} \tag{11}$$

Where:

α = 0.44957793697812

β = 1.59008857225388

γ = 0.800060559678137

BRfs = 1.71

BRem = 2.48

Note: Use this for only 50 mph or greater. For all other speeds, use the first function.

Agency 4

Equation 12 shows the function to calculate the target offset for Agency 4 for less than 15 mph.

$$Y = e^{\alpha * x1 + \beta * x2 + \gamma * x3 + \delta * x4 + \varepsilon} \tag{12}$$

Where:

α = 0.0274028627945936

β = -0.365424602568491

γ = -0.0647471243973006

δ = 0.00274109982104838

ε = 3.97538728646928

BRfs = 1.79

BRem = 2.47

Equation 13 shows the function to calculate target offset for Agency 4 for 15 to 49 mph.

$$Y = e^{\alpha * x1 + \beta * x2 + \gamma * x3 + \delta * x4 + \varepsilon} \tag{13}$$

Where:

α = 0.0523970090139681

β = -0.415507442365703

γ = -0.205363127717044

δ = 0.00808233532936333

ε = 3.2299077706614

BRfs = 1.79

BR_{em} = 2.47

Equation 14 shows the function to calculate target offset for Agency 4 for 50 to 87.5 mph.

$$Y = e^{\alpha * x1 + \beta * x2 + \gamma * x3 + \delta * x4 + \varepsilon} \tag{14}$$

Where:

α = 0.0214991836193287

β = -0.361122585021164

γ = -0.04.32384513655584

δ = 0.001.88358250208743

ε = 4.46329047422774

BR_{fs} = 1.79

BR_{em} = 2.47

The function to calculate target offset for Agency 4 for 87.5 mph or greater is shown in Equation 15.

$$Y = e^{\alpha * x1 + \beta * x2 + \gamma * x3 + \delta * x4 + \varepsilon} + \zeta \tag{15}$$

Where:

α = 0.0214991836193287

β = -0.361122585021164

γ = -0.0432384513655584

δ = 0.00188358250208743

$\varepsilon = 4.46329047422774$

$\zeta = 437.4$

$BR_{fs} = 1.79$

$BR_{em} = 2.47$

4.3.2 Tuned Train Type Simulation Matrix

To simplify the analysis, each of the four agencies would be configured with emergency brake backup enabled and blended braking only, as this is the primary configuration for most agencies. The 10 speed/grade combinations and 39 consists shown in Section 3 were included.

4.3.3 Tuned Train Type Results

The analysis of the Monte Carlo tuned train type algorithm simulation results is intended to statistically quantify the safety and performance characteristics of the enforcement algorithm for each scenario simulated. The results are separated into four main sections of analysis: (1) EDA, (2) overall results, (3) analysis of overruns, and (4) analysis of undershoots.

Tuned Train Type Exploratory Data Analysis

An analysis of these simulations shows that the data were not biased by variation in speed. In certain cases, there is variation between the input speed and the actual speed at the point of enforcement. Figure 10 shows the Q-Q plot of all penalty application speed differences for each simulation. As can be seen, the cruise control of the model performed well, as exemplified by the following:

- 99.99 percent of simulations were within ±10 mph of the target simulation speed.
- 99.43 percent of simulations were within ±5 mph of the target simulation speed.

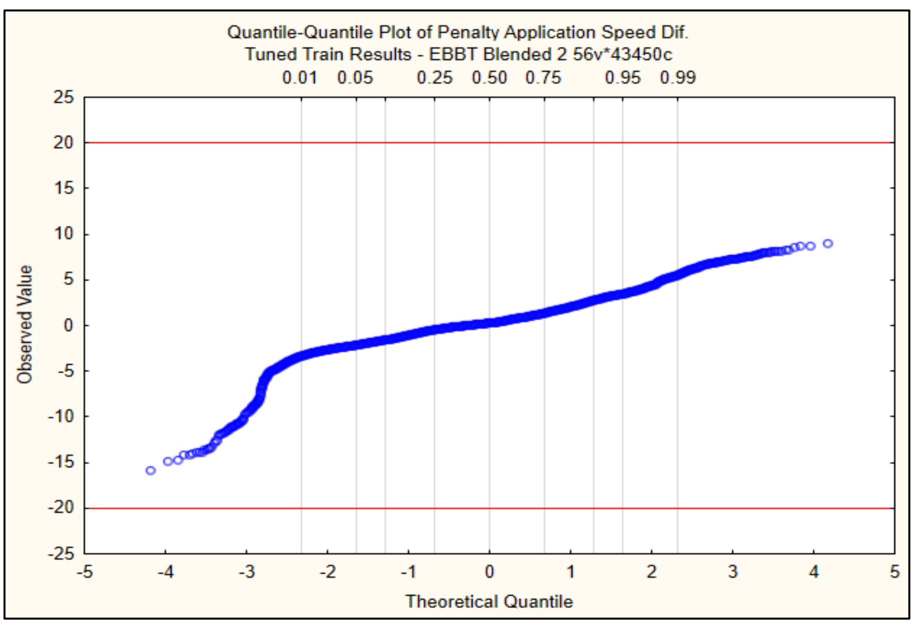

Figure 10. Tuned Train Q-Q Plot of Penalty Application Speed Differences for all Simulations

Figure 11 shows the overall spread of data in a scatterplot of stopping location relative to the target versus the penalty application speed difference. The histogram shows that most of the data is centered on a penalty application speed difference of zero, and most simulations stop close to the target position.

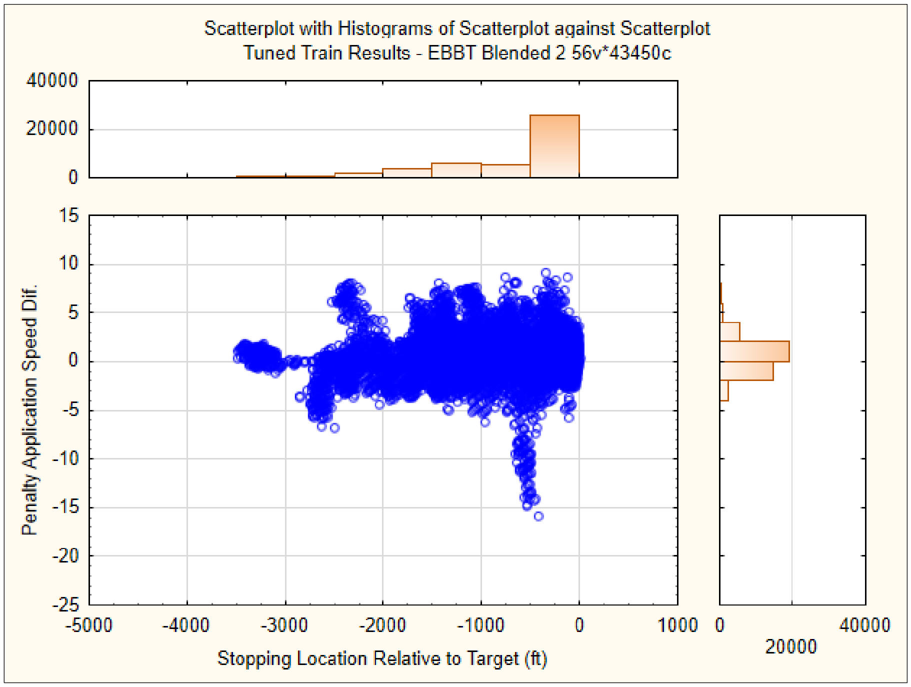

Figure 11. Tuned Train Scatterplot of Stopping Location Relative to Target vs. Penalty Application Speed Difference

Tuned Train Type Overall Results

Table 38 shows the overall results of the simulation testing after the data was investigated for reliability and underlying characteristics were understood.

Table 38. Tuned Train Overall Simulation Test Results by Emergency Brake Backup Setting and Brake Application Type

Train Type	Probability of Stopping Short of Target	Probability of Stopping Short of Performance Limit
Combined	99.96%	30.16%

As shown in Table 38, the probability of stopping short of the target is 99.96 percent. This meets the previously established safety objective of being able to stop short of the target with a probability equal to or greater than 99.5 percent. The probability of stopping short of the performance limit is 30.16 percent.

Table 39 shows the statistics for each agency train type for emergency brake backup setting enabled and blended brake application type. The probability of stopping short of both the target and the performance limit was similar for each of the brake application types with Agency 3 being slightly lower at 99.88 percent.

There was more variation in the results for Agency 3, but this agency also covers more vehicle types. With further regression and division of the fleet into similar types of vehicles, the overruns may be reduced. Further analysis and target offset changes could be used to reduce the undershoot percentages for Agency 1 and Agency 4. The modifications made for this enhancement have resulted in the algorithm being overly conservative. Additional refinements can be made to the algorithm to reduce the probability of stopping short of the performance limit while still meeting the safety objective.

Table 39. Tuned Train Type Overall Simulation Test Results by Emergency Brake Backup Setting and 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
Agency 1	Enabled	Blended	99.99%	40.53%
Agency 2	Enabled	Blended	99.99%	00.00%
Agency 3	Enabled	Blended	99.88%	26.16%
Agency 4	Enabled	Blended	99.99%	33.52%

Table 40 through Table 43 show the results for each of the four configurations with an additional measure of performance: Enforcement location relative to target (mean), which is the mean difference between the target stopping location and the enforcement location in each scenario.

Table 40 shows the results from using the passenger train type with the emergency brake backup setting enabled. For some simulations, the train stopped past the target, i.e., the maximum stopping location relative to the target is greater than zero. Overruns only occurred for Agency 3 for 10-mph flat and 1.5 percent increasing grade simulations (see Table 42). The max overrun distance from these two groups is 10.5 feet.

Table 40. Tuned Train Type Results Breakdown for Agency 1

		Stopping Location Relative to Target (feet)			Enforcement Location Relative to Target (feet)
Target Speed at Braking (mph)	Grade	Mean	Minimum	Maximum	Mean
10	2.4d	-204.2	-362.2	-108.4	-331.9
10	1.5i	-60.8	-125.7	-16.7	-157.2
10	3d	-250.4	-429.7	-153.8	-377.4
10	1.5d	-177.0	-305.3	-87.8	-302.8
10	0.0f	-96.8	-175.8	-45.8	-208.6
25	3.7d	-721.2	-1,003.9	-465.8	-1,233.3
50	3d	-1,405.6	-1,825.6	-967.8	-2,817.4
90	0.0f	-1,629.8	-2,190.6	-990.1	-4,864.1
90	1.5d	-2,718.2	-3,483.6	-2,007.3	-6,338.2
90	1.5i	-1,257.7	-1,737.1	-782.9	-4,324.0

Table 41. Tuned Train Type Results Breakdown for Agency 2

		Stopping Location Relative to Target (feet)			Enforcement Location Relative to Target (feet)
Target Speed at Braking (mph)	Grade	Mean	Minimum	Maximum	Mean
10	3d	-43.6	-90.1	-1.9	-161.7
10	0.0f	-29.2	-50.1	-11.3	-136.3
10	1.5i	-22.8	-37.9	-5.9	-124.2
10	2.4d	-58.4	-93.5	-16.9	-153.9
10	1.5d	-44.5	-70.3	-23.6	-143.9
25	3.7d	-159.3	-243.5	-78.1	-643.7
50	3d	-317.2	-538.4	-126.7	-1,954.0
90	1.5d	-632.6	-954.2	-218.0	-4,692.3
90	0.0f	-375.6	-532.1	-193.3	-3,893.2
90	1.5i	-312.6	-450.1	-118.8	-3,493.4

Table 42. Tuned Train Type Results Breakdown for Agency 3

		Stopping Location Relative to Target (feet)			Enforcement Location Relative to Target (feet)
Target Speed at Braking (mph)	Grade	Mean	Minimum	Maximum	Mean
10	0.0f	-44.6	-73.8	3.6	-142.8
10	1.5i	-34.3	-62.0	10.5	-119.5
10	2.4d	-91.2	-167.4	-21.1	-189.3
10	3d	-106.5	-183.9	-41.2	-216.4
10	1.5d	-72.7	-131.4	-9.3	-183.1
25	3.7d	-431.5	-589.1	-231.0	-894.8
50	3d	-1,247.0	-1,593.1	-950.7	-2,601.3
90	0.0f	-1,305.2	-1,876.1	-753.8	-4,234.3
90	1.5i	-750.4	-1,313.1	-333.7	-3,391.1
90	1.5d	-2,073.8	-2,717.8	-1,509.2	-5,257.5

Table 43. Tuned Train Type Results Breakdown for Agency 4

		Stopping Location Relative to Target (feet)			Enforcement Location Relative to Target (feet)
Target Speed at Braking (mph)	Grade	Mean	Minimum	Maximum	Mean
10	0.0f	-82.5	-109.8	-46.8	-198.1
10	1.5i	-36.0	-60.3	-12.5	-134.2
10	3d	-381.6	-751.1	-285.4	-576.1
10	1.5d	-177.9	-216.3	-143.1	-322.1
10	2.4d	-258.0	-294.0	-227.5	-434.3
25	3.7d	-1,629.5	-2,120.6	-1,262.7	-2,449.1
50	3d	-1,612.0	-3,151.5	-1,161.0	-3,142.4
90	0.0f	-789.4	-1,352.7	-210.2	-4,790.3
90	1.5d	-1,757.6	-2,442.8	-1,315.5	-6,105.5
90	1.5i	-467.4	-848.0	-71.2	-4,122.1

Tuned Train Type Characterization of Overruns

In total, 19 simulations failed to stop before the target location. Table 44 breaks down the simulations that stopped past the target location grouped by consist. All the overruns were on simulations utilizing the longer, 17-car consists. The most overruns occurred on 10 mph simulations with a 1.5 percent incline grade.

Table 44. Tuned Train Type Overruns Breakdown by Consist, Speed, and Grade

					Stopping Location Relative to Target (feet)		
Consist	Vehicle Count	Target Speed at Braking (mph)	Grade	Count	Mean	Minimum	Maximum
4	17	10	1.5i	11	2.4	0.1	10.5
4	17	10	0.0f	5	1.7	0.3	3.6
2	17	10	1.5i	1	2.2	2.2	2.2
15	17	10	1.5i	1	1.0	1.0	1.0
15	17	10	0.0f	1	1.7	1.7	1.7

Tuned Train Type Characterization of Undershoots

The established criteria for a simulation to be considered an undershoot, or to have stopped short of the performance limit, is as follows: The probability that a given train, under the given operating conditions, will stop short of the target by more than 500 feet for speeds less than 30 mph and more than 1,200 feet for speeds greater than or equal to 30 mph.

In total, 13,103 simulations stopped short of the performance limit. Table 45 breaks down the undershoots by agency, speed, and grade. Agency 1 and Agency 3 had the highest number of undershoots; mostly caused by greater conservatism built into stopping at higher speeds or downhill grades. Agency 2 had no undershoots.

Table 45. Specified Consist Undershoot Breakdown by Speed and Grade

				Stopping Location Relative to Target (feet)		
Agency	Target Speed at Braking (mph)	Grade	Count	Mean	Minimum	Maximum
Agency 1	90	1.5d	1,760	-2718.2	-3483.6	-2007.3
Agency 1	25	3.7d	1,746	-723.1	-1,003.9	-500.7
Agency 3	90	1.5d	1,650	-2,073.8	-2,717.8	-1,509.2
Agency 1	90	0.0f	1,636	-1,669.2	-2,190.6	-1,200.4
Agency 1	50	3d	1,289	-1,514.9	-1,825.6	-1,200.4
Agency 3	50	3d	1,059	-1,326.1	-1,593.1	-1,200.1
Agency 3	90	0.0f	1,050	-1,473.9	-1,876.1	-1,200.1
Agency 1	90	1.5i	880	-1,522.6	-1,737.1	-1,298.6
Agency 3	25	3.7d	530	-529.9	-589.1	-500.0
Agency 4	25	3.7d	440	-1,629.5	-2,120.6	-1,262.7
Agency 4	90	1.5d	440	-1,757.6	-2,442.8	-1,315.5
Agency 4	50	3d	436	-1,616.0	-3,151.5	-1,203.0
Agency 4	90	0.0f	84	-1,256.5	-1,352.7	-1,202.6
Agency 4	10	3d	75	-597.1	-751.1	-518.4
Agency 3	90	1.5i	28	-1,229.4	-1,313.1	-1,200.0
		Totals	13,103			

Tuned Train Type Comparison to Baseline

Using the tuned train type enhancement shows a marked improvement on the probability of overruns. Table 45 shows the overall baseline results for the probability of stopping short of the target compared to the tuned train type enhancement results for those four agencies. It is important to note that the baseline number is taken from the passenger train type simulations with the emergency brake backup enabled and a blended braking type. Overall, the probability of stopping short of the target with the tuned train type enhancement was 99.96 percent compared to 98.18 percent for the baseline.

Table 46. Comparison Table Tuned Train Type and Baseline—Probability of Stopping Short of Target

	Probability of Stopping Short of Target		
EA Train Type	**Baseline**	**Tuned**	**% Difference**
Agency 1	98.18%	99.99%	1.81%
Agency 2		99.99%	1.81%
Agency 3		99.88%	1.70%
Agency 4		99.99%	1.81%
Overall	98.18%	99.96%	1.78%

Table 47 shows the overall baseline results for the probability of stopping short of the performance limit compared to the tuned train enhancement results. The improvement in safety shown in Table 46 came with some loss in operational efficiency with the overall probability of stopping short of the performance limit increasing by 6.65 percent. Agency 2 had no undershoots and therefore increased operational efficiency by 23.51 percent.

Table 47. Comparison Table Tuned Train Type and Baseline—Probability of Stopping Short of Performance Limit

	Probability of Stopping Short of Performance Limit		
EA Train Type	**Baseline**	**Tuned**	**% Difference**
Agency 1	23.51%	40.53%	17.02%
Agency 2		0.00%	-23.51%
Agency 3		26.16%	2.65%
Agency 4		33.52%	10.01%
Overall	23.51%	30.16%	6.65%

Table 48 shows another comparison between the baseline and tuned train type enhancement results, this time comparing the consists that stopped beyond the target location. Again, note that the overruns are from the emergency brake backup enabled with blended braking simulations only. As seen in Section 3.2.3, the overruns from the larger 17 vehicle consists of 4, 2, and 15 still exist but were reduced. Consists 38 and 39 that were persistently higher in the overrun results are now reduced to zero. Also, the mean overrun distance has been reduced for most cases.

Table 48. Comparison Table Tuned Train Type and Baseline Overruns by Consist

		Baseline Overruns				Tuned Train Type Overruns			
			Stopping Location Relative to Target (feet)				Stopping Location Relative to Target (feet)		
Consist	Vehicle Count	Count	Mean	Min.	Max.	Count	Mean	Min.	Max.
38	14	251	21.56	0.02	122.33				
39	14	248	20.87	0.06	128.19				
4	17	76	8.17	0.15	28.45	16	2.21	0.09	10.48
12	15	73	9.00	0.06	44.63				
2	17	42	6.23	0.14	24.66	1	2.24	2.24	2.24
15	17	31	14.67	0.27	53.48	2	1.35	1.02	1.69
19	7	20	35.45	0.74	131.56				
9	17	18	10.04	0.30	44.48				
17	7	10	8.34	0.92	19.21				
18	5	6	34.19	12.08	91.89				
35	7	3	10.07	5.69	13.43				
31	7	2	5.14	5.03	5.25				
27	7	1	15.68	15.68	15.68				
23	8	1	4.66	4.66	4.66				
	Total	**782**				**19**			

4.4 Enhancement 4 – Adaptive Braking

The final enhancement simulated was an adaptive braking algorithm. The adaptive algorithm uses data gathered from previous brake applications to calculate the brake rate and then "adapt" the braking values to predict the train braking distance more accurately. An algorithm that can take measurements to more accurately estimate either the brake force or time for the brake application will enable a more accurate calculation for stopping distance of a specific train. This enhancement was implemented by modifying the *Calculate Brake Force* function described in Appendix A.

The adaptive braking algorithm measures the #16 line pressure every time step following a brake application. If the #16 line pressure has not varied by more than 1 PSI in a 5 second interval, then the total train force is recalculated using the average acceleration across the previous 10 seconds and the mass of the train. Using the total force, F_{NET}, the brake force, F_{BRK}, can be calculated as shown in Equation 16.

$$F_{BRK} = F_{NET} - F_{LOC} - F_{GRD} - F_{CRV} - F_{RES} \tag{16}$$

Where the following are calculated by the baseline algorithm:

F_{LOC} is the Locomotive Tractive Force

F_{GRD} is the Grade Force

F_{CRV} is the Curving Resistance

F_{RES} is the Resistive Forces

Once F_{BRK} is calculated, the full service nominal brake force, $Full\ Serv\ F_{B\ nom}$, can be calculated as shown.

$$Full\ Serv\ F_{B\ nom} = \frac{60 * F_{BRK}}{\#16Line_{CUR}} \tag{17}$$

This value is stored for future use by the PTC braking enforcement algorithm and the simulation ends. The emergency brake force is then calculated based on the updated full service nominal brake force. It is assumed that the emergency brake force will be 20 percent more than the full service brake force.

$$Max\ Emergency\ F_{B\ limit} = Full\ Serv\ F_{B\ nom} * 1.2 \tag{18}$$

It is also assumed that the emergency limiting valve setting is 90 psi.

Once the emergency brake force is calculated, it is then divided by the emergency valve setting to give the slope of the emergency brake force curve.

$$M_{emer} = \frac{Max\ Emergency\ F_{B\ limit}}{90} \tag{19}$$

Figure 12 shows the process flow of the adaptive algorithm.

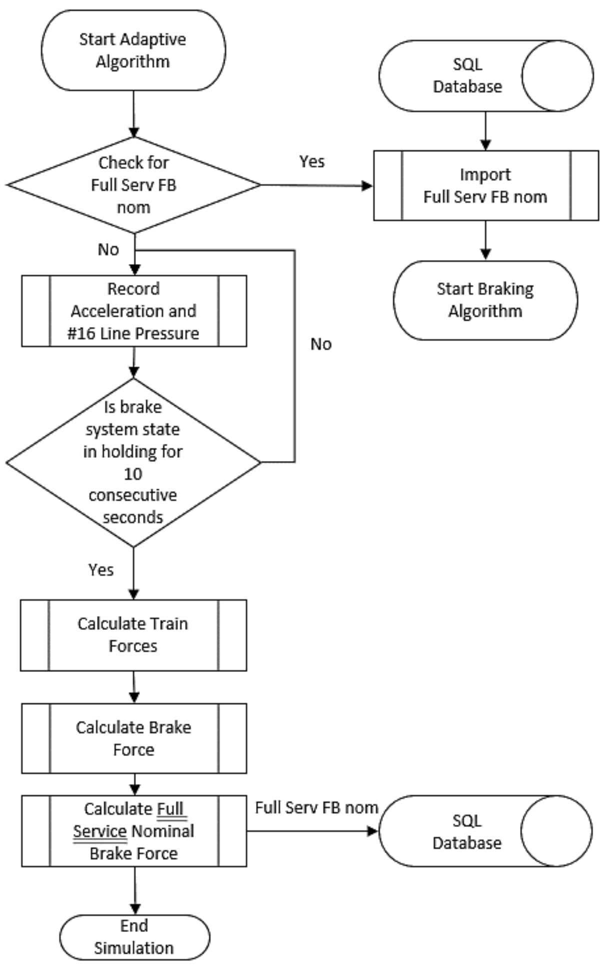

Figure 12. Adaptive Algorithm Flow

4.4.1 *Adaptive Simulation Matrix*

There were no changes made to the simulation matrix shown in Section 3 for the adaptive enhancement. All configurations, consists, and speed/grade combinations were run.

4.4.2 *Adaptive Results*

The analysis of the Monte Carlo adaptive algorithm simulation results is intended to statistically quantify the safety and performance characteristics of the enforcement algorithm for each scenario simulated. The results are separated into four main sections of analysis: (1) EDA, (2) overall results, (3) analysis of overruns, and (4) analysis of undershoots.

Adaptive Exploratory Data Analysis

In certain cases, there is variation between the input speed and the actual speed at the point of enforcement. Figure 13 shows the Q-Q plot of all penalty application speed differences for each simulation. As shown below, the cruise control of the model performed well, as exemplified by the following:

- 99.87 percent of simulations were within ±10 mph of the target simulation speed.
- 98.81 percent of simulations were within ±5 mph of the target simulation speed.

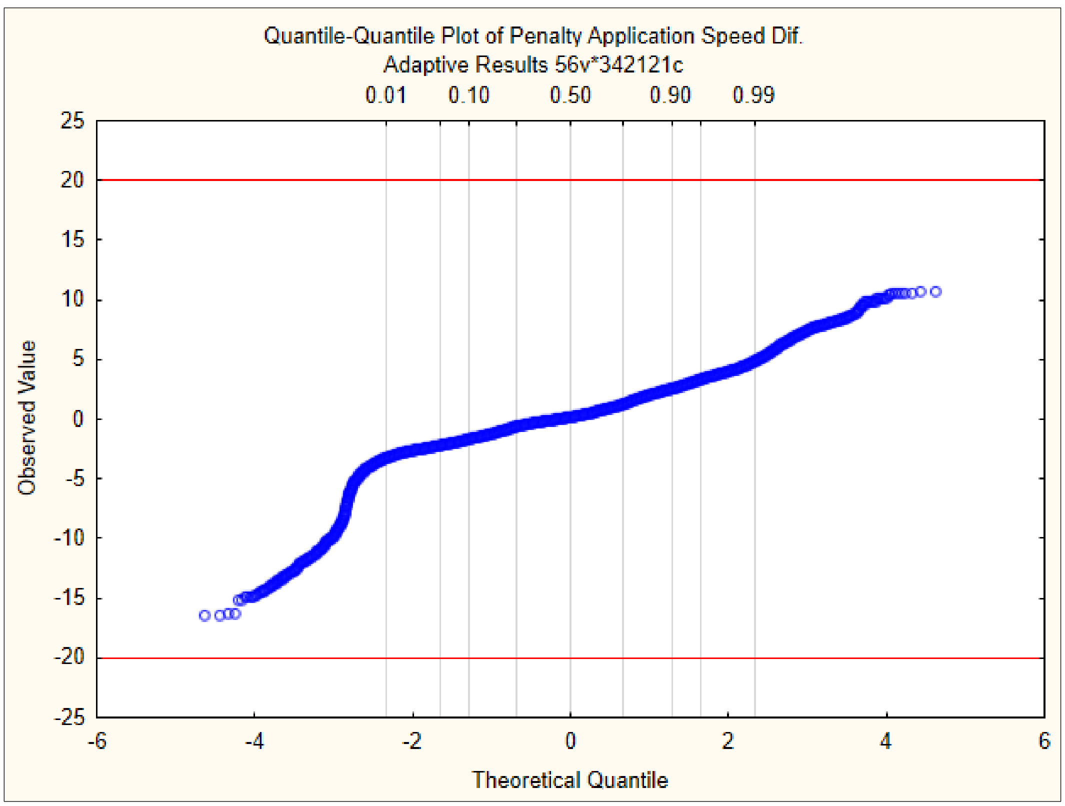

Figure 13. Adaptive Q-Q Plot of Penalty Application Speed Differences for all Simulations

Figure 14 shows the overall spread of data in a scatterplot of stopping location relative to the target versus the penalty application speed difference. The histogram shows that most of the data is centered on a penalty application speed difference of zero, and most of the simulations stop close to the target position.

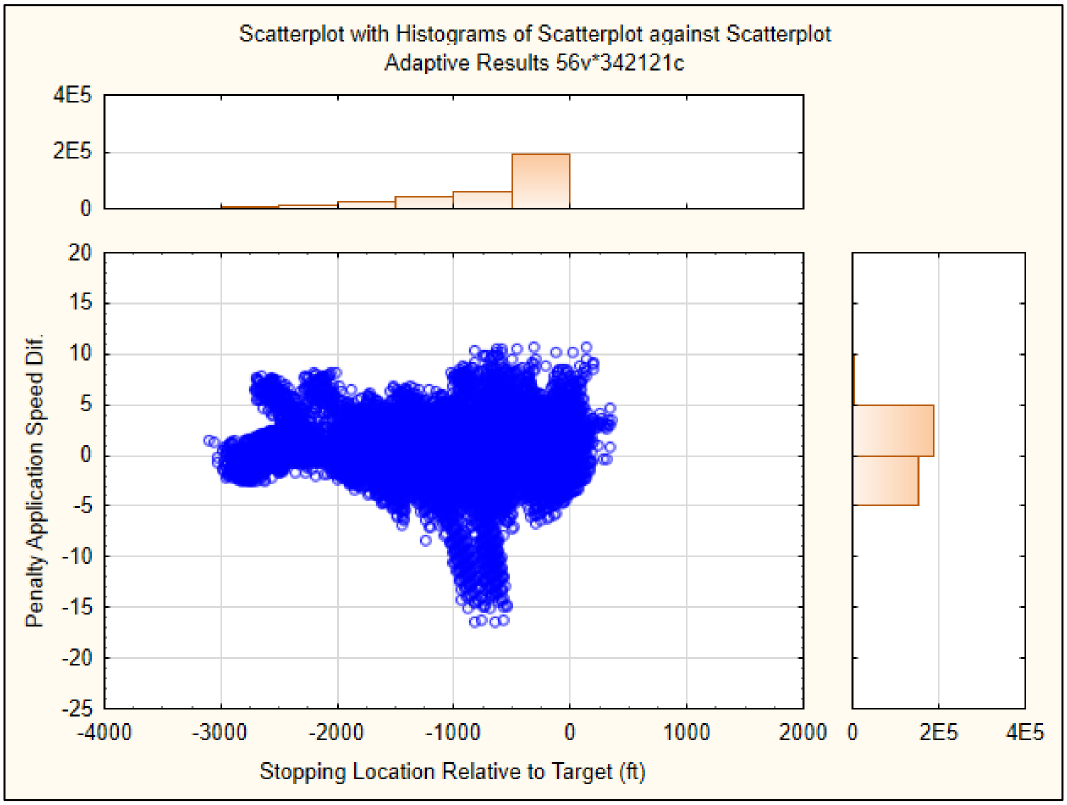

Figure 14. Adaptive Scatterplot of Stopping Location Relative to Target vs. Penalty Application Speed Difference

Adaptive Overall Results

Table 49 shows the results after the data was investigated for reliability and the underlying characteristics were understood.

Table 49. Adaptive Overall Simulation Test Results by Emergency Brake Backup Setting and Brake Application Type

Probability of Stopping Short of Target	Probability of Stopping Short of Performance Limit
99.13%	26.90%

As shown in Table 49, the probability of stopping short of the target is 99.13 percent. The probability of stopping short of the performance limit is 26.90 percent.

Table 50 shows the statistics for each emergency brake backup setting (i.e., enabled or disabled) and brake application type (i.e., blended or pneumatic only). The probability of stopping short of both the target and the performance limit was similar for each of the brake application types, but the probability of stopping short of the target was slightly higher for scenarios where the emergency brake backup setting was enabled.

Table 50. Adaptive Overall Simulation Test Results by Emergency Brake Backup Setting and 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
Passenger	Enabled	Blended	99.95%	35.50%
Passenger	Enabled	Pneumatic Only	99.95%	35.92%
Passenger	Disabled	Blended	99.85%	34.88%
Passenger	Disabled	Pneumatic Only	99.85%	35.33%
Commuter	Enabled	Blended	99.24%	18.33%
Commuter	Enabled	Pneumatic Only	99.18%	18.79%
Commuter	Disabled	Blended	97.28%	18.10%
Commuter	Disabled	Pneumatic Only	97.79%	18.54%

Table 51 through Table 54 details the results for each of the four configurations with an additional measure of performance: Enforcement location relative to target (mean), which is the mean difference between the target stopping location and the enforcement location in each scenario.

Table 51 shows the results using the passenger train type with the emergency brake backup setting enabled. For some simulations, the train stopped past the target, i.e., the maximum stopping location relative to the target is greater than zero. There were overruns on simulations at 10 mph on flat and 1.5 percent increasing grade using both brake application types. The maximum overrun among these four groups was 31.8 feet.

Table 51. Adaptive Results Breakdown Passenger with Emergency Brake Backup Enabled

			Stopping Location Relative to Target (feet)			Enforcement Location Relative to Target (feet)
Brake Application Type	Target Speed at Braking (mph)	Grade	Mean	Minimum	Maximum	Mean
Blended	10	0.0f	-54.0	-97.8	31.8	-161.2
		1.5d	-83.8	-147.2	-14.7	-197.6
		1.5i	-43.7	-77.8	0.4	-135.2
		2.4d	-239.6	-635.8	-125.9	-354.7
		3d	-326.7	-1,030.5	-184.8	-439.9
	25	3.7d	-881.0	-2,109.1	-564.1	-1,379.3
	50	3d	-1,603.7	-3,031.9	-752.7	-3,069.4
	90	0.0f	-1,189.9	-2,111.5	-62.8	-4,403.0
		1.5d	-1,825.8	-2,953.2	-86.3	-5,413.4
		1.5i	-826.6	-1,549.1	-58.6	-3,735.5
Pneumatic Only	10	0.0f	-53.9	-95.7	25.3	-161.3
		1.5d	-84.4	-155.9	-12.3	-195.2
		1.5i	-43.7	-81.3	2.9	-135.2
		2.4d	-241.5	-617.2	-128.0	-354.4
		3d	-329.1	-1013.2	-180.2	-441.9
	25	3.7d	-880.5	-2,065.5	-536.5	-1,383.2
	50	3d	-1,574.8	-2,945.2	-533.4	-3,084.6
	90	0.0f	-1,192.0	-2,113.8	-66.3	-4,405.7
		1.5d	-1,782.1	-2,927.5	-69.8	-5,426.1
		1.5i	-828.2	-1,527.5	-62.2	-3,740.8

Table 52 shows a similar result as the previous tables with overruns in the 10 mph flat and 1.5 percent increasing grade simulations. There are also overruns in the 90 mph for all grades.

Table 52. Adaptive Results Breakdown Passenger with Emergency Brake Backup Disabled

			Stopping Location Relative to Target (feet)			Enforcement Location Relative to Target (feet)
Brake Application Type	Target Speed at Braking (mph)	Grade	Mean	Minimum	Maximum	Mean
Blended	10	0.0f	-53.8	-97.8	43.1	-161.2
		1.5d	-83.6	-147.2	-14.5	-197.6
		1.5i	-43.7	-77.8	0.5	-135.2
		2.4d	-239.0	-631.0	-125.9	-354.6
		3d	-326.7	-1,030.5	-184.8	-439.9
	25	3.7d	-881.1	-2,109.1	-564.1	-1,379.4
	50	3d	-1,603.6	-3,031.9	-752.7	-3,069.6
	90	0.0f	-1,157.8	-2,111.5	2.1	-4,402.9
		1.5d	-1,787.1	-2,953.2	-38.7	-5,413.4
		1.5i	-775.2	-1,549.1	80.2	-3,735.5
Pneumatic Only	10	0.0f	-53.7	-95.7	35.7	-161.3
		1.5d	-84.1	-151.8	-10.2	-195.2
		1.5i	-43.8	-81.3	2.9	-135.2
		2.4d	-241.2	-617.2	-128.0	-354.1
		3d	-329.0	-1,022.2	-180.2	-442.1
	25	3.7d	-880.3	-2,065.5	-542.2	-1,382.6
	50	3d	-1,575.4	-3,096.8	-533.4	-3,086.3
	90	0.0f	-1,159.3	-2,113.8	32.6	-4,405.8
		1.5d	-1,747.3	-2,947.3	25.3	-5,427.5
		1.5i	-775.9	-1,581.2	111.5	-3,739.9

Table 53 shows overruns for all 10 mph groups using both brake application types. The largest overrun distance is 49.2 feet.

Table 53. Adaptive Results Breakdown Commuter with Emergency Brake Backup Enabled

			Stopping Location Relative to Target (feet)			Enforcement Location Relative to Target (feet)
Brake Application Type	Target Speed at Braking (mph)	Grade	Mean	Minimum	Maximum	Mean
Blended	10	0.0f	-74.9	-125.4	13.6	-181.8
		1.5d	-89.8	-168.7	6.7	-203.2
		1.5i	-69.8	-122.6	13.1	-161.4
		2.4d	-99.5	-230.1	49.2	-216.8
		3d	-125.1	-269.6	20.1	-247.2
	25	3.7d	-395.9	-700.2	-83.0	-892.3
	50	3d	-931.1	-1,704.1	-79.8	-2407.4
	90	0.0f	-1,059.1	-2,057.8	-89.7	-4256.8
		1.5d	-1,572.2	-2,725.8	-79.2	-5,149.5
		1.5i	-829.3	-1,508.5	-133.4	-3712.4
Pneumatic Only	10	0.0f	-74.8	-131.8	39.4	-181.9
		1.5d	-90.5	-170.9	-6.1	-201.0
		1.5i	-69.7	-122.4	13.2	-161.3
		2.4d	-100.1	-242.4	41.9	-213.1
		3d	-128.3	-295.3	30.4	-250.1
	25	3.7d	-398.0	-723.0	-79.2	-892.5
	50	3d	-906.2	-1,708.3	-81.3	-2,414.9
	90	0.0f	-1,058.7	-2,061.2	-87.5	-4,256.3
		1.5d	-1,529.8	-2,762.3	-81.3	-5,155.8
		1.5i	-829.4	-1,506.6	-141.7	-3,715.7

Table 54 shows that the largest overrun occurs for pneumatic-only braking at 90 mph on a 1.5 percent downgrade and is 356.8 feet.

Table 54. Adaptive Results Breakdown Commuter with Emergency Brake Backup Disabled

			Stopping Location Relative to Target (feet)			Enforcement Location Relative to Target (feet)
Brake Application Type	**Target Speed at Braking (mph)**	**Grade**	**Mean**	**Minimum**	**Maximum**	**Mean**
Blended	10	0.0f	-74.7	-125.4	21.3	-181.8
		1.5d	-89.5	-168.7	14.9	-203.2
		1.5i	-69.8	-122.6	13.2	-161.4
		2.4d	-98.7	-230.1	59.5	-216.8
		3d	-124.3	-269.6	27.4	-247.2
	25	3.7d	-393.6	-700.2	58.0	-892.3
	50	3d	-930.5	-1,704.1	10.3	-2,407.4
	90	0.0f	-1,005.9	-2,057.8	254.3	-4,256.8
		1.5d	-1,527.3	-2,725.8	204.7	-5,149.5
		1.5i	-750.5	-1508.5	205.4	-3,712.4
Pneumatic Only	10	0.0f	-74.7	-131.8	51.2	-181.9
		1.5d	-90.4	-170.9	-5.2	-201.0
		1.5i	-69.7	-122.4	13.3	-161.3
		2.4d	-99.7	-242.4	48.5	-213.1
		3d	-127.9	-295.3	37.9	-250.1
	25	3.7d	-395.5	-723.0	39.7	-892.6
	50	3d	-900.1	-1,708.3	182.0	-2,414.9
	90	0.0f	-1,006.9	-2,061.2	179.7	-4,256.3
		1.5d	-1,479.9	-2,762.3	356.8	-5,155.8
		1.5i	-751.5	-1,506.6	203.2	-3,715.7

Adaptive Characterization of Overruns

In total, 2,964 simulations failed to stop before the target location. Table 55 breaks down the simulations that stopped past the target location grouped by enforcement algorithm train type, speed, and grade consist. The overruns were evenly distributed between brake application types. The commuter enforcement algorithm type had the most overruns making up the top seven rows when sorted by count, which represents 90 percent of the overruns.

Table 56 breaks down the simulations that stopped past the target location grouped by consist. Nine out of the 40 consists in the matrix had overruns. The top five consists shown, ranked by count, are the five most common consists that have overruns.

Table 55. Adaptive Overruns Breakdown by EA Train Type, Speed, and Grade

EA Train Type	Target Speed at Braking (mph)	Grade	Count	Stopping Location Relative to Target (feet) Mean	Minimum	Maximum
Commuter	10	2.4d	770	12.84	0.01	59.46
Commuter	90	0.0f	735	55.29	0.06	254.28
Commuter	10	1.5i	323	4.10	0.005	13.30
Commuter	10	3d	260	8.51	0.03	37.89
Commuter	90	1.5i	236	39.82	0.49	205.37
Commuter	90	1.5d	213	95.83	0.22	356.84
Commuter	10	0.0f	159	9.10	0.09	51.25
Passenger	10	0.0f	89	9.26	0.04	43.06
Commuter	50	3d	83	43.56	0.17	182.05
Passenger	90	1.5i	65	23.23	0.02	111.51
Commuter	25	3.7d	10	18.76	2.66	58.04
Passenger	10	1.5i	9	0.87	0.01	2.88
Commuter	10	1.5d	5	6.61	0.12	14.87
Passenger	90	1.5d	4	15.22	5.31	25.27
Passenger	90	0.0f	3	12.64	2.15	32.63
		Total	2964			

Table 56. Adaptive Overruns Breakdown by Speed and Grade

Consist	Vehicle Count	Count	Stopping Location Relative to Target (feet) Mean	Minimum	Maximum
38	14	1,127	18.42	0.005	188.78
39	14	952	19.38	0.01	176.82
18	5	305	63.51	0.08	356.84
17	7	280	61.10	0.11	342.11
19	7	260	60.75	0.40	338.98
12	15	17	3.55	0.01	18.07
15	17	13	2.70	0.11	6.41
4	17	6	1.92	0.31	4.07
9	17	4	2.31	1.19	3.50
	Total	**2,964**			

Adaptive Characterization of Undershoots

The established criteria for a simulation to be considered an undershoot, or to have stopped short of the performance limit, is as follows: The probability that a given train, under the given operating conditions, will stop short of the target by more than 500 feet for speeds less than 30 mph and more than 1,200 feet for speeds greater than or equal to 30 mph.

In total, 92,018 simulations stopped short of the performance limit.

Table 57 breaks down the undershoots by enforcement algorithm type, speed, and grade. While the commuter algorithm had more overruns than the passenger train type, the passenger train type had more undershoots than the commuter train type, as shown by the top three rows in Table 57 representing the passenger train type and being about half of the undershoots.

Table 57. Adaptive Undershoot Breakdown by Speed and Grade

EA Train Type	Target Speed at Braking (mph)	Grade	Count	Stopping Location Relative to Target (feet) Mean	Minimum	Maximum
Passenger	25	3.7d	16,254	-880.7	-2,109.1	-536.5
Passenger	50	3d	15,244	-1,671.6	-3,096.8	-1,200.0
Passenger	90	1.5d	15,029	-1,964.8	-2,953.2	-1,200.2
Commuter	90	1.5d	10,784	-1,971.1	-2,762.3	-1,200.2
Passenger	90	0.0f	8,313	-1,623.5	-2,113.8	-1,200.6
Commuter	90	0.0f	6,908	-1,603.1	-2,061.2	-1,200.3
Commuter	25	3.7d	5,825	-593.8	-723.0	-500.2
Commuter	50	3d	5,139	-1,381.0	-1,708.3	-1,201.3
Passenger	90	1.5i	3,202	-1,313.9	-1,581.2	-1,200.0
Commuter	90	1.5i	2,982	-1,292.1	-1,508.5	-1,200.0
Passenger	10	3d	1,458	-701.8	-1,030.5	-500.1
Passenger	10	2.4d	880	-578.0	-635.8	-546.0
		Total	92,018			

Adaptive Comparison to Baseline

Table 58 shows the overall baseline results for the probability of stopping short of the target compared to the adaptive enhancement results. Overall, the probability of stopping short of the target was 99.13 percent for the adaptive enhancement compared to 97.90 percent for the baseline. The largest difference in safety performance was seen in simulations using the passenger train type with the emergency brake backup setting disabled; both showing over 3 percent improvement from the baseline.

Table 58. Comparison Table Adaptive and Baseline—Probability of Stopping Short of Target

Train Type	EBB Setting	Brake Application Type	Probability of Stopping Short of Performance Limit Baseline	Adaptive	% Difference
Passenger	Enabled	Blended	23.51%	35.50%	11.99%
		Pneumatic Only	24.22%	35.92%	11.70%
	Disabled	Blended	24.21%	34.88%	10.67%
		Pneumatic Only	24.07%	35.33%	11.26%
Commuter	Enabled	Blended	18.54%	18.33%	-0.21%
		Pneumatic Only	18.29%	18.79%	0.50%
	Disabled	Blended	18.55%	18.10%	-0.45%
		Pneumatic Only	18.29%	18.54%	0.25%
		Overall	**21.21%**	**26.90%**	**5.69%**

Table 59 shows the overall baseline results for the probability of stopping short of the performance limit compared to the adaptive enhancement results. The improvement in safety shown in Table 58 came with some loss in operational efficiency with the probability of stopping short of the performance limit increasing by 5.69 percent.

Table 59. Comparison Table Adaptive and Baseline—Probability of Stopping Short of Performance Limit

			Probability of Stopping Short of Performance Limit		
Train Type	**EBB Setting**	**Brake Application Type**	**Baseline**	**Adaptive**	**% Difference**
Passenger	Enabled	Blended	23.51%	35.50%	11.99%
		Pneumatic Only	24.22%	35.92%	11.70%
	Disabled	Blended	24.21%	34.88%	10.67%
		Pneumatic Only	24.07%	35.33%	11.26%
Commuter	Enabled	Blended	18.54%	18.33%	-0.21%
		Pneumatic Only	18.29%	18.79%	0.50%
	Disabled	Blended	18.55%	18.10%	-0.45%
		Pneumatic Only	18.29%	18.54%	0.25%
		Overall	**21.21%**	**26.90%**	**5.69%**

Table 60 also compares the baseline and adaptive enhancement results—this time comparing the consists that stopped beyond the target location. As seen in Section 3.2.3, the overruns from the larger consists of 38, and 39 still exist but were reduced. Smaller consists 17, 18, and 19—for which there were a high number of overruns in the baseline results—had their overrun counts reduced to almost zero with the adaptive enhancement. Also, the mean overrun distance has been reduced for most cases.

Table 60. Comparison Table Adaptive and Baseline Overruns by Consist

		Baseline Overruns				**Adaptive Overruns**			
			Stopping Location Relative to Target (feet)				**Stopping Location Relative to Target (feet)**		
Consist	**Vehicle Count**	**Count**	**Mean**	**Min.**	**Max.**	**Count**	**Mean**	**Min.**	**Max.**
38	14	2,077	52.86	0.02	306.94	1,127	18.42	0.005	188.78
39	14	2,070	51.29	0.02	305.67	952	19.38	0.01	176.82
19	7	623	87.69	0.41	493.04	260	60.75	0.40	338.98
17	7	543	79.46	0.92	570.77	280	61.10	0.11	342.11
18	5	533	96.01	0.34	718.74	305	63.51	0.08	356.84
4	17	407	7.12	0.03	37.18	6	1.92	0.31	4.07
12	15	355	10.65	0.06	49.82	17	3.55	0.01	18.07
15	17	215	12.06	0.11	53.78	13	2.70	0.11	6.41
2	17	181	6.98	0.14	24.66	-	n/a	n/a	n/a
9	17	173	11.09	0.14	44.48	4	2.31	1.19	3.50
35	7	12	10.07	5.69	13.43	-	n/a	n/a	n/a
31	7	8	5.14	5.03	5.25	-	n/a	n/a	n/a
27	7	4	15.68	15.68	15.68	-	n/a	n/a	n/a
30	5	4	6.24	6.24	6.24	-	n/a	n/a	n/a
23	8	4	4.66	4.66	4.66	-	n/a	n/a	n/a
	Total	**7,209**				**2,964**			

5. Field Testing

Field testing of enforcement algorithm enhancements was conducted to verify the improvements shown in the simulation results. The field testing was conducted at the Transportation Technology Center (TTC) in Pueblo, CO, and made use of the facility's Railroad Test Track (RTT). The RTT is a 13.5-mile track loop with a variety of grades and curves, making it an appropriate test track for enforcement algorithm testing. The testing was conducted on a portion of this track with a maximum grade of 1.47 percent. The test consist included one GP 40-2 freight locomotive, one F40PH-2 passenger locomotive, and six Amfleet Heritage E-5 railcars. Table 61 provides a matrix of the test conditions.

Due to equipment availability, the testing was limited to pneumatic only braking. The lead locomotive had brakes cut out on one truck to simulate the AW-3 load conditions of the railcars. The testing required an interface that was installed on a freight locomotive.

5.1 Preparation

In preparation for field testing of the enforcement algorithm, the following tasks were completed:

- Test locomotive setup/checkout. It was necessary to verify that the onboard locomotive computer could determine locomotive location and speed, head end brake pipe pressure, tail end brake pipe pressure from an end of train (EOT) device, and throttle notch. As shown in Figure 15, using a separate computer running National Instruments LabVIEW software, the onboard locomotive computer was capable of interacting with the enforcement algorithm and setting/releasing brakes as required by the EA.

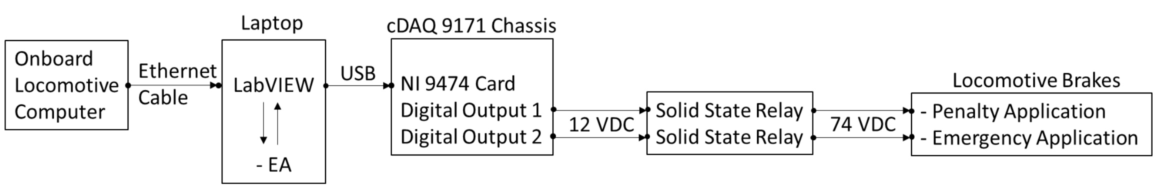

Figure 15. Overall System Setup

- Enforcement algorithm software setup/checkout commenced with communication between the LabVIEW program and the verification of the onboard locomotive computer. The team verified that the software modifications necessary for the simulation software to operate in the field were implemented correctly.

- The test consist setup included determining the specific consist to be used (i.e., one GP 40-2 freight locomotive, one New Jersey Transit (NJT) F40PH-2 passenger locomotive, and six Amfleet Heritage E-5 railcars), taking measurements on the brake system components, scaling the test consist, and installing the test instrumentation.

- A track file was loaded onto the computer and contains surveyed grade and curve data for the RTT and was accessed by the enforcement algorithm as needed for stopping distance prediction.

With the full consist built and instrumentation installed, a final checkout was conducted to ensure all systems were working together as expected with no issues.

5.2 Constraints

Before the testing could begin, the wheel slide system was verified to be fully operational on the six Heritage cars. When running the test, the NJT locomotive was located next to the six Heritage cars to provide air pressure to the main reservoir pipe. The lead locomotive computer ran the EA test application software setup to send braking signals to the locomotive consist.

Initially, the test plan included tests at a maximum speed of 90 mph. However, equipment capable of testing at this speed was not available; thus, the maximum speed was reduced to 75 mph.

5.3 Operation Sequence

Each test was run using the following sequence:

1. The train was setup to begin the test at a location where it could achieve the required speed before the expected enforcement.
2. Once the train was running at least 1 mph, the enforcement braking software was initialized with a target location on the RTT track and the consist information.
3. The locomotive engineer operated the train toward the target location using dynamic brakes to maintain speed.
4. The EA software calculated the stopping distance and determined when the brakes need to be applied.
5. The LabVIEW software initiated a brake application based on an indication from the EA software.
6. The locomotive engineer disabled the dynamic brakes after the penalty occurred by turning off the generator field switch.
7. The train came to a stop.
8. The position of the train stop was recorded.
9. The train was reset for the next test.

5.4 Track Testing

The lead locomotive of the test consist (DOT 203) was equipped with a laptop running the LabVIEW and enforcement algorithm software. This laptop received locomotive output data though broadcast messages from the onboard locomotive computer. The LabVIEW program received the train speed, GPS position, and head end brake pipe pressure through these messages and passed this data to the EA software. The EA then predicted when a brake application was required and sent a brake command to the LabVIEW program, which initiated a penalty and/or emergency brake application though relays attached to the electropneumatic brake valves on the locomotive. The EA laptop was also used to record speed, location, locomotive throttle notch, and brake pipe pressure data throughout each test for use in determining when the brakes were applied, where the train stopped, and the stopping distance. The EA laptop interfaced with the onboard locomotive computer over an ethernet connection and communicated with LabVIEW to enforce a penalty brake application when necessary.

5.4.1 Test Configuration

The field testing was configured to test the enhancements to the base case enforcement algorithm for a number of test scenarios, which covered a range of operating conditions. The test scenarios were determined by the following independent test variables:

- Train speeds: 5, 10, 50, and 75 mph
- Track grades: 0.0, -1.47, and +1.47 percent
- Algorithms tested: Baseline, TAM, Specified Consist, Tuned Train Type

Table 61 lists the specific test scenarios. The tests were run using the passenger train type and pneumatic braking due to the type of equipment available for the testing. The consist was made up of one GP 40-2 freight locomotive, one F40PH-2 passenger locomotive, and six Amfleet Heritage E-5 railcars. Thirty-six test scenarios were tested, and each scenario was run twice for a total of 72 tests passes.

Table 61. Field Test Scenarios

Test ID	Train Length	Train Speed	Track Grade	Tested Enhancement
1.1, 1.2	Two locomotives, six cars	5 mph	Flat	None – Baseline
1.3, 1.4	Two locomotives, six cars	10 mph	Flat	None – Baseline
1.5, 1.6	Two locomotives, six cars	50 mph	Flat	None – Baseline
1.7, 1.8	Two locomotives, six cars	75 mph	Flat	None – Baseline
1.9, 1.10	Two locomotives, six cars	5 mph	Decline	None – Baseline
1.11, 1.12	Two locomotives, six cars	10 mph	Decline	None – Baseline
1.13, 1.14	Two locomotives, six cars	50 mph	Decline	None – Baseline
1.15, 1.16	Two locomotives, six cars	75 mph	Decline	None – Baseline
1.17, 1.18	Two locomotives, six cars	5 mph	Incline	None – Baseline
1.19, 1.20	Two locomotives, six cars	10 mph	Incline	None – Baseline
1.21, 1.22	Two locomotives, six cars	50 mph	Incline	None – Baseline
1.23, 1.24	Two locomotives, six cars	75 mph	Incline	None – Baseline
2.1, 2.2	Two locomotives, six cars	5 mph	Flat	TAM
2.3, 2.4	Two locomotives, six cars	10 mph	Flat	TAM
2.5, 2.6	Two locomotives, six cars	5 mph	Decline	TAM
2.7. 2.8	Two locomotives, six cars	10 mph	Decline	TAM
2.9, 2.10	Two locomotives, six cars	5 mph	Incline	TAM
2.11, 2.12	Two locomotives, six cars	10 mph	Incline	TAM
3.1, 3.2	Two locomotives, six cars	10 mph	Flat	Specified Consist
3.3, 3.4	Two locomotives, six cars	50 mph	Flat	Specified Consist
3.5, 3.6	Two locomotives, six cars	75 mph	Flat	Specified Consist
3.7, 3.8	Two locomotives, six cars	10 mph	Decline	Specified Consist
3.9, 3.10	Two locomotives, six cars	50 mph	Decline	Specified Consist
3.11, 3.12	Two locomotives, six cars	75 mph	Decline	Specified Consist
3.13, 3.14	Two locomotives, six cars	10 mph	Incline	Specified Consist
3.15, 3.16	Two locomotives, six cars	50 mph	Incline	Specified Consist
3.17, 3.18	Two locomotives, six cars	75 mph	Incline	Specified Consist
4.1, 4.2	Two locomotives, six cars	10 mph	Flat	Tuned Train Type
4.3, 4.4	Two locomotives, six cars	50 mph	Flat	Tuned Train Type
4.5, 4.6	Two locomotives, six cars	75 mph	Flat	Tuned Train Type

Test ID	Train Length	Train Speed	Track Grade	Tested Enhancement
4.7, 4.8	Two locomotives, six cars	10 mph	Decline	Tuned Train Type
4.9, 4.10	Two locomotives, six cars	50 mph	Decline	Tuned Train Type
4.11, 4.12	Two locomotives, six cars	75 mph	Decline	Tuned Train Type
4.13, 4.14	Two locomotives, six cars	10 mph	Incline	Tuned Train Type
4.15, 4.16	Two locomotives, six cars	50 mph	Incline	Tuned Train Type
4.17, 4.18	Two locomotives, six cars	75 mph	Incline	Tuned Train Type

For each test scenario, a target stopping location was selected on the RTT to provide the proper track grade for the scenario. For decline scenarios, the target was R14, a -1.47 percent grade. For incline scenarios, the target was R8, a 1.47 percent grade. Flat scenarios had a target located at R24. These locations were entered into the enforcement algorithm, along with the generic consist information and other required inputs. An appropriate starting location was determined based on required speed, and the train was moved to this location to start each test run.

The train was accelerated to the specified test speed based on the detailed test plan for that scenario. The train then proceeded toward the target stopping location, with the enforcement algorithm monitoring the speed, location, and brake pipe pressure of the train. When the enforcement algorithm determined that an enforcement brake application was necessary, it sent a signal to the LabVIEW software, which applied a brake application.

Once the train had stopped, the absolute stopping location were recorded and the location relative to the target was measured and recorded before resetting the train for the next test run.

5.5 Measurement Definitions

The following measurements were taken during the field test for each test run:

- Enforcement position: The location in footage relative to a specific point on the track was measured by the LabVIEW program and recorded by the enforcement algorithm software.
- Stopping location: The location in footage relative to a specific point on the track was measured by the LabVIEW program and recorded by the enforcement algorithm software once the train had come to a stop.
- Stopping location relative to the target: The difference in footage between the stopping location and the target location was calculated in post-processing.
- Stopping distance: The difference in footage between the point of penalty brake application and stopping location was calculated in post-processing.

5.6 Field Test Results

Table 62 shows the results of the field testing. Based on the results, it is assumed that the equipment had a lower brake rate than the equipment included in the simulation matrix. The enforcement location for many of the tests were further from the target compared to the simulation results. The test train also stopped closer to the target or overran the target more than predicted in the simulation results. This indicates that the test train had a longer stopping distance relative to the worst-case train generated in the Monte Carlo simulation process.

Despite the differences in overall stopping distances, the field test results shared some similarities with the simulation results. Overruns occurred primarily on the lower speed simulations in both the field testing and simulations. The distance by which the train overran the target in the field testing falls within or slightly outside the distribution of stopping locations predicted by the simulation results. Due to the equipment limitations, only the 5-mph and 10-mph scenarios can be directly compared because the 90-mph field tests were limited to 75 mph during the testing, thus not a match to the simulation speed.

Table 62. Field Test Results

	Grade	**Speed**	**Stopping Location Relative to Target (feet)**			**Enforcement Location Relative to Target (feet)**
			Mean	**Minimum**	**Maximum**	**Mean**
Baseline	Decline	5	20.8	7.1	34.6	-131.1
		10	53.50	53.20	53.80	-263.30
		50	-1,430.80	-1,457.00	-1,404.60	-4,347.40
		75	-1,497.80	-2,854.40	-141.20	-6,016.70
	Flat	5	6.8	5.7	7.8	-99.1
		10	27.60	22.40	32.80	-195.50
		50	-339.50	-347.00	-332.00	-2,643.80
		75	-1,099.50	-1,145.60	-1,053.30	-5,898.00
	Incline	5	-8.5	-9.7	-7.3	-105.9
		10	36.00	25.00	46.90	-184.20
		50	-56.60	-90.50	-22.70	-2,061.20
		75	-425.00	-454.90	-395.20	-4,086.20
Specified Consist	Decline	10	36.25	24.00	48.50	-252.00
		50	-1,432.30	-1,490.90	-1,373.80	-4,441.70
		75	-779.50	-855.10	-703.90	-6,567.80
	Flat	10	-2.80	-54.10	48.60	-205.50
		50	-379.80	-471.40	-288.30	-2,684.80
		75	-164.10	-224.10	-104.00	-4,851.10
	Incline	10	44.70	39.00	50.30	-174.10
		50	-67.00	-78.90	-55.20	-2,063.40
		75	-571.80	-603.60	-540.10	-4,212.90
TAM	Decline	5	-40.80	-45.70	-35.90	-86.30
		10	-39.80	-48.60	-31.00	-145.70
	Flat	5	-38.60	-41.80	-35.40	-251.40
		10	-39.50	-39.80	-39.30	-144.20
	Incline	5	-39.80	-41.70	-37.90	-83.20
		10	-43.20	-44.20	-42.10	-138.40
Tuned Train Type	Decline	10	-18.50	-36.50	-0.50	-339.30
		50	-148.80	-186.10	-111.60	-3,077.50
		75	-124.90	-222.20	-27.60	-6,045.60
	Flat	10	39.60	38.20	41.10	-216.50
		50	-1,066.80	-1,075.50	-1,058.10	-3,436.10
		75	-70.15	-45.10	-95.20	-4,633.30
	Incline	10	39.80	37.60	41.90	-197.80
		50	-320.50	-337.80	-303.30	-2,300.60
		75	-1,087.50	-1,089.40	-1,085.70	-4,898.60

Figure 16 shows the stopping distance from the target for both the baseline and the specified consist simulations. There was overall improvement in the average stopping location for the specified consist algorithm. The specified consist enhancement stopped the train short of the target with a small impact to operational efficiency.

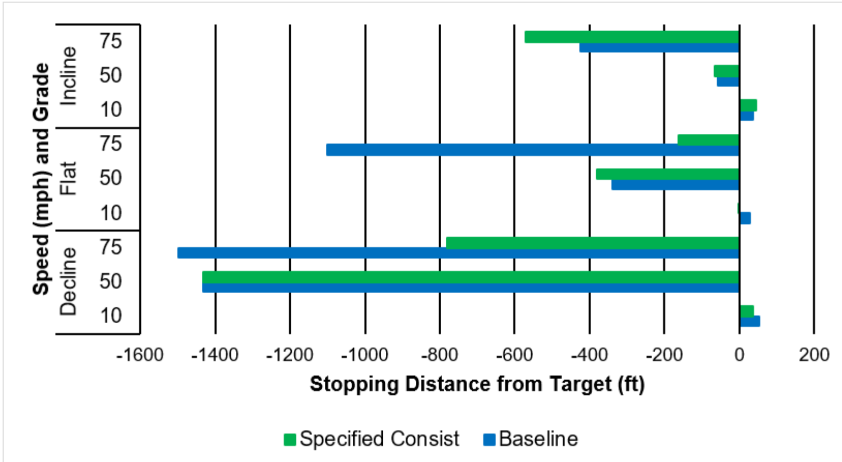

Figure 16. Baseline vs. Specified Consist Mean Stopping Distance Location Relative to Target

Figure 17 shows the stopping distance from the target for both the baseline and tuned train type simulations. The tuned train type performed better on the decline than the baseline EA. Because there was no data available for the regression analysis to determine the tuned values, the values for the tuned train brake force could only be assumed. Assumptions were made based on similar equipment, but without extensive modeling and further field testing, the results can only be used to show the trends. Additionally, the tuned type braking algorithm applied the brakes farther from the target for the flat and incline at higher speeds, which, in turn, stopped the train farther from the target. Given the higher rate of overruns for the original baseline EA, this would indicate that the tuned train enhancement could be safer.

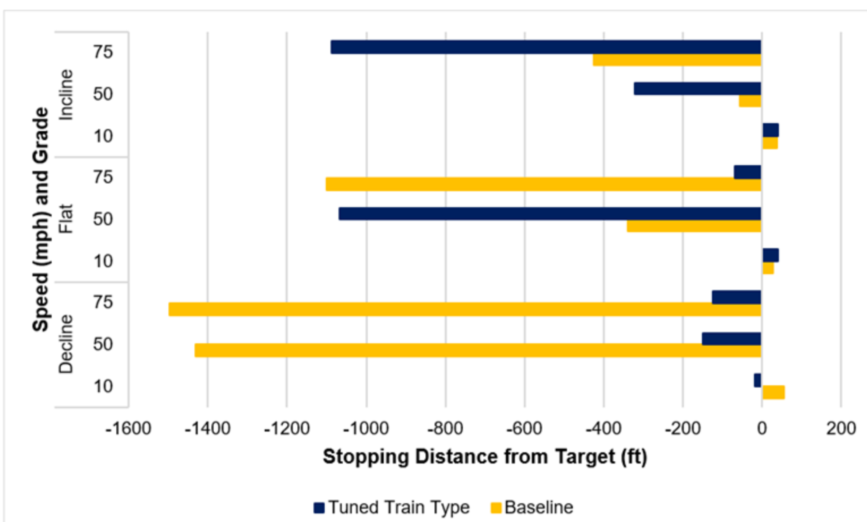

Figure 17. Baseline vs. Tuned Train Type Mean Stopping Distance Location Relative to Target

TAM stopped before the target and did not have any overruns compared to the baseline. On all track grades, TAM was relatively consistent with the mean stopping distance while the baseline EA showed greater variation in the results. The TAM algorithm uses an emergency brake application, that delays braking to allow a train to stop before the target more frequently than the corresponding baseline tests.

6. Conclusion

The primary objective of this project was to identify, develop, simulate, and test methods to improve predictive braking enforcement algorithms for passenger and commuter trains in an I-ETMS PTC system design. The following enhancements were developed, simulated, and field tested:

- TAM
- Specified consist calculations
- Tuned train types

The research team was unable to field test the last enhancement, an adaptive algorithm, due to time limitations.

All the enhancements showed improvements compared to the baseline. The TAM enhancement allows consists to get closer to the target location without unwarranted penalty brake enforcements. The specified consist enhancement improves the accuracy of the brake rate calculation, particularly for short trains. The tuned train type enhancement improved the performance of the algorithm by tuning the parameters of the algorithm to the equipment used by each individual agency. The level of improvement was different for each agency, based on the level of variation of the equipment used by the agency, but the results did show an overall improvement. The adaptive braking enhancement increased the overall probability of stopping short of the target by 1.23 percent and increased the overall probability of stopping short of the performance limit by 5.69 percent.

The results from field testing the first three enhancements were similar to the simulation results. Most of the overruns in both the field testing and simulations occurred at lower speeds.

A secondary objective of this project was to modify the simulation environment to support simulation of EMU and DMU equipment. The team developed a process to support all types of EMU and DMU equipment. They updated the ICD between the simulation environment and the enforcement algorithm to include the changes needed to allow the necessary data to be sent to the enforcement algorithm. TTCI implemented the changes in the modeling software, but simulation of a vendor product was unable to be completed due to outside constraints. The simulation of braking algorithm performance for EMU and DMU equipment will be completed for each railroad as needed outside of the scope of this project.

The methods identified during this project, along with the expansion of the simulation capabilities for passenger and commuter equipment, demonstrate opportunities for continued enhancement of the PTC braking algorithm performance for these train types.

7. References

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Appendix A: Baseline Braking Enforcement Algorithm

1. Baseline Algorithm Overview

The enforcement algorithm is based on the version developed for the North American Joint Positive Train Control (NAJPTC) project. 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 revisions to the logic, while retaining many of the methods and concepts from the original version.

The primary objective of the predictive braking enforcement algorithm is to enforce the PTC train movement authority and speed limits. This is accomplished 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 requires 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 A1 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 many assumptions and unknowns in the prediction calculation. The nominal prediction is located at the mean of this distribution, 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.

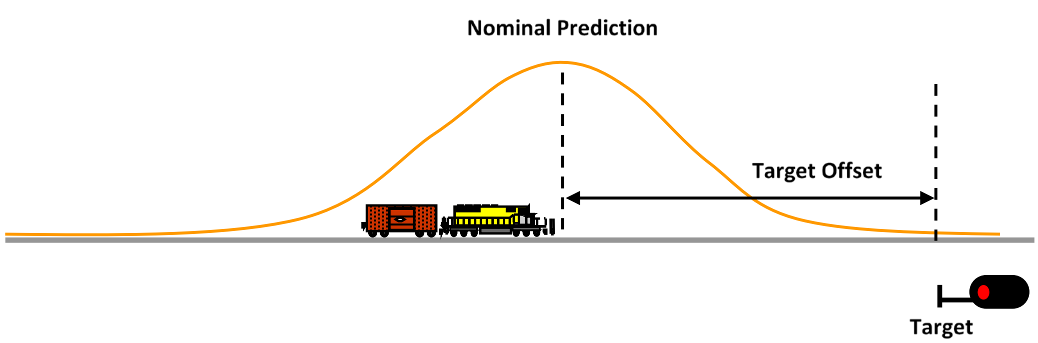


Figure A1. Illustration of Target Offset

The target offset is based on a regression of the results of a Monte Carlo sensitivity analysis of passenger 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.

1.1 Detailed Baseline Algorithm Definition

This section defines the functions, equations, and logic flow of the predictive braking enforcement algorithm. The intent is that 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.

1.1.1 Initialization

This section describes the functions necessary for initialization of the algorithm. The primary objective of these functions is to set all the fixed data used by the enforcement algorithm. Although the term initialization is used, the design of these functions are 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.

Update Consist Data

This function initializes, updates, or modifies 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)

Derive Nominal Brake Force Curve

The nominal brake force curve is used to estimate 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 this data is not available to 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. Equation A1 calculates the nominal full service brake force for the train.

$$Full\ Serv\ F_{B\ nom} = \frac{BR_{fs} * W_t * 2000 * 1.467}{32.17} \tag{A1}$$

Where:

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

W_t – Weight of the train in tons

The service limiting valve setting is also assumed to be 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, shown in Equation A2.

$$M = \frac{Full\ Serv\ F_{B\ nom}}{60} \tag{2}$$

This slope, along with the #16 line pressure, is 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, shown in Equation A3.

$$Max\ Emergency\ F_{B\ limit} = \frac{BR_{EM} * W_t * 2000 * 1.467}{32.17} \tag{3}$$

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

1.1.2 Main Process

This section describes the primary high-level functions of the enforcement algorithm that make up the main processing loop shown in Figure A2 that 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.

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

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

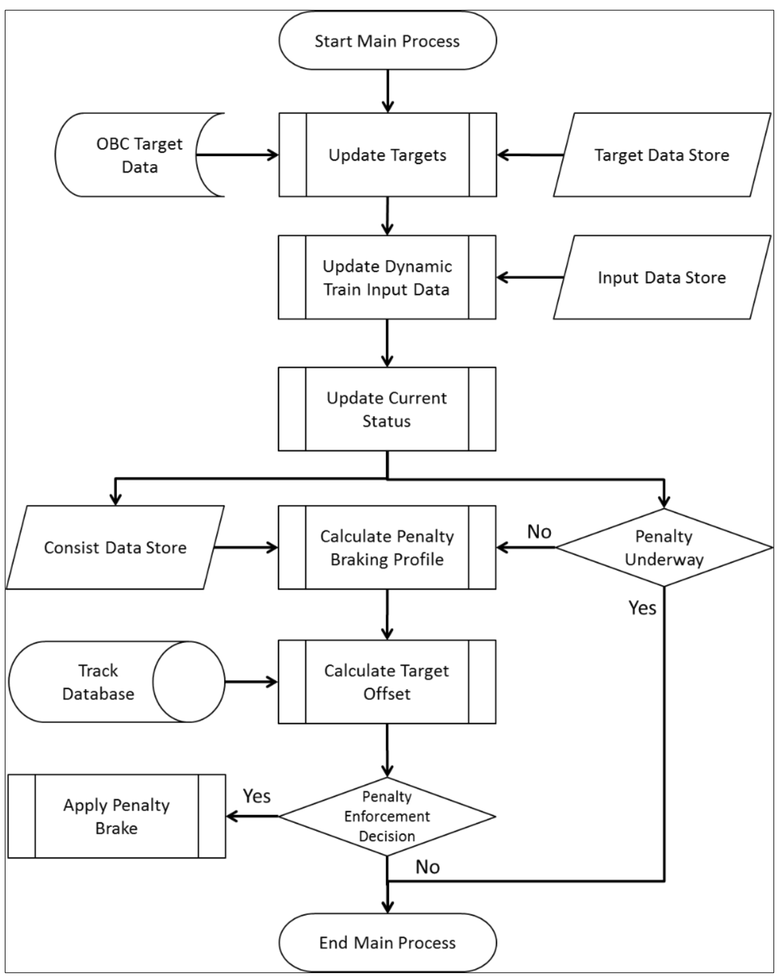


Figure A2. Main Process Flow Diagram

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
- Head-end Brake Pipe Pressure: Current brake pipe pressure at the lead locomotive in pounds per square inch (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)

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 (Section 1.1.3), the average track grade and curvature under the train is determined (Section 1.1.4), forces acting on the train are calculated (Section 1.1.5), and the locomotive dynamic braking force acting on the train, if any, is estimated (Section 1.1.6).

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*.

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. The C*alculate Penalty Braking Profile* function is described in detail in Section 1.1.6.

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. This function is described in detail in Section 1.1.7.

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.

For non-zero speed targets, the predicted location of the train at the target speed is added to an adjusted target offset and compared against the target location. The adjusted target offset allows for less conservatism in the algorithm as the train speed approaches the target speed, based on the potential error at various points along the predicted braking curve.

1.1.3 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 in every iteration through the main processing loop, as well as updating the predicted air brake system status for each time step during the penalty braking profile prediction, as described in Section 1.1.6.

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 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 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 the resulting brake force. Figure A3 illustrates the *Update Air Brake System Status* function flow.

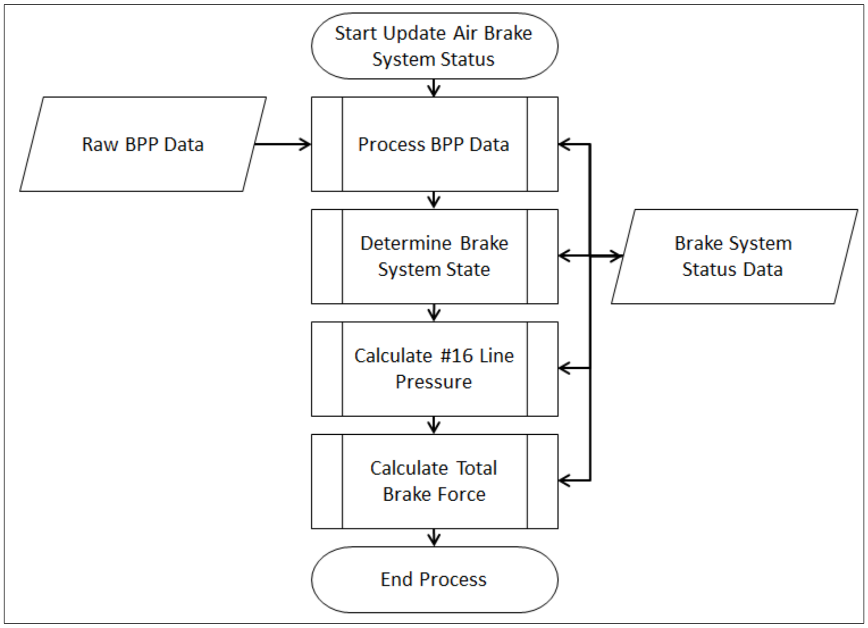


Figure A3. Update Air Brake System Status Flow Diagram

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

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

The model of the air brake system described in the following subsections includes several 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 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 at which brake pipe pressure is vented to the #16 line during a brake application. The rate is assumed to be 2.5 psi/s.
- Release Rate, REL_{Rate}. The rate at which brake pipe pressure is vented out of the #16 line during a brake release. 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 "Derive Nominal Brake Force Curve."
- Maximum emergency brake force limit, calculated in Section 1.1.5.

Process Brake Pipe Pressure Data

This function takes the raw front brake pipe pressure and processes it for use in detecting 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 A4 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 brake pipe pressure data from the onboard system for the most recent sample with the previous two samples.

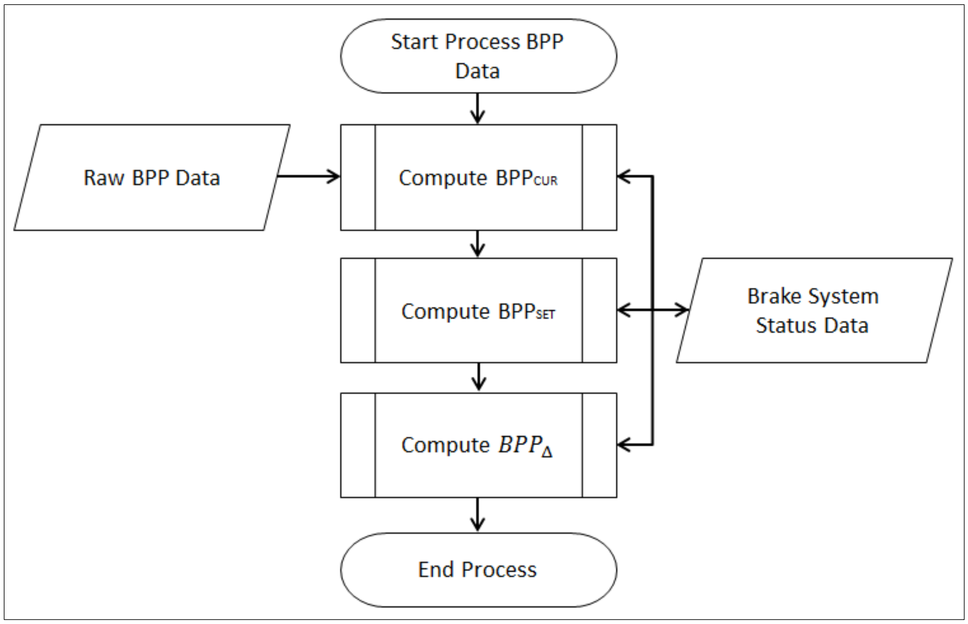


Figure A4. Process BPP Data Flow Diagram

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 Equation A4:

$$\text{If } BPP_{CUR} > BPP_{SET}, \text{ then } BPP_{SET} = BPP_{CUR}. \tag{A4}$$

The final function of this process determines the change in brake pipe pressure since the last time step, BPP_{Δ}, using Equation A5:

$$BPP_{\Delta} = BPP_{CUR} - BPP_{PREV} \tag{A5}$$

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.

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 A5 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. A number of functions 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.

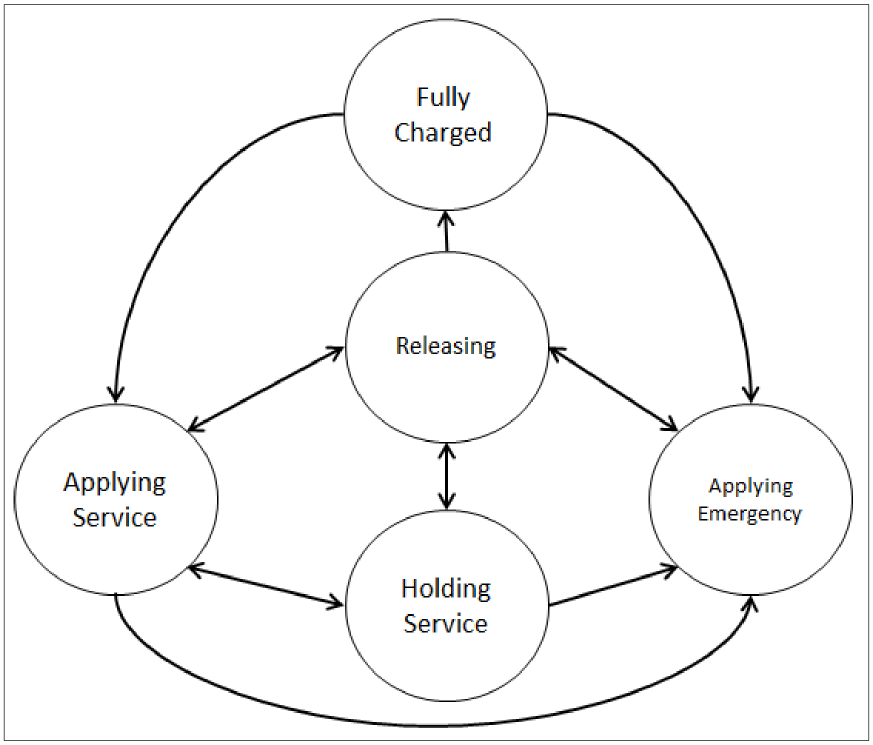


Figure A5. Brake System State Diagram

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 A6 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.

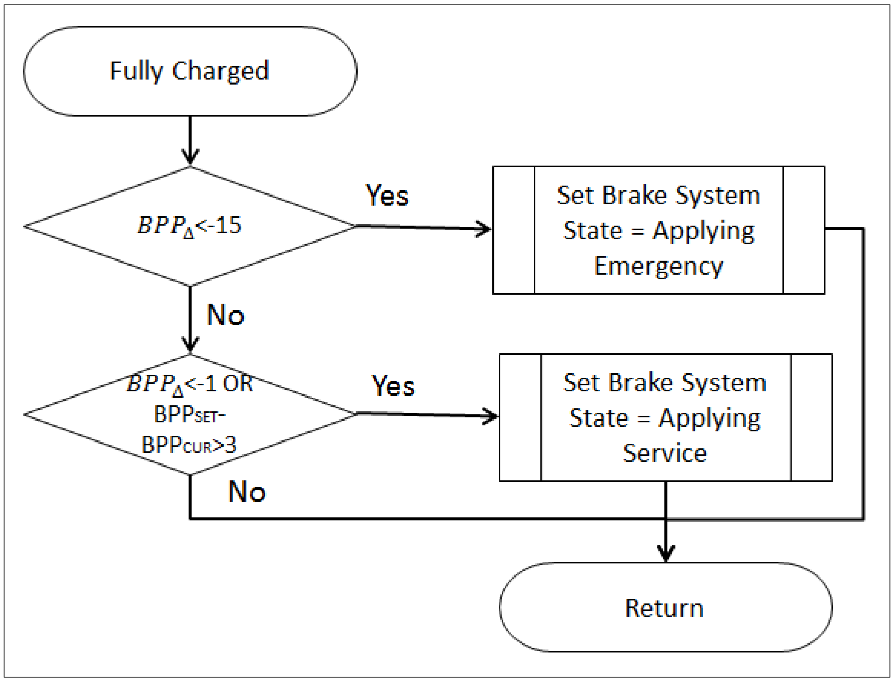


Figure A6. Fully Charged State Flow Diagram

Applying Service Brake System State

As the state diagram in Figure A5 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 A7, which shows the flow diagram for the applying service state.

As Figure A7 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.

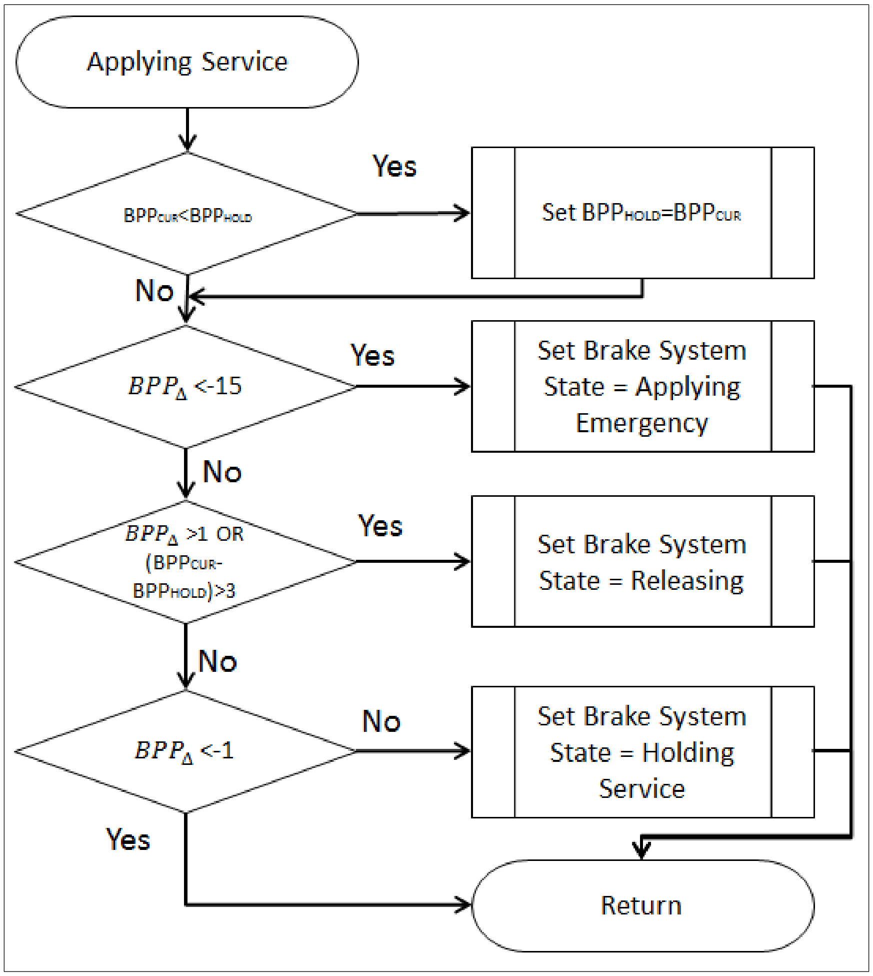


Figure A7. Applying Service State Flow Diagram

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.

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 A8 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.

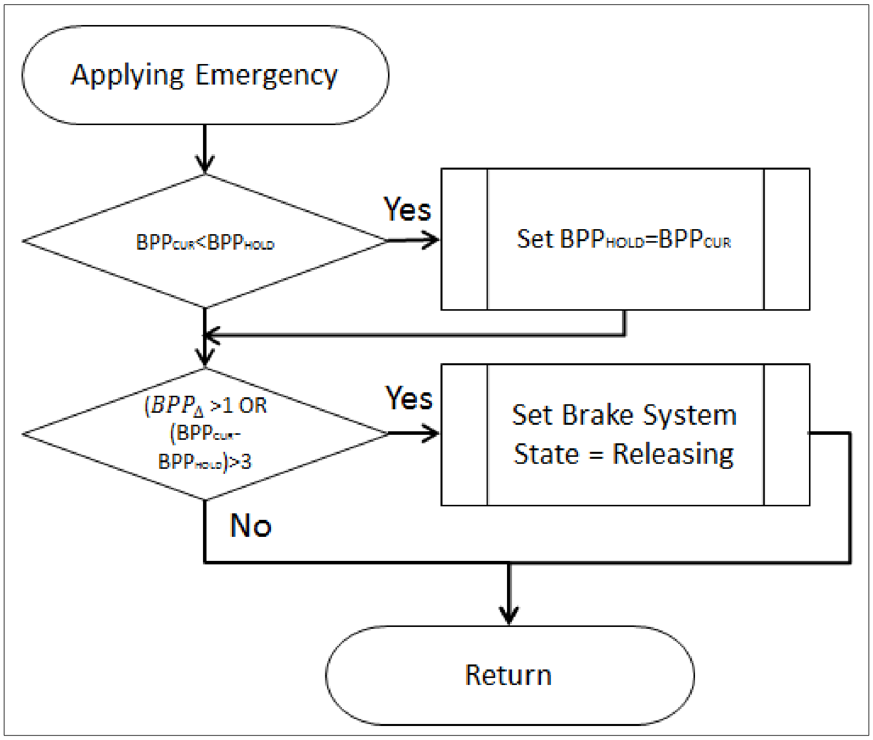


Figure A8. Applying Emergency State Flow Diagram

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.

Holding Service Application Brake System State

If the brake system state is set to holding service application, the process flow depicted in Figure A9 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.

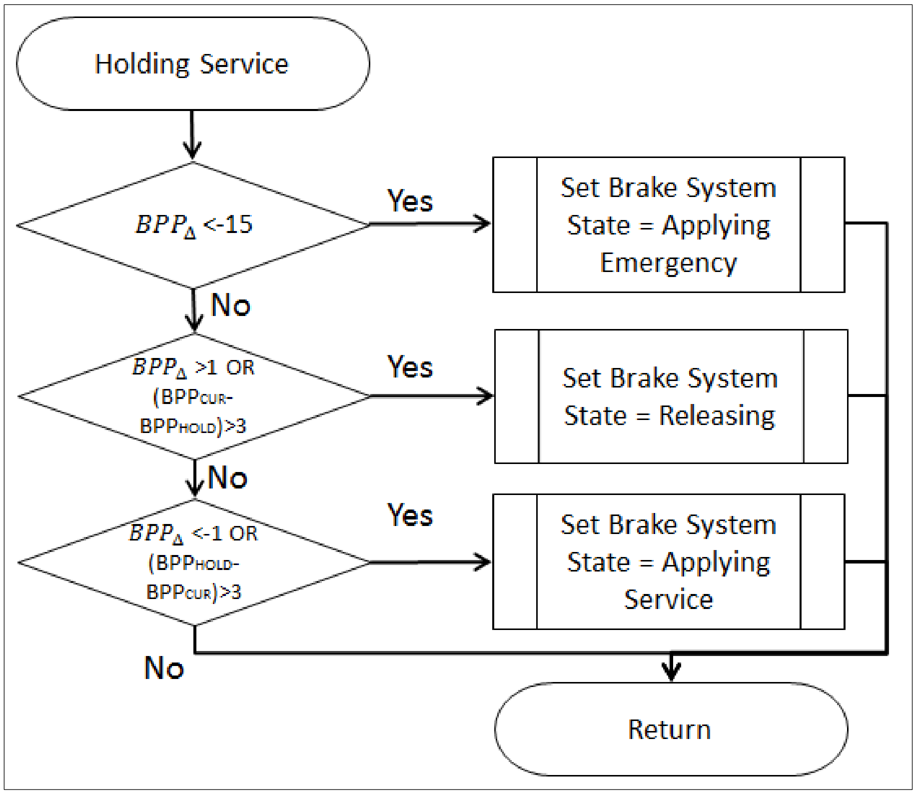


Figure A9. Holding Service Application State Flow Diagram

Releasing Brake System State

Figure A10 illustrates the process flow for the releasing brake system state. 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.

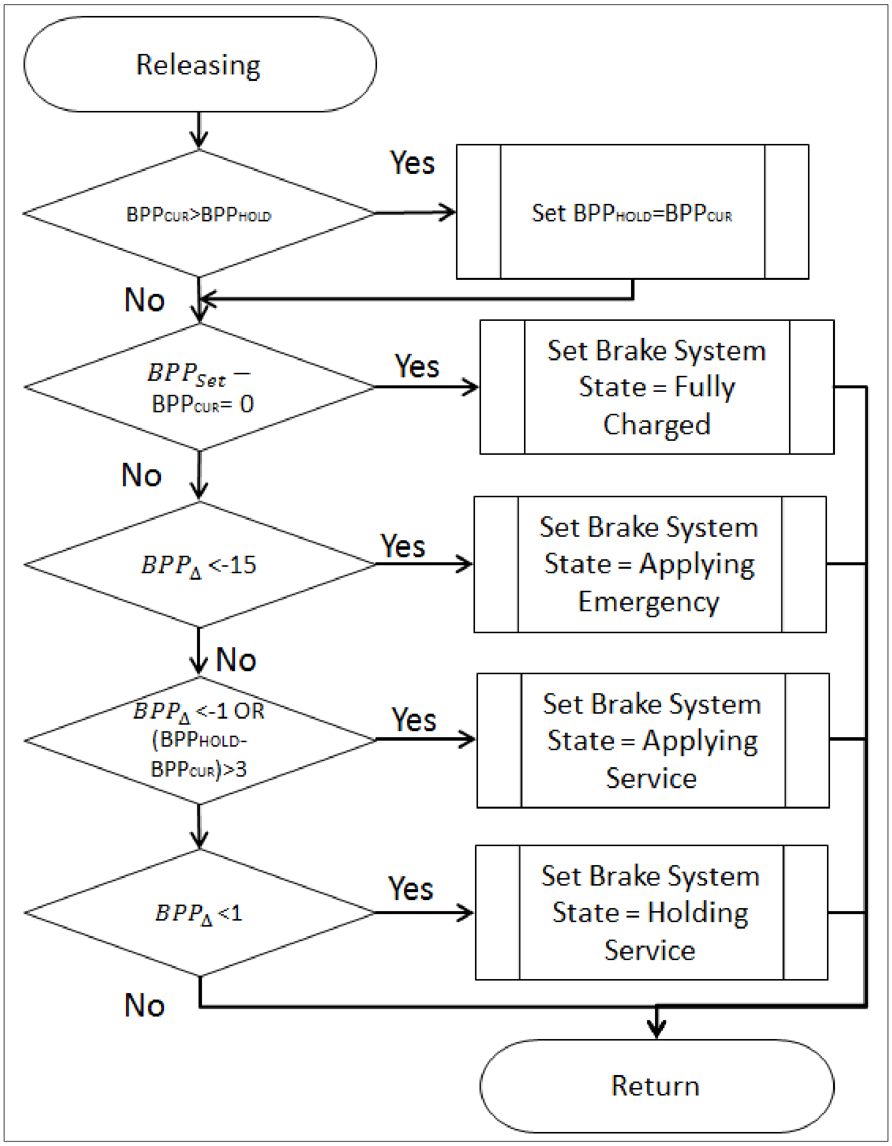


Figure A10. Releasing Brake State Flow Diagram

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 Equation A6:

$$\#16Line_{CUR} = \#16Line_{PREV} + |BPP_{\Delta}| * APP_{RATE} \quad \text{(A6)}$$

If the brake state is releasing the control reference pressure is set according to Equation A7:

$$\#16Line_{CUR} = \#16Line_{PREV} - |BPP_{\Delta}| * REL_{RATE} \tag{A7}$$

The #16 line pressure variable is capped based on the full service reduction and application rate. Equation A8 shows the following if statement used to calculate the #16 line pressure during the applying service brake state:

$$\begin{gathered}\text{If } \#16Line_{CUR} > App_{Rate} * Full\ Service\ Reduction, \\ \text{then } \#16Line_{CUR} = App_{Rate} * Full\ Service\ Reduction\end{gathered} \tag{A8}$$

1.1.4 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.

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, shown in Equation A9.

$$\%Grd_{CUR} = Grade\ Under\ Head\ End\ of\ Train \tag{A9}$$

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, Crv_{CUR}, shown in Equation A10.

$$|Crv_{CUR}| = Curvature\ Under\ Head\ End\ of\ Train \tag{A10}$$

1.1.5 Calculate Train Forces

The *Calculate Train Forces* process performs calculations to determine the net force acting on the train (i.e., 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 shown in Equation A11:

$$F_{NET} = \sum F = F_{LOC} + F_{GRD} + F_{CRV} + F_{RES} + F_{BRK} \tag{A11}$$

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.

Calculate Locomotive Force

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

Calculate Grade and Curving Forces

The grade force, F_{GRD}, is computed using Equation A12:

$$F_{GRD} = -20 * W_{TRAIN} * \%Grd_{CUR} \tag{A12}$$

Where W_{TRAIN} is the weight of the train in tons and $\%Grd_{CUR}$ is the grade under the train, as described in Section 1.1.4. The negative sign in Equation A12 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 Equation A13:

$$F_{CRV} = -0.8 * W_{TRAIN} * Crv_{CUR} \tag{A13}$$

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 1.1.4. 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.

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. Equation A14 calculates the resistive forces by using a form of the Modified Davis Equation, which is used to calculate the resistance of a given rail vehicle:

$$R_u = 0.6 + \frac{20}{w} + 0.01V + \frac{KV^2}{wn} \tag{A14}$$

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 Equation A14 by the weight of the vehicle in tons, W_{VEH}, gives the resistance in lbs./vehicle, R_{VEH} as shown in Equation A15:

$$R_{VEH} = 0.6W_{VEH} + 20n + 0.01W_{VEH}V + KV^2 \tag{A15}$$

Multiplying Equation A15 by the number of cars, N_{CARS}, and locomotives, N_{LOCS}, gives the resistance in lbs. for the train:

$$R_{TRAIN} = 0.6W_{TRAIN} + 20n_{TOTAL} + 0.01W_{TRAIN}V + (K_{LOCOS}N_{LOCS} + K_{CARS}N_{CARS})V^2 \quad \text{(A16)}$$

Where W_{TRAIN} is the total weight of the train in tons, n_{TOTAL} is the total number of axles in the train, K_{LOCOS} is the aerodynamic coefficient for locomotives and K_{CARS} is the aerodynamic coefficient for trailing cars (Equation A16). The aerodynamic coefficients for locomotives and trailing cars are assumed in Equation A17:

$$K = \begin{cases} 0.663 \text{ } for \text{ } locomotives \\ 0.464 \text{ } for \text{ } trailing \text{ } cars \end{cases} \quad \text{(A17)}$$

Substituting in the aerodynamic coefficients and introducing a negative sign to produce a negative result, tending to decelerate the train, resulted in Equation A18 for the resistive forces acting on the train:

$$F_{RES} = -(0.6W_{TRAIN} + 20n_{TOTAL} + 0.01W_{TRAIN}V + (0.663N_{LOCS} + 0.464N_{CARS})V^2) \quad \text{(A18)}$$

Calculate Brake Force

The brake force, FB_{RK}, is the retarding force acting on the train due to the brakes being applied. Equation A19 is calculated by using the current #16 line pressure, and the nominal brake force curve.

$$F_{BRK} = M * \#16Line_{CUR} \quad \text{(A19)}$$

Where:

$$M = \frac{Full\ Serv\ F_{B\ nom}}{60} \quad \text{(A20)}$$

For a service application, the brake force is limited to the nominal full service brake force by not allowing the #16 line pressure to exceed the full service limiting valve setting, shown in Equation A20. 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 “Derive Nominal Brake Force Curve” (see Equation A21).

$$Max\ Emergency\ F_{B\ limit} = \frac{BR_{EM} * W_t * 2000 * 1.467}{32.17} \quad \text{(A21)}$$

Where

BR_{EM} – Full service Brake Rate (assumed to be 2.2 mph/s)

W_t – Weight of the Train

1.1.6 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 A2, 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 A18.

The prediction of the brake profile is performed by employing a numerical integration process so 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 the 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 minimal

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. Equation A22 shows that the acceleration is calculated according to Newton's Second Law of Motion:

$$\sum F = ma \tag{A22}$$

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.

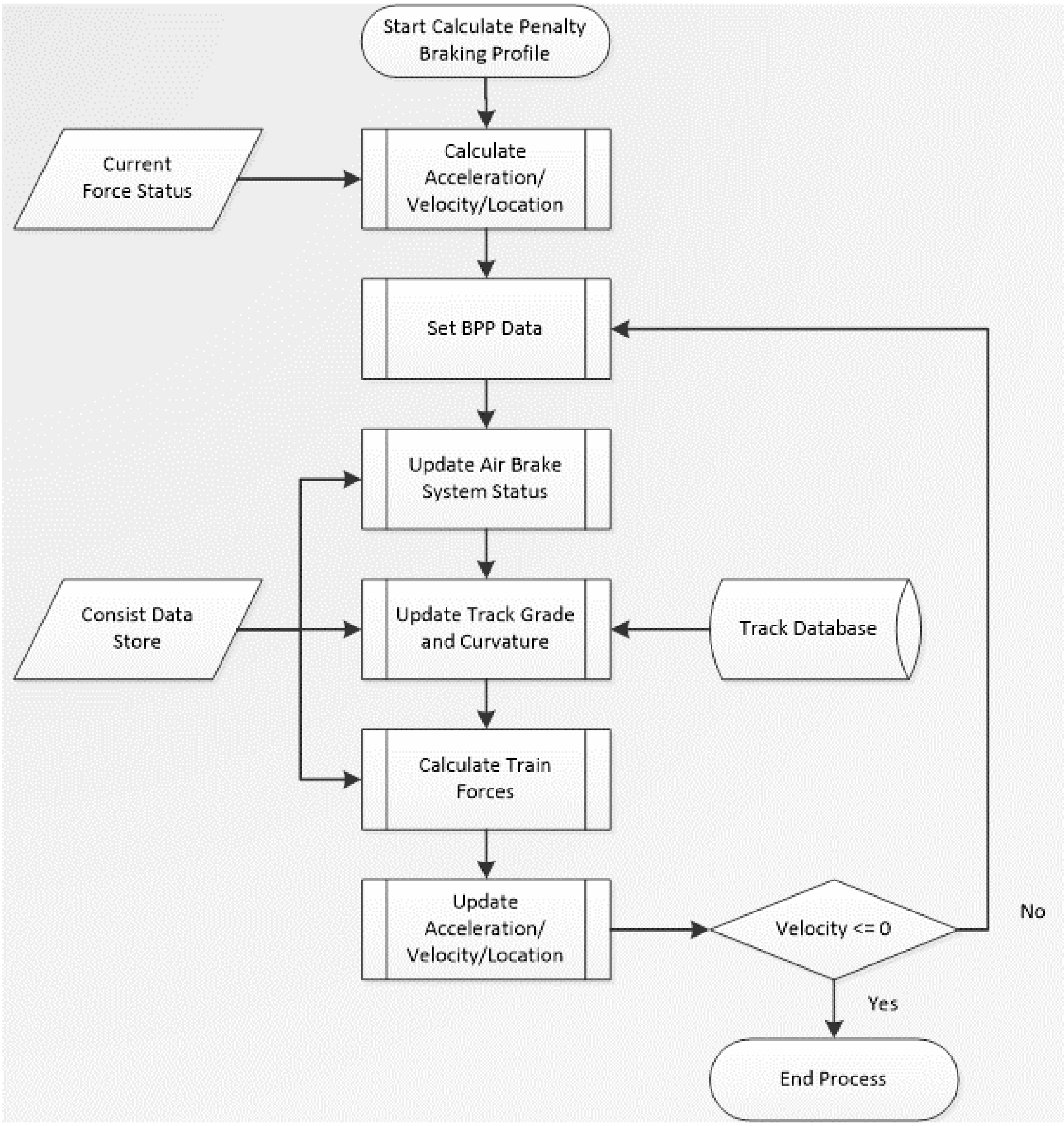


Figure A18. Calculate Penalty Braking Profile Flow Diagram

Equation A23 shows that the predicted velocity in ft/s, v, over the integration time step, Δt, can be determined by using the current velocity according to:

$$v = v_{PREV} + a\Delta t \tag{A23}$$

Equation shows that the predicted location, x, can be determined by using the current location:

$$x = x_{PREV} + v_{PREV}\Delta t + \frac{a}{2}\Delta t^2 \tag{A24}$$

Next, the predicted brake pipe pressure is set, based on the assumption that the penalty brake has been applied. Equation A25 shows 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.

$$BPP_{FRONT,t} = BPP_{FRONT,CUR} - 4.0t \tag{A25}$$

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 the brake system parameters for the next predicted time step using the *Update Air Brake System Status* process defined in Section 1.1.3.

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 1.1.5.

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 1.1.5.

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

1.1.7 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 following parameters were evaluated in the regression analysis:

- Train type
- Train loading condition
- 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}

A parametric study was conducted, and the results were analyzed to develop the following target offset for the baseline algorithm. Only a subset of the above parameters were determined to be significant enough to include in the target offset calculation.

The function to calculate target offset is as follows:

For all functions below:

x1= Speed in mph

x2= Grade percentage where negative numbers are downhill and positive numbers are uphill

x3= Number of Axles

x4= Tonnage

Y=Target Offset

Equation A26 shows the target offset for the passenger train type on grades less than -1.5 percent:

$$Y = e^{\alpha * x1 - \beta * x2 - \gamma * x3 + \delta * x4 + \varepsilon} \tag{A26}$$

Where:

α = 0.02877159418937

β = 0.52024302210580

γ = 0.10643216711654

δ = 0.00478652624487

ε = 2.91098192085966

Equation A27 shows the target offset for the commuter train type on grades less than -1.5 percent:

$$Y = e^{\alpha * x1 - \beta * x2 - \gamma * x3 - \delta * x4 + \varepsilon} \tag{A27}$$

Where:

α = 0.02422682963971

β = 0.27760401317607

γ = 0.00982063624213

δ = 0.00076059405268

ε = 4.18443894145074

Equation A28 shows the target offset for the passenger train type on grades greater than or equal to -1.5 percent and less than or equal to 0 percent:

$$Y = e^{\alpha * x1 - \beta * x2 - \gamma * x3 + \delta * x4 + \varepsilon} \tag{A28}$$

Where:

$\alpha = 0.02665747375462$

$\beta = 0.07744562066466$

$\gamma = 0.01233698712438$

$\delta = 0.00043771722939$

$\varepsilon = 4.05429471391045$

Equation A29 shows the target offset for the commuter train type on grades greater than or equal to -1.5 percent and less than or equal to 0 percent:

$$Y = e^{\alpha * x1 + \beta * x2 + \gamma * x3 - \delta * x4 + \varepsilon} + 40 \tag{A29}$$

Where:

$\alpha = 0.02589299600983$

$\beta = 0.05012573399897$

$\gamma = 0.00742943264279$

$\delta = 0.00086370791514$

$\varepsilon = 4.18372989872593$

Equation A30 shows the target offset for the passenger train type on grades greater than 0 percent and less than or equal to 1.5 percent:

$$Y = e^{\alpha * x1 - \beta * x2 - \gamma * x3 - \delta * x4 + \varepsilon} + 10 \tag{A30}$$

Where:

$\alpha = 0.02601886782110$

$\beta = 0.08436290498468$

$\gamma = 0.00042064646800$

$\delta = 0.00010601722185$

$\varepsilon = 4.02919125447124$

Equation A31 shows the target offset for the commuter train type on grades greater than 0 percent and less than or equal to 1.5 percent is:

$$Y = \alpha * x1 + \beta * x2 + \gamma * x3 - \delta * x4 + \varepsilon \tag{A31}$$

Where:

$\alpha = 4.6967380235870$

$\beta = 0.7300763764126$

$\gamma = 1.4799294165874$

δ = 0.1038766476643

ε = 84.1078733106973

Equation A32 shows the target offset for the passenger train type on grades greater than 1.5 percent:

$$Y = \alpha * x1 - \beta * x2 + \gamma * x3 - \delta * x4 + \varepsilon \tag{A32}$$

Where:

α = 4.1293387502740

β = 4.5412745179055

γ = 1.0639806833138

δ = 0.0794333198226

ε = 12.0249725577054

Equation A33 shows the target offset for the commuter train type on grades greater than 1.5 percent:

$$Y = \alpha * x1 + \beta * x2 + \gamma * x3 - \delta * x4 \tag{A33}$$

Where:

α = 3.5398933846185

β = 2.6809655099635

γ = 2.3889474628919

δ = 0.0793465433872

If any of the above equations result in a negative target offset value, the target offset should be set to zero.

Appendix B: Interface Control Document: Enforcement Algorithm Evaluation Process Overview and Communications Interface Specification (Revision 8, June 13, 2021)

1. Document Description

This document describes the concept of operations (ConOps) 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 Transportation Technology Center, Inc.'s (TTCI) testing environment.

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
Revision 7 – Changed CRC bytes in Init message and EA status message to add needed fields	November 1, 2018
Revision 8 – Added EMU/DMU fields	June 13, 2021

2. Definitions

Definitions:

- Enforcement Algorithm (EA): EA is a software designed to predict train stopping distance to enforce externally defined limits on train movement.
- Test Controller and Logger (TCL): TCL is a 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 components and acts as a gateway between the two applications during each simulation. TCL determines consist, track, and target stopping location inputs for each test. Simulated train inputs are passed from TOES to EA via TCL at regular time intervals throughout the simulation and TCL initiates a penalty brake application in TOES upon receiving the command from EA.
- Passenger Test Controller and Logger (P-TCL): P-TCL is a software that performs the same functions as the TCL software for simulations involving passenger and commuter trains using the Passenger Train Braking Performance Model (PTBPM). Throughout this document, where P-TCL and PTBPM serve the same functions as TCL and TOES, respectively, they are included in parentheses.
- EA Initialization Module (EA-Init): EA-Init is a software application used to initialization the test process with EA software. This module is used in the freight simulation environment and 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. In the passenger simulation environment, the functionality of the EA Initialization Module is performed internally by P-TCL.
- Virtual Machine (VM): Virtual machine software contains the supplier's EA software.

3. Concept of Operations

This section describes the ConOps for EA evaluation in both a simulation and field test environment.

Revision 8 of this document includes changes to support the use of EMU/DMU equipment in TTCI's Monte Carlo simulations. The EA supplier will provide the research team with the maximum brake force and tractive effort of each EMU/DMU unit type. A consist may include multiple EMUs/DMUs. The authors will build the nominal vehicle and consist models using these agreed upon values. These nominal maximum values will be varied when P-TCL uses the Monte Carlo method to generate the consists that will be used in the simulation process.

3.1 Simulation Testing

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

1. TCL (P-TCL) starts EA-Init and TOES (PTBPM) 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 (P-TCL) over TCP/IP using the data port.
4. TCL (P-TCL) propagates the TOES (PTBPM) simulation by one second, receives train status data and sends this data to EA over TCP/IP using the data port.
5. Steps 3 and 4 are repeated until EA determines a penalty brake application is necessary. At this time EA updates the status code in the status message sent in Step 3 to instruct TCL (P-TCL) to apply the penalty brake. TCL (P-TCL) then initiates the penalty application in TOES (PTBPM) 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 (P-TCL), using the data port and EA-Init, using the admin port.
7. EA-Init shuts down and TCL (P-TCL) proceeds with the next test until the end of the test batch.

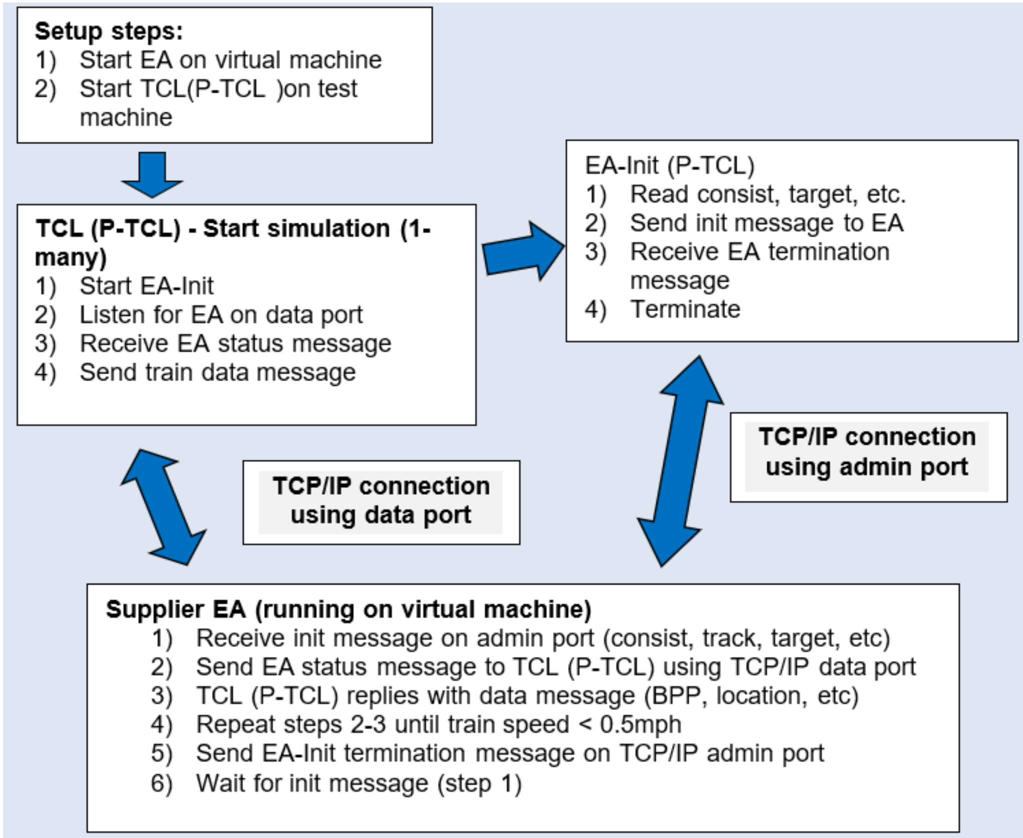


Figure B1. Simulation Test Process Flow

The TCL (P-TCL) software can run multiple simulations on a single test machine, thus, the supplier EA software should be able to set both the admin port and data port using configuration files.

3.2 Field Testing

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

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

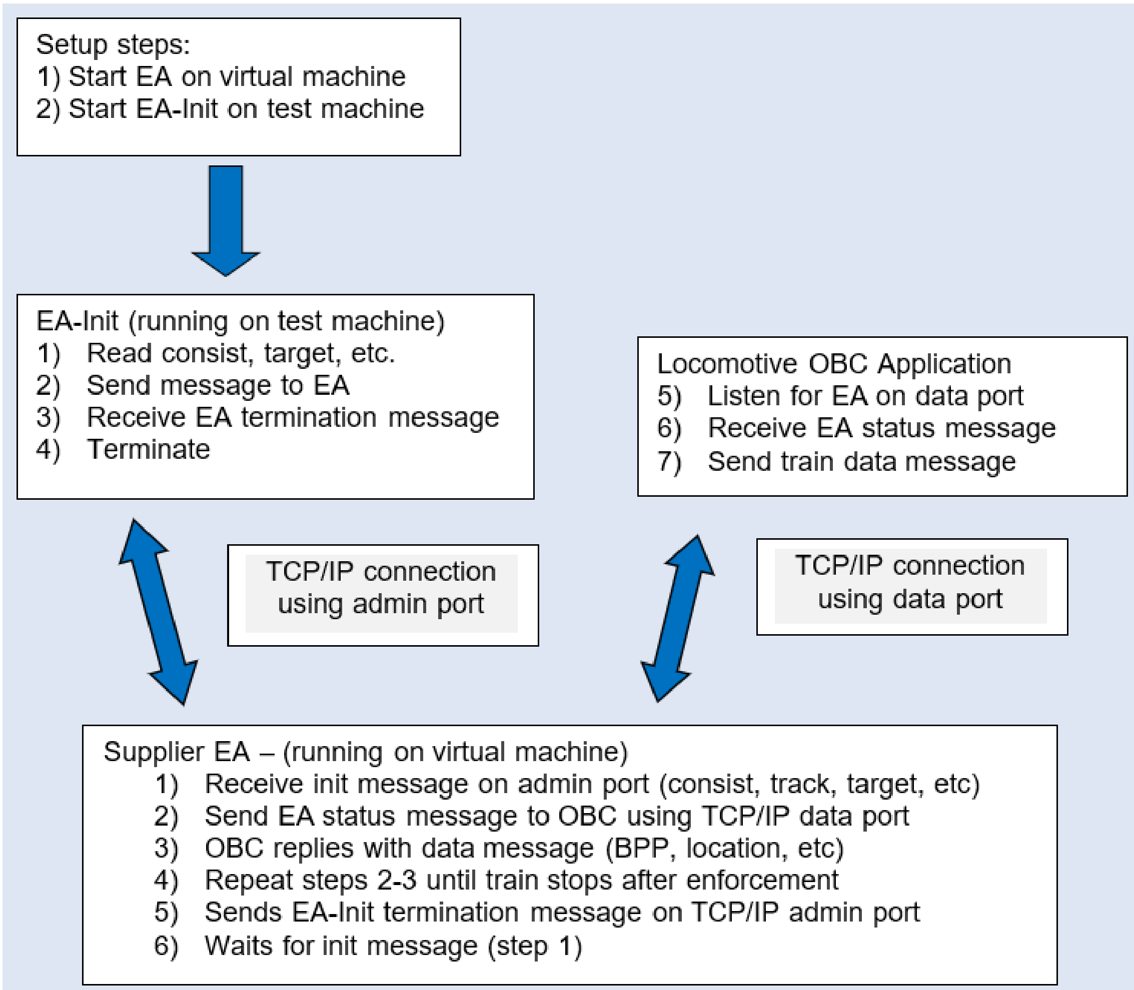


Figure B2. Field Test Process Flow

3.3 Track Data

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

3.4 Machine Configuration

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

- As a VM 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 test environment (i.e., note that for simulation testing, multiple simulations are planned to be run concurrently)

The current test machines run on Microsoft® Windows® Server 2016 operating system with 8 GB of RAM. The research team and the EA supplier can create a mutually agreeable machine configuration for running the provided EA software.

3.5 Protocol Test Application

The authors 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 Attachment A).

4. Interface Specifications

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

4.1 Initialization Message Specification

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

Table B1. Initialization Message

Field Name	Description	Data Length	Data Type	Notes
START_BYTES	Bytes for Framing	2 bytes	21930 (0x55aa)	Static
MESSAGE_ID	Message Identifier	1 byte	3 (0x03)	Static
TRACK_FILE_ID	The track file number	2 bytes	Unsigned short	None
TARGET_LOCATION	The Target stopping Location (footage)	4 bytes	Unsigned Integer	None
TARGET_SPEED	The target speed (mph)	1 byte	Unsigned integer	None
START_LOCATION	The initial starting track location (in feet)	4 bytes	Unsigned Integer	None
TRAIN_TYPE	Train Type 0 – Unknown 1 – General Freight 2 – Unit Freight 3 – Intermodal 4 – Passenger 5 – High speed Passenger 6 – Tilt train 7 - Commuter	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

Field Name	Description	Data Length	Data Type	Notes
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
LOCOMOTIVES	The number of locomotives	1 byte	UINT	0-24
For each Loco				
POSITION	The locomotive position in the train	2 bytes	unsigned short	0-999
TONNAGE	The tonnage of the locomotive	2 bytes	unsigned short	20-300
STATUS	Locomotive Status 0 – Unknown 1 – Run 2 – Isolated	1 byte	UINT	0-2
LENGTH	The length of the locomotive (feet)	1 byte	UINT	60-90
HORSEPOWER	Locomotive Horsepower	2 bytes	unsigned short	0-10000
End For				
Emergency Brake Backup	0 – False 1 - True	1 byte	UINT	0-1
EMU_TYPE	EMU Type 0 – not EMU 1 – HR_EMU 2 – NS_MC_EMU 3 – NS_MCEW_EMU 4 – NS_300_EMU 5 – SR_FLRT3_DMU 6 – SR_KSS_EMU	1 byte	UINT	0-6
Spare		2 bytes		unused
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 railroad customer plans to supply the enforcement algorithm with a total train braking force that is calculated offline by a preprocessor. In these cases, the railroad 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.

The EMU_TYPE field indicates whether the consist is an EMU consist and, if so, which type of EMU is used within the consist. If an EMU Type of zero is provided in the initialization message, the supplier's algorithm will use the standard method for calculating the stopping position of the consist. If a value other than zero is provided as the EMU Type, Wabtec will use the EMU Type and the Train Type to determine how to calculate the stopping location of the consist. Only the passenger or commuter train types will be used with EMUs\DMUs.

4.2 Train Data Message Specification

Table B2 specifies the format for the train data message that is sent to the EA software. This message is sent from the TCL (P-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 B2. Train Data Message

Field Name	Description	Data Length	Data Type	Notes
START_BYTES	Bytes for Framing	2 bytes	21930 (0x55aa)	Static
TRN_LOC	Current Train Location (footage)	8 bytes	Double	Sent as feet, must be within limits defined in track data file
TRN_SPD	Current Train Speed (mph)	8 bytes	Double	mph 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	1 byte	Byte	HGFEDCBA (LSB) 1 = High

Field Name	Description	Data Length	Data Type	Notes
	• 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			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
EMU_BRAKE_PERCENT	Percentage of Total EMU Brake Force	1 byte	UINT	0-100
EMU_TRACTIVE_PERCENT	Percentage of Total EMU Tractive Effort	1 byte	UINT	0-100
SPARE	(not used)	3 bytes	Byte	Not used
END_BYTES	Bytes for Framing	2 bytes	30875 (0x789b)	Static

EMU_Brake_Percent

The EMU_Brake_Percent field specifies the current brake force being generated by the EMU consist as a percentage of the maximum brake force that can be generated by the EMU consist. This will be calculated by summing the brake force produced by each EMU/DMU in the consist and then dividing the total by the sum of the maximum brake force for each EMU/DMU unit. The resulting value will be multiplied by 100 to convert it to a percentage.

$$\text{EMU\_Brake\_Percent} = \frac{\sum Current\ EMU\ brake\ force}{\sum Maximum\ EMU\ brake\ force} x\ 100$$

EMU_Tractive_Percent

The EMU_Tractive_Percent field specifies the current tractive force being generated by the EMU consist as a percentage of the maximum tractive force that can be generated by the EMU consist. This will be calculated by summing the tractive effort produced by each EMU/DMU in the consist and then dividing the total by the sum of the maximum tractive effort for each EMU/DMU unit. The resulting value will be multiplied by 100 to convert it to a percentage.

$$\text{EMU\_Tractive\_Percent} = \frac{\sum Current\ EMU\ \text{tractive effort}}{\sum Maximum\ EMU\ tractive\ effort}\, x\ 100$$

The EMU_BRAKE_PERCENT field specifies the current brake force being generated by the EMU consist as a percentage of the maximum brake force that can be generated by the EMU consist.

The EMU_TRACTIVE_PERCENT field specifies the current tractive force being generated by the EMU consist as a percentage of the maximum tractive force that can be generated by the EMU consist.

4.3 EA Status Message Specification

Table B3 specifies the format for the EA status message. This message is sent by the EA software to the TCL (P-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 B3. 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
Warning Time	Enforcement Warning Time	1 byte	UINT8	0-255
Spare		3 bytes		
END_BYTES	Bytes for Framing	2 bytes	30875 (0x789b)	Static

Attachment A: Protocol Test Application

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

- Simulates TCL (P-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. Figures B1 and B2 illustrate the operation of the test application. The first shows the train data message screen and the second shows the initialization message screen.

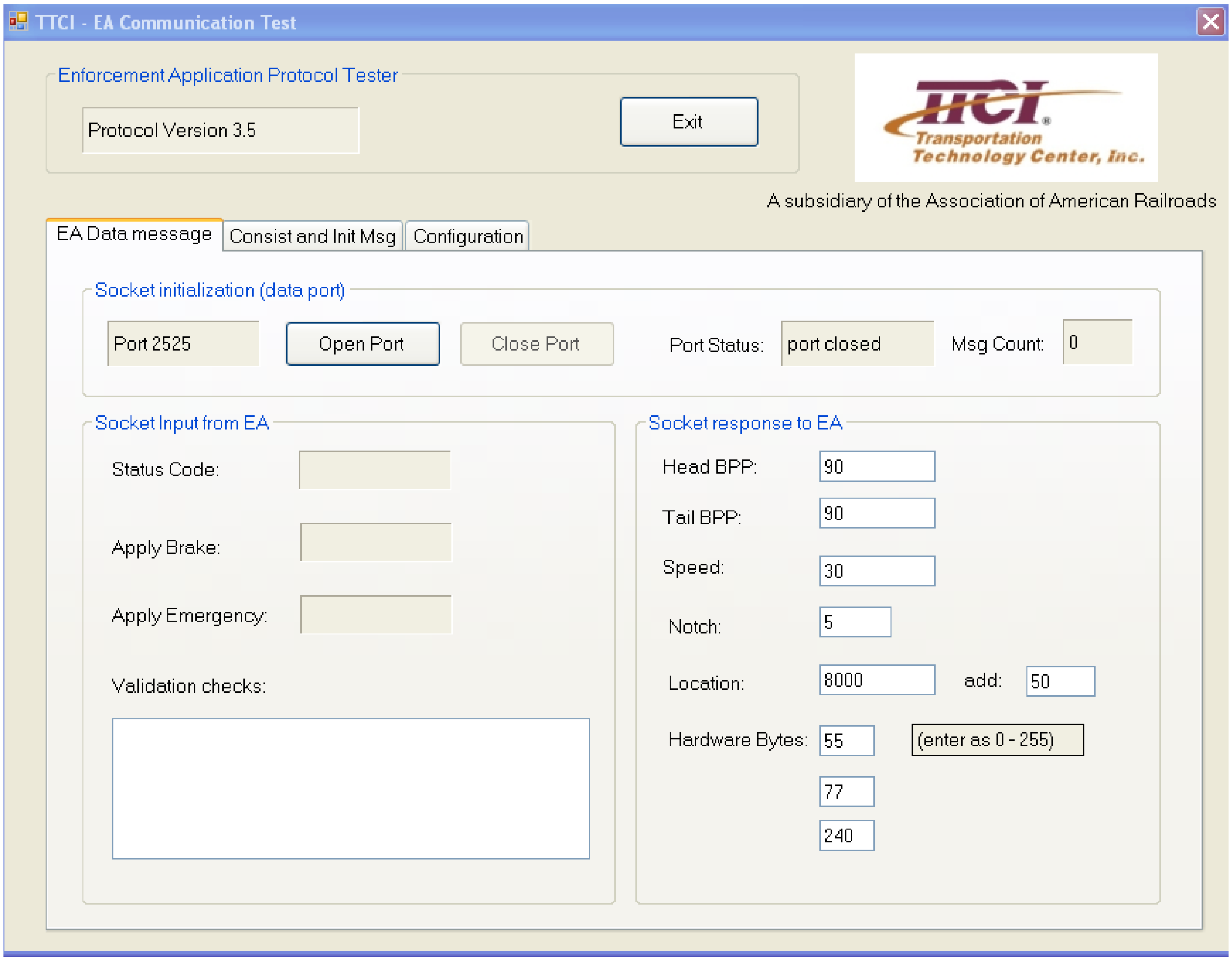
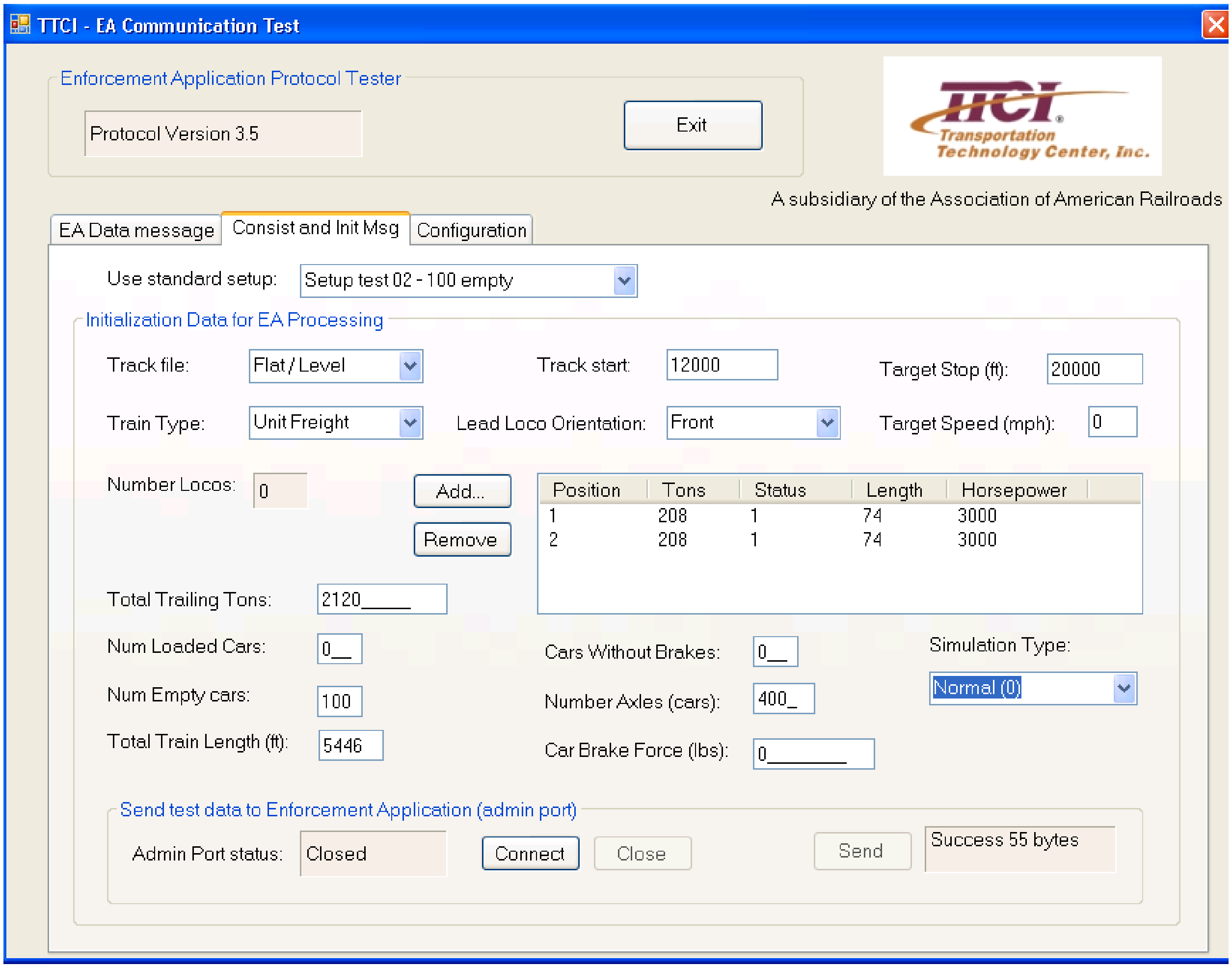


Figure B1. EA Protocol Test Application – Data Message Tab



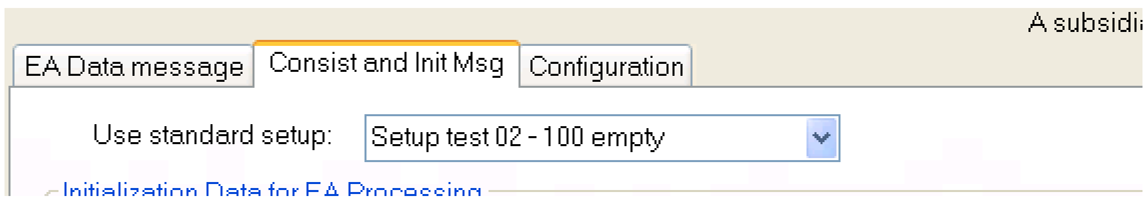
B2. EA Protocol Test Application – Initialization Message Tab

Attachment B: Installation and Setup Testing

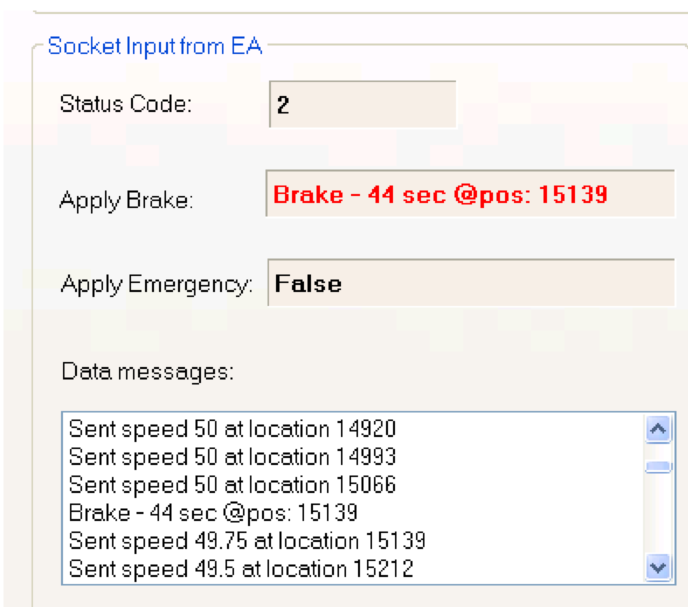
1. Introduction

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 simulation environment.
2. Using the protocol test app the input parameters are entered by selecting a setup test using the EA Comms test application. This causes the loading of parameters to the screen fields.



3. After starting the simulation test, the application sends the test date to the EA software, and the EA software should trigger a brake application to be displayed on the EA Data message tab.



4. The brake position should be recorded for each of the test scenarios in the test matrix.
5. After installation of the VM image or EA software at TTCI's test lab, the test matrix is executed to validate the installation process.
6. As a final step, a TCL (P-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 (PTBPM) variations and TCL's (P-TCL's) use of the cruise control feature to maintain train speed.

2. 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 TTCI's test environment.

Abbreviations and Acronyms

ACRONYM	EXPLANATION
AG	Advisory Group
DMU	Diesel Multiple Unit
ConOps	Concept of Operations
F_{CRV}	Curving Resistance
EMU	Electric Multiple Unit
EOT	End of Train
EA	Enforcement Algorithm
EA-Init	EA Initialization Module
EDA	Exploratory Data Analysis
FRA	Federal Railroad Administration
F_{GRD}	Grade Force
ICD	Interface Control Document
IP	Internet Protocol
I-ETMS™	Interoperable Electronic Train Management System
F_{LOC}	Locomotive Tractive Force
NJT	New Jersey Transit
NAJPTC	North American Joint Positive Train Control
N_{Car}	Number of Cars in Consist
N_{LOCO}	Number of Locomotives in Consist
OBC	Onboard Computer
P-TCL	Passenger Test Controller Logger
PTBPM	Passenger Train Braking Performance Model
PTC	Positive Train Control
psi	Pounds Per Square Inch
Q-Q	Quantile-Quantile
RTT	Railroad Test Track
RAM	Random Access Memory
F_{RES}	Resistive Forces
BR_{sc}	Specified Consist Brake Rate
BR_{scem}	Specified Consist Emergency Brake Rate

ACRONYM	EXPLANATION
TCL	Test Controller and Logger
TOES^{TM}	Train Operations and Energy Simulator
TCP	Transmission Control Protocol
TTC	Transportation Technology Center
TTCI	Transportation Technology Center, Inc.
TAM	Total Approach Management
VM	Virtual Machine
W_t	Weight of Train in Tons