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Office of Research,
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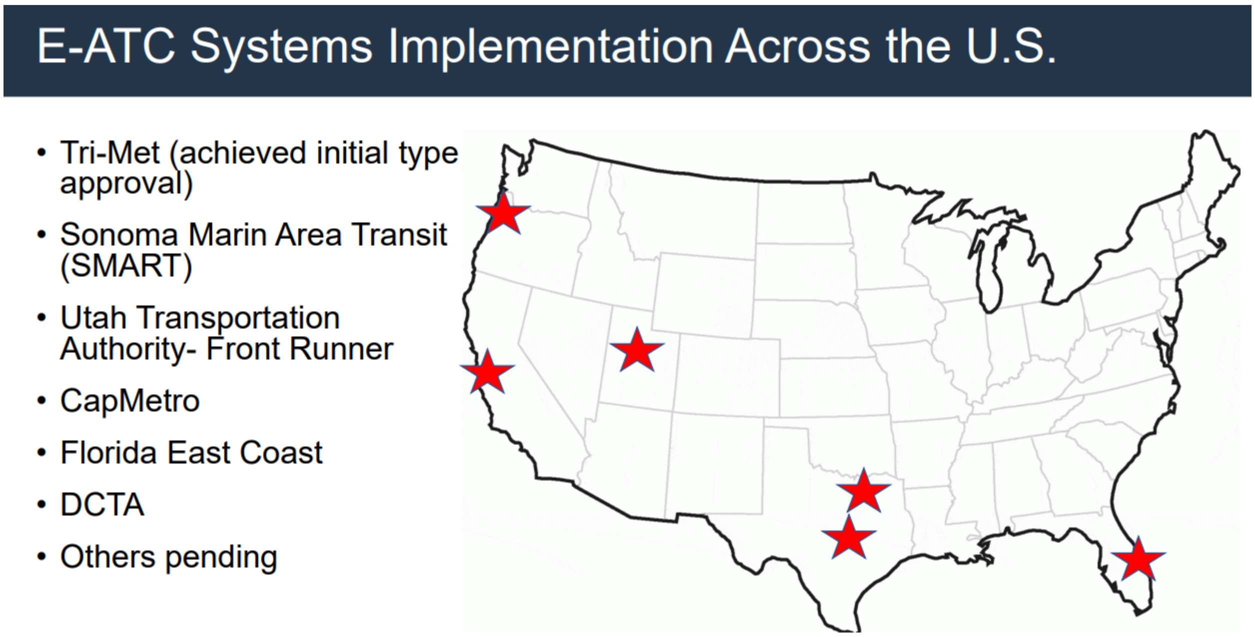
Washington, DC 20590

Enhanced Automatic Train Control Braking Algorithm Research and Development



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14. ABSTRACT
The primary objective of the project was the evaluation of the braking enforcement methodology used by the railroads that have implemented an E-ATC PTC system. The methodology developed under this project can be used by the industry to verify that the braking enforcement algorithms meet established safety and operational efficiency objectives. The methodology makes use of Monte Carlo simulation techniques to statistically evaluate the performance characteristics of the enforcement algorithm coupled with small samples of field testing that is used to validate the results achieved from the simulation modeling process.

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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

Inches	0		1			2			3		4			5
Centimeters	0	1	2	3	4	5	6	7	8	9	10	11	12	13

QUICK FAHRENHEIT - CELSIUS TEMPERATURE CONVERSIO

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

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

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Executive Summary

Under a research project sponsored by the Federal Railroad Administration (FRA), Transportation Technology Center, Inc. (TTCI), found that the braking enforcement methodology used by the Enhanced Automatic Train Control (E-ATC) Positive Train Control (PTC) system has at least a 99.99 percent probability of stopping a train short of a given target for the operations and equipment evaluated. Potential opportunities for improving the operational efficiency of the E-ATC braking enforcement methodology were also identified, including an increase in the "time-in-block" timers and modification of the braking curve used for determining the minimum block length, based on a regression analysis of simulated stop distance data. The E-ATC enforcement algorithm evaluation process developed by TTCI can be used in further research and development of methods for improving the safety and performance of the E-ATC braking enforcement methodology.

The primary objective of the project was to evaluate the braking enforcement methodology used by railroads that have implemented an E-ATC PTC system. The methodology developed under this project can be used by the industry to verify that the braking enforcement algorithms meet established safety and operational efficiency objectives. The Monte Carlo simulation process was adapted from similar evaluations of other freight and passenger PTC braking enforcement algorithms. The methodology makes use of Monte Carlo simulation techniques to statistically evaluate the performance characteristics of the enforcement algorithm coupled with small samples of field testing used to verify the results achieved from the simulation process.

To achieve the primary objective described above, researchers developed an E-ATC test application to replicate the functionality of the E-ATC systems implemented in the field. Along with the new E-ATC test application, TTCI utilized existing simulation tools to simulate braking performance of passenger and freight equipment used by the E-ATC railroads. In the E-ATC PTC braking algorithm simulation test methodology, the Passenger Train Braking Performance Model (PTBPM) and the Train Operation and Energy Simulator (TOES™) were used to perform PTC brake enforcement tests on a large scale for a broad range of operating scenarios. Each operating scenario was simulated multiple times, wherein parameters that affect the train stopping distance were varied according to distributions representing their actual, real-world variability in a Monte Carlo method. This allowed for evaluation of the full range of potential outcomes from a PTC penalty enforcement in each of the operating scenarios simulated, providing a complete statistical view of the safety and performance characteristics of the algorithm.

TTCI researchers collected field test data from four participating railroads, which was used to model the equipment used in the field tests within the PTBPM and TOES™ and verify that the performance of the models are representative of the equipment in the field.

1. Introduction

One of the objectives of Positive Train Control (PTC) is to improve the safety of railroad operations through the enforcement of certain operational limits, including authority and speed limits. In the Enhanced Automatic Train Control (E-ATC) PTC system, movement authority information is transmitted to a locomotive onboard computer from the wayside signaling system. The locomotive onboard computer also contains a braking enforcement algorithm, which predicts the stopping distance of the train and enforces limits by automatically initiating a penalty brake application to prevent a violation. Braking enforcement is conceived as the final opportunity to safely prevent a violation, stopping the train only when the locomotive crew has failed to take adequate action to do so. This project, sponsored by the Federal Railroad Administration (FRA) and performed by Transportation Technology Center, Inc. (TTCI), evaluated the safety and operational performance of the E-ATC braking enforcement algorithm, using a simulation methodology over a broad range of operating scenarios and equipment used by railroads deploying the E-ATC system.

1.1 Background

TTCI and FRA have worked together with the Class I freight railroads and commuter/passenger railroads in the U.S. to develop a methodology for analyzing PTC braking algorithm safety and performance characteristics. The methodology developed has been accepted by the industry and FRA and has been used to demonstrate that the braking algorithms used by PTC systems to stop trains short of a target violation do so within an acceptable safety margin.

The braking enforcement function of the system is critical in ensuring that trains comply with movement authorities and speed limits. There are several parameters that can affect the braking distance of a train and it is not practical, or even possible, to provide the onboard system with all the information required to predict the stopping distance with absolute certainty. Many of the necessary data elements are not provided to the onboard system, and there is a level of uncertainty in those that are. Thus, there can be a significant difference between the stopping distance predicted by the braking enforcement algorithm and the actual stopping distance of a given train. This can be described by a statistical distribution of potential stopping locations about the predicted stopping location, as Figure 1 illustrates.

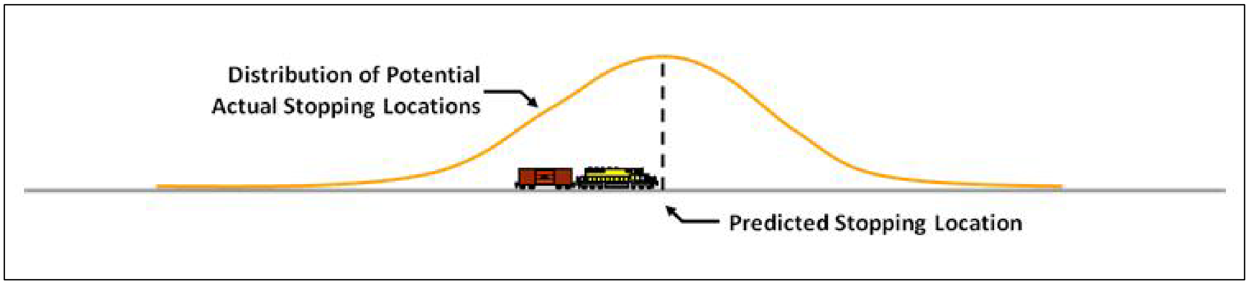

Figure 1. Illustration of potential difference between predicted and actual train stopping location

A previous research effort established a metric that can be used in evaluating the safety performance of PTC braking algorithms for freight trains; specifically, that the algorithm be demonstrated to stop the train short of the target stopping location with a 99.5 percent probability and 99 percent confidence level. [1] Additionally, a methodology for evaluating the performance of the PTC braking enforcement algorithms used in North American freight train operations was developed and implemented. Based on this research effort, a similar methodology was conceived and documented for evaluating the performance of the PTC braking enforcement algorithms used in passenger and commuter train operations and a Passenger Train Braking Performance Model (PTBPM) was developed to support the methodology.

Railroads implementing E-ATC can benefit from having its algorithm evaluated by the methodology previously developed by TTCI and FRA. This analysis can help demonstrate that the E-ATC braking algorithm will enforce authority limits to stop the train from violating such limits with a high probability under a wide range of operating conditions and can also be used to identify potential improvements to the algorithm.

1.2 Objectives

The specific objectives of this project were to:

- Develop a software test application that implements the E-ATC braking enforcement methodology.
- Integrate the E-ATC test application into current freight and passenger PTC braking algorithm simulation environments.
- Evaluate the E-ATC algorithm using the Monte Carlo simulation methodology used for other PTC braking enforcement algorithms.
- Identify potential future enhancements to the E-ATC braking algorithm that could improve safety and/or operational efficiency.

1.3 Overall Approach

TTCI worked with industry experts to gain an understanding of how E-ATC operates, the equipment used in E-ATC, the E-ATC braking algorithm logic, and the envelope of scenarios within which E-ATC operates. Using this knowledge and TTCI's expertise with train braking simulation models and PTC braking algorithm evaluation, TTCI developed a test application, implementing the E-ATC braking algorithm logic and integrating it into the simulation environment used to evaluate PTC braking algorithms. The E-ATC braking algorithm was evaluated by simulations, and safety and performance characteristics were estimated through analysis of the simulation results. TTCI also documented recommended potential enhancements/improvements and recommended simulation modifications to support potential future evaluation and improvements of E-ATC.

1.4 Scope

The scope of the simulations was limited to equipment and operational scenarios provided by the participating railroads and may not be representative of operations outside of these scenarios. The scope also included development of a software test application to simulate the E-ATC operations. This software test application was based on information provided by the participating railroads and reflects the functional information provided. The scope of the project included identification of potential opportunities for enhancement of the E-ATC braking algorithm but did not include any further development or simulation of these potential enhancements.

1.5 Organization of the Report

- Section 2 presents the approach used to simulate the E-ATC braking algorithm and describes the gathering of information from the Advisory Group.
- Section 3 introduces the E-ATC system braking enforcement methodology and describes the development of the E-ATC test application and integration into the simulation environment for use in the evaluation.
- Section 4 describes the process used to develop the modeling of the consists and vehicles used by the railroads that operate E-ATC.
- Section 5 defines the test matrices used for the simulations.
- Section 6 provides results for both the passenger and freight simulations.
- Section 7 documents the suggested improvements that could be examined further in future projects.
- Section 8 summarizes the findings of the project.

2. PTC Braking Enforcement Algorithm Evaluation Approach

Research efforts associated with PTC braking enforcement algorithms for freight operations have demonstrated a successful methodology for evaluating algorithm safety and performance for a broad range of operations. [2] The methodology, which uses computer modeling, has proven to be a cost-effective and safe technique for demonstrating the accuracy and reliability of the algorithms. The same methodology has been applied to algorithms for passenger and commuter rail operations.

The enforcement algorithm evaluation methodology combines computer simulation and field testing to provide a high level of statistical confidence in the result. The purpose of the simulation component of the methodology is to statistically quantify the safety and performance characteristics of the enforcement algorithm. This is achieved by running large batches of braking enforcement simulations with Monte Carlo variation of train and environmental characteristics that affect train stopping distance over a broad range of operational scenarios. Then, a limited amount of field testing is used to provide verification of the simulation results using actual hardware inputs to the enforcement algorithm.

This evaluation methodology provides the capability to evaluate the enforcement algorithm over a broad range of operating scenarios that could not be tested efficiently in the field.

2.1 Simulation Testing

The simulation testing component of the enforcement algorithm evaluation methodology makes use of computer software tools to run Monte Carlo simulations, which results in a set of output data that is analyzed to estimate the statistical probability and confidence that the algorithm will meet the specified safety and performance criteria. The Monte Carlo methodology involves running large numbers of simulations with inputs to the simulations randomly assigned based on the practical and physical distributions and limits that define the system.

2.1.1 Overview of the Simulation Testing Process

The simulation testing process evaluates the enforcement algorithm over the full range of operating scenarios that the system is expected to encounter. This methodology also takes into consideration the practical variability of the parameters that can have a significant effect on the stopping distance of the train. The simulations are organized into scenarios, each representing a potential operating scenario the system may encounter. Each scenario is defined by the nominal train consist, the nominal track profile, the initial speed and location of the train, and the target stopping position.

Multiple braking enforcement simulations are run for each scenario. The scenarios that make up the complete simulation matrix are intended to include the boundary operating conditions and represent the full range of conditions that can occur in the field. The simulation scenarios are organized into batches to make the simulation process more efficient.

For each individual simulation, the train is modeled approaching the target at the specified target speed and the enforcement algorithm initiates a penalty brake application to prevent a violation of the stop target. The response of the train is then simulated to determine the location of the train stop. The result of each simulation represents a single possible stopping location for the given scenario with the version of enforcement algorithm being tested. The results of the entire set of simulations for the scenario are then aggregated to define the distribution of possible stop locations. This data is analyzed to determine the safety and performance characteristics of the enforcement algorithm for the given scenario. These characteristics are then analyzed to quantify the overall safety and performance characteristics of each version of enforcement algorithm.

2.1.2 Identification and Quantification of Variable Parameters

There are several parameters that affect train stopping distance in a PTC enforcement scenario. Using the Monte Carlo method, these parameters are varied randomly according to expected real-world variability. To best represent revenue service conditions, the input distributions for these parameters were quantified based on a combination of research, a literature review, field measurements, and expert opinion.

Tables 1 and 2 show the list of all parameters varied in the simulations along with their distributions and minimum and maximum values for the passenger train simulations and freight train simulations, respectively. For parameters represented by a normal distribution, the minimum and maximum values describe the values that are ±3 standard deviations (3σ) from the mean value.

Table 1. Train and environmental parameters varied for Monte Carlo simulations – passenger trains

Parameter	Units	Distribution	Min.	Max.	Source
Atmospheric pressure	psi	Normal (Gaussian)	10.2	19.2	Historical NOAA* U.S. weather data
Ambient air temperature	°F	Normal (Gaussian)	21.7	86.5	Historical NOAA U.S. weather data
Brake pipe leakage rate	psi/min	Right normal (Gaussian)	0	5.35	Expert opinion
Error in reported track grade	percent	Uniform	-0.5%	0.5%	According to accuracy of grade data in track database
Position error	feet	Normal (Gaussian)	-10.8	10.8	V-PTC build 1A testing results
Speed error	mph	Normal (Gaussian)	-0.48	0.48	V-PTC build 1A testing results
Brake unit COF adjustment factor		Normal (Gaussian)	0.80	1.2	Expert opinion
Brake unit effectiveness ratio		Normal (Gaussian)	0.85	1.15	AAR standards
D.B. effort adjustment factor		Normal (Gaussian)	0.85	1.2	Expert opinion
Head-end brake pipe pressure error	psi	Uniform	-0.5	0.5	Variability as specified by accuracy of Dynisco Model PT311JA pressure transducer
Rear-end brake pipe pressure error	psi	Uniform	-0.5	0.5	Accuracy of ±3 psig per AAR Standard S-5701

**NOAA = National Oceanic and Atmospheric Administration*

Table 2. Train and environmental parameters varied for Monte Carlo simulations – freight trains

Parameter	Units	Distribution	Min	Max	Source
Ambient pressure	psi	Half normal	10.2	14.7	Historical NOAA* weather data for United States
Ambient air temperature	°F	Normal	21.7	86.5	Historical NOAA weather data for United States
Brake pipe pressure leakage	psi/min	Normal	0.01	5.00	Expert opinion and limited measured data
Brake unit coefficient of friction adjustment factor		Normal	-20.0	20.00	Expert opinion and data from AAR Reports R-469, "Brake Shoe Performance Evaluation" and R-565A, "Brake Shoe Performance Test II"
DP comms link outage	seconds	Half normal	0	8	Expert opinion and information provided by railroads
Reported head-of-train (HOT) pressure error	psi	Flat	-0.5	0.5	Variability as specified by accuracy of Dynisco Model PT311JA pressure transducer
Reported end-of-train (EOT) pressure error	psi	Flat	-3	3	Accuracy of ±3 psig per AAR Standard S-5701 [4]
Location error	feet	Normal	-10.8	10.8	V-PTC Build 1A testing results
Percent operable brakes	percent	Flat	99.72	99.72	Expert opinion and information provided by railroads
Error in reported speed	mph	Normal	-0.48	0.48	V-PTC Build 1A testing results
Error in reported track grade	percent	Flat	-0.05	0.05°	According to accuracy of grade data in track database

**NOAA = National Oceanic Atmospheric Administration*

2.1.3 Simulation Environment

The PTC braking enforcement evaluation methodology requires two simulation environments: one for simulating freight train operations and one for simulating passenger and commuter train operations. This section describes the two simulation environments.

Freight Simulation Environment

The simulation testing portion of the freight enforcement algorithm evaluation methodology requires three components, as Figure 2 illustrates:

1. **Train Operation and Energy Simulator (TOES^{TM}):** A longitudinal train dynamics model for freight trains. TOES includes a complete fluid dynamics model of the fright air brake system allowing for accurate modeling of a wide variety of air brake equipment, making it the ideal tool for performing braking enforcement algorithm testing.
2. **The Test Controller/Logger (TCL):** A software application that can generate the simulation inputs to the model from input provided by the user, run large batches of simulations using Monte Carlo simulation techniques, and log the required output.
3. **Enforcement algorithm under evaluation:** This is implemented as a standalone software application incorporating a common interface to the simulation test components to receive train status and command brake enforcement applications.

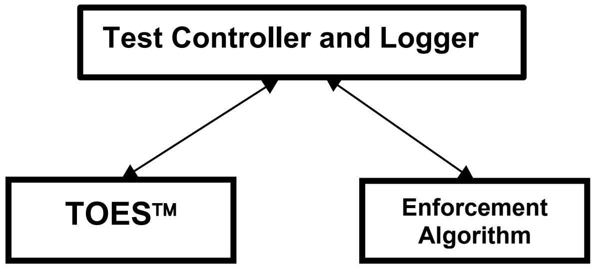

Figure 2. Freight simulation testing tools

Passenger Simulation Environment

As illustrated in Figure 3, the simulation testing portion of the passenger enforcement algorithm evaluation methodology requires the following three components:

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

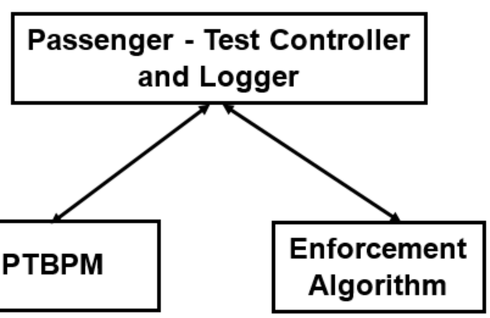

Figure 3. Passenger simulation testing tools

2.2 E-ATC Information to Support Simulation Analysis

To better understand the operation of the system and to collect the data needed for this analysis, TTCI contacted the railroads that use E-ATC. Through work with FRA and the American Public Transportation Association (APTA) E-ATC users group, several railroads were invited to participate in the project. An advisory group (AG) was formed consisting of representatives from most of the E-ATC railroads as well as Alstom, the supplier of the E-ATC system.

The railroads were provided questionnaires requesting the following information that was required to develop and execute the evaluation of the E-ATC braking enforcement methodology:

- Vehicle specific data, to understand the vehicles used in E-ATC operations:
  - Brake system specifications
  - General vehicle data
- Operational data, to understand the breadth of E-ATC enforcement scenarios:
  - Consist configurations
  - Control line diagrams, which provide information specific to the E-ATC implementation at specific locations.
- Field test data
- E-ATC implementation information

Alstom provided a general introduction of the functionality of the E-ATC system. TTCI worked with the railroads to gather the specific information needed to implement the E-ATC braking methodology within the existing software environment. Control line diagrams were used to develop the simulation matrix for project. The information gathered from the control line diagrams included track alignment, block length, and time-in-block delays, which are described further in Section 3.

3. Development and Integration of an E-ATC Braking Algorithm Test Application

To evaluate the safety and performance characteristics of the E-ATC braking algorithm within the existing simulation environment, it was necessary to use a standalone software application that implements the braking enforcement methodology of the system and interfaces the simulation environment. Because such a standalone application was not available for the E-ATC system, TTCI worked with Alstom and the E-ATC railroads to implement a software test application that emulates the E-ATC braking enforcement methodology for use in the evaluation. This section provides a high-level overview of how the E-ATC system functions to enforce targets, the test application logic that TTCI implemented to support the project, and how the test application was integrated into the existing simulation environment.

3.1 Overview of E-ATC Braking Enforcement Methodology

E-ATC combines both onboard and wayside components to enforce movement authorities provided to the train. The wayside component provides information to the train through coded signals in the track which are picked up by cab signal pickups on the locomotive. The onboard component uses the information provided by the wayside component to determine the target stopping location, calculates whether the train is predicted to stop short of that location and, if not, triggers a penalty brake application. Figure 4 provides an overview of the E-ATC braking enforcement methodology.

The wayside component determines when a train has entered a block with a status that indicates the train is required to stop before reaching the end of the block. The wayside equipment associated with each block is configured with a static timer for each train type (passenger or freight), based on the worst-case stopping distance for that train type, the track configuration, and the block size. The timer is triggered when the train enters the block, which allows the train to move a certain distance into the block prior to beginning the onboard predictive braking calculation. When the timer expires, the wayside system changes the signal code, which is picked up by the locomotive and triggers the onboard system to begin the onboard predictive braking calculation.

Upon receiving the appropriate code, the onboard component determines the minimum block length (MBL) based on the train type and maximum authorized speed (MAS), which is used to determine the target stopping location for the train. At this time, the onboard component also begins the predictive braking distance calculation based on the train type and actual speed of the train. When the system determines that the calculated braking distance will exceed the target, a penalty brake application is initiated.

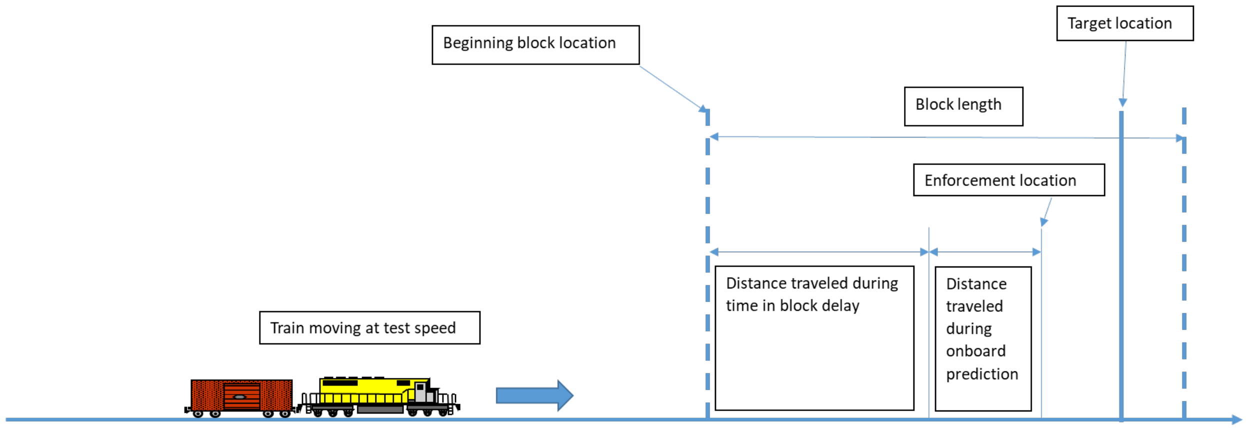

Figure 4. E-ATC enforcement methodology

3.2 Development of E-ATC Braking Enforcement Test Application and Integration with Simulation Environment

TTCI worked with Alstom and the railroads on the AG to determine how the E-ATC system functions so that a test application could be developed that mimics the functionality of the system in a way that could be integrated into the existing PTC braking algorithm evaluation simulation environment.

As described in Section 2.1, the existing simulation methodology simulates the train approaching the target stop location, sending train status data (e.g., location, speed) to the PTC braking enforcement algorithm at periodic intervals and applying a penalty brake application after receiving a command from the PTC braking enforcement algorithm application. The existing simulation environment does not model the block signaling system, which is an integral component of the E-ATC system. As described in Section 3.1, the E-ATC system does not receive train location data directly; rather, it calculates the target location and the distance to the target based on when the cab signal code changes.

As a result, to simulate the E-ATC braking enforcement methodology while minimizing changes to the existing simulation environment, the test application that was developed combines the wayside and onboard functionality of the E-ATC system. The test application was developed such that the information from the simulation environment can be utilized in the same way that the E-ATC system would gather and use this information in the actual implementation.

As part of the simulation environment set up for each scenario, a number of parameters were established that are used by the E-ATC test application:

- Location of beginning of enforcement block
- MAS for enforcement block
- Time-in-block timer duration

This information was static for each simulation and was used by the E-ATC test application during the simulation.

Figure 5 shows the logic implemented by TTCI for the E-ATC braking enforcement algorithm test application. The "Main Process" described in the flowchart describes the logic that is executed every simulation second.

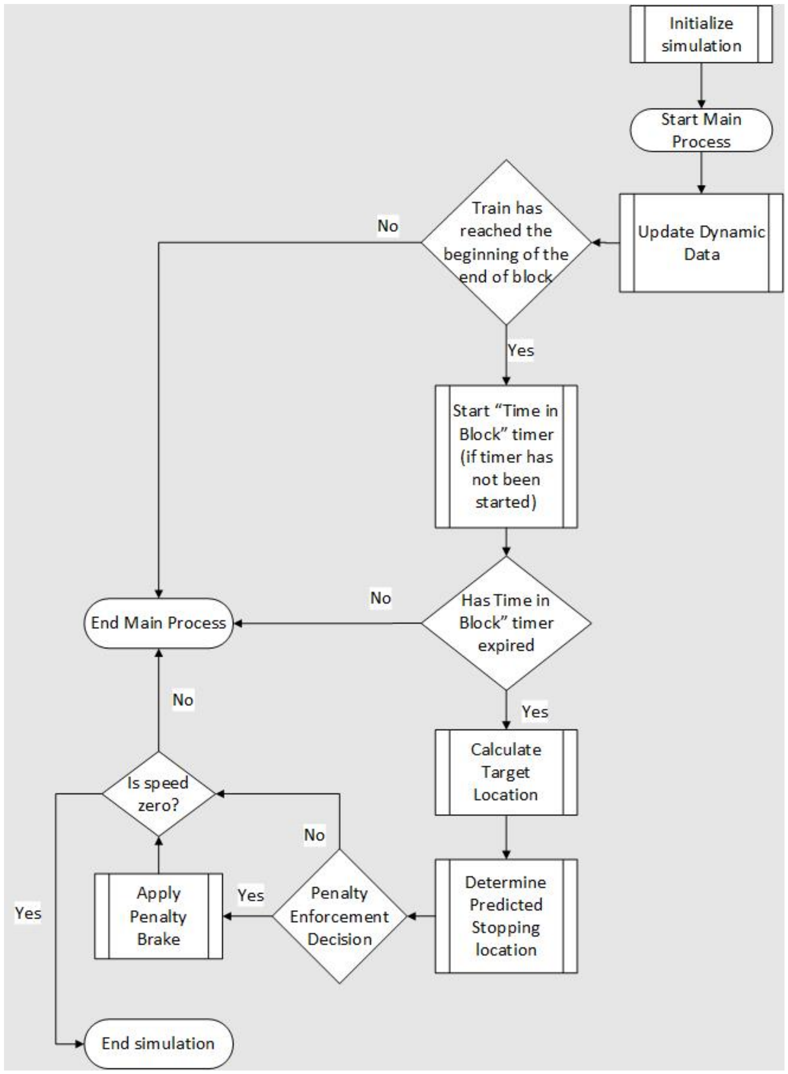

Figure 5. E-ATC test application logic flow

During the "Update Dynamic Data" process, data on train location and train speed is provided to the E-ATC test application. When the E-ATC test application determines that the location of the train has passed the beginning of the block, the time-in-block timer begins to count down, which mirrors the wayside timer in the E-ATC system. When this timer expires, the E-ATC test application calculates the MBL based on the MAS for the train in the block, in the same way the onboard calculation is performed at the time the cab signal code changes, following the expiration of the wayside timer. The E-ATC test application then determines the predicted stopping distance based on the current speed of the train, as the E-ATC onboard system does. Finally, the E-ATC test application performs a calculation to determine if the penalty brake should be applied, using the same equation that is used by the E-ATC onboard system. This Main Process is repeated using the updated data from the simulation environment until the train is stopped and the simulation ends.

Only minor changes were required to the simulation environment to support the braking enforcement evaluation using the E-ATC test application. Database changes were made to both the freight and passenger simulation environments to include tables specifying the initialization information needed by the E-ATC test application. These tables include values for parameters such as the enforcement block location, MAS for the enforcement block, and time-in-block timer duration for each simulation scenario.

Additionally, minor changes to the interface between TCL and the enforcement algorithm and the interface between P-TCL and the enforcement algorithm were required to support the E-ATC test application. These changes were required to send information from the train that is specific to the E-ATC test application.

4. Vehicle and Consist Model Development and Verification

Before the Monte Carlo simulation process was executed, the passenger equipment models developed as part of this effort were verified for accuracy. This was done by simulating field tests using PTBPM and comparing the results with field test data. A number of passenger equipment models and freight equipment models were used in the effort as well, but these were previously verified during prior PTC braking algorithm modeling efforts.

4.1 Vehicle and Consist Model Development

Three passenger vehicles needed to be modeled in PTBPM. The vehicles shown below were created using characterization data provided by the participating railroads:

- Stadler GTW DMU.
- Siemens passenger coach.
- SC44 charger locomotive

4.2 Summary of Verification Methodology

Field test data was provided by the AG for the equipment that needed to be modeled. Using this data, the field tests were simulated in PTBPM and the results of the simulations compared against the results from the field test data. Comparisons between the simulations and field testing were intended to verify that PTBPM accurately simulates the performance of the vehicles modeled. Information on the tracks was compiled from track charts or other track information provided by the testing railroad and models were created in PTBPM that included the grade and milepost information. Consists also were modeled based on information provided by the railroad. Parameters such as brake rate, brake pipe length, types and locations of brake shoes and pads, powered vehicle types, dimensions, and weight were used to help accurately create the vehicle models.

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

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

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

4.3 Verification Results

Tables 3 through 6 show the verification results for the field test simulations. The simulation name, load condition, brake application type, speed, and approximate grade describe the configuration of the test. The stop distance from the field test and simulation result are shown, as well as the difference between the PTBPM and field test stopping distances along with a percent difference. Finally, an average percent difference is presented, which is the average percent difference of all individual tests for a specific test scenario.

Table 3. Railroad 1 field test verification results

Simulation Name	Load Condition	Brake Application	Brake Type	Speed (mph)	Grade Description	Field Test Stop Dist. (ft)	PTBPM Stop Dist. (ft)	Difference (ft)	% Dif.	Average % Diff
7	AW0	Emergency Brake	Pnuematic Only	59.03026324	Grade Adjusted	558.40	594.49	36.09	6.46%	2.97%
8	AW0	Emergency Brake	Pnuematic Only	59.03026324	Grade Adjusted	588.58	594.49	5.91	1.00%	
9	AW0	Emergency Brake	Pnuematic Only	59.03026324	Grade Adjusted	585.96	594.49	8.53	1.46%	
10	AW3	Emergency Brake	Pnuematic Only	59.03026324	Grade Adjusted	607.94	621.23	13.29	2.19%	2.63%
11	AW3	Emergency Brake	Pnuematic Only	59.03026324	Grade Adjusted	604.66	621.23	16.57	2.74%	
12	AW3	Emergency Brake	Pnuematic Only	59.03026324	Grade Adjusted	603.35	621.23	17.88	2.96%	
13	AW0	Service Brake	Pnuematic Only	59.03026324	Grade Adjusted	684.06	671.52	-12.54	-1.83%	-1.28%
14	AW0	Service Brake	Pnuematic Only	59.03026324	Grade Adjusted	681.76	671.52	-10.24	-1.50%	
15	AW0	Service Brake	Pnuematic Only	59.03026324	Grade Adjusted	674.87	671.52	-3.35	-0.50%	
16	AW3	Service Brake	Pnuematic Only	59.03026324	Grade Adjusted	674.54	709.47	34.93	5.18%	4.45%
17	AW3	Service Brake	Pnuematic Only	59.03026324	Grade Adjusted	680.12	709.47	29.35	4.32%	
18	AW3	Service Brake	Pnuematic Only	59.03026324	Grade Adjusted	683.07	709.47	26.40	3.86%	

Table 4. Railroad 2 field test verification results

Simulation Name	Load Condition	Brake Application	Brake Type	Speed (mph)	Grade Description	Field Test Stop Dist. (ft)	PTBPM Stop Dist. (ft)	Difference (ft)	% Dif.	Average % Diff
80	AW2	Emergency Brake	Pnuematic Only	20	<0.3%	221	205.8	-15.2	-6.90%	-2.98%
82	AW2	Emergency Brake	Pnuematic Only	20	<0.3%	187	205.8	18.8	10.03%	
87	AW2	Emergency Brake	Pnuematic Only	30	<0.3%	360	378.0	18.0	5.00%	
99	AW2	Emergency Brake	Pnuematic Only	30	<0.3%	392	378.0	-14.0	-3.57%	
89	AW2	Emergency Brake	Pnuematic Only	45	<0.3%	754	748.8	-5.2	-0.69%	
102	AW2	Emergency Brake	Pnuematic Only	45	<0.3%	769	748.8	-20.2	-2.63%	
97	AW2	Emergency Brake	Pnuematic Only	60	<0.3%	1241	1124.8	-116.2	-9.36%	
278	AW2	Emergency Brake	Pnuematic Only	60	<0.3%	1149	1124.8	-24.2	-2.10%	
230	AW2	Emergency Brake	Pnuematic Only	70	<0.3%	1648	1491.4	-156.6	-9.50%	
279	AW2	Emergency Brake	Pnuematic Only	70	<0.3%	1524	1491.4	-32.6	-2.14%	
247	AW2	Emergency Brake	Pnuematic Only	79	<0.3%	1926	1860.5	-65.5	-3.40%	
248	AW2	Emergency Brake	Pnuematic Only	79	<0.3%	1970	1860.5	-109.5	-5.56%	
249	AW2	Emergency Brake	Pnuematic Only	79	<0.3%	1950	1860.5	-89.5	-4.59%	
250	AW2	Emergency Brake	Pnuematic Only	79	<0.3%	1986	1860.5	-125.5	-6.32%	
81	AW2	Full Service Brake	Pnuematic Only	20	<0.3%	279	272.0	-7.0	-2.50%	-0.19%
83	AW2	Full Service Brake	Pnuematic Only	20	<0.3%	265	272.0	7.0	2.65%	
84	AW2	Full Service Brake	Pnuematic Only	30	<0.3%	566	536.3	-29.7	-5.25%	
98	AW2	Full Service Brake	Pnuematic Only	30	<0.3%	553	536.3	-16.7	-3.02%	
88	AW2	Full Service Brake	Pnuematic Only	45	<0.3%	997	961.9	-35.1	-3.52%	
100	AW2	Full Service Brake	Pnuematic Only	45	<0.3%	1046	961.9	-84.1	-8.04%	
96	AW2	Full Service Brake	Pnuematic Only	60	<0.3%	1625	1618.8	-6.2	-0.38%	
103	AW2	Full Service Brake	Pnuematic Only	60	<0.3%	1671	1618.8	-52.2	-3.12%	
225	AW2	Full Service Brake	Pnuematic Only	70	<0.3%	2137	2140.6	3.6	0.17%	
226	AW2	Full Service Brake	Pnuematic Only	70	<0.3%	2212	2140.6	-71.4	-3.23%	
233	AW2	Full Service Brake	Pnuematic Only	79	<0.3%	2709	2663.5	-45.5	-1.68%	
235	AW2	Full Service Brake	Pnuematic Only	79	<0.3%	2550	2663.5	113.5	4.45%	
243	AW2	Full Service Brake	Pnuematic Only	79	<0.3%	2701	2663.5	-37.5	-1.39%	
245	AW2	Full Service Brake	Pnuematic Only	79	<0.3%	2579	2663.5	84.5	3.28%	
273	AW2	Full Service Brake	Pnuematic Only	79	<0.3%	2627	2663.5	36.5	1.39%	
274	AW2	Full Service Brake	Pnuematic Only	79	<0.3%	2542	2663.5	121.5	4.78%	
275	AW2	Full Service Brake	Pnuematic Only	79	<0.3%	2637	2663.5	26.5	1.00%	
276	AW2	Full Service Brake	Pnuematic Only	79	<0.3%	2435	2663.5	228.5	9.38%	
277	AW2	Full Service Brake	Pnuematic Only	79	<0.3%	2626	2663.5	37.5	1.43%	

Table 5. Railroad 3 field test verification results

Simulation Name	Load Condition	Brake Application	Brake Type	Speed (mph)	Grade Description	Field Test Stop Dist. (ft)	PTBPM Stop Dist. (ft)	Difference (ft)	% Dif.	Average % Diff
1	AW0	Maximum brake	Pnuematic Only	59.03	Grade Adjusted	620.08	661.88	41.81	6.74%	4.55%
2	AW0	Maximum brake	Pnuematic Only	59.03	Grade Adjusted	636.48	661.88	25.40	3.99%	
3	AW0	Maximum brake	Pnuematic Only	59.03	Grade Adjusted	643.04	661.88	18.84	2.93%	

Table 6. Railroad 4 field test verification results

Simulation Name	Load Condition	Brake Application	Brake Type	Speed (mph)	Grade Description	Field Test Stop Dist. (ft)	PTBPM Stop Dist. (ft)	Difference (ft)	% Dif.	Average % Diff
FSB1	Close to AW0	Full Service Brake	Dynamic	15.4	Level	122.9	132.6	9.7	7.87%	3.02%
FSB2				15.9		133.5	139.8	6.3	4.68%	
FSB3				20.2		193.0	209.3	16.3	8.43%	
FSB4				20.0		193.1	205.8	12.7	6.57%	
FSB5				30.1		382.8	419.8	37.0	9.67%	
FSB6				29.8		376.0	412.4	36.4	9.68%	
FSB7				40.1		679.6	696.7	17.1	2.52%	
FSB8				39.7		637.4	684.5	47.0	7.38%	
FSB9				44.7		862.8	845.6	-17.2	-2.00%	
FSB10				44.9		811.2	852.3	41.1	5.07%	
FSB11				60.3		1503.1	1452.1	-50.9	-3.39%	
FSB12				59.9		1452.3	1434.5	-17.8	-1.22%	
FSB13				79.5		2622.0	2416.6	-205.4	-7.83%	
FSB14				77.5		2428.6	2305.1	-123.5	-5.08%	
EB1		Emergency	Pneumatic	15.0		97.5	87.4	-10.1	-10.37%	-2.86%
EB2				14.6		90.3	83.3	-7.0	-7.80%	
EB3				21.1		173.6	163.2	-10.4	-5.98%	
EB4				20.8		166.7	159.0	-7.8	-4.65%	
EB5				30.0		311.9	317.5	5.7	1.82%	
EB6				31.5		345.8	348.7	2.8	0.82%	
EB7				40.9		552.9	577.0	24.0	4.35%	
EB8				40.3		550.1	560.7	10.6	1.93%	
EB9				45.0		671.2	694.2	23.0	3.42%	
EB10				45.3		721.0	703.2	-17.8	-2.47%	
EB11				59.3		1178.8	1183.5	4.8	0.40%	
EB12				60.4		1319.0	1226.2	-92.8	-7.04%	
EB13				78.7		2151.8	2035.1	-116.6	-5.42%	
EB14				77.7		2185.5	1986.3	-199.2	-9.12%	

Most of the simulations met the goal of having the stopping distance within ± 5 percent of the overall stopping distance, but some resulted in a percent difference greater than ±5 percent. However, the average percent difference for each scenario modeled was less than ±5 percent. From these results, it was determined that the models were representative of the actual performance of the vehicles for the purposes of braking algorithm evaluation.

5. Development of the Simulation Matrix

After gathering information from various agencies, a simulation matrix was developed to document the scenarios needed to fully evaluate the E-ATC braking algorithm. Block lengths can be set by each agency, so track charts and control line diagrams were used to compile average block lengths used for the simulations.

5.1 Freight Simulation Matrix

The freight consists provided by the E-ATC railroads were mixed freight type trains and were consistent with those used in interchange service. Therefore, the mixed freight consists built for previous freight braking simulation efforts were determined to be valid to use in the simulation matrix for the E-ATC braking algorithm evaluation.

5.1.1 Freight Consists

Table 7 shows the freight consist makeups included in the simulation matrix.

Table 7. Freight consist description – consist makeup

Consist Name	Length (ft.)	No. of Locos	No. of Loaded Cars	No. of Empty Cars	Power	Trailing Tonnage
M000AHE	74	1	0	0	N/A	0
M000BHE	222	3	0	0	N/A	0
M003CHE	243	1	3	0	Head End	384
M003EHE	275	1	3	0	Head End	381
M003GHE	203	1	3	0	Head End	360
M003IHE	203	1	0	3	Head End	136
M010CHE	798	2	2	8	Head End	560
M010EHE	720	2	9	1	Head End	1,072
M010GHE	735	2	5	5	Head End	686
M010IHE	795	2	10	0	Head End	1,379
M040CHE	2,482	3	25	15	Head End	3,741
M040EHE	2,523	3	34	6	Head End	4,090
M040GHE	2,461	2	12	28	Head End	2,505
M040IHE	2,849	2	7	33	Head End	2,174
M100CDE	6,638	5	45	55	DP - H/E	6,810
M100CHE	6,638	5	45	55	Head End	6,810
M100EDE	5,845	5	53	47	DP - H/E	8,382
M100EHE	5,845	5	53	47	Head End	8,382
M100GDE	6,680	5	56	44	DP - H/E	8,918
M100GHE	6,680	5	56	44	Head End	8,918
M100IDE	5,894	6	72	28	DP - H/E	10,007
M100IHE	5,894	6	72	28	Head End	10,007

5.1.2 Freight Block Lengths

Control line diagram information was used to create a list showing the actual block lengths, grades, speeds, and delay timers associated with each block. Control line diagrams are similar to track charts, but they contain more information, such as block lengths and any timers associated with either passenger or freight traffic in the block. Each agency has its own control line diagram associated with its track and is able to set the block lengths and delays based on the MBL equation and the physical makeup of the track.

From this data, the speeds and grades used in the simulations were selected. Simulations were run at the maximum authorized speed (MAS) and half of the MAS to show the effect that speed would have on the stopping location.

Based on this information, it was determined that the simulation matrix would be run over the grade and speed combinations shown in Figure 6.

Freight Simulation Matrix

Speed (mph)	-1	-0.9	-0.8	-0.8	-0.1	-0.5	-0.4	-0.3	-0.3	-0.1	0	0.1	0.25	0.3	0.4	0.5	0.6	0.75	0.9	1
40									x		x					x				
30	x					x					x							x		
20	x			x							x		x			x		x		x
10						x					x									
0																				

Track Grade (percentage)

Figure 6. Freight simulation matrix speed and grade

5.2 Passenger Simulation Matrix

A passenger simulation matrix was developed to include both the typical operations of each agency that provided information and the "extreme" cases.

5.2.1 Passenger Consists

Table 8 lists the consists used for the passenger simulations.

Table 8. Passenger consist description

Passenger Consist Makeup			
DMU (1)			
DMUs (3)			
Locomotives (2)	Coach cars (4)		
Locomotive (1)	Comet car (1)	Bi-level Bombardier coach cars (2)	Bi-level Bombardier cab car (1)
Locomotive (1)	Bi-level Bombardier coach cars (3)		

5.2.2 Passenger Block Lengths

Similar to the method used for freight, control line diagram information was used to create a list showing the actual block lengths, grades, speeds, and delay timers associated with each block.

From this data, the speeds and grades used in the simulations were selected. Included in the simulation matrix was the running of consists at half the maximum authorized speed to show the effect that speed would have on the stopping location. Based on this information, it was determined that the simulation matrix would be run over the grade and speed combinations shown in Figure 7.

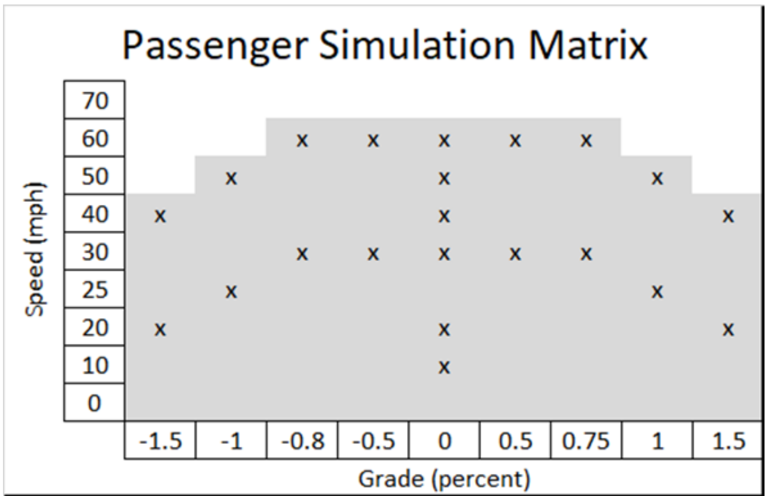

Figure 7. Passenger simulation matrix grade and speed combinations

6. Evaluation of Simulation Results

Following execution of the simulations described in Section 5, a thorough exploratory data analysis, or EDA, was performed. EDA is a method of using visual mediums (e.g., scatterplots, quantile-quantile, or QQ, 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 an EDA is to ensure that the dataset is complete and that there are no anomalies caused by errors in processing of the simulation that would therefore reflect an unrealistic result of the braking enforcement algorithm simulations.

Among others, the following measures of performance were analyzed:

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

Results were generated once the EDA was completed. The overall results of the simulation testing are represented by the following 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.

Further analysis of simulations that resulted in an overrun or undershoot was also conducted. The results for each set of simulations (freight and passenger) are presented in detail in the following subsections.

6.1 Freight Results

6.1.1 Exploratory Data Analysis

The initial data analysis removes any duplicated runs, simulations that enforce within 10 seconds of the start of the simulation, simulations with errors, and simulations where the speed is greater than 20 mph above the desired speed, verifying that there is enough data to perform the analysis. Figure 8 shows a QQ plot showing the difference between the initial speed and the penalty application speed for each simulation. This plot can identify issues with the TCL cruise control functionality, which is intended to maintain a consistent speed prior to the PTC enforcement. Overall, the model's cruise control performed acceptably, as no simulations were greater than ±3 mph of the target simulation speed.

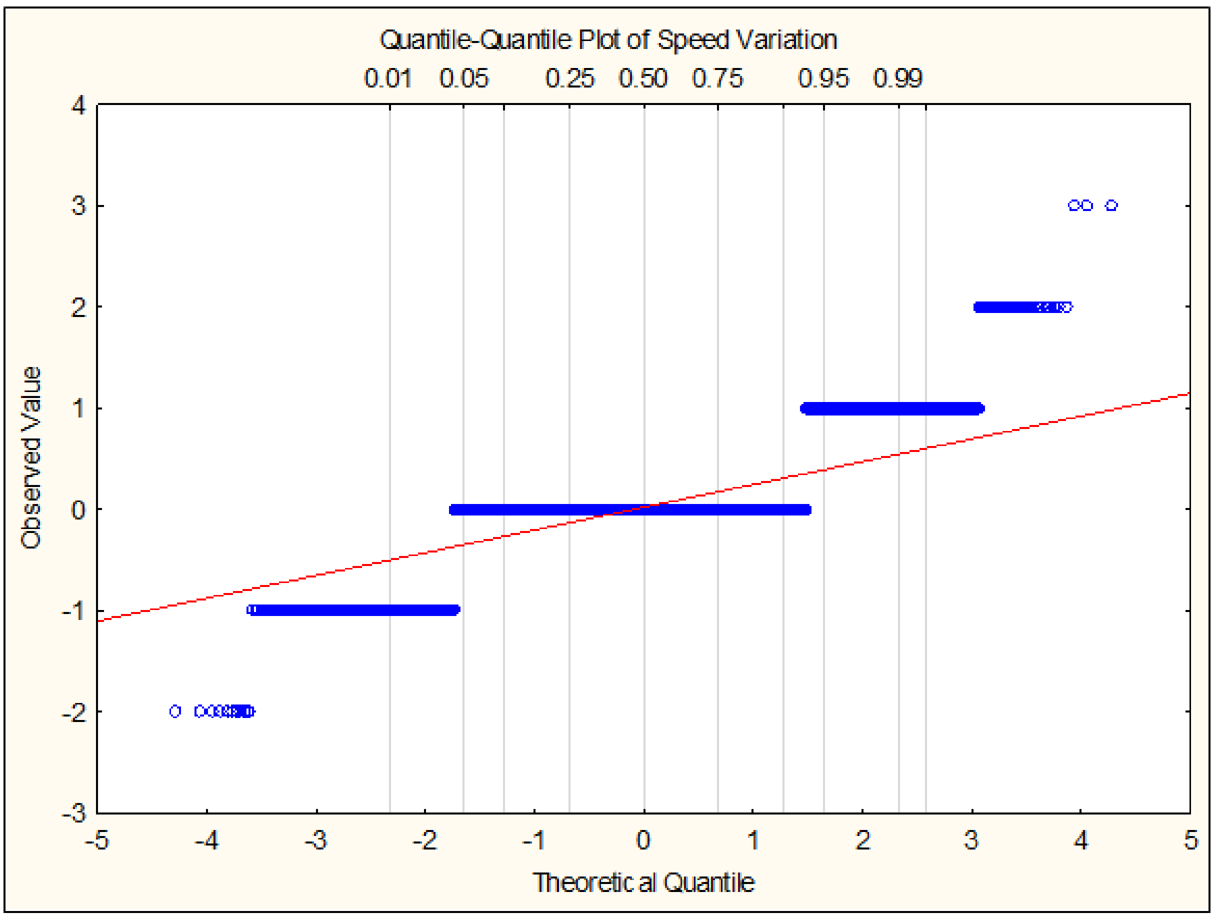

Figure 8. QQ plot of freight speed variation from initial speed to speed at enforcement

Figure 9 shows the overall spread of data in a scatter plot of stopping location relative to target versus penalty application speed difference. Positive values indicate the consist stopped before the target.

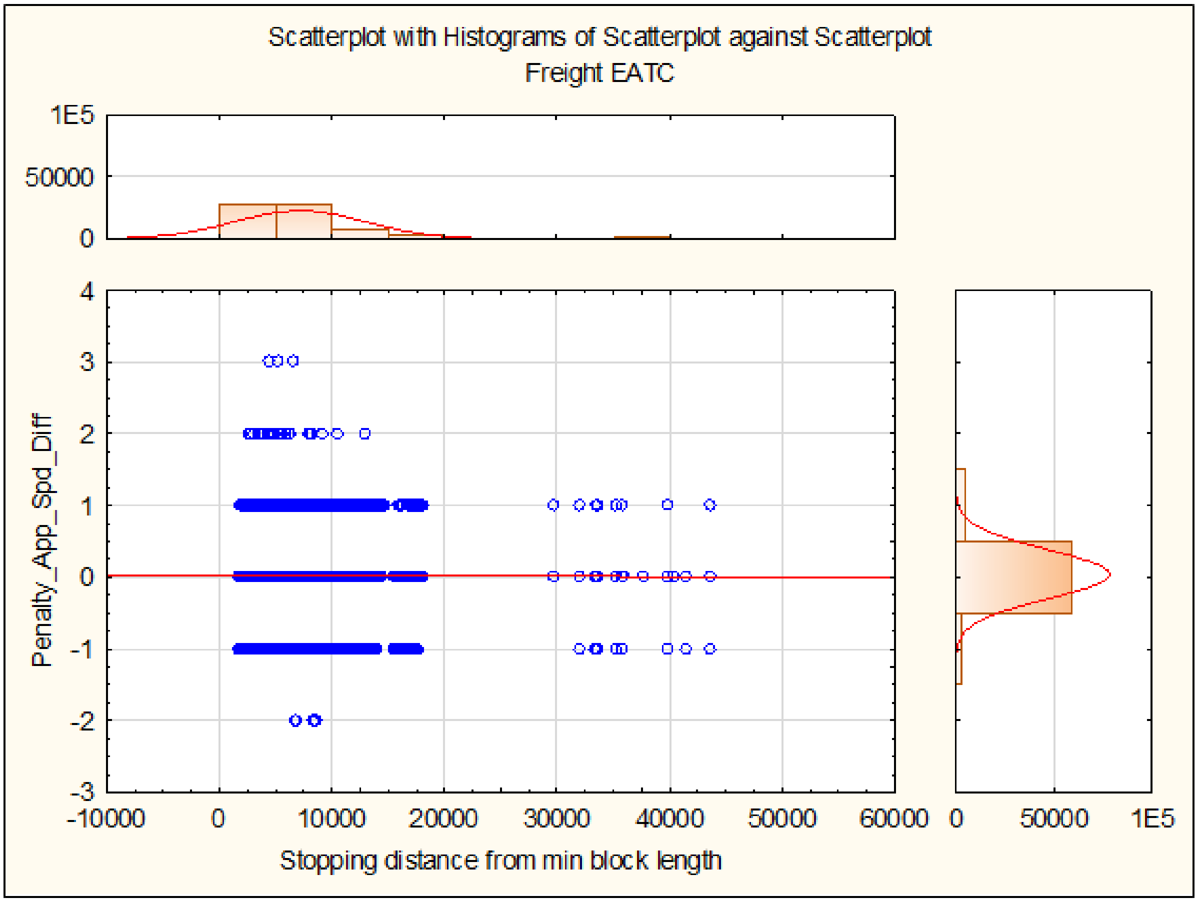

Figure 9. Scatterplot of stopping distance from the MBL versus penalty application speed difference for freight consists

6.1.2 Overall Results Summary for Freight Simulations

Table 9 shows the overall results of the freight simulations 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 9. Overall enforcement algorithm freight simulation test results

Train Type	Speed	Probability of Stopping Short of Target	Probability of Stopping Short of Performance Limit
Freight	< 30 mph	99.99%	99.99%
	>= 30 mph	99.99%	99.99%

The data for E-ATC freight simulations showed all consists stopped before the end of block, as shown in Figures 10 and 11. Several speed and grade combinations had more than one block length associated with them in the control line diagrams. Comparing the stopping distance to both the shortest and longest block length values shows the range of distances where a train could stop from the end of the block. The closest distance to the end of the block was 1,764 feet (considering the simulation that was closest to the target and the shortest block length), while the furthest distance to the end of the block was over 28,884 feet (considering the simulation that was furthest from the target and the longest block length).

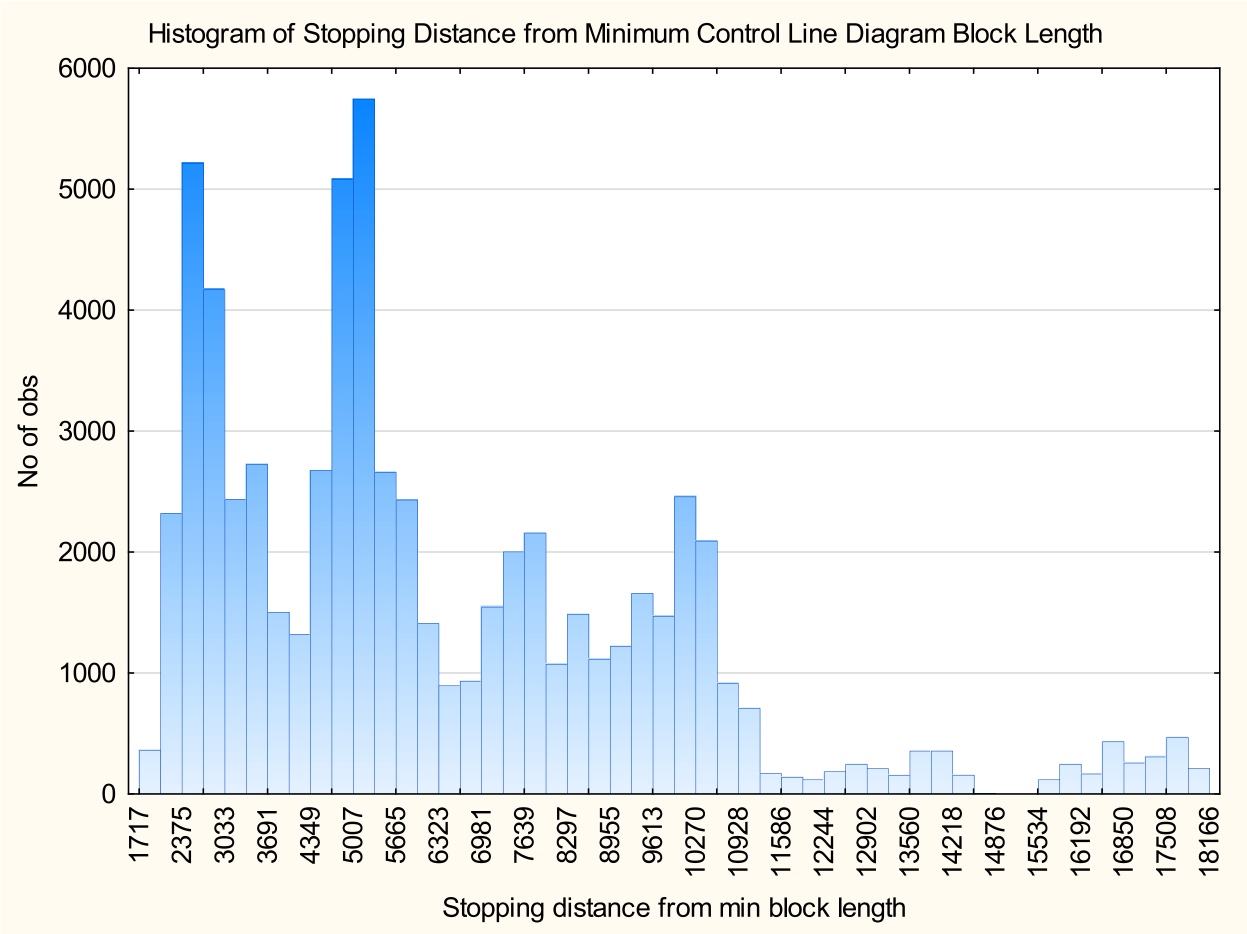

Figure 10. Histogram of freight stopping location relative to end of block considering shortest block length

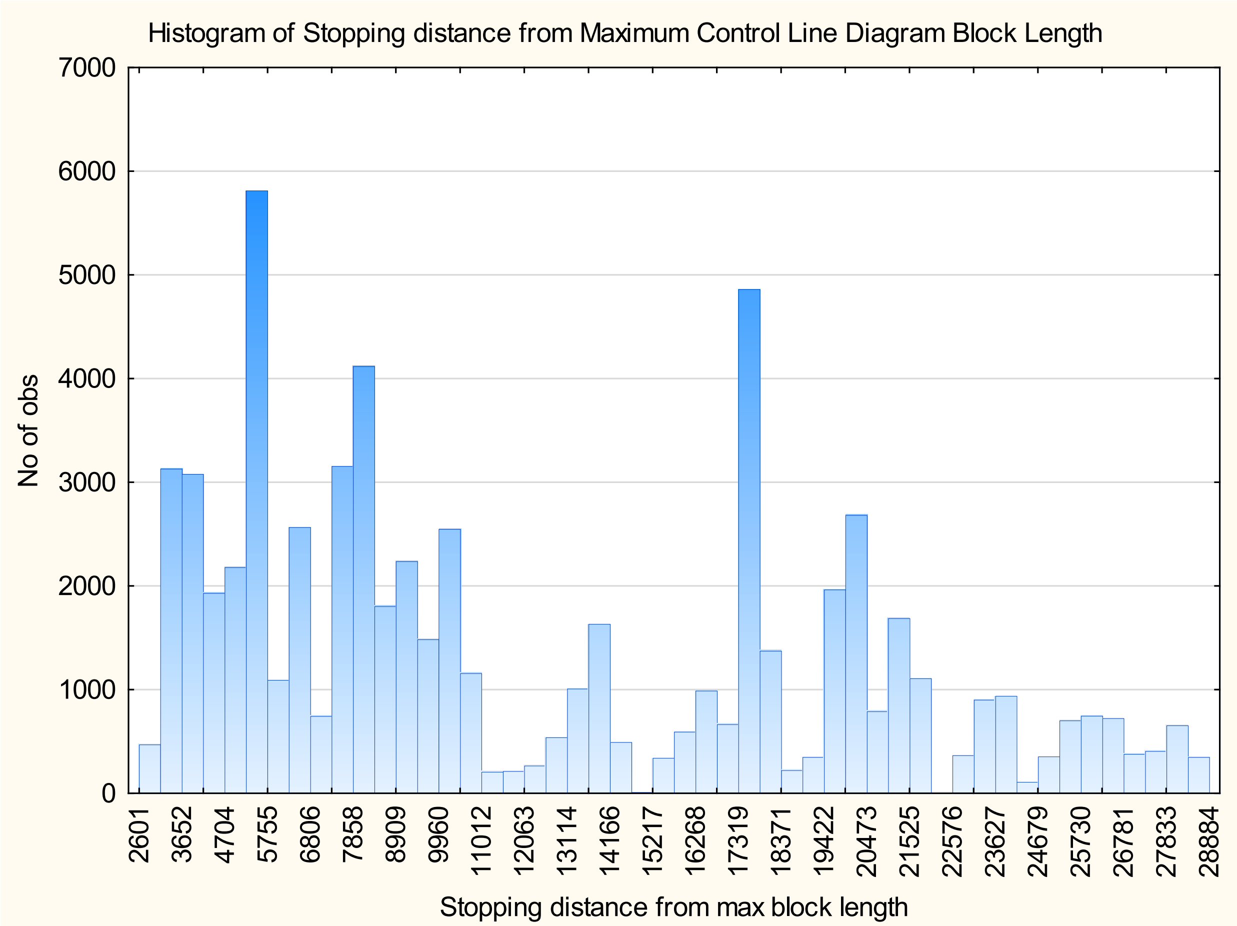

Figure 11. Histogram of freight stopping location relative to maximum end of block considering longest block length

6.1.3 Overruns

There were no overruns in any of the freight simulations.

6.1.4 Undershoots

All trains stopped at least 1,502 feet from the target in the simulations.

E-ATC calculates the predicted stopping distance for a train based on consist type and maximum authorized speed. Table 10 shows the comparison of this predicted stopping distance with the simulated stopping distance.

The minimum variation between the predicted and simulated stopping distance was 1,092 feet for a simulation using a 100-car consist with head-end power, on a 1 percent decline track at 10 mph. The maximum variation between the predicted and simulated stopping distance was 12,051 feet for a simulation using a 3-car consist with head-end power on a 0.5 percent incline track at 40 mph.

Table 10. Comparison of predicted and simulated stopping distances for freight consists

Track Grade (Percent)	Initial Train Velocity (mph)	Predicted Stopping Distance Mean	Simulated Stopping Distance Mean	Difference between Stopping Distance (Predicted – Simulated) Mean (ft.)	Difference between Stopping Distance (Predicted – Simulated) Min. (ft.)	Difference between Stopping Distance (Predicted – Simulated) Max. (ft.)
-1.00	10	2,452	486	1,966	1,092	2,294
-1.00	15	3,714	804	2,910	1,768	3,449
-1.00	20	5,181	1,177	4,004	2,448	4,772
-1.00	30	8,724	2,113	6,611	4,062	7,932
-0.75	10	2,452	371	2,081	1,612	2,314
-0.75	10	2,452	436	2,016	1,341	2,306
-0.75	20	5,181	1,079	4,102	2,763	4,762
-0.50	15	3,714	637	3,077	2,327	3,466
-0.50	30	8,724	1,743	6,981	5,199	7,973
-0.25	20	5,181	845	4,336	3,421	4,818
-0.25	40	13,083	2,460	10,623	8,627	11,931
0.00	10	2,452	277	2,175	1,890	2,333
0.00	15	3,714	504	3,210	2,740	3,487
0.00	20	5,181	780	4,401	3,685	4,818
0.00	30	8,724	1,461	7,263	6,071	8,015
0.00	40	13,083	2,308	10,775	8,973	11,954
0.25	10	2,452	252	2,199	1,989	2,329
0.25	20	5,181	722	4,458	3,822	4,845
0.50	10	2,452	217	2,235	2,077	2,342
0.50	20	5,181	653	4,528	4,009	4,842
0.50	40	13,083	2,014	11,069	9,727	12,051
0.75	10	2,452	191	2,260	2,125	2,346
0.75	15	3,714	375	3,339	3,085	3,518
0.75	20	5,181	597	4,583	4,148	4,865
0.75	30	8,724	1,160	7,564	6,823	8,105
1.00	10	2,452	176	2,275	2,151	2,351
1.00	20	5,181	564	4,617	4,243	4,864

6.2 Passenger Results

6.2.1 Exploratory Data Analysis

For the passenger simulations, in certain cases, there is variation between the input speed and the actual speed at the point of enforcement due to a) the use of pneumatic brakes on steep downgrades or b) insufficient tractive effort to maintain the speed on steep upgrades. Figure 12 shows a QQ plot showing the difference between the initial speed and the penalty application speed for each simulation. As in the freight simulations, the cruise control performed acceptably despite having some simulations where the input speed and the actual speed at the point of enforcement were greater.

The following describes the amount of data for some select differences between the target enforcement speed and actual enforcement speed:

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

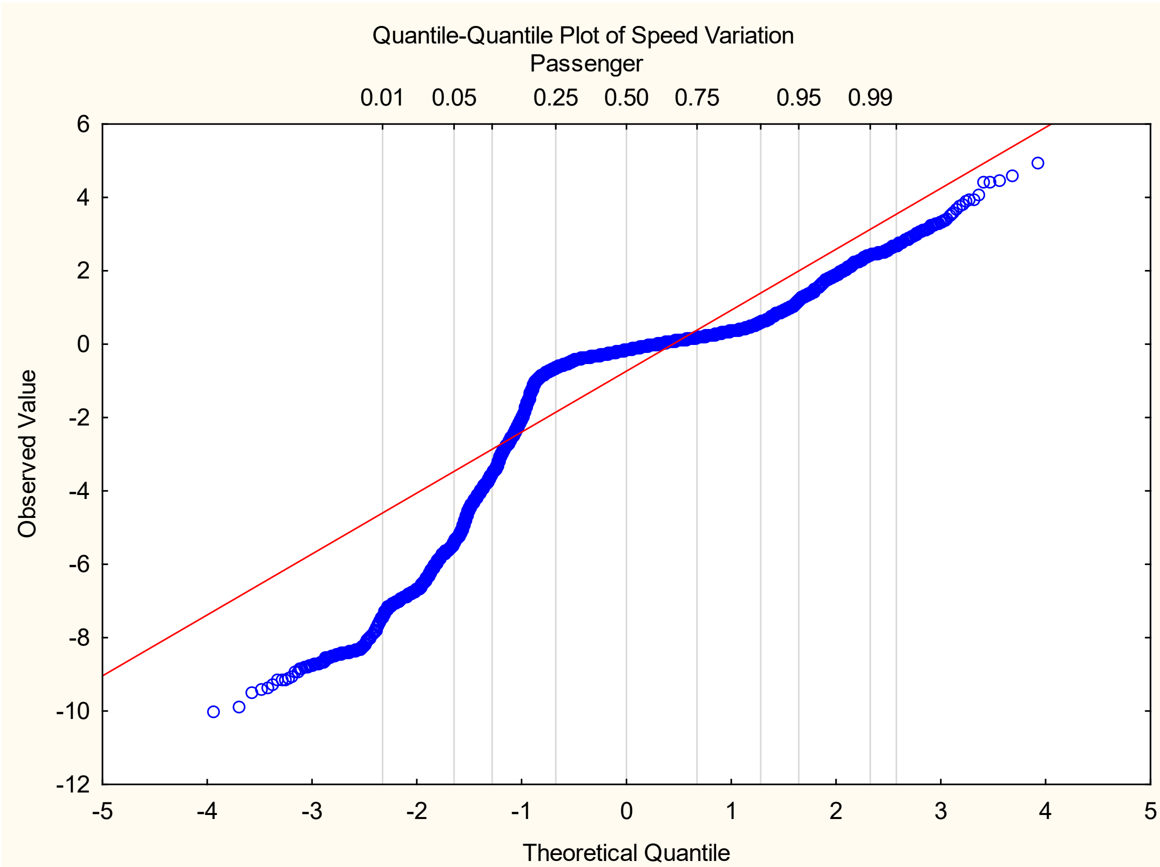

Figure 12. QQ plot of penalty application speed variation for all passenger simulations

Figure 13 shows the overall spread of data in a scatter plot of stopping location relative to target versus penalty application speed difference. The graph shows simulations that had a wider range of penalty application speed difference did not heavily bias the results by removing overruns or undershoots.

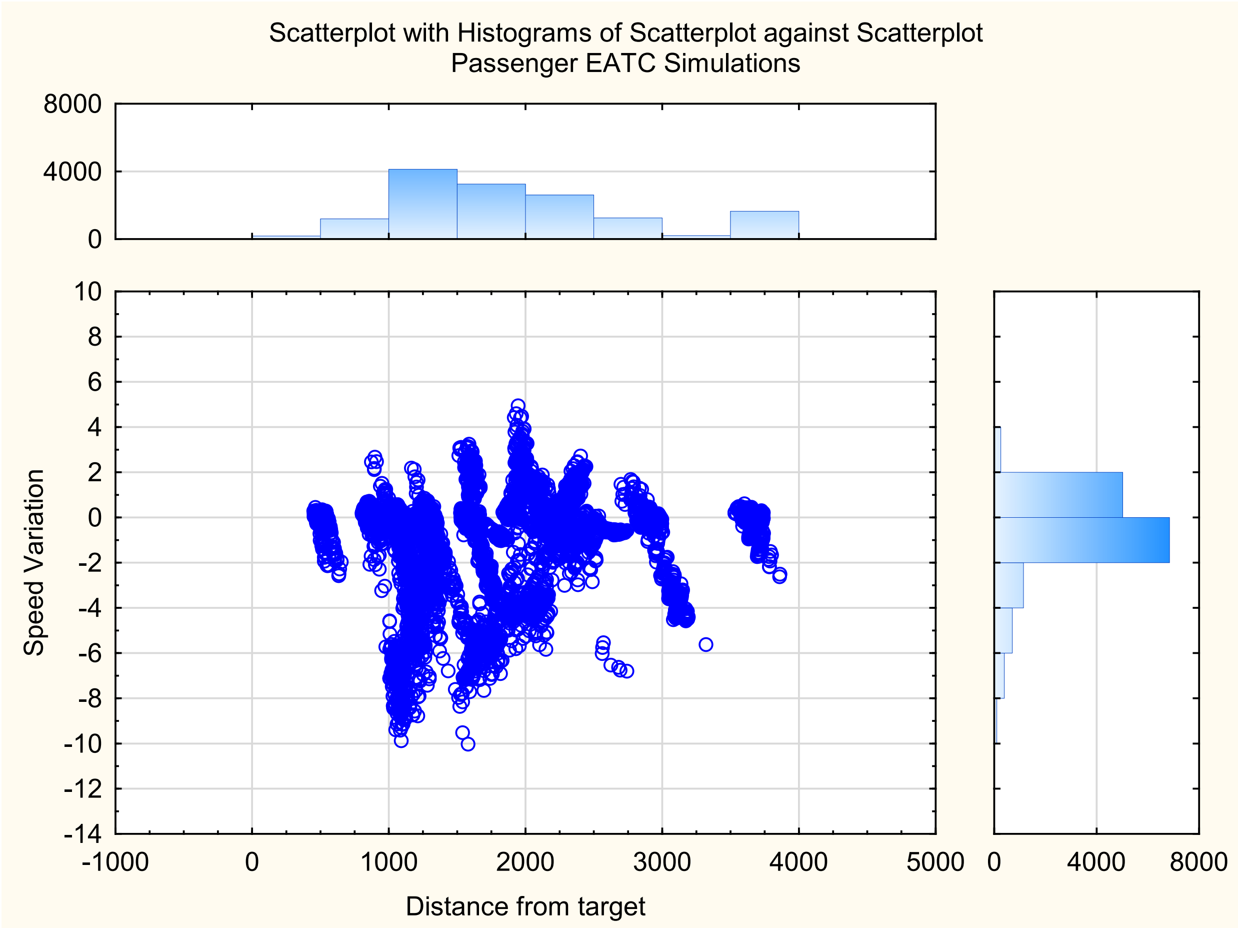

Figure 13. Scatter plot of stopping location relative to target versus penalty application speed difference

6.2.2 Overall Results Summary for Passenger Simulations

Results were generated after the data was investigated for reliability to understand the underlying characteristics. Table 11 shows the overall results of the passenger simulations by presenting the same two main statistics shown for the freight simulations:

- 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 11. Overall enforcement algorithm passenger simulation test results

Train Type	Speed	Probability of Stopping Short of Target	Probability of Stopping Short of Performance Limit
Passenger	< 30 mph	99.99%	96.21%
	≥30 mph	99.99%	98.99%

As shown in Table 11, the probability of stopping short of the target was at least 99.99 percent. This meets the previously established safety objective of being able to stop short of the target with a probability of 99.5 percent. The probability of stopping short of the performance limit was 96.21 percent for trains traveling less than 30 miles per hour and 98.99 percent for trains traveling at least 30 miles per hour.

Figure 14 shows that the data for E-ATC passenger simulations stopped before the end of the shortest block length. The closest a train stopped was 278 feet from the end of block and the maximum distance between the end of block and stop location was 6,660 feet. Comparing stopping location to the longest block lengths (Figure 15) showed similar results for the maximum distance, and the closest a train stops to the end of the longest block length was 560 feet.

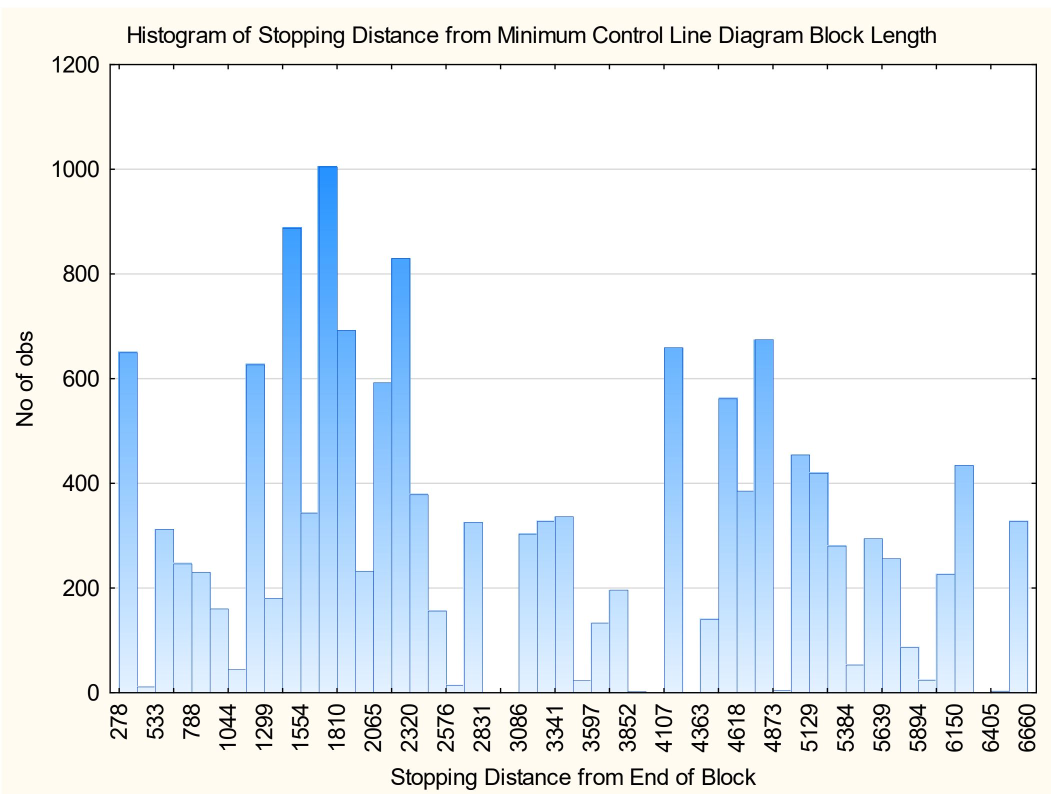

Figure 14. Histogram of passenger stopping location relative to end of block considering shortest block length

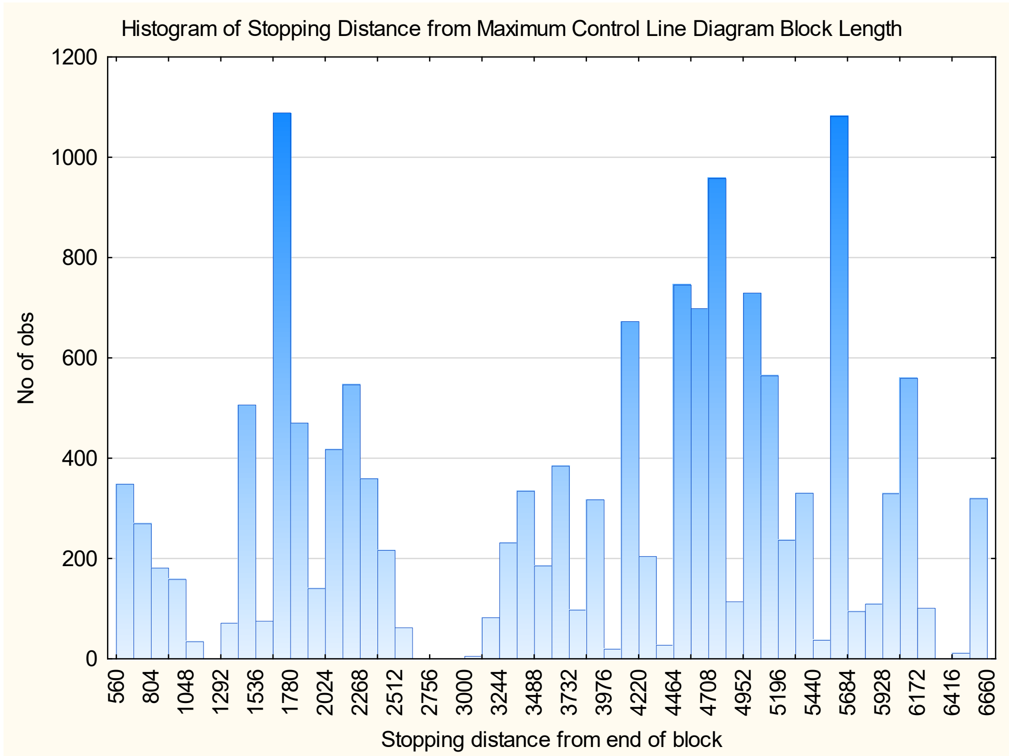

Figure 15. Histogram of passenger stopping location relative to end of block considering longest block length

6.2.3 Overruns

There were no overruns in any of the passenger simulations.

6.2.4 Undershoots

In total, 14,227 out of 14,510 simulations stopped short of the performance limit. Table 12 shows the comparison of the predicted stopping distance with the simulated stopping distance. The minimum variation between the predicted and simulated stopping distance was 812 feet for a simulation on a flat track traveling at 10 mph. The maximum variation between the predicted and simulated stopping distance was 5,340 feet for a simulation on 0.5 percent incline track at 60 mph.

Table 12: Comparison of predicted and simulated stopping distances for passenger consists

Track Grade (Percent)	Initial Train Velocity (mph)	Predicted Stopping Distance Mean	Simulated Stopping Distance Mean	Difference between Stopping Distance (Predicted – Simulated) Mean (ft.)	Difference between Stopping Distance (Predicted – Simulated) Min. (ft.)	Difference between Stopping Distance (Predicted – Simulated) Max. (ft.)
-1.50	20	3,445.73	345.79	3,099.95	2,829.72	3,313.87
-1.50	40	3,738.85	860.35	2,878.50	2,120.72	3,371.37
-1.00	25	4,446.18	404.40	4,041.77	3,679.65	4,256.00
-1.00	50	4,844.76	1137.32	3,707.44	2,571.12	4,315.91
-0.80	30	5,507.18	403.90	5,103.28	4,899.69	5,292.58
-0.80	60	5,990.04	1289.37	4,700.67	3,993.64	5,326.84
-0.50	30	5,545.15	476.88	5,068.28	4,709.98	5,303.55
-0.50	60	6,000.15	1365.48	4,634.67	3,611.62	5,319.90
0.00	10	928.41	70.36	858.05	812.15	899.08
0.00	20	3,371.56	213.18	3,158.38	3,024.87	3,266.46
0.00	30	5,508.22	404.74	5,103.48	4,853.12	5,296.05
0.00	40	3,693.21	648.98	3,044.22	2,656.07	3,356.53
0.00	50	4,797.94	943.81	3,854.13	3,275.34	4,313.84
0.00	60	5,990.67	1292.49	4,698.18	3,908.59	5,329.44
0.50	30	5,510.45	392.43	5,118.02	4,912.54	5,295.82
0.50	60	5,982.72	1222.90	4,759.82	4,038.17	5,339.78
0.80	30	5,507.23	403.92	5,103.31	4,898.68	5,291.91
0.80	60	5,990.03	1289.67	4,700.36	3,988.21	5,328.19
1.00	25	4,398.07	283.20	4,114.88	3,967.81	4,237.33
1.00	50	4,784.34	847.51	3,936.83	3,417.14	4,332.89
1.50	20	3,370.49	188.70	3,181.79	3,105.93	3,259.65
1.50	40	3,683.93	571.20	3,112.73	2,806.02	3,365.45

7. Identification of E-ATC Enhancements

The simulation results indicated that the E-ATC system may be overly conservative in predicting the stopping location of the train. It would be desirable to improve the operational efficiency by reducing the conservatism of the stopping distance prediction while still meeting its safety objectives. As part of the analysis of the results from this project, several potential enhancements to the system that could help the railroads achieve this goal were identified.

The first potential enhancement would be to review all time-in-block timers. This is the time, if any, that the train is allowed to travel into the block before the signal code is changed to cause the onboard system to begin the penalty braking prediction. Many of these timers could be increased to allow the train to travel further into the block while still meeting the safety objectives.

The next potential enhancement would be to modify the braking curve used to determine the MBL. Since the blocks are fixed, it would be impractical to change the existing block layout of any railroad. This enhancement would only affect the MBL calculation in the braking prediction. The existing curve was developed using a generalized worst-case train consist. Using the data gathered in this effort as a starting point, a more accurate curve can be developed using regression analysis and simulated data.

The last potential enhancement would be to modify the slowing/stopping braking curve used in the enforcement braking calculation. This analysis would be very similar to what would be done for the MBL equation. By improving this equation, a train would be able to get closer to the stop target without being forced to apply the brakes.

Other potential enhancements were identified but are not discussed further here as they were deemed too cost-prohibitive to implement – for example, providing track information to the onboard system. This would allow the train to compensate for track characteristics such as grade but would require major changes to the E-ATC braking methodology. The potential enhancements described in this report would not require significant changes to the design of the system to implement in the field and would require a small amount of field testing to verify.

7.1 Identification of Additional Equipment

One of the tasks of the project was to identify any additional equipment used in the field that could not be modeled in current simulation environments. Through the work to develop the simulation matrix, it was determined that all of the equipment currently being used by the railroads implementing E-ATC can be modeled by either PTBPM or TOES.

8. Conclusion

As the primary objective of the project, the E-ATC enforcement braking methodology was evaluated using simulation of freight and passenger equipment and operational scenarios expected to be encountered by the E-ATC system. E-ATC was shown to meet the previously established safety objective of having a probability of stopping short of the target of greater than 99.5 percent.

Table 13 shows the overall results of the simulation of the E-ATC enforcement methodology. There were no overruns in either the passenger or freight simulations. However, the probability of stopping short of the performance limit was very high for both the freight and commuter simulations.

Table 13. Overall simulations results

Train Type	Speed	Probability of Stopping Short of Target	Probability of Stopping Short of Performance Limit
Freight	< 30 mph	99.99%	99.99%
	≥ 30 mph	99.99%	99.99%
Passenger	< 30 mph	99.99%	96.21%
	≥ 30 mph	99.99%	98.99%

To achieve these results, an E-ATC enforcement algorithm software test application was created and evaluated that replicates the functionality of the E-ATC systems implemented in the field. This test application can also be used as a foundation for developing and evaluating potential improvements to the E-ATC systems. A list of potential enhancements was developed based on the analysis of the simulation results which could be developed and evaluated further in a follow-on phase of this project.

9. References

1 Federal Railroad Administration. (June 2009). Development of an Adaptive Predictive Braking Enforcement Algorithm [DOT-FRA-ORD-09/13]. Washington, DC: U.S. Department of Transportation.

2 Federal Railroad Administration. (August 2013). Development of an Operationally Efficient PTC Braking Enforcement Algorithm for Freight Trains [DOT/FRA/ORD-13/34]. Washington, DC: U.S. Department of Transportation.

Abbreviations and Acronyms

ACRONYMS	EXPLANATION
E-ATC	Enhanced – Automatic Train Control
I-ETMS	Interoperable Electronic Train Management System
TCL	Test Control Logger
TOES	Train Operation and Energy Simulator
P-TCL	Passenger Test Control Logger
PTBPM	Passenger Train Braking Performance Model