

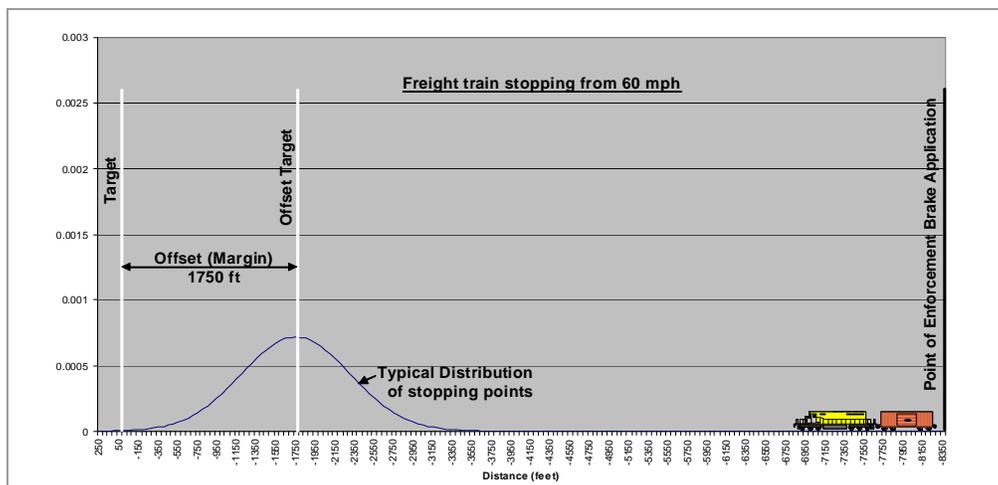


## Development of an Adaptive Predictive Braking Enforcement Algorithm

### SUMMARY

Predictive enforcement braking is one of the key concepts behind positive train control (PTC) systems. If a train is on the verge of overrunning a target stopping location, such as an authority limit, the system enforces a brake application to stop the train safely short of the limit. The concept depends on an algorithm that can predict the stopping distance of the train. Errors in stopping distance prediction can result in target overruns, target underruns, or unnecessary enforcements, which can negatively impact railroad safety or operations. Due to the uncertainty of many parameters that affect stopping distance, PTC enforcement algorithms have traditionally used a target offset to ensure that no trains overshoot the target, as Figure 1 shows. However, this can force the algorithm to be overly conservative and result in unnecessary or early warnings and enforcements.

The Federal Railroad Administration (FRA) contracted Transportation Technology Center, Inc. (TTCI) to research techniques for improving the accuracy of PTC enforcement algorithms by adapting the algorithm to the characteristics of each specific train. The development followed a progressively staged approach. In the first stage, a base case enforcement algorithm was implemented, and in each of the following stages, a new adaptive function was developed and integrated with the algorithm and tested. The adaptive functions developed included a propagation time, a train weight, and a braking efficiency adaptive function.



**Figure 1. Example Distribution of Stopping Points for Freight Train Stopping from 60 mph**

Each stage of enforcement algorithm development was tested in a simulation environment and on track in the field to determine the performance of the algorithm. The results of the testing indicate significant improvement in the performance of the enforcement algorithm with each of the adaptive features. The concept of measuring train characteristics and adapting an enforcement algorithm was shown to be feasible for the train operating conditions tested.



## BACKGROUND

Positive train control (PTC) is an emerging technology intended to enhance railroad safety. The underlying concept is that movement authorities are transmitted digitally to the controlling locomotive of each train. The locomotive tracks the location of the train with respect to its authority and speed limits and automatically applies brakes after a warning to prevent the train from violating any limit in the event of human failure. Enforcement braking is an event of last recourse when the locomotive engineer has failed to take adequate action.

A typical requirement for enforcement braking, per the North American Joint Positive Train Control/Illinois Department of Transportation (NAJPTC/IDOT) project, is that the train must stop short of an authority limit with a 0.999995 certainty. Additionally, the train must stop within 500 feet (ft) when the initial train speed is less than or equal to 30 mph or within 1,000 ft when the initial train speed is greater than 30 mph, with 90 percent probability.

Many variables affect braking distance, several are indeterminate and some are known to a degree, but without the assurance required for fail-safe operation. Therefore, when assumed values are used, a wide variability can be between actual and predicted braking distance. Therefore, the onboard system must establish a conservative target short of the authority limit to achieve the 0.999995 certainty of not passing the target. When this is done, far less than 90 percent of freight trains stop within the specified distance from the target. The effect on operations is that the system will frequently warn the crew and attempt to enforce a stop considerably earlier than the crew would stop the train under normal handling.

## OBJECTIVES

This project identified, developed, and tested proof-of-concept methods to improve predictive enforcement braking algorithms to minimize the target offset required, while still meeting safety requirements using adaptive techniques.

## METHODS

The project was divided into preparatory tasks, followed by four stages of enforcement algorithm development and testing. The preparatory tasks included the development of a simulation test environment (funded internally by TTCI) and a parametric study to evaluate the contribution of some of the key variables to stopping distance prediction.

### Simulation Test Environment

Simulating train braking performance with the use of a model can drastically increase the number of tests that can be performed without the time and expense of testing in the field. TTCI's Train Operations and Energy Simulator (TOES™) is an appropriate model for such testing. It can accurately model the complete brake system and train-level dynamics of any given train to determine the stopping distance, given any operating conditions and track profile.

To execute the number of simulations required efficiently, a test controller and logger (TCL) application was developed to generate the input files and execute the batches of simulations and to provide a communications interface between the TOES™ model and the enforcement algorithm under evaluation.

The TCL can operate in one of two modes: (1) to evaluate the effect of varying different car characteristic parameters on train stopping distance, and (2) to evaluate an enforcement algorithm by testing it on a range of possible train consists.

In both of these modes, the user provides the TCL with a nominal train consist, track profile, the desired parameter(s) to vary, the allowable variance for the given parameter(s), and the desired number of simulations. For each of the simulations, the TCL generates a specific train consist, based on the nominal consist, by varying each of the parameters for each car in the train using a Monte Carlo method. In the first mode, the TCL executes each of the simulations from a defined steady state speed by enforcing a full-service brake application on the given consist and running the model until the train comes to a stop.

In the second mode, the user also provides the TCL with a target stopping location. The TCL



executes each simulation by starting the train moving toward the target. TOES™ advances in 1-second increments (simulation time), providing feedback data to the TCL after each second. The TCL passes this data to the enforcement algorithm, which determines whether or not a penalty brake application is necessary to avoid a target overrun. If no penalty is necessary, the process continues. Otherwise, the enforcement algorithm sends a message to the TCL, which initiates the penalty application in the TOES™ model. Figure 2 shows a block diagram of this process.

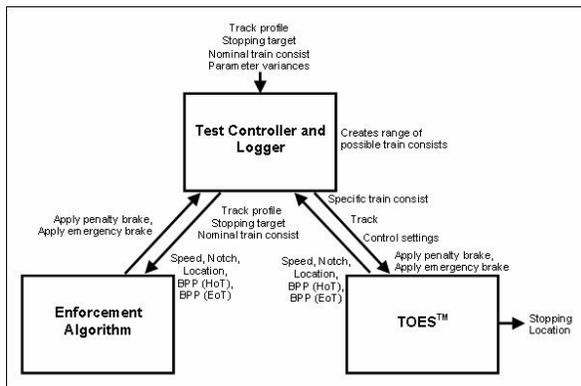


Figure 2. Simulation Test Environment

### Parametric Study

Four key parameters that affect stopping distance were selected for this study: brake valve type, brake cylinder piston stroke, brake force, and car weight. A test matrix was developed to determine the effect each of these parameters has on stopping distance. The test matrix includes a range of train types, speeds, loads, and track grades. For each test, 100 runs were executed using the TCL and TOES™, where one of the four parameters was allowed to vary while the other parameters remained constant.

### Base Case Enforcement Algorithm

The base case enforcement algorithm selected for this study was used in the NAJPTC/IDOT project.

A combination of simulation testing and field testing was used to evaluate the performance of this algorithm (and the adaptive algorithms developed in the following stages). A simulation test matrix was developed incorporating a variety of train lengths, speeds, loads, and track grades. For each test, 100 simulations were run

using the TCL and TOES™ model, where all variables were allowed to vary within their specified range.

A subset of the simulation test matrix was tested in the field. The test consist was instrumented to provide data to a train control computer, which was passed to the enforcement algorithm. When the enforcement algorithm determined a penalty application was needed to prevent a target overrun, it sent a signal to the train control computer, which applied the penalty brake.

### Adaptive Enforcement Algorithms

The propagation time adaptive algorithm is designed to measure the brake propagation time when a brake test is performed. This measurement is then used to determine the propagation time for a full-service brake application, which replaces the value assumed in the base case algorithm.

The concept behind the train weight adaptive algorithm is that acceleration and forces acting on a train can be estimated and used to solve for the train weight, using Newton's second law of motion. This weight replaces the assumed weight used by the base case algorithm.

The braking efficiency adaptive algorithm is based on the concept of estimating the deceleration and forces acting on a train during a service brake application and using them in Newton's second law of motion to solve for the brake force. This is used to estimate the brake force for a full-service application, which replaces the value assumed by the base case algorithm.

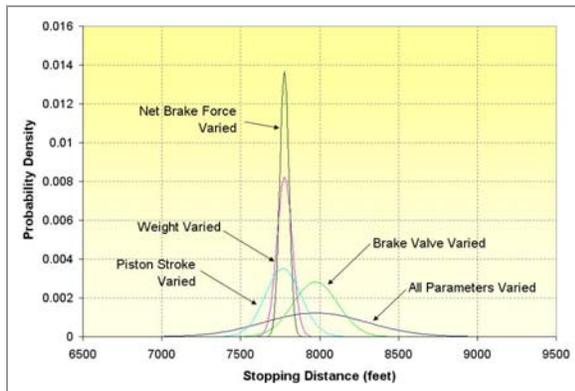
## RESULTS

Figure 3 shows the results from one of the parametric study test scenarios; a long, loaded, general freight train stopping from 60 mph on flat grade. The example shows the stopping distance distribution for this operating scenario due to varying each parameter individually. The widest variation was due to brake valve type for this scenario. However, the most significant parameter varied for other operating scenarios, most notably for short trains where brake cylinder piston stroke was the most significant.

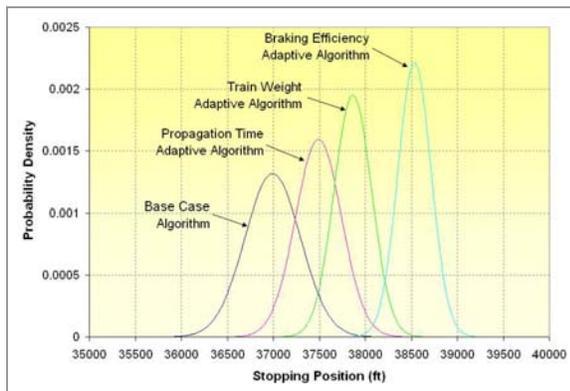
The results of the enforcement algorithm simulation tests were used to produce stopping



location distributions for each test scenario. Plotting the distributions for each of the algorithms together illustrates how they perform in comparison with each other. Figure 4 shows an example of the stopping location distributions for each algorithm for a 75-car loaded unit freight train travelling 60 mph on flat grade, with a target stopping location of 40,000 ft.



**Figure 3. Stopping Distances for a Long, Loaded, General Freight Train Stopping from 60 mph on Flat Grade**



**Figure 4. Sample Distributions of Stopping Location with Incremental Adaptive Functions**

With the addition of each adaptive function, the distribution of stopping locations moved closer to the target stopping location, without altering the percentage of trains that overshot the target. Also, the standard deviation of the distribution was decreased for each stage, indicating better accuracy in the prediction.

Although the results from all test scenarios did not exhibit these exact characteristics, the final algorithm did show improvement over the base case algorithm in each of the test scenarios.

The field test results showed general agreement with the simulation results. Improvements in estimating the forces in the train weight and braking efficiency algorithms have the potential to provide more accurate estimations.

## CONCLUSIONS

The performance of predictive braking enforcement algorithms can be severely impacted by the combination of unknown variables that affect train braking distance. By automatically measuring certain train characteristics and adapting the algorithm, a more accurate stopping distance prediction is possible.

The results of this project indicate that this concept is feasible. However, the field test results show that more work is necessary to develop an implementation-ready algorithm that provides sufficient accuracy and repeatability for general use in PTC systems. This project focused on unit trains. More research is needed to prove the concept on other train types.

A full report contains all of the results from the parametric study, enforcement algorithm evaluation simulation tests, and field tests.

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**KEYWORDS:** positive train control, enforcement braking, enforcement algorithm, adaptive enforcement algorithm

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