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Transportation

**Federal Railroad
Administration**

Development of an Adaptive Predictive Braking Enforcement Algorithm

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13. ABSTRACT (Maximum 200 words) 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. But this can force the algorithm to be overly conservative, resulting in unnecessary or early warnings and enforcements. Federal Railroad Administration (FRA) contracted Transportation Technology Center, Inc. (TTCI) to research proof-of-concept techniques for improving the accuracy of PTC enforcement algorithms by adapting the algorithm to the characteristics of each specific train. The project included a parametric study of some of the key variables that can affect stopping distance, followed by the development and testing of the adaptive functions.				
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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)

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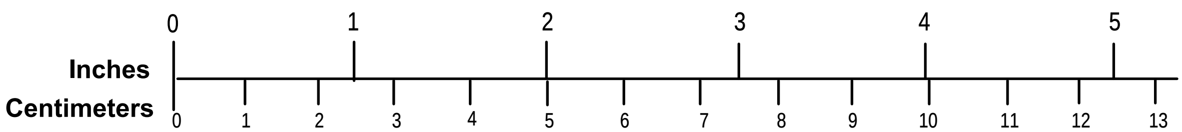
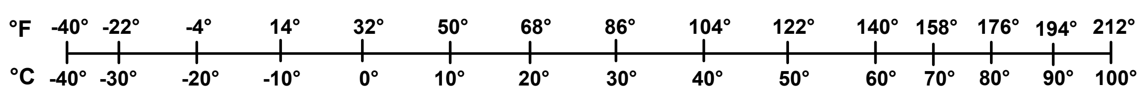
QUICK INCH - CENTIMETER LENGTH CONVERSION



QUICK FAHRENHEIT - CELSIUS TEMPERATURE CONVERSION



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Executive 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 as a margin of safety to ensure that no trains overshoot the target. But this can force the algorithm to be overly conservative, resulting in unnecessary or early warnings and enforcements.

The Federal Railroad Administration (FRA) contracted the Transportation Technology Center, Inc. (TTCI) to research proof-of-concept techniques for improving the accuracy of PTC enforcement algorithms by adapting the algorithm to the characteristics of each specific train. The project included a parametric study of some of the key variables that can affect stopping distance, followed by the development and testing of the adaptive functions.

A simulation test environment was developed (funded internally by TTCI) to allow for stop distance testing and enforcement algorithm evaluation of a large number of test scenarios without the time and expense of field testing. The simulation test environment included modifications to TTCI's Train Operations and Energy Simulator (TOES^{TM}), as well as the development of a test controller and logger (TCL) application to generate and run the batches of simulations and to provide a communications interface between TOES and the enforcement algorithm under evaluation.

During the parametric study, the simulation test environment was used to evaluate the sensitivity of stopping distance with respect to several different parameters for several test scenarios. Each parameter was allowed to vary individually using a Monte Carlo method, while the others were held constant, for each test scenario. The parametric study showed the relative impact of each of the parameters in relation to the other parameters for each test scenario. Plots of the resulting stopping distance distributions for each test scenario can be found in the report appendix. Analysis of the plots revealed that the parameter with the largest effect on stopping distance is dependent on the train type and the operating scenario. The results of the parametric study also illustrate how using worst-case assumptions can affect the performance of an enforcement algorithm.

The adaptive algorithm 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.

The propagation time adaptive algorithm was designed to measure the brake propagation time when a brake test is performed. This measurement was 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 to solve for the brake force with the known service brake pipe pressure reduction. This is used to estimate the brake force for a full-service application, which replaces the value assumed by the base case algorithm.

Each stage of development included evaluation of the enforcement algorithm with the addition of the new adaptive function in the simulation environment as well as on an actual train and was tested on track at the Transportation Technology Center (TTC). In each of the test environments, the algorithms were evaluated in several test scenarios representing a variety of trains, speeds, and track profiles.

Figure 1 shows an example of the results of the simulation testing evaluation of the enforcement algorithms developed for a sample operating scenario. The figure shows the distribution of stopping locations for each of the four stages of enforcement algorithm development for a 75-car loaded unit freight train traveling 60 mph on flat grade, with a target stopping location of 40,000 ft.

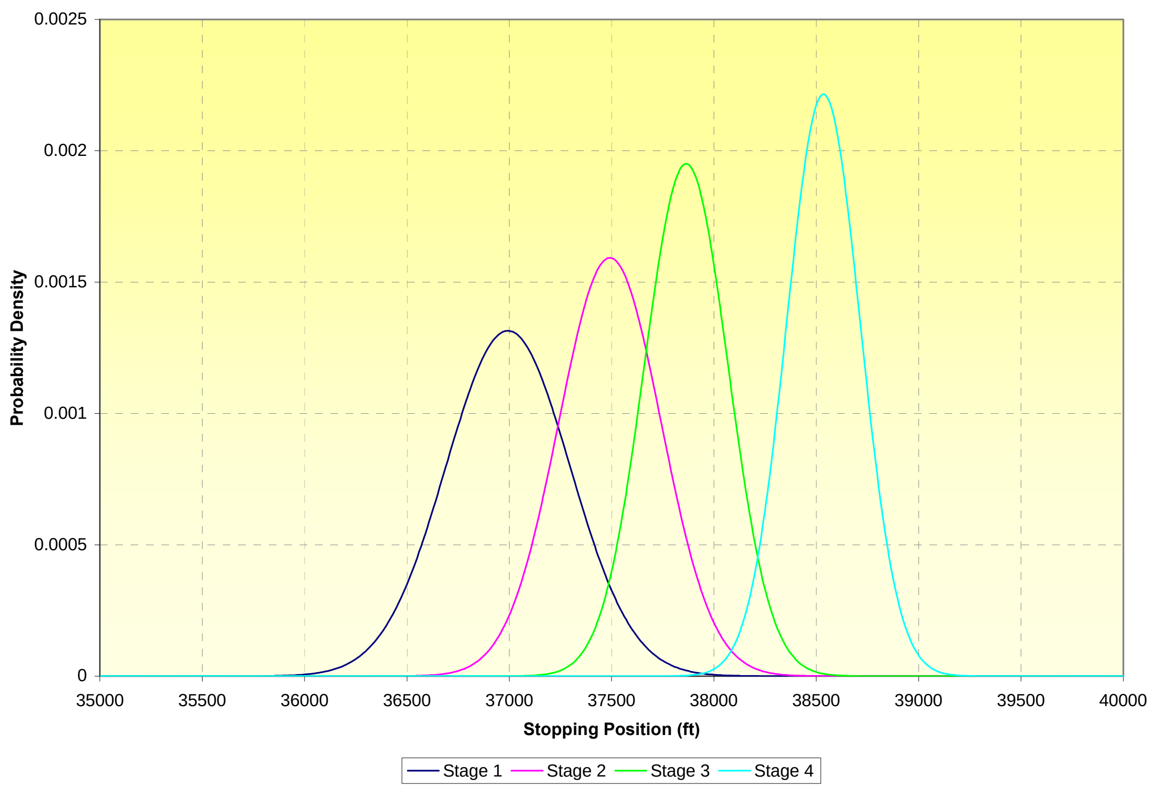

Figure 1. Distribution of Stopping Locations for each of the Enforcement Algorithms Developed for a 75-car Loaded Unit Freight Train traveling 60 mph on Flat Grade

Figure 1 shows that with each added adaptive feature, the stopping location distribution was tighter and the mean stopping location was closer to the target. This indicates a general positive effect on the performance of the enforcement algorithm for each of the adaptive enforcement algorithm developments.

The results of the evaluation of the algorithms developed indicated a general improvement in the stopping distance prediction with the addition of the adaptive functions. However, potential improvements for each of the adaptive functions were also identified individually, as detailed in the report. The project concluded that the concept of adapting an enforcement algorithm to the characteristics of a specific train was proven feasible, and that it can have an appreciable positive effect on the performance of the enforcement algorithm.

1. Introduction

Enforcement braking is one of the essential underlying concepts of positive train control (PTC) technology, as it is the mechanism for preventing violation of limits, such as authorities or speed restrictions, in the event of human failure. For enforcement braking to be practical and effective, it must prevent a train from violating any limits, but must also be transparent to the locomotive crew when the train is being handled according to normal operating practices. Testing and use of prototype PTC systems has revealed that current enforcement algorithms have difficulty meeting these objectives. The Federal Railroad Administration (FRA) contracted the Transportation Technology Center, Inc. (TTCI) to research techniques for improving the accuracy of PTC enforcement algorithms.

1.1 Background

PTC is an emerging train control technology intended to enhance safety and potentially improve train performance and plant capacity. The underlying concept of the technology is that movement authorities are transmitted digitally to the controlling locomotive of each train. The locomotive tracks the location of the train with respect to its authority and speed limits and automatically applies brakes to prevent the train from violating any limit in the event of human failure. This is done by implementing a predictive enforcement braking algorithm that regularly predicts the stopping distance of the train, given the current conditions, and applies the brakes if the predicted stopping distance indicates that a limit will be violated if a penalty brake application is not initiated. Enforcement braking is an event of last recourse when the locomotive engineer has failed to take adequate action. A full-service penalty brake application is used for enforcement in current PTC systems.

A typical requirement for enforcement braking, per the North American Joint Positive Train Control (NAJPTC)/Illinois Department of Transportation (IDOT) project,[1] is that the train must stop short of an authority limit with a 0.999995 certainty (the safety limit). Additionally, the train must stop within a distance not exceeding the greater of 500 feet (ft) or 15 percent of the initial distance to the enforced limit at the time predictive enforcement braking was invoked, with 90 percent probability when initial train speed is less than or equal to 30 mph; or within a distance not exceeding the greater of 1,000 ft or 15 percent of the initial distance to the enforced limit at the time predictive enforcement braking was invoked, with 90 percent probability, when initial train speed is greater than 30 mph (the performance limit). Figure 2 illustrates these objectives.

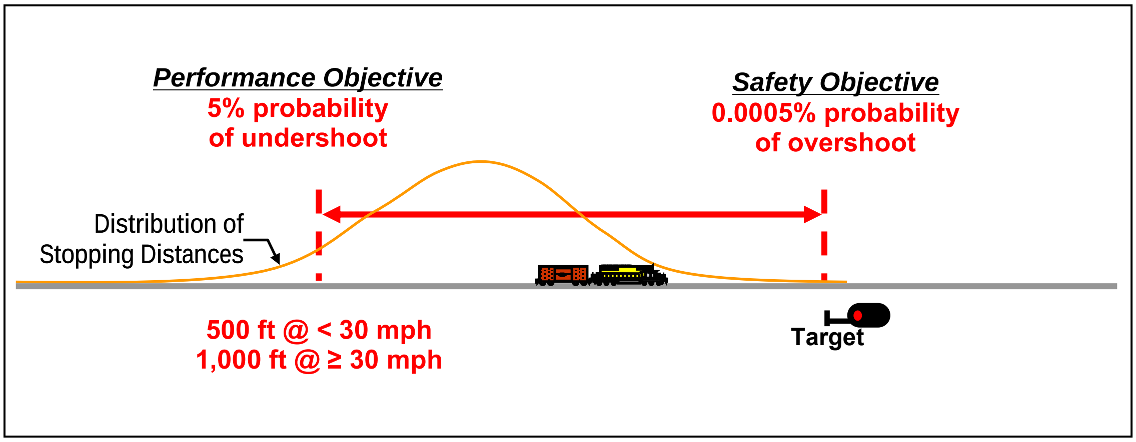

Figure 2. Typical PTC Enforcement Braking Objectives

Of the many variables that affect the 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 exist between actual braking distance and the computed predicted braking distance. Figure 3 shows a typical variance generated from computer simulations performed as part of the NAJPTC/IDOT project. In this example, the onboard system must establish a conservative target 1,762 ft short of the authority limit (offset by 1,762 ft of margin) so that the train achieves at least the 0.999995 certainty of not passing the actual target. However, achieving the safety limit results in the majority of the trains stopping outside of the performance target. The effect on operations is that the system will typically warn the crew and attempt to enforce the train to a stop considerably earlier than the crew would stop the train under normal handling, forcing the train crew to start braking sooner than necessary.

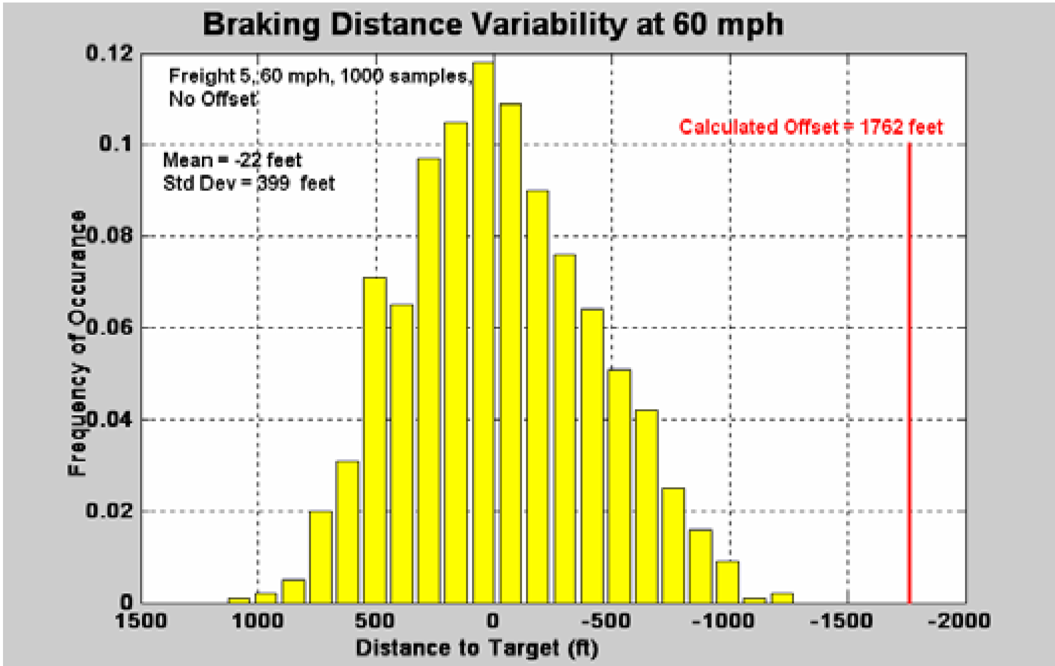

Figure 3. Stopping Distance Distribution Generated from Simulations Performed as Part of the NAJPTC/IDOT Project for Freight Train Traveling 60 mph

1.2 Objectives

The project identified, developed and tested proof-of-concept methods to improve predictive enforcement braking algorithms to minimize the target offset required.

1.3 Overall approach

The project consisted of eight major tasks, with four tasks executed in a preparatory phase and the remaining four in a developmental phase. Figure 4 shows the overall project plan as a block diagram of the eight major tasks and associated subtasks. In the preparatory phase, the foundation was laid for using train operations and energy simulator (TOES™) to evaluate any enforcement algorithm. Task 1 was the development of a test controller/logger (TCL) application to interface the TOES™ model with an enforcement algorithm, and Task 2 modified the standard TOES™ software. Both of these tasks were funded internally by TTCI. The preparatory phase also included a parametric study of the effect that various train characteristics have on stopping distance (Task 3) and writing a specification for the interface between the TCL and the enforcement algorithm (Task 4).

The developmental phase consisted of the progressive development of an enforcement algorithm that can adapt to actual train characteristics. The developmental phase of the project was further broken into four stages, as Figure 4 shows. In the first stage, the performance of the base case enforcement algorithm was selected and evaluated under several test scenarios to define a baseline level of performance against which the subsequent adaptive improvements were compared (Task 5). Three stages of adaptive algorithm development followed, each building on the improvements from the previous stage. These stages included the development of an algorithm to measure and correct for the actual brake pipe propagation time (Task 6), actual train weight (Task 7), and actual braking efficiency (Task 8). In each stage of development, the new algorithm was designed and integrated into the algorithm from the previous stage. The new algorithm was then evaluated in the same test scenarios as for the base case algorithm using the TOES™ model and the software developed in the preparatory phase. Finally, the algorithm was tested on a subset of the simulation test scenarios in the field on an actual train.

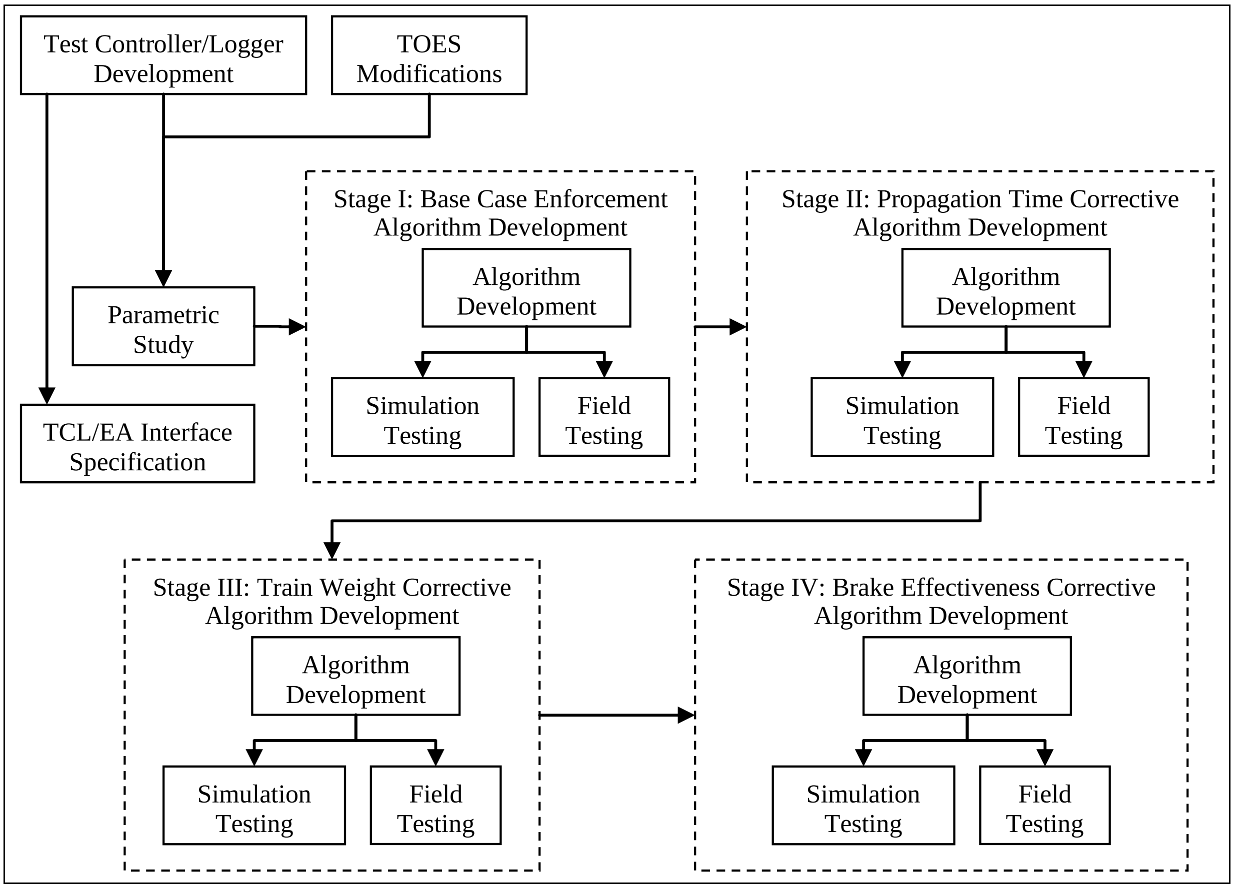

Figure 4. Overall Project Plan

1.4 Scope

This project researched the techniques discussed to determine their potential to reduce the target offset required without affecting the safety objectives of the enforcement algorithm. If these proof-of-concept techniques prove to be successful, a specification for an improved enforcement algorithm may be produced for use in both current and future PTC systems. Development of such a specification is, however, outside the project scope, and considered to be potential follow-on work.

Additionally, this project focused on analyzing and developing techniques for adapting a generic enforcement algorithm to the specific characteristics of a given train. Other nonadaptive methods have been suggested for improving enforcement algorithms by reducing the target offset required, but these are not considered in the scope this effort.

Finally, many types of railroad cars exist, each with significantly different braking characteristics. Although all car types may need to be considered in a braking enforcement algorithm implemented in a fully functional PTC system, the types of cars used in this proof-of-concept investigation are limited. The enforcement algorithms were tested using a single unit test train for the field tests and a limited number of car types were used for the tests performed in a simulation environment. Testing and further developments necessary for car types not included in this study are considered to be potential future work.

1.5 Organization of the Report

This report is organized into eight sections. Section 1 is an introduction and provides a general overview of the background, objectives, approach, and scope of the project.

Section 2 provides details of the simulation test environment developed for evaluating the effects of various braking parameters and enforcement algorithm performance. This includes development of the TCL software (Task 1), modifications to the TOES™ software (Task 2), and the interface to the enforcement algorithm (Task 4).

Section 3 focuses on the parametric study of variables that affect train stopping distance (Task 3). This includes the objectives, processes, and results of the study.

Sections 4, 5, 6, and 7 discuss the implementation and testing of each stage of the enforcement algorithm development (Tasks 5, 6, 7, and 8). The objective, analysis, design, implementation, testing and results of each stage are presented within these sections.

Finally, Section 8 summarizes the results from all stages of the project and provides conclusions and recommendations for future work.

2 Simulation Test Environment Development

Simulating train braking performance with the use of a model can significantly increase the number and range of tests that can be performed in a given time without the expense of testing in the field. TTCI's TOES™ model was selected for such testing, because 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. The TOES™ model can be used in two distinct ways in enforcement algorithm development:

- To determine the effect of varying different input parameters on train stopping distance for a variety of trains and operating scenarios (grades, speeds, etc.)
- To evaluate the performance of an enforcement algorithm under a variety of operating scenarios by simulating a train approaching a target, providing inputs to the algorithm, and responding to an enforcement command from the algorithm.

To execute the number of simulations required efficiently, a front-end application was needed to generate the input files and execute the batches of simulations, as well as provide a communications interface between the TOES™ model and the enforcement algorithm. The TCL application details are described in subsection 2.1. Subsection 2.2 describes the TOES™ model and the modifications needed for enforcement algorithm testing, and subsection 2.3 discusses the interface between TCL and the enforcement algorithm.

2.1 Test Controller and Logger

The first project task was to develop a TCL software application that enables the use of the TOES™ model for stopping distance tests and enforcement algorithm evaluation. The TCL can operate in one of two modes. In the first mode, the TCL is used to evaluate the effect of varying different car characteristic parameters on train stopping distance. In the second mode, the TCL is used to evaluate an enforcement algorithm by testing it on a range of possible train consists.

2.1.1 TCL Stop Distance Test Mode

The conceptual block diagram shown in Figure 5 illustrates how the TCL controls TOES™ in stop distance test mode. In this mode, the user provides the TCL with a nominal train consist, a track profile, the desired parameter(s) to vary, the distribution and allowable variance for each of the given parameter(s), and the desired number of simulations. The TCL then generates a specific train consist for each of the given number of simulations. For the first consist generated, the TCL inputs nominal or mean values for each of the given varied parameters for each car. Best-case values are input for each car in the second consist generated and worst-case values are input for each car in the third consist generated. The TCL generates the remaining consists by allowing each of the given parameters to vary within its allowable range for each car in the consist.

Once the specific train consists have been created, the TCL provides the TOES™ model with the first train consist, the track profile, the starting location, and the starting speed. The TCL sends the command for a full-service brake application followed by the command to continue until the train has come to a stop. The model runs with the given information and outputs a stopping distance. This process is then repeated for each of the train consists generated by the TCL to create a range of stopping distances.

The nominal train consists can be made up of any type of car that is defined within the TOES™ model. A large number of prebuilt vehicles are in the TOES™ library and custom vehicles can also be created. Likewise, custom track can be built for use in the TOES™ model. TCL allows for variance of car characteristics that affect braking distance, including brake valve type, brake cylinder piston stroke, brake shoe force, and vehicle weight.

For a given parameter on a given car type, the user determines how the parameter is allowed to vary by choosing between a normal (Gaussian) distribution (with a given mean and standard deviation) or a flat distribution (with given minimum and maximum values). In the case of brake valve type, the user can specify the probability of each of the possible brake valve types being installed on a given car. The user can also choose a truncated normal distribution where the tails of the distribution are cut off.

This flexibility in how the parameters are allowed to vary enables the user to determine the effect that each of the parameters has on stopping distances for any type of car and any type of train, individually or in combination with other parameters.

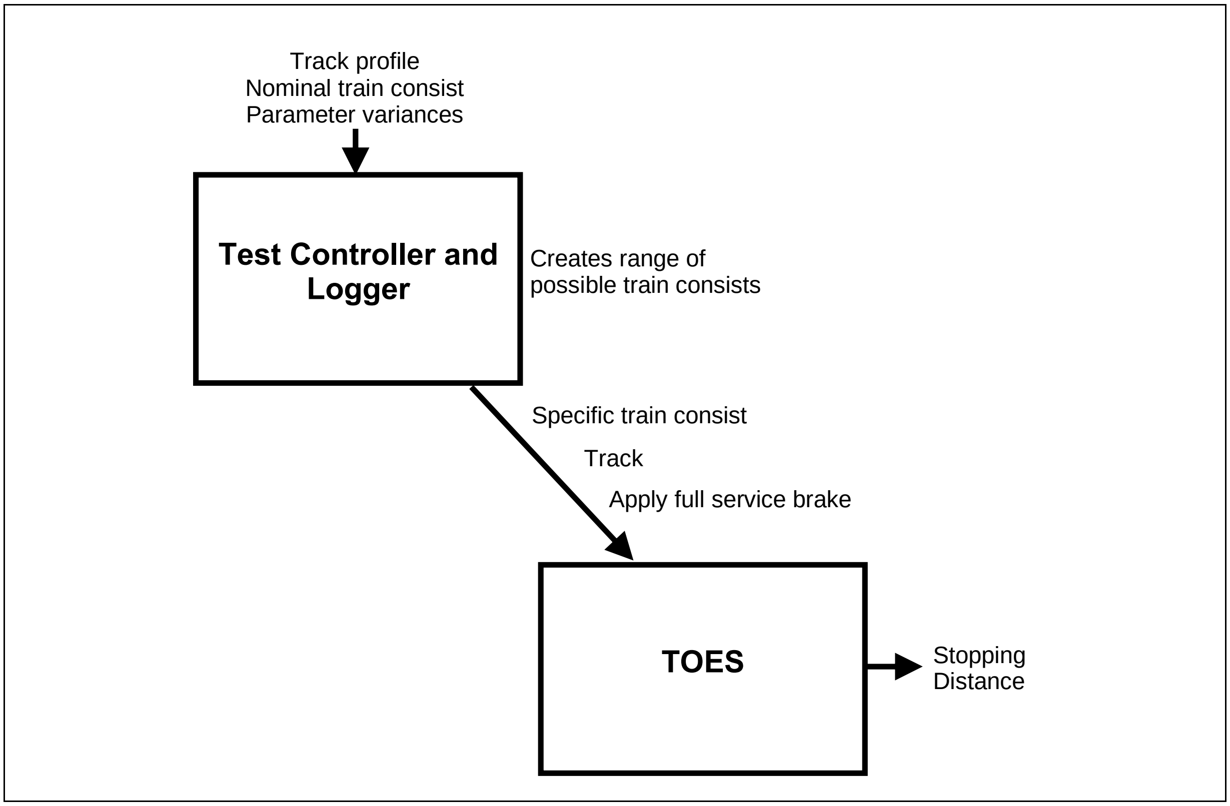

Figure 5. Block Diagram of TCL and TOES™ Running in Stop Distance Mode

2.1.2 TCL Enforcement Algorithm Evaluation Mode

Figure 6 shows a conceptual block diagram of TCL in the enforcement algorithm evaluation mode. In this mode, the user provides the TCL with a stopping target location in addition to the nominal train consist, track profile, parameter(s) and associated variance(s).

As in the stop distance test mode, the TCL generates the specific consists and provides these, along with the track profile, to the TOES™ model. The TOES™ model advances one second of simulation time and then provides feedback to the TCL, including train speed and location, locomotive notch, head-end brake pipe pressure, and tail-end brake pipe pressure. The TCL passes this information along to the enforcement algorithm, which determines whether or not a penalty brake application is necessary. If the enforcement algorithm determines that no penalty is necessary, the TCL commands the TOES™ model to advance another second of simulation time. This process is repeated until the enforcement algorithm determines that a penalty application is necessary to prevent an overrun of the specified target. At this point, the enforcement algorithm sends a message to the TCL, which then sends a brake application command to the TOES™ model. The process continues until the train reaches a stop and a stopping location is determined.

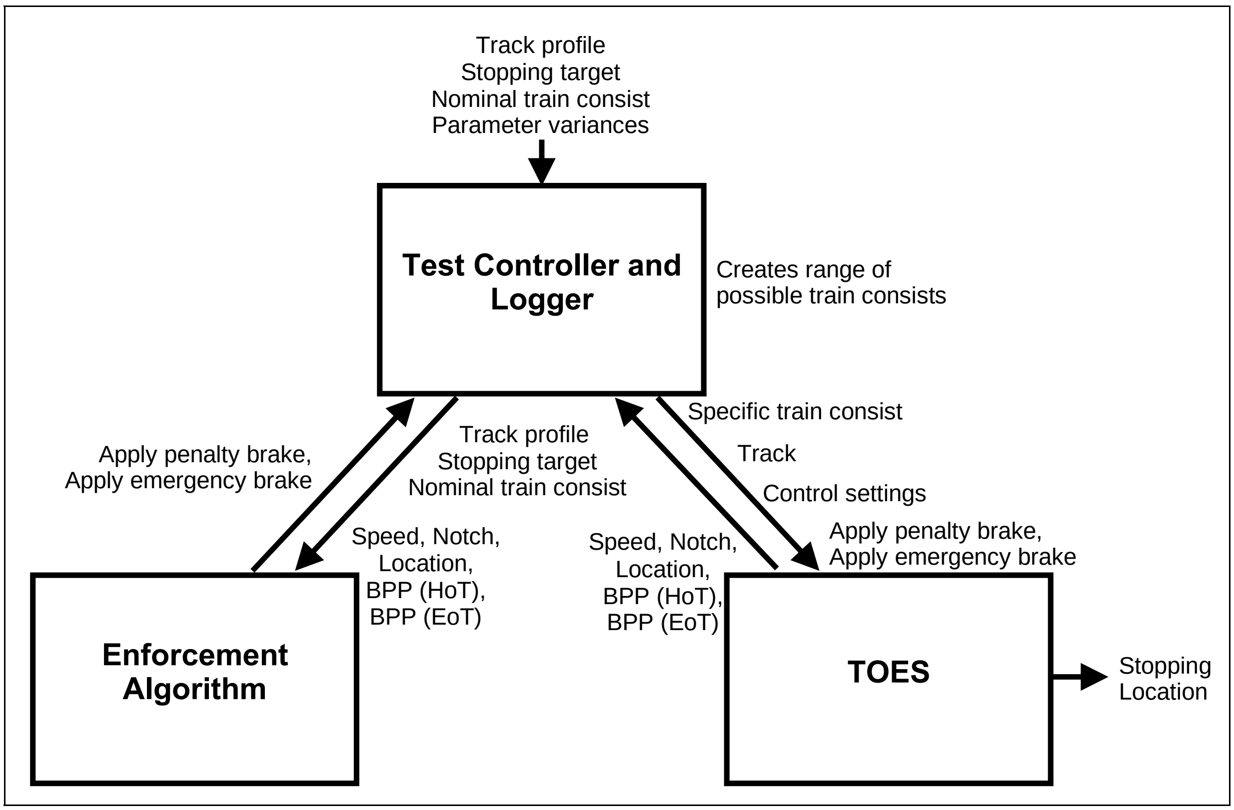

Figure 6. Block Diagram of TCL, TOES™, and an Enforcement Algorithm Running in Enforcement Algorithm Evaluation Mode

This entire process is repeated for each of the specified number of train consists, generating a range of stopping locations. This range of stopping distances can be compared against the target stopping location to determine how well the enforcement algorithm performed in the particular operating scenario.

2.2 Train Operations and Energy Simulator

TOES™ is a longitudinal train dynamics model, which means it simulates how a train reacts to different train handling scenarios over a track in the longitudinal dimension (i.e., down the track, as opposed to vertical, lateral, or other dimensions).

TOES™ individually models every vehicle in the train and outputs the state of each vehicle at every time step (typically one second although user selectable) of the simulation. The outputs include (among others) location, velocity, acceleration, coupler forces, brake pipe pressures and brake cylinder pressures for every vehicle in the train, as well as averaged over the entire train. These outputs can be used for a variety of applications including incident investigations, train make-up studies, equipment evaluations, energy conservation studies, as well as stopping distance studies.

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

To use the model in the arrangement depicted in Figure 6, some minor software modifications were necessary. Typically, a TOES™ simulation is run in one of two ways:

- Interactively—where the user enters commands one at a time into a command prompt and receives real-time feedback on the screen as the simulation progresses.
- Automatically—where the user enters a series of commands into a command file and the software automatically executes each of the commands in sequence.

For the test setup depicted in Figure 5, the TCL generates a command file for each simulation that includes the commands to start at a given speed and location, initiate a penalty brake application, and continue until the train is stopped. TOES™ is then run in an automated mode, executing the commands generated by the TCL for each simulation.

For the test setup depicted in Figure 6, however, TOES™ must accept commands from the TCL, as opposed to the keyboard or command file, and must also send feedback to the TCL, as opposed to the screen. These modifications (which were funded by TTCI) enable the TCL to interact with TOES™ to evaluate any enforcement algorithm that is capable of interfacing with the TCL.

2.3 TCL and Enforcement Algorithm Interface

The final component of the test arrangement shown in Figure 6 is the enforcement algorithm under evaluation. Although the TCL development and modifications to the TOES™ software were completed To evaluate the enforcement algorithms developed for this project, this test setup could be used to evaluate any enforcement algorithm capable of interfacing the TCL software. To enable this type of testing, a communications interface specification was required. The communication between the TCL and enforcement algorithm is described briefly in this section. The complete technical communications specification can be found in Appendix A.

Enforcement algorithms developed to date use brake pipe pressures at the head and tail end to determine the state of the brake system and estimate the current braking force at any given time. They use this information, along with the current speed and location of the train, and grade and curvature information from a track database, to determine the stopping distance of the train. In addition to these parameters, the adaptive enforcement algorithms developed in this project also use locomotive throttle and dynamic brake settings. All of these parameters must be provided to the enforcement algorithm once per second. Additionally, when the enforcement algorithm determines an enforcement brake application is necessary, there must be a method for communicating this to the train model. The communications interface between the TCL and the enforcement algorithm enables these functions.

The TCL and enforcement algorithm communicate over a TCP/IP interface, as the diagram in Figure 7 shows. The TCL and TOES™ applications are run on a single computer and communicate using Windows API messages. The enforcement algorithm application can be run either on the same computer or on another computer connected by an Ethernet connection. If the enforcement algorithm is run on the same computer as the TCL and TOES™, the TCL can automatically start the enforcement algorithm, allowing for automated testing of large batches of simulations.

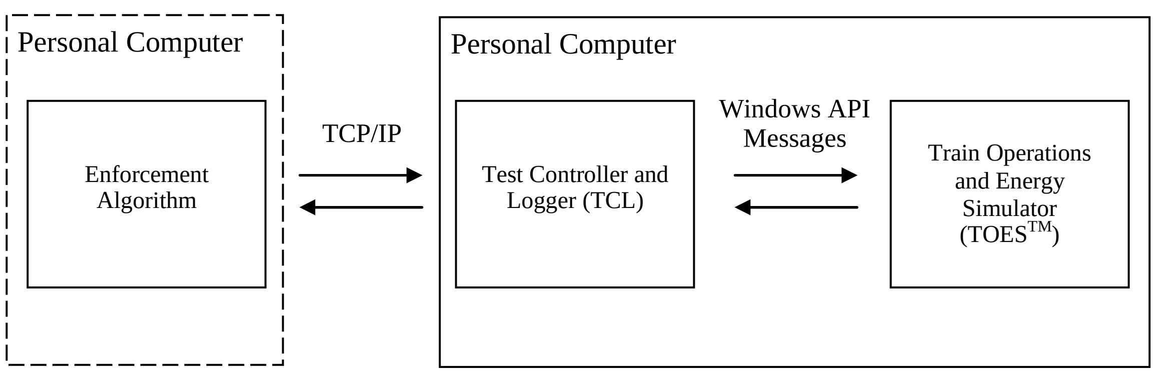

Figure 7. Block Diagram of Communications Between an Enforcement Algorithm and the Simulation Test Environment

During normal simulation operation, the TCL sends a message containing train status information, as discussed above, to the enforcement algorithm once every second (simulation time). The TCL then waits for the enforcement algorithm to send back a message indicating the enforcement algorithm health status and potentially a request to initiate a brake application. If the message does not contain a brake application request, the TCL sends a command to the TOES™ application to advance the simulation by one second and waits for the TOES™ application to respond. The parameters—returned to the TCL in the TOES™ response—are delivered to the enforcement algorithm in the next message. This process is repeated until a brake application request is sent by the enforcement algorithm.

When the enforcement algorithm sends a message containing a request to initiate a brake application, the TCL sends a command to TOES^{TM} to initiate the brake application in the model. The simulation is then carried on, with TOES^{TM} continuing to update the TCL on train status information and the TCL forwarding this information on to the enforcement algorithm. This process is continued until the train comes to a stop. When the enforcement algorithm has completed running (i.e., train velocity is less than 0.5 mph), a final message is sent to the TCL indicating the enforcement algorithm has completed.

3 Parametric Study of Variables Affecting Stopping Distance

Numerous variables affect train stopping distance. In developing an enforcement algorithm that predicts train stopping distance, understanding the effects of these variables is important to determine which variables must be known, what level of accuracy is needed, and to compensate for unknown variables. A parametric study of some of the major contributors to stopping distance provided insight into the effects these variables have on stopping distance. This section describes the objectives, methodology and results from the parametric study.

3.1 Parametric Study Objectives

The high-level objective of the parametric study was to gain an understanding of the effects of some of the variables that affect stopping distance. Specifically, the parametric study sought to:

- Determine the relative impact on stopping distance of certain variables to identify which variables have the most significant effect on stopping distance,
- Determine the absolute range of stopping distances, based on the independent variation of certain variables, for different test scenarios, and
- Analyze the potential impact on stopping distance prediction if worst-case assumptions are used for various parameters.

3.2 Parametric Study Scope

Due to the large number of possible freight car types, and the large number of variables that can affect stopping distance, a complete parametric study of variables that affect stopping distance would be a considerable effort. Although this may be ultimately necessary to develop an ideal enforcement algorithm, the purpose of this study was to provide a general understanding of some of the more significant parameters. Therefore, the train types investigated in this study were limited to unit and general freight trains as discussed in subsection 3.3.2, and the number of variables considered in detail was limited as discussed in subsection 3.3.1.

3.3 Parametric Study Methodology

The parametric study made use of the TCL operating in stop distance test mode, as described in subsection 2.1.1, to analyze the sensitivity of stopping distance to various train consist parameters. This section describes the process of selecting parameters to investigate, developing the test matrix, determining the variability of each parameter, running the tests, and analyzing the output data.

3.3.1 Selection of Input Parameters

To study the potential sources of variability in stopping distance, many potential parameters were investigated on a conceptual level. Table 1 shows a list of the potential parameters that was compiled based on experience and conversations with industry experts.

Table 1. Parameters That Can Potentially Affect Train Stopping Distance

Location	Speed	Track Grade
Track curvature	Initial Brake Pipe Pressure	Brake Pipe Pressure Gradient
Number and Order of Cars	Train Length	Weight/Locomotive
Weight/Car	Potential Braking Force/Car	Potential Braking Force/Locomotive
Brake Valve Type/Car	Brake Pipe Length/Car	Brake Rigging Type/Car
Brake Shoe Type/Car	Dimensions/Brake Cylinder/Car	Piston Stroke/Brake Cylinder/Car
Aerodynamic Drag/Car	Bearing Friction Resistance/Car	Rolling Resistance/Car
Ambient Pressure	Ambient Pressure	Operative Brakes/Car

For each of the parameters listed in the table, the following were considered on a conceptual level:

- Accuracy to which the parameter is typically known in current PTC systems,
- Accuracy to which the parameter could be known and difficulty in obtaining this level of accuracy,
- Potential variability of the parameter from the assumed value, and
- Effect that the variation of the parameter could have on stopping distance.

Four of the parameters were selected for further investigation in this parametric study on the basis of the considerations listed above:

- Weight/Car–the gross weight of the car. This is defined as the total weight of the car, including lading.
- Brake Valve Type/Car–the brake valve type of the car. The brake valve is a device mounted on each car that compares the pressure in the train line brake pipe to the auxiliary reservoir on the car. Based on this comparison, the brake valve allows air to move between the various reservoirs to apply, release, or hold a brake application.
- Piston Stroke/Brake Cylinder/Car–the distance the brake cylinder piston travels when a brake application is made. The brake cylinder piston pushes the brake shoes, through a system of lever rods, against the wheels when a brake application is made.
- Potential Braking Force/Car–this is defined as the sum of the forces applied to the wheels by the brake shoes with 50 psi in the brake cylinder.

3.3.2 Development of the Parametric Study Test Matrix

The parameters listed above can have a varying effect on stopping distance based on the specific train operating scenario. For example, varying the brake valve type on every car of a 100-car train may have a significant impact on the stopping distance of the train, whereas varying the brake valve type on every car of a 10-car train may have very little impact. Therefore, testing the sensitivity of stopping distance to each of the parameters is necessary in a variety of operating scenarios.

To develop the operating scenarios under which to test the various parameters, several test variables were selected and reasonable values for each of the test variables were determined. Table 2 shows the test variables and the values they can hold. The table is separated into two train types, general freight and unit freight. The general freight train was defined as a combination of 100-ton box cars, tank cars, hopper cars, gondolas, and single platform flat cars. The unit train was made up of 110-ton aluminum coal hoppers. Taking every combination of the test variables resulted in 96 test scenarios.

Four tests were designed for each of the 96 test scenarios. In each of the four tests, one of the braking parameters listed above was allowed to vary within a specified range, while the other three were held constant at a nominal value. Thus, the stopping distance sensitivity to each of the four parameters was tested in each of the 96 test scenarios, resulting in a test matrix of 384 tests. The complete test matrix by test ID, along with train definitions for each test scenario, is contained in Appendix B.

Table 2. Parametric Study Test Variables

Train Type	Test Variable	ID	Value
General Freight	Train Length	Short	10 cars
		Medium	40 cars
		Long	100 cars
	Train Load	Loaded	263k/car
		Empty	64k/car
	Train Speed	Fast	60 mph*
		Slow	10 mph
	Track Grade	Flat	0%
		Incline	1%
		Decline	-1%
		Crest	0.5% to -0.5%
		Trough	-0.5% to 0.5%
	Train Power	Head end	3 AC4400 (long), 2 SD40 (short, med)
Unit Freight	Train Length	125 cars	125 cars
	Train Load	Loaded	286k/car
		Empty	45k/car
	Train Speed	Fast	60 mph*
		Slow	10 mph
	Track Grade	Flat	0%
		Incline	1%
		Decline	-1%
		Crest	0.5% to -0.5%
		Trough	-0.5% to 0.5%
	Train Power	Head end	4 AC4400
		Distributed	2 AC4400 at head, 2 AC4400 at rear

* Fast speed = 40 mph for downgrades, max speed for inclines, and not used for unit freight on 1% incline

3.3.3 Determination of Variability of Input Parameters

To accurately model the sensitivity of stopping distance to each of the selected parameters, the nominal value and variability of each parameter must be known for each car type considered. For the weight/car parameter, data from wheel impact load detector (WILD) sites in various parts of the country was used.

For the general freight cars, the data set included 100-ton cars traveling over WILD sites in Bagdad, California (BNSF Railway), Millican, Texas (Union Pacific Railroad), and Mill Creek, Pennsylvania (Norfolk Southern Railway), over a 1-year period for a total of 221,311 cars. The gross weights for the sample of cars were sorted into a histogram, and the mean and sample standard deviation were used to fit the data to a normal distribution, which is overlaid on the histogram data, as Figure 8 shows. The data indicates that, for general freight cars, approximately 99.7 percent (3 standard deviations) fall within approximately +/- 10 percent of the mean weight.

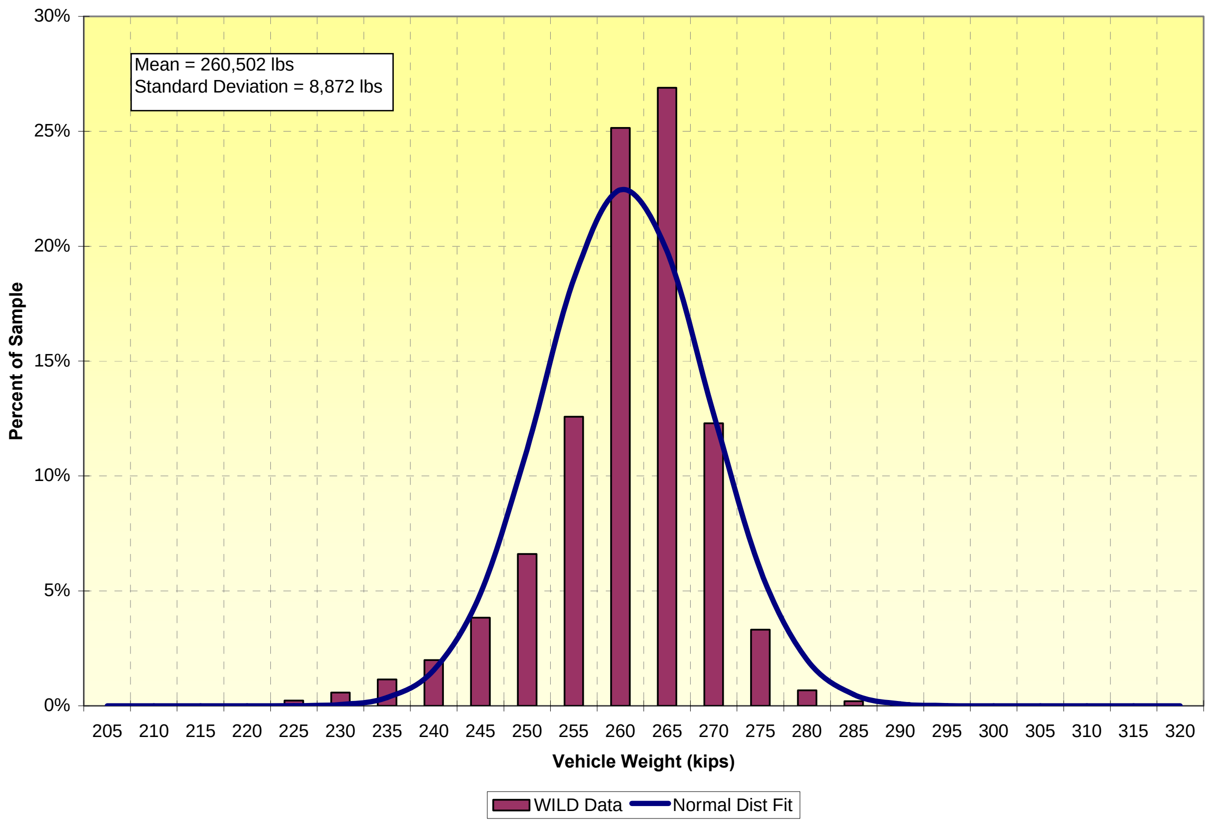

Figure 8. Distribution of Vehicle Weights for Loaded 100-ton Cars Traveling Over Three WILD Sites Over a One-year Period

For the unit train cars, the data set included 110-ton coal cars travelling over the WILD site at Martin Bay, Nebraska (UP) over a 1-year period for a total of 12,791 cars. As with the general freight data, the mean and sample standard deviation were calculated, and used to create a normal distribution, which was overlaid on a histogram of the original data, as Figure 9 shows.

For unit coal cars, the data indicates that approximately 99.7 percent (three standard deviations) fall within approximately +/- 3.5 percent of the mean weight.

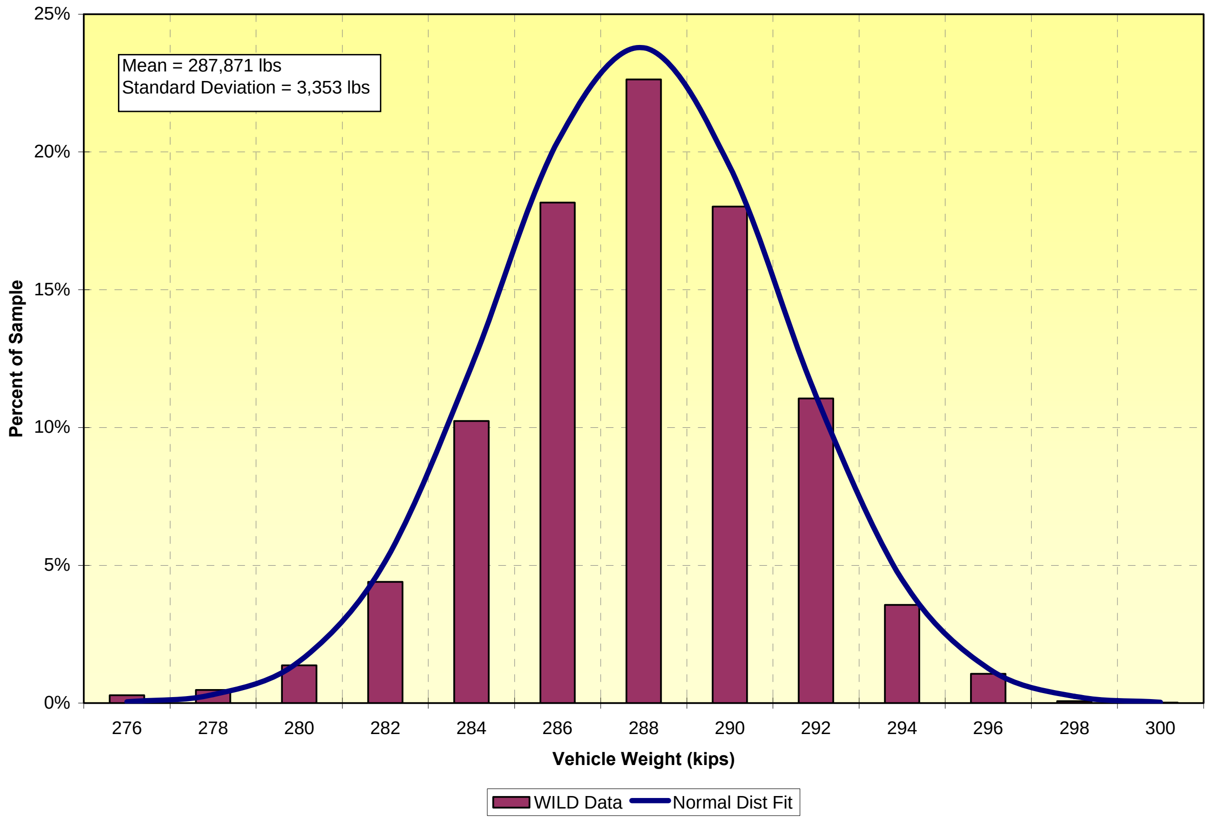

Figure 9. Distribution of Vehicle Weights for Loaded 110-ton Cars Traveling Over a WILD Site Over a One-year Period

For the brake valve type/car parameter, data was not readily available on the distribution of brake valve types for the various car types. Therefore, experience and conversations with industry experts were used to identify a reasonable estimate of this distribution. For general freight cars it was assumed that, given a randomly selected car, a 40 percent probability exists that it will contain an ABD (or similar) type brake valve, a 30 percent probability it will contain an ABDW (or similar) type brake valve, and a 30 percent probability it will contain an ABDX (or similar) type brake valve. For unit trains, a 50 percent probability was assumed that a randomly selected car will be equipped with an ABDW (or similar) type brake valve, and a 50 percent probability it will be equipped with an ABDX (or similar) type brake valve.

For the final two parameters, piston stroke/brake cylinder/car and potential braking force/car, data was again not readily available, but the AAR *Manual of Standards and Recommended Practices* and the *Field Manual of the AAR Interchange Rules* provide an indication of the allowable range for each of these parameters.[2,3]

For the piston stroke/brake valve/car parameter, Rule 3 in the *Field Manual of the AAR Interchange Rules* indicates initial set-up values and nominal piston travel for various types of brake cylinders.[3] For this study, the assumptions were that general freight cars contain standard 10- X 12-inch body mounted brake cylinders and that unit freight cars contain Wabco TMX truck-mounted brake cylinders. According to Rule 3, the piston stroke for the standard 10- X 12-inch brake cylinder is set to 7-1/2 inches (in) with a tolerance of +/- ¼ in and can nominally vary between 7 in and 9 in, and the piston stroke for the Wabco TMX brake cylinder is set to 2 in with a tolerance of +/- 1/8 in and can nominally vary between 1-1/2 in and 3 in. Recognizing that some cars may have brake cylinders with piston strokes outside the specified ranges, piston stroke was assumed to vary within a normal distribution about the initial set position, with the upper limit of the nominal variance assumed to be three standard deviations from the mean for each type of brake cylinder.

To determine a reasonable range for the potential braking force/car parameter, section 4.1 of S-401 in the AAR *Manual of Standards and Recommended Practices* was referenced.[3] This section indicates the allowable range of both loaded and empty braking ratios for cars built new, rebuilt, or converted from cast iron to composition brake shoes. The loaded braking ratio is defined as the net brake force with a 30-pound-per-square-inch (psi) brake pipe reduction from a nominal 90-psi brake pipe divided by the gross rail load (GRL) of the vehicle, while the empty braking ratio is defined as the net brake force with a 30-psi brake pipe reduction from a nominal 90-psi brake pipe divided by the tare weight of the vehicle.

In the case of general freight cars not equipped with empty/load equipment, the lowest allowable braking force is limited by the lower limit of the loaded braking ratio, 8.5 percent, while the highest allowable braking force is limited by the upper limit of the empty braking ratio, 38 percent. For a vehicle with a 64,000-pound tare weight and 263,000-pound GRL, this results in a potential brake force/car range of 22,355 pounds of force (lbf) to 24,320 lbf. Recognizing that some cars may have braking ratios outside this range, it was assumed that the potential braking force/car for general freight cars is normally distributed about the center of this range (23,338 lbf), with the limits of this range assumed to be three standard deviations from the mean.

For unit coal cars equipped with empty/load equipment, the braking force for a loaded car and for an empty car must be determined separately. For new cars, the loaded braking ratio is specified to be between 11 percent and 14 percent. It was assumed from this data that the potential braking force/car for a loaded unit freight car with a 286,000-pound GRL would follow a normal distribution with a mean at the center of this range (12.5 percent or 35,750 lbf), with the limits of this range assumed to be three standard deviations from the mean. The empty braking ratio for new cars is specified to be between 15 percent and 32 percent. It was assumed from these figures that the potential braking force/car for an empty unit freight car with a 45,000-pound tare weight would follow a normal distribution with a mean located at the center of this range (23.5 percent or 10575 lbf), with the limits of this range assumed to be three standard deviations from the mean.

3.3.4 Execution of Parametric Study Tests

Having identified the test scenarios, parameters of variation and their associated variances, the tests were executed individually using the TCL software, in conjunction with the TOES™ model, as described in subsection 2.1.1. For each test, the track was selected and the nominal test consist was setup according to the test matrix described in subsection 3.3.2. The parameter of interest was then selected to vary according to the range specified in subsection 3.3.3. Each test was made up of 100 individual simulations, which defined the simulation set for that test. Each simulation within that simulation set was run with a unique consist, wherein each car had a different value for the parameter of interest, as described in subsection 2.1.1.

3.4 Parametric Study Results and Conclusions

The result of each of the simulations in the parametric study is a single stopping distance for the specific train generated by the TCL for the given speed and track profile. By grouping all of the simulations in a simulation set together, it is possible to generate a distribution of stopping distances for the nominal train, speed and track profile specified for that simulation set. Analysis of these stopping distance distributions can provide information about the effect of the varied parameters on stopping distance.

To illustrate the distribution of stopping distances for a given simulation set, the mean and standard deviation of the stopping distances were calculated and used to plot the probability density. Figure 10 shows an example of stopping distance distribution for a long, loaded, mixed freight train traveling 60 mph on level grade with brake valve type as the varied parameter.

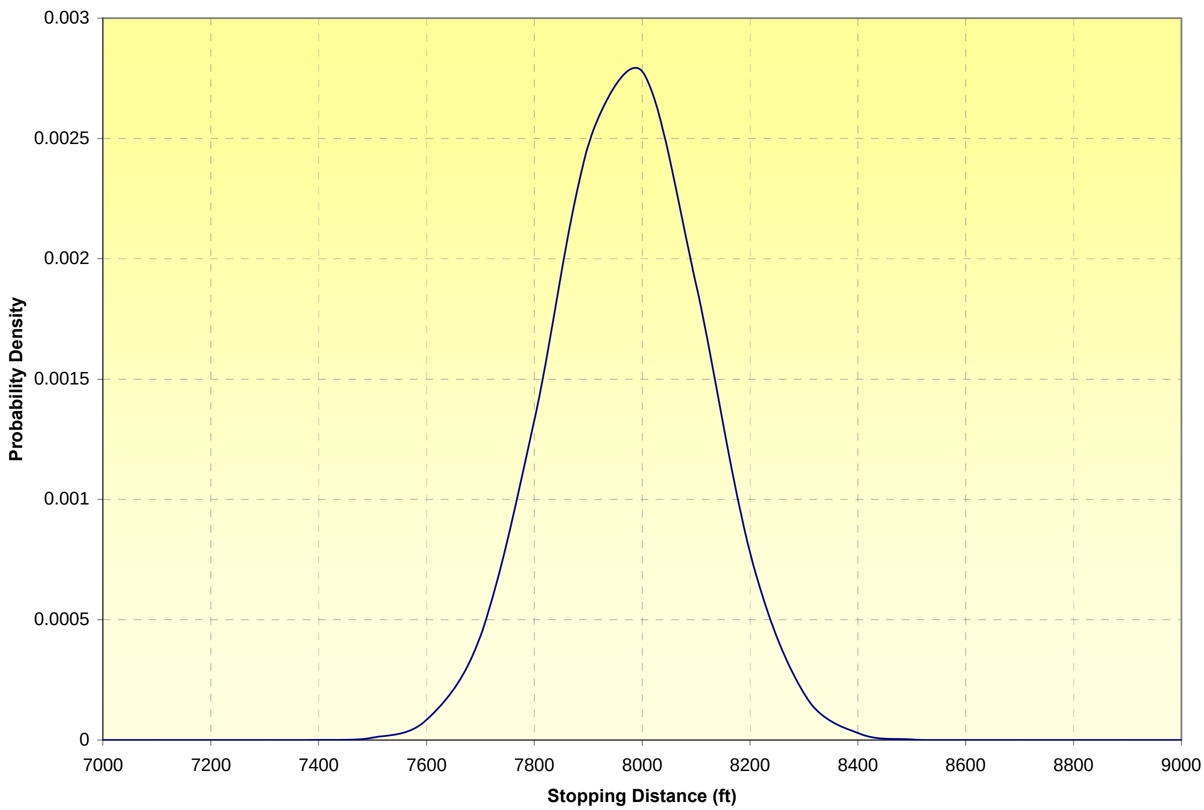

Figure 10. Stopping Distance Distribution for a Long, Loaded, Mixed Freight Train Traveling 60 mph on Level Grade with Brake Valve Type Varied

By grouping simulation sets by test scenario and plotting each group on a single chart, comparison of the relative effect of each independent parameter is possible for the given test scenario. Figure 11 shows an example of the stopping distance distribution for each of the varied parameters for a long, loaded, mixed freight train traveling 60 mph on level grade.

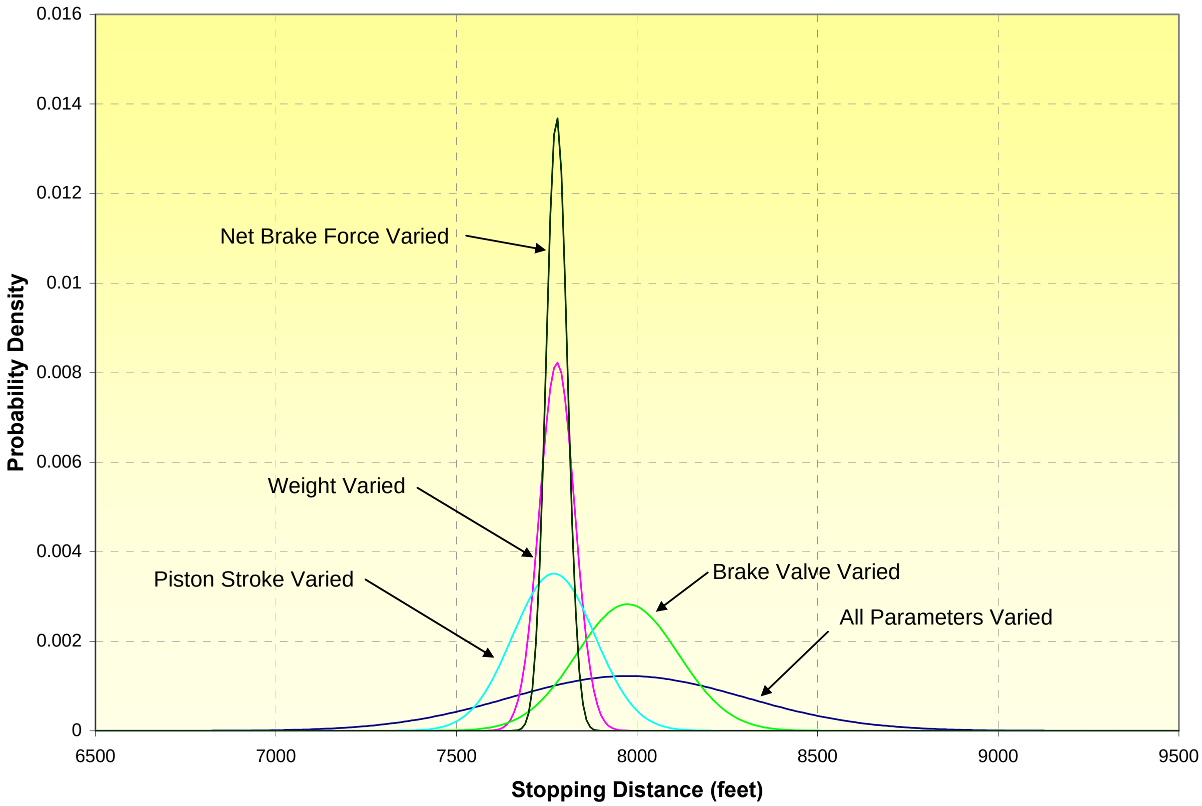

Figure 11. Stopping Distance Distributions for a Long, Loaded, Mixed Freight Train Traveling 60 mph on Level Grade with Various Parameters Varied

For the four parameters investigated, Figure 11 shows that uncertainty in brake valve type had the largest effect on stopping distance in this operating scenario. Brake cylinder piston stroke also had a relatively significant effect, while weight and net brake force had relatively less impact on stopping distance.

An interesting note about the chart in Figure 11 is that the stopping distance distribution generated by varying brake valve is centered on a different point than the others. This is due to the method of independent variation of the parameters. Brake valve type can only be one of three values, ABD, ABDW, or ABDX. If all else is held equal, the stopping distance of a train containing all ABDW brake valves will be between the stopping distance of the train if it contained all ABD brake valves or all ABDX brake valves, but it will not be centered directly between the two. This means that if brake valve type is allowed to vary, it will produce a mean value different from the value produced by assuming all brake valve types are of the nominal (ABDW) type. When the parameters are varied independently, nominal values are used for the parameters that are not being varied, including ABDW brake valve types. Therefore, when the brake valve parameter is allowed to vary, the mean is shifted.

Appendix C contains charts similar to the one in Figure 11 for all of the operating scenarios from the parametric analysis. These charts are useful for quickly observing the relative effects of the various parameters for different operating scenarios.

By further grouping the simulation sets into groups of similar test consists, trends can be observed within the data. To enable observation of more simulation sets together, it is useful to graph the standard deviation of the stopping distances of each simulation set together, rather than plotting the entire distribution. An example of this is shown in Figure 12 for a long, loaded, mixed freight train. In Figure 12, each column represents the standard deviation of the stopping distance for an individual simulation set. The columns are grouped by track profile and speed.

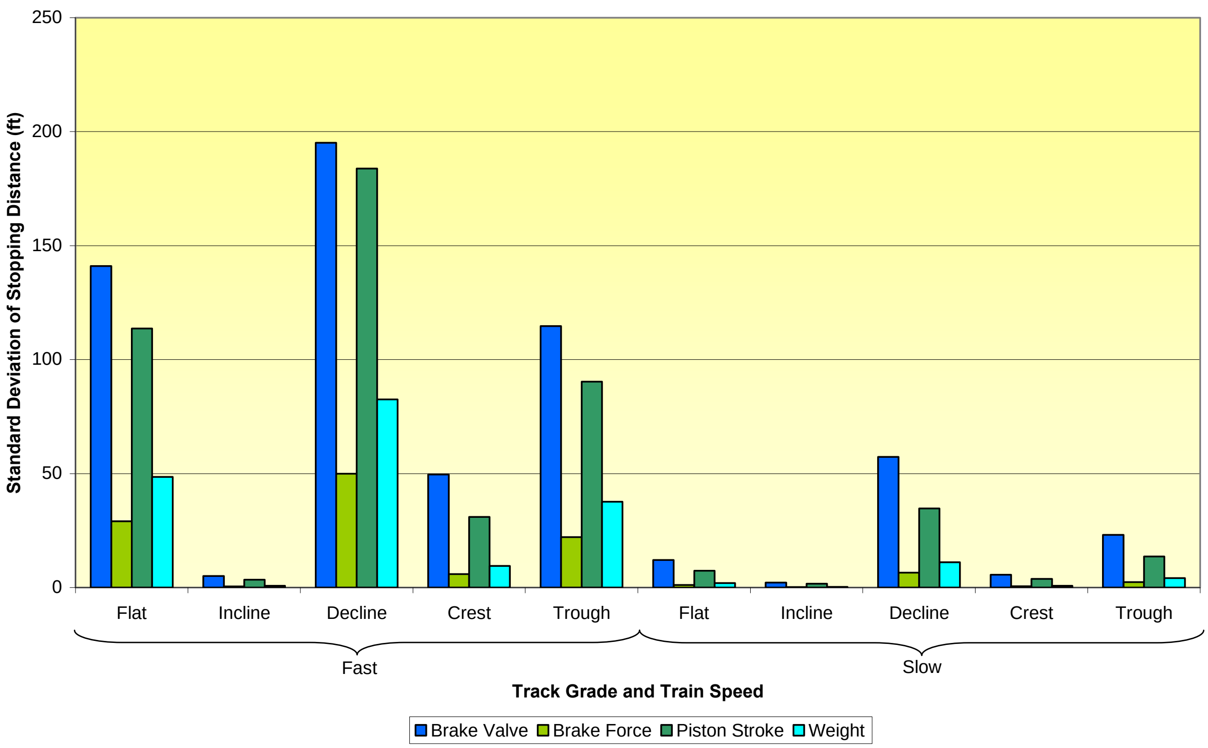

Figure 12. Standard Deviations of Stopping Distance for a Long, Loaded, Mixed Freight Train for Various Test Scenarios

The data in Figure 12 indicates that, for all of the parameters, the effect on stopping distance is more pronounced on a decline, and relatively insignificant on an incline. This trend follows for other train types as well, indicating that stopping distance prediction is more difficult on a decline than on an incline.

Figure 12 data also confirms that for this train type, brake valve had the largest effect on stopping distance. This trend, however, is not consistent for all train types. For example, Figure 13 shows a similar column chart of standard deviations of stopping distances for the short, loaded, mixed freight train tests. This chart clearly indicates that brake valve type is the least significant parameter for this train type. To provide a logical explanation for this, an understanding of how brake valve type affects stopping distance is needed. Brake valve type affects the propagation time of the brake signal, which affects the time it takes for the braking force to build up. On a short train, this time is relatively short, and changing brake valve types has much less of an effect than on a long train, where propagation time is significant.

Other similar trends can be observed by looking at column charts of standard deviations of stopping distances for all of the parametric study tests. All of these charts can be found in Appendix D.

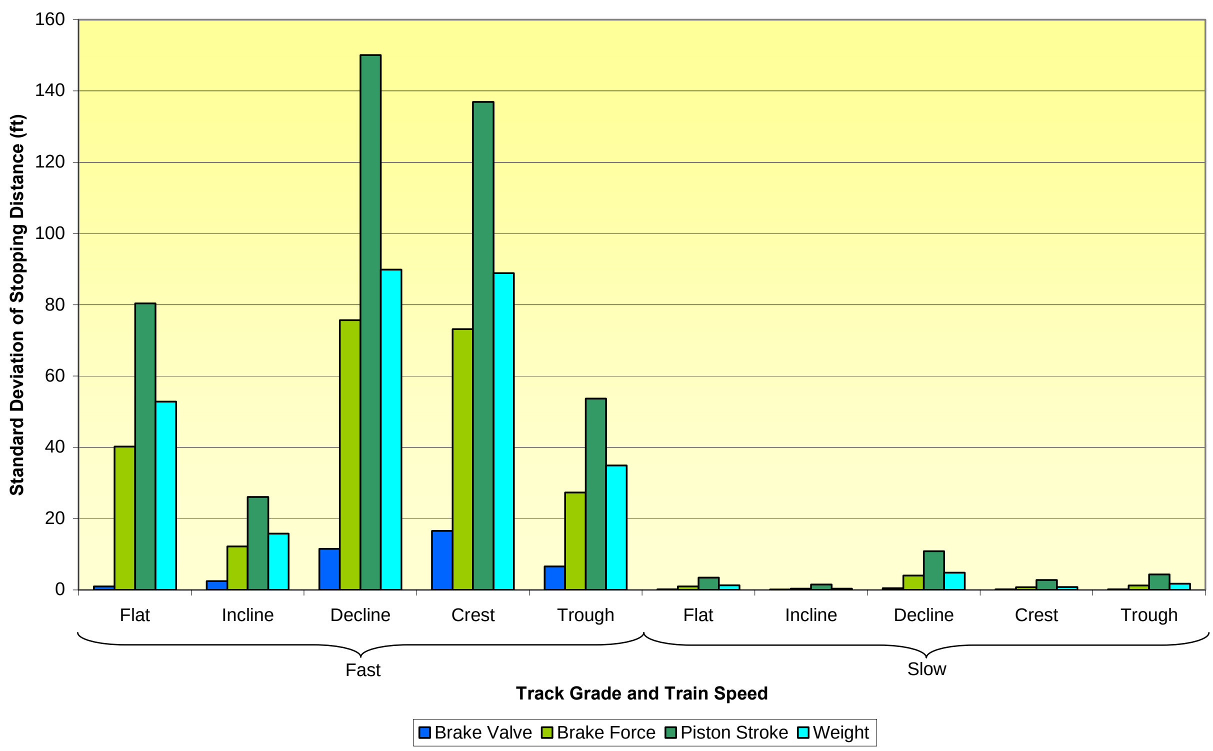

Figure 13. Standard Deviations of Stopping Distance for a Short, Loaded Mixed Freight Train for Various Test Scenarios

Observations from the data contained within the charts presented thus far reveal that the relative significance of the parameters tested is dependent on the specific operating scenario. This is important for enforcement algorithm development, as it illustrates the need to consider all parameters rather than focusing on one or two. The design of a method for determining a reasonable safety offset based on train type, speed, and track profile may also benefit from these observations.

In addition to observing the effects of the various parameters relative to each other, another of the objectives of the parametric study was to determine the absolute range of stopping distances due to independently varying each of the given parameters. This can be done by looking at the simulations that contain all best-case values and the simulations that contain all worst-case values for each simulation set. For example, the simulation set for a long, loaded, mixed freight train traveling 60 mph on level grade with piston stroke as the varied parameter included one simulation where every car was assigned a 6-inch piston stroke and another where every car was assigned a 9-inch piston stroke. The stopping distance for each these simulations was 7,107 ft and 8,661 ft, respectively. This equates to an absolute range of stopping distances of 1,554 ft, due to the variation of piston stroke for this test scenario.

Although this value, based on the assumption of best and worst case values for all cars in the train, indicates the possible range of stopping distances, it may not indicate the statistically realistic range of stopping distances. To illustrate this, Figure 14 shows a histogram of the 100 simulations from this simulation set. It shows the bulk of the simulations resulted in stopping distances between 7,700 and 7,900 ft (i.e., a range of 200 ft), which is much tighter than the 1,554-foot range of the absolute best and worst case simulations.

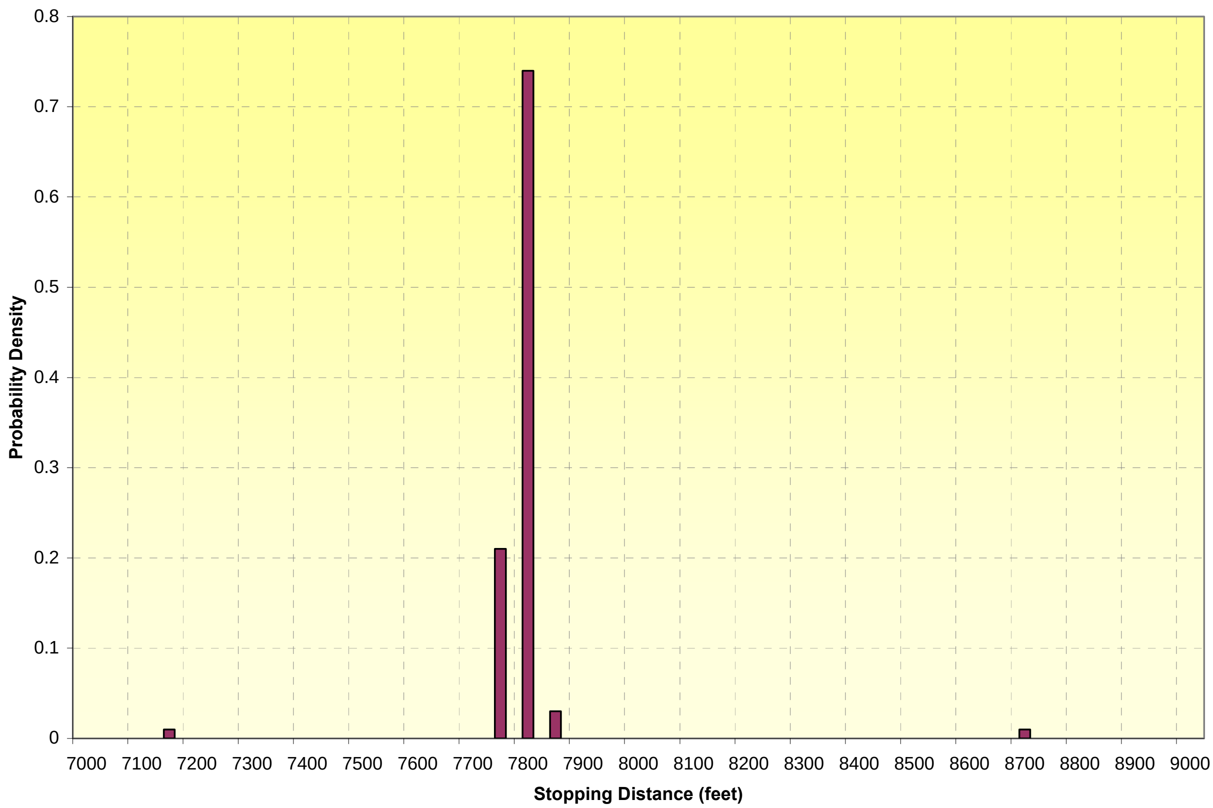

Figure 14. Histogram of Stopping Distances for a Long, Loaded, Mixed Freight Train Traveling 60 mph on Level Grade with Piston Stroke Varied

A more statistically realistic range would be between points on the distribution that are three standard deviations on either side of the mean stopping distance. This is illustrated in Figure 15, where the distribution generated from the calculated mean and standard deviation has been overlaid on the histogram from Figure 14. The range between the points shown in Figure 15 is

682 ft, which is significantly less than the 1,554-foot absolute range, but still a factor of 3 larger than the 200-foot range shown in the histogram. The reason for this is that the mean and standard deviation of the sample were calculated using all 100 simulations from the simulation set, which includes the nominal, best and worst case simulations. Including the extremes in the calculation of the standard deviation has a significant effect due to the relatively small sample size of 100 simulations. This can be seen in Figure 16, which shows the distribution generated from calculating the standard deviation without using results from the nominal, best case, and worst case simulations overlaid on the distribution and histogram from Figure 15.

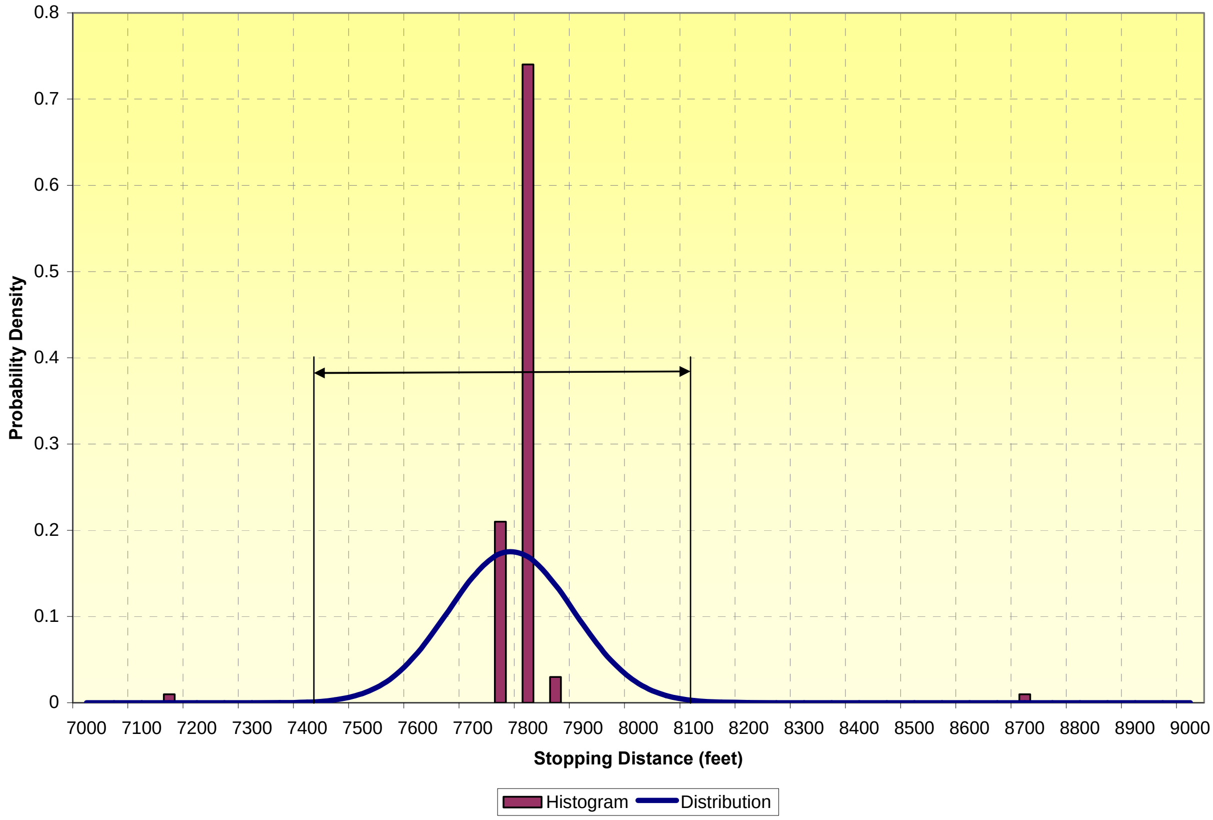

Figure 15. Comparison of Distribution of Stopping Distances against Histogram

The distribution shown in Figure 16 has a range of 125 ft between the points located three standard deviations on either side of the mean, and, as the figure shows, lines up closely to the histogram. This indicates that when calculating standard deviations for determining a statistically realistic range of stopping distances for a given operating scenario, care should be taken to include only the randomly generated tests, and that an increased sample size may also be beneficial.

Figure 16 also illustrates that, regardless which distribution is used, the best and worst case stopping distances should be considered extreme outliers from the distribution. Statistically speaking, the worst case is nearly six standard deviations from the mean if the wider distribution is considered and nearly 32 standard deviations from the mean if the narrower distribution is considered. While the exact number of standard deviations varies, this general theme is represented in all of the simulation sets, not just the example shown in Figure 16. The use of worst case assumptions can thus have a significant impact on the accuracy of stopping distance prediction, which can result in trains being enforced well before the train crew would normally take action, and stopping trains well short of the intended target. This conclusion is consistent with reports from PTC systems currently in use and under evaluation**.**

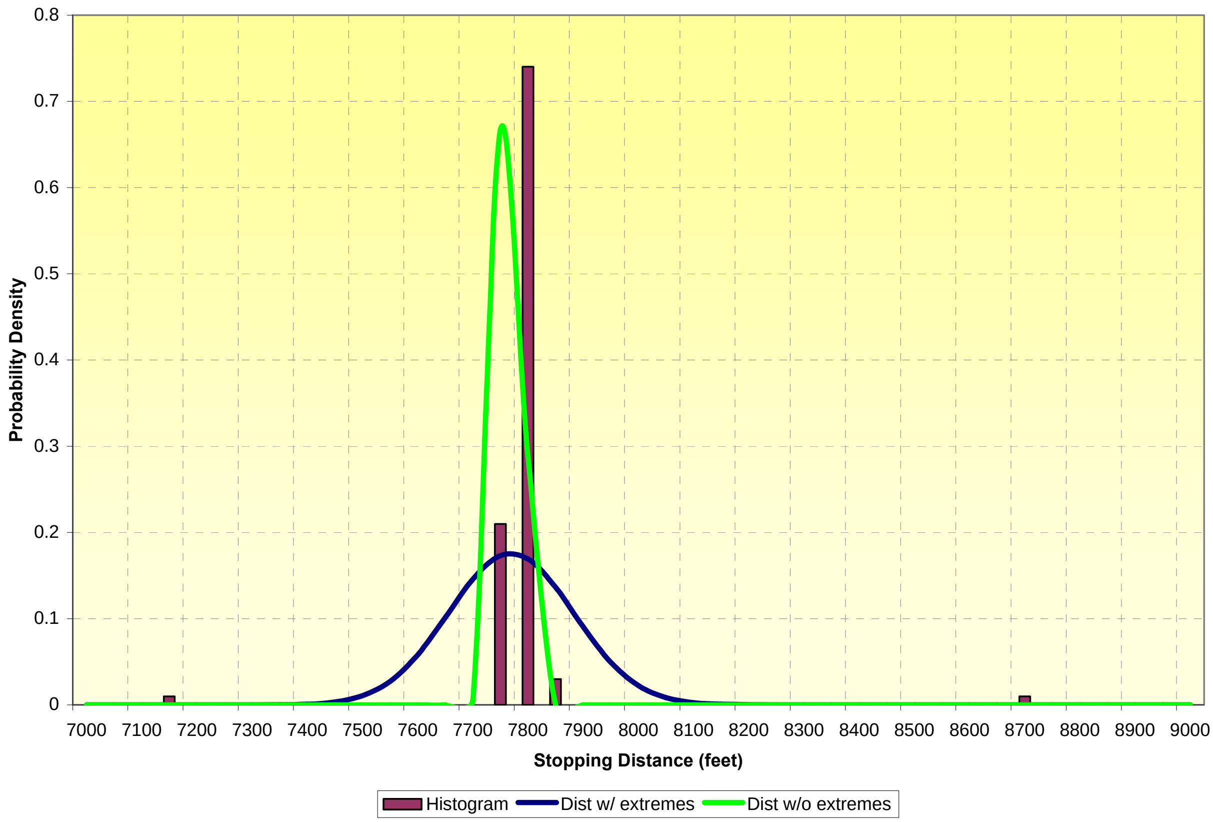

Figure 16. Comparison of Distribution of Stopping Distances Calculated Without Best and Worst Case to Distribution Calculated With Best and Worst Case and Histogram

If the narrower distribution from Figure 16 is considered, the effect of varying piston stroke on stopping distance appears to be somewhat insignificant with a standard deviation of only 21 ft. The reason for this is the method used to generate the trains for the simulations. By independently assigning a value for piston stroke to each car of a 100-car train based on a normal distribution, the mean of the values assigned will tend toward the mean of the normal distribution used to assign the values. Therefore, the mean piston strokes for each of the trains are approximately equal.

In other words, despite the fact that the piston stroke on each individual car can vary widely, the net effect on the entire train will be nearly the same for every simulation. This becomes more pronounced as the number of cars in the train increases (i.e., "law of large numbers"). Although the example given is for the piston stroke parameter, the brake force/car and weight/car parameters also exhibit the same characteristics, because they were varied in the same manner.

This understanding leads to several potential conclusions:

- The effect of each of these parameters can have a significant effect on stopping distance, but because of the large sample of cars within a single train, it is statistically unlikely.
- The assumption that each of these parameters varies within the constraints of a normal distribution is incorrect.
- The assumption that each of these parameters is independent from car to car, and independent of each other is incorrect. For example, if a car has a long piston stroke, it may be more likely to have a lower brake force as well if the car has not been maintained recently. Similarly, if a block of cars within a train all contain the same commodity, they will likely all be loaded the same in relation to the GRL of the car. These types of interdependencies are not considered in the method used in this study.

To identify which one or combination of these conclusions is accurate, additional research is needed. A more complete parametric study is recommended as a part of future work in this area. This study should include all (or as many as practical) of the variables listed in Table 1. The study should also use data collected from statistically random samples of revenue service trains whenever possible for determining accurate input distributions for each parameter. Finally, a more rigorous regression analysis needs to be performed to ensure that the interdependence of the parameters from car to car and from parameter to parameter is considered.

4 Base Case Enforcement Algorithm Development and Testing

The intent of this study was to develop methods for improving enforcement algorithm performance that could be implemented in any enforcement algorithm. However, to demonstrate the potential improvement from implementing the methods to be developed, an algorithm needed to be selected as a base case. The base case algorithm was tested unaltered to establish a baseline level of performance. The newly developed methods were then implemented in the base case algorithm and the algorithm was retested. The test results were compared to the baseline performance to provide an indication of the improvement due to the newly developed methods. This section describes the selection, implementation, and testing of the base case enforcement algorithm.

4.1 Base Case Enforcement Algorithm Selection and Description

The base case enforcement algorithm selected for this study is an algorithm designed by Wabtec Railway Electronics (WRE) and originally implemented by WRE with Lockheed Martin Corporation (LMC) for the IDOT PTC project, as part of the NAJPTC program. This algorithm is summarized in this section and more formally defined in "Braking and Prediction Algorithm Definition."[4] This algorithm is nonproprietary and has formed the basis for other PTC implementations, so it is considered to be a good baseline choice.

The enforcement algorithm estimates a conservative stopping distance for the train assuming a penalty brake application is initiated under the conditions at the moment the calculation is made. This estimate is made using a numerical integration method based on a force-acceleration model of the train. The stopping distance is then biased using a safety offset determined by the speed of the train at the initial conditions, to ensure an acceptable probability of stopping short of the target. If the stopping location determined from this method is beyond the authority limit of the train, a penalty brake application is enforced.

The components of the enforcement algorithm are grouped into five functional divisions:

- Set Parameters,
- Monitor Brake System,
- Monitor Grade,
- Calculate Braking Distance, and
- Enforcement.

The set parameters function establishes the parameters used in the stopping distance calculation. This includes externally defined parameters from the ground system (e.g., train length, train weight, number and types of cars), assumed parameters (e.g., car braking forces, brake valve types, percent operative brakes), and calculated or estimated parameters (e.g., brake application rate, train resistive forces).

The monitor brake system function uses head- and tail-end brake pipe pressure data from the locomotive onboard system to estimate the current state of the brake system. This involves estimating the auxiliary reservoir pressures based on whether the brakes are released, applying, applied, or recharging. This information is used to estimate the available braking force for the braking distance calculation.

The monitor grade function uses location data from the locomotive onboard system, along with data from the track database to estimate the track grade and curvature forces acting on the train at the current location for use in the braking distance calculation. The function assumes the train weight is distributed uniformly throughout the length of the train. A method for determining grade force on a train with a nonuniform mass distribution is described in the algorithm definition document but not currently implemented.

The calculate braking distance function uses data from the other functions to make the braking distance calculation. The algorithm relates the acceleration of the train to the forces acting upon it by the equation of motion defined by Newton's second law:

$$\sum F = -F_G - F_B + F_L - F_R = m_T a\,, \tag{1}$$

where F_G, F_B, F_L, and F_R are, respectively, the grade force, braking force, locomotive tractive effort, and combined resistive forces, m_T is the mass of the train and a is the acceleration of the train.

The locomotive tractive effort in the above equation is assumed to be zero for a penalty brake situation. The grade force in the above equation is determined from the monitor grade function and is a function of the location of the train at each given time interval.

The braking force is modeled as a two segment piecewise linear function of time, as illustrated in Figure 17. $F_{B\text{-}max}$ is the maximum available brake force for the train (determined from the monitor brake system function), F_{B0} is the brake force at the time of the penalty application (also determined from the monitor brake system function) and t_{appl} is the brake propagation time (as estimated in the set parameters function based on the length of the train).

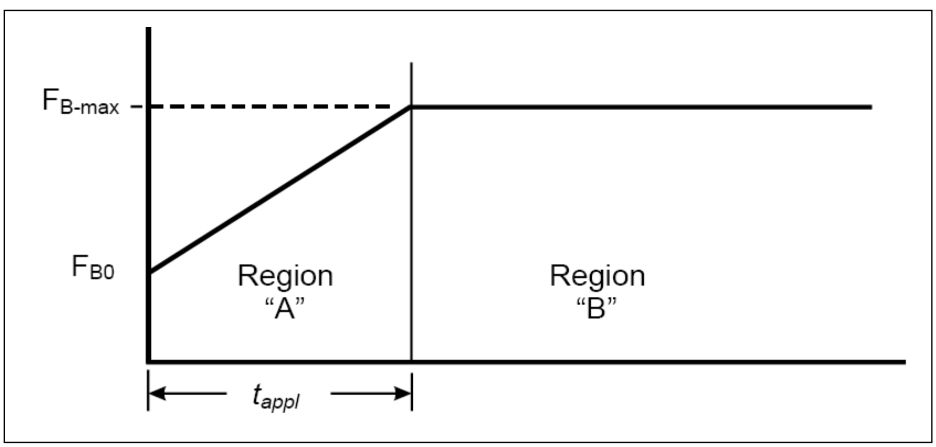

Figure 17. Braking Force vs. Time as Modeled by the Base Case Enforcement Algorithm

The resistive forces are estimated for a group of cars or locomotives by using a modified version of the Davis equation:

$$R = 0.6w + 20n + 0.01wv + 0.07Nv^2\text{, for freight cars and} \tag{2}$$

$$R = 0.6w + 20n + 0.01wv + 0.294Nv^2\text{, for freight locomotives,} \tag{3}$$

where R is the total resistive forces acting on the group of cars or locomotives, w is the weight of the group of cars or locomotives, in tons, n is the number of axles on the group of cars or locomotives, v is the velocity of the train, in mph, and N is the number of cars or locomotives in the group.

The algorithm solves the stated equation of motion for acceleration and integrates once and twice with respect to time to determine the change in velocity, Δv, and position, Δx, for each time interval, Δt. This numerical integration process is continued until the velocity, $v(t)$, is equal to zero, where the corresponding position, $x(t_{final})$, is the calculated stopping position and $x(t_{final})-x(t_{initial})$ is the calculated stopping distance.

The enforcement function calculates the safety offset and triggers the penalty brake application as necessary. The safety offset is calculated based on the initial speed of the train:

$$OFFSET = 145 + 0.025v + 0.5188v^2 \tag{4}$$

This offset is added to the previously calculated stopping location, and the result is compared to the authority limit of the train. If the predicted stopping location, with the safety offset included, is beyond the limit, the enforcement function triggers a penalty brake application.

4.2 Implementation of the Base Case Enforcement Algorithm

To test the performance of the enforcement algorithm and to enable the addition of the new adaptive methods, a functional software implementation of the algorithm was needed. The IDOT PTC implementation of the enforcement algorithm is embedded in the onboard computer software of the PTC system for which it was designed. Because of this, modifications were necessary to have the enforcement algorithm run as a standalone piece of software.

The interfaces between the enforcement algorithm and the input sensors, as well as the interface between the enforcement algorithm and the brake system, were also embedded as part of the onboard system. Therefore, modifications were also needed to allow inputs from—and to allow sending brake commands to—an outside source, such as the TCL or the field test equipment.

The IDOT PTC implementation also includes code necessary for the overall PTC system, but not necessary for independent enforcement algorithm performance testing. Therefore, modifications were also needed to simplify some of the code and eliminate some of the unnecessary functions.

The TTCI base case implementation of the enforcement algorithm includes two other modifications, in addition to those mentioned above. The IDOT PTC implementation of the algorithm assumes a worst case value of 85 percent operative brakes, which is the minimum allowed. However, because the train crew has to manually cut out the brakes on cars in the train, discussions are ongoing whether or not the percent operative brakes can be input by the train crew at the time the brake is cut out. By assuming 100 percent operative brakes and performing all of the tests with 100-percent operative brakes, the stopping distance prediction was evaluated independently of this parameter.

Additionally, the speed dependent safety offset described at the end of section 4.1 was removed in the TTCI implementation of the base case algorithm. The safety offset for a train traveling 60 mph is over 2,000 ft. The impact of this safety offset on the performance of the algorithm is that very few trains will stop within the performance specification (1,000 ft short of the target), and in fact, the predicted stopping distance will not be within this specification. Although a safety offset of some type will ultimately be necessary, by eliminating this offset for this study, the accuracy and performance of the stopping distance prediction algorithm, both with and without the adaptive methods, can be evaluated more precisely.

4.3 Base Case Enforcement Algorithm Testing

The objective of testing the base case enforcement algorithm was to establish the performance characteristics of the algorithm. This was quantified by measuring the following parameters:

- Proximity of stopping location to target stopping location. This value was measured and recorded for each test run. A mean value was then calculated for each test scenario from all of the test runs for that scenario.
- Repeatability of stopping location. This was determined by using the mean stopping location from each test scenario to determine the standard deviation and maximum deviation from the mean of the individual test runs.
- Probability of overshooting the target. This was calculated by dividing the number of runs where the stopping location was beyond the target location by the total number of test runs for each test scenario, expressed as a percent.
- Probability of undershooting the target by less than 500 ft for test scenarios under 30 mph, and by less than 1,000 ft for test scenarios above 30 mph. This was calculated by dividing the number of runs where the stopping location was less than the specified distance short of the target by the total number of test runs for each test scenario, expressed as a percent.

4.3.1 Enforcement Algorithm Test Methodology

To test the performance of the base case algorithm, a combination of simulation testing and field testing was used. The purpose of simulation testing was to test the enforcement algorithm using more test scenarios with a more statistically meaningful number of test trains than was practical with field testing. Therefore, the simulation testing was the basis for measuring performance and the field testing was used to validate the results of the simulation testing. In addition to the overall objective of evaluating the performance of the base case enforcement algorithm, the field test data was also used to validate the simulation testing and to develop the adaptive routines in the subsequent development tasks.

4.3.1.1 Simulated Testing

To develop the test matrix for simulation testing, several test variables were selected including train length, train load, initial train speed, and track profile. For each of these variables, several potential states were selected, and a value assigned to each state. Table 3 shows the test variables used to define the simulation test matrix. All the trains in the test matrix are defined as unit trains, which are made up of either aluminum or steel hopper cars, as defined in the table. A total of 70 test scenarios are defined by the possible combinations of variables in Table 3. Seven additional test scenarios were defined by the field test matrix and were also included in the simulation test matrix. Appendix E contains the complete enforcement algorithm evaluation simulation test matrix.

Table 3. Test Variables for Enforcement Algorithm Simulation Testing

Test Variable	ID	Value
Train Length	Short	75 cars
	Long	125 cars
Train Load	Loaded Steel	286k/car
	Empty Steel	64k/car
	Empty Aluminum	45k/car
Train Speed	Slow	10 mph
	Fast	60 mph*
Track Grade	Flat	0%
	1% Incline	1%
	1% Decline	-1%
	½% Decline	-0.5%
	Crest	0.5% to -0.5%
	Trough	-0.5% to 0.5%

* Fast speed = 40 mph for downgrades, max speed for inclines, and not used for loaded 1% incline

Each of the 77 test scenarios was tested using the TCL in enforcement algorithm evaluation mode, as described in subsection 2.1.2. Each test was setup by selecting the track and nominal test consist according to the test matrix. One hundred test consists were generated for each test scenario specified in the test matrix. For each of these test consists, the variable parameters for each car, discussed in subsection 3.3, were all allowed to vary according to the ranges specified in subsection 3.3.3.

Each test consist was started sufficiently far in advance of a target stopping location traveling at the initial speed indicated in the test matrix. The simulation was advanced one second at a time, with messages passed back and forth between the TOES™ model, the TCL, and the enforcement algorithm, as described in subsection 2.1.2. When the enforcement algorithm sent a message to initiate a penalty application, the brakes were applied in the model and the train came to a stop. The stopping location was recorded in the output data for the simulation to be used in the performance evaluation analysis.

4.3.1.2 Field Testing

The field test configuration is shown in Figure 18. A standard laptop personal computer (PC) containing the base case enforcement algorithm was placed in the lead locomotive of the test consist. The train control PC, normally used in testing at the Facility for Accelerated Service Testing (FAST), was used to provide input to the PC running the enforcement algorithm. This train control computer was also used to record speed, location, locomotive notch, and brake pipe pressure data throughout each test for use in determining when the brakes were applied, where the train stopped, and other characteristics of the test.

The test consist was instrumented to measure the following, which were read into the train control computer and used by the enforcement algorithm:

- Head-end brake pipe pressure using a pressure transducer located on the brake pipe on the lead locomotive.
- Tail-end brake pipe pressure using a two-way end-of-train (EOT) device. The EOT transmits the brake pipe pressure at the tail end up to a head-end unit located on the lead locomotive. However, due to difficulties interfacing the train control computer with the head-end unit, a data acquisition computer was mounted on the last car that interfaces the EOT unit through a serial RS-232 interface and transmits the tail-end brake pipe pressure to the train control computer over a wireless 802.11 interface.
- Train speed and location using a global positioning system (GPS) unit located on the lead locomotive. Train location was translated from the GPS coordinates into a footage referenced to the surveyed start point of the Transportation Technology Center (TTC) railroad test track (RTT) loop.
- Locomotive notch from the locomotive control stand.

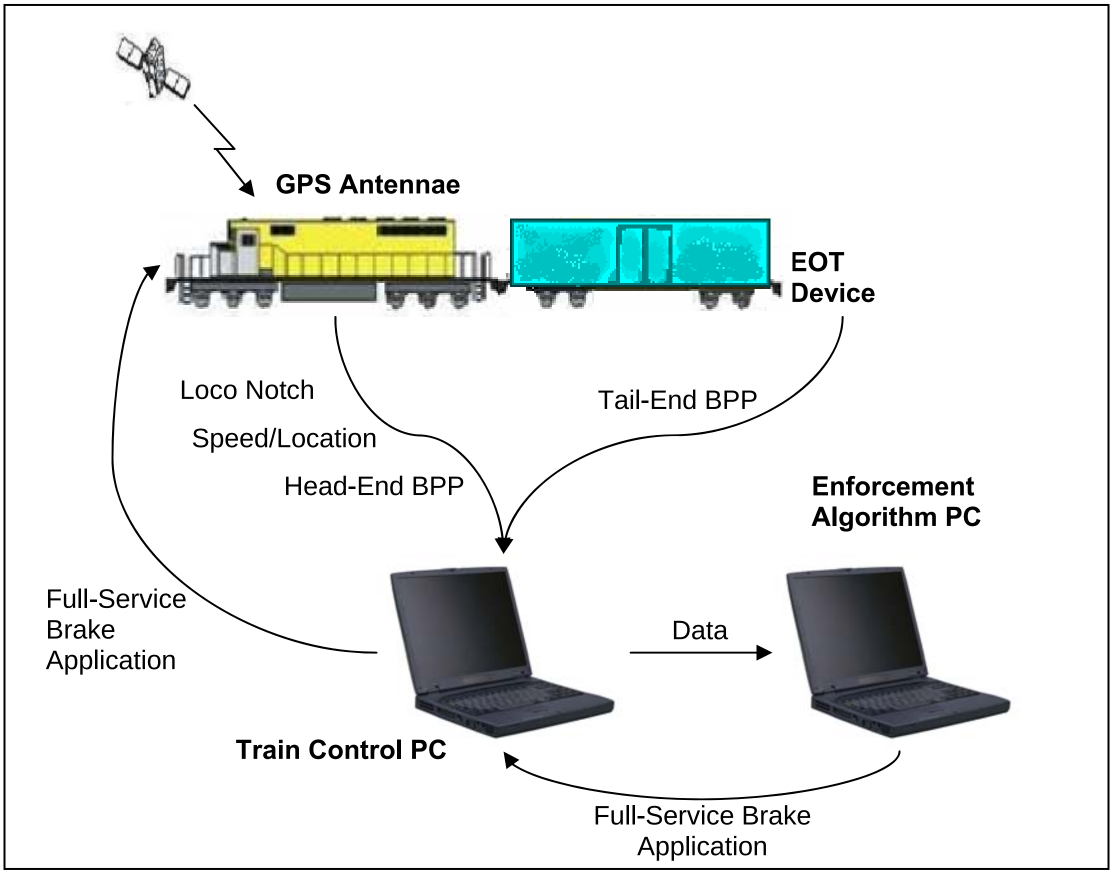

Figure 18. Field Test Configuration

In addition to the instrumentation listed above, the test consist was instrumented to measure the following, collected by a separate data acquisition computer:

- Tail-end brake pipe pressure using a pressure transducer. This was used as an independent method for verifying the accuracy of the EOT device.
- Coupler force on the rear locomotive using an instrumented coupler. This data was collected for later use in the train weight adaptive enforcement algorithm development.
- Periodic train location using an automatic location detector (ALD) tag reader and ALD tags surveyed at various points around the RTT. The ALD tag reader is a sensor mounted on the lead locomotive that is triggered when it moves over a reflective ALD tag. This was used as an independent method for verifying the accuracy of the GPS location.

A track file loaded on the enforcement algorithm PC contained surveyed grade and curve data for the RTT and was accessed by the enforcement algorithm as needed for stopping distance prediction. The enforcement algorithm PC interfaced with the train control PC over an Ethernet connection to receive train status data and to enforce a full-service penalty application when necessary.

The enforcement algorithm tests were run at various locations around the 13.5-mile RTT. Three test consists were used as Table 4 shows. The test consists were made up of cars used in the FAST train. The cars were a mix of steel and aluminum hoppers with a 315,000-pound rated GRL. The locomotive consists were made up of locomotives used in the FAST train and other locomotives available on site. The test consist was scaled to determine the exact weight of each car before the field testing.

Table 4. Field Test Consists

Consist ID Number	Train Load	Train Length
1	Loaded	Short (10 cars)
2	Loaded	Medium (40 cars)
3	Loaded	Long (80 cars)

The testing consisted of seven different test scenarios that challenged the performance of the base case enforcement algorithm under a range of operating conditions including varying train lengths, speeds, and grades. To determine the test scenarios, several distinct possible states were selected for each of these three independent test variables, and values were assigned to each state. Table 5 displays the variables along with their potential states and the values of each state. The states designated with “(N)” represent the nominal state for that test variable.

Table 5. Test Variables for Field Testing

Test Variable	ID	Value
Train Length	Short	10 cars
	Medium	40 cars
	Long (N)	75 cars
Train Speed	Fast	60 mph
	Medium (N)	40 mph
	Slow	10 mph
Track Grade	Flat (N)	-0.026%
	Incline	1.01%
	Decline	-1.47%
	Crest	0.79% to -0.62%

Ideally, every combination of test variables would be field tested. However, this would require 36 different test scenarios, which would take a considerable amount of time to field test. Therefore, a set of test scenarios was selected from the potential 36 that would test the extreme values of each test variable independently.

To achieve this set of test scenarios, each test variable was first assigned a nominal state, indicated by “(N)” in Table 5. Each test scenario was then defined by varying the value of one of the test variables and using the nominal value for the other three test variables. This resulted in seven different test scenarios, which Table 6 shows.

Table 6. Original Field Test Scenarios

Variable	Length	Speed	Grade
Length	Short	Medium	Flat
	Medium	Medium	Flat
Speed	Long*	Fast	Flat
	Long	Slow	Flat
Grade	Long*	Medium	Incline
	Long	Medium	Decline
	Long*	Medium	Crest

Due to the time it takes to test loaded 75-car consists, some of the long consists were replaced with medium consists. The scenarios for which this was done are indicated in Table 6 with an asterisk in the length column. The test scenarios were then sorted by consist makeup and assigned a test ID number. Table 7 shows the final test scenarios along with their associated test ID numbers.

Table 7. Final Field Test Scenarios

Test ID	Consist ID	Number of Cars	Speed	Grade
1	3	40	40	Flat
2	3	40	60	Flat
3	3	40	40	Incline
4	3	40	40	Crest
5	2	10	40	Flat
6	4	80	10	Flat
7	4	80	40	Decline

For each test scenario, a target stopping location was selected on the RTT that provided the proper track grade for the scenario. This location was entered into the enforcement algorithm, along with the generic consist information and other required inputs. An appropriate starting location was then determined, and the train was moved to this location to start each test run.

Before each test run, a standing brake test was performed. To perform the brake test, a 15-psi brake pipe reduction was made by the locomotive engineer and the brake pipe pressures were recorded by the test control PC. When it was determined that the brake pipe reduction had reached the end of the test consist, the brakes were released to begin the test run. The brake pipe pressure data collected from this brake test was used later in the development of the adaptive enforcement algorithm.

Following the brake test, the train was accelerated to the specified test speed. The train proceeded toward the target stopping location, with the enforcement algorithm monitoring the speed and location relative to the target. When the enforcement algorithm determined that an enforcement brake application was necessary to avoid overrunning the target, it signaled the control system to drop power, apply a full-service brake application, and bail the independent brake. The independent brake was bailed for all test scenarios, as the enforcement algorithm assumes the independent brake to be bailed for all trains except those less than nine cars in length. Once the train was stopped, the absolute stopping location was recorded and the location relative to the target was estimated and recorded before resetting the train for the next test run. Appendix H shows pictures from the field test.

4.3.2 Results of Base Case Enforcement Algorithm Testing

The output of any one enforcement algorithm test, whether run in a simulation or in the field, was a stopping location relative to the target stopping location. For the simulation tests, each test was repeated 100 times, with varying specific train characteristics. By looking at the relative stopping location of all 100 of these simulations together, it was possible to generate statistical data that provides an indication of the performance of the enforcement algorithm for the particular test scenario.

For the field tests, each test was repeated three times, at most, and each time with the same test consist. This sample size is not sufficient for generating statistical data about the performance of the enforcement algorithm for the particular test scenario. However, the field data can be used to validate the results of the simulation tests, as well as provide a general indication of the performance of the enforcement algorithm although not a statistically justified one.

4.3.2.1 Simulation Test Results

The mean and standard deviations of the stopping location were calculated from the individual stopping locations of each of the simulations for a single test scenario. This data was used to generate the probability density curve for the test scenario. This provides a graphical representation of the performance of the enforcement algorithm for each test scenario. Figure 19 shows an example of this for a 75-car loaded unit freight train traveling 60 mph on flat grade. The target stopping location for this example is 40,000 ft. This graph shows that the enforcement algorithm regularly stops the train well short of the target.

The performance measures discussed at the beginning of section 4.3 were used to statistically describe the performance of the enforcement algorithm for each test scenario. The mean stopping location relative to the target for this example was 3,006 ft, with a standard deviation of 303 feet. Zero percent of trains overshot the target, 1 percent of trains undershot the target by less than the specified 1,000 ft.

Appendix F contains stopping location probability density curves for all of the test scenarios in the test matrix. Appendix G has a table of the statistical data for each of the test scenarios in the test matrix. In both of these appendices, three test scenarios occur with no data. For these three test scenarios, keeping the train under control through the use of dynamic brake alone was not possible. Use of air brakes to control the speed of the train was considered outside of the scope of this study. Therefore, these test scenarios were not executed.

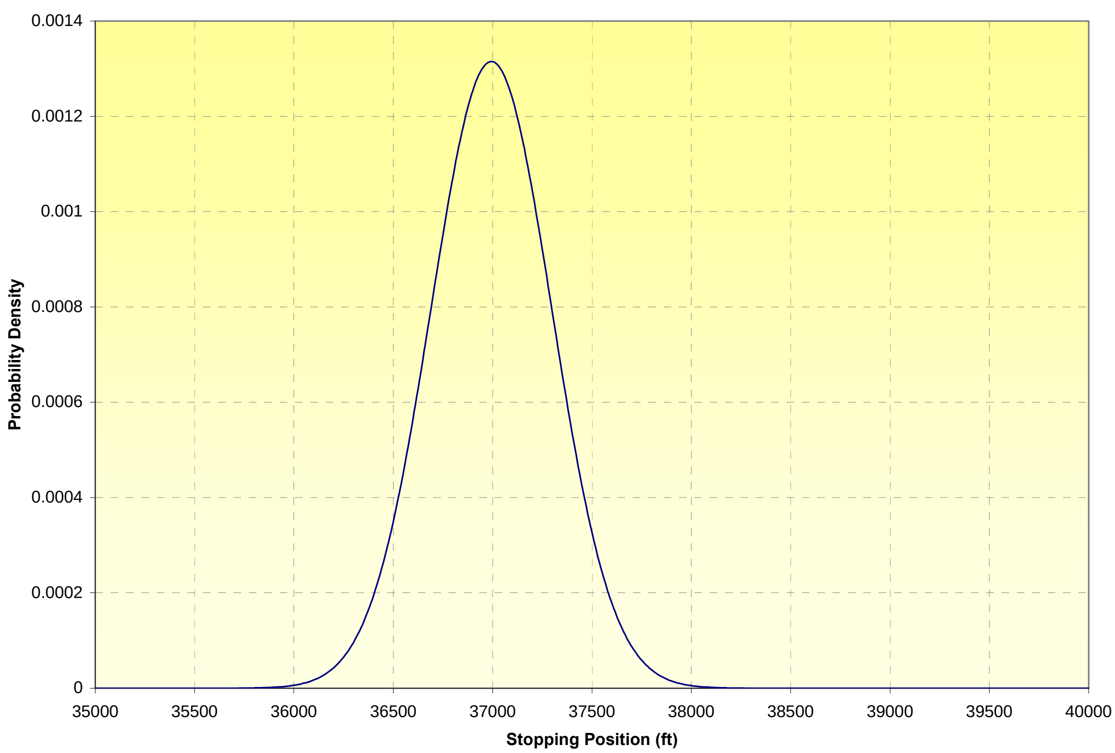

Figure 19. Stopping Location Probability Density Curve for a 75-car Loaded Unit Freight Train Traveling 60 mph on Flat Grade

By observing the data in Appendices F and G for all of the test scenarios together, some general statements about the performance of the base case enforcement algorithm can be made. First, the data shows that, in general, the base case algorithm performed well from the standpoint of the safety objective of stopping short of the target. Although the worst case train overshot the target in many of the cases, the worst-case train is statistically very unlikely, as discussed in the parametric study results section. Only two test scenarios resulted in any of the randomly generated trains overshooting the target. Both of these test scenarios had empty aluminum trains moving 10 mph up a 1 percent incline. The significance of each of these characteristics is discussed in the following paragraphs.

The data also indicates that the base case algorithm undershot the target by more than the specified amount in many cases. The empty aluminum test scenarios are one exception. This is primarily due to the empty/load devices present on aluminum hoppers. The empty/load device senses whether the vehicle is loaded or not, and limits the amount of pressure that is allowed to build in the brake cylinder if the vehicle is empty. This has the effect of limiting the amount of brake force produced by the vehicle, which prevents sliding the wheels on the lightweight aluminum cars. Because the base case enforcement algorithm has no knowledge of the empty/load device, it assumes a larger amount of braking force for these cars than is actually produced. This delayed the enforcement application more than would be the case if the actual brake force were known for trains made up of empty aluminum hoppers. This delayed enforcement had the effect of stopping some of the empty aluminum trains past the target in the 1-percent incline cases, as discussed earlier. If the braking efficiency of the train were measured, the effect due to empty/load devices could be minimized.

Another exception is the test scenarios on the 1-percent incline. Because a large amount of the retarding force on the train in these test scenarios is due to the grade, the enforcement algorithm can more accurately predict the stopping distance for these scenarios. This allowed the algorithm to be less conservative, which caused the trains to stop closer to the target. In the case of the empty aluminum trains, it also had the negative effect of stopping some of the trains past the target. Conversely, the enforcement algorithm was very conservative on the declined track, due to the difficulty in predicting stopping distance on a down grade, and therefore, many trains stopped well short of the target in these cases.

The final generalization made from the simulation results for the base case enforcement algorithm evaluation is related to the speed of the train. In most cases, the enforcement algorithm stopped the slow (10 mph) trains within both the safety and the performance objectives. In many of these cases, the standard deviation of the stopping distances was less than 50 ft, meaning that the enforcement algorithm could be conservative and still easily meet the performance objective of being less than 500 ft short of the target. The exception was on the 1-percent decline cases. An important note about the slow cases is that, although the algorithm met the performance objective of stopping within 500 ft of the target, a train pulling into a siding that is nearly as long as it is may have difficulty clearing all the way in if the algorithm is enforcing a penalty several hundred feet short of the target.

The results of the simulation testing are based on the assumptions for the parameters and their variances discussed in the parametric study section. The recommendation is that the actual parameters that can vary and their variances need to be examined more closely to provide a more accurate evaluation of the algorithm performance.

4.3.2.2 Field Test Results

The base case enforcement algorithm was initially field tested during the week of July 21, 2008. This test incorporated all the test scenarios described in the field test methodology, subsection 4.3.1.2. Each test was repeated three times to evaluate the repeatability of stopping location, given the same test conditions. Table 8 summarizes the results from the field evaluation of the base case enforcement algorithm.

Table 8. Base Case Algorithm Field Test Results from July 2008 Field Test

Test	Number of Cars	Mean Speed (mph)	Standard Deviation of Speed (mph)	Grade	Mean Distance to Target (ft)	Standard Deviation of Distance to Target (ft)
1	40	40.4	0.4	Flat	1,294	30
2	40	58.5	2.0	Flat	1,673	299
3	40	38.7	0.7	Incline	479	75
4	40	40.2	0.6	Crest	923	38
5	10	39.9	0.3	Flat	1,397	40
6	75	9.9	0.2	Flat	146	15
7	75	38.9	0.8	Decline	3,895	140

In general, the field test results confirm the conclusions drawn from the simulation tests. For example, the decline was the most conservative, which stops the train nearly 4,000 ft short of the target. Also, the enforcement algorithm stopped all of the trains short of the target, but in four of the seven test scenarios, it undershot the target by more than the specified distance. The cases where it did stop within the specified distance short of the target were the incline, crest, and slow cases, which agree with the simulation results.

As Table 8 shows, the standard deviation of the stopping location was relatively small in most cases. This indicates that the stopping distance for the exact same consist in relatively similar conditions is reasonably repeatable. This is particularly the case for scenarios 3 and 4, the incline and crest tests, and scenario 6, the slow speed test, which agrees with the conclusions drawn from the simulation testing. The largest standard deviation was on test scenario 2, the 60 mph test. This is likely due to the difficulty in getting the speed exactly the same for each test run, which is indicated by the large standard deviation in speed for this test.

5 Propagation Time Adaptive Algorithm Development and Testing

The purpose of the first of the adaptive developments to the base case enforcement algorithm is to adapt to the specific brake propagation time of the train. The brake propagation time of a train is defined as the time between when the penalty brake is applied and when full brake cylinder pressure is reached on all cars in the train (except the locomotives that are bailed off).

When the penalty brake is applied, air from the brake pipe on the locomotive is vented to the atmosphere, resulting in a pressure drop on the brake pipe. This pressure drop is sensed by the brake valve on each car, which then allows air to flow from the auxiliary reservoir into the brake cylinder on that car. The brake valve also vents additional air from the brake pipe, which helps to propagate the brake pipe pressure drop to the next car. The brake signal is propagated from car to car down the length of the train.

The time that it takes for this brake signal to propagate through the train is primarily a function of the brake valve type on each car in the train, the length of brake pipe between each brake valve, and the rate that the air moves through the brake pipe, which is primarily a function of the ambient pressure and temperature. If an enforcement algorithm had data for these parameters, a reasonably accurate estimation of brake propagation time could be made. However, no method currently exists for an enforcement algorithm to easily obtain this data, so assumptions must be made.

In the case of the IDOT PTC enforcement algorithm, the propagation time for a full-service brake application on a freight train is estimated from the following quadratic equation, which was empirically determined to provide a good fit:

$$T_{appl} = 12.22 + 0.0156 L_{TRAIN} - 0.000000278 L_{TRAIN}^2 , \quad (5)$$

where T_{appl} is the brake propagation time and L_{TRAIN} is the length of the train in feet.

Figure 20 illustrates the potential error between estimated and actual propagation times. The graph compares propagation times estimated by the IDOT PTC enforcement algorithm against propagation times determined through TOES™ simulations assuming ABD brake valves on every car, and assuming ABDX brake valves on every car, for unit freight trains ranging in length from 10 cars (753 ft) to 150 cars (8,185 ft). As the graph shows, the potential error in propagation time is great when estimations are used. The graph also illustrates how drastically propagation time can vary based on brake valve type (in some cases by more than 90 percent between a train equipped with all ABD and one equipped with all ABDX brake valves).

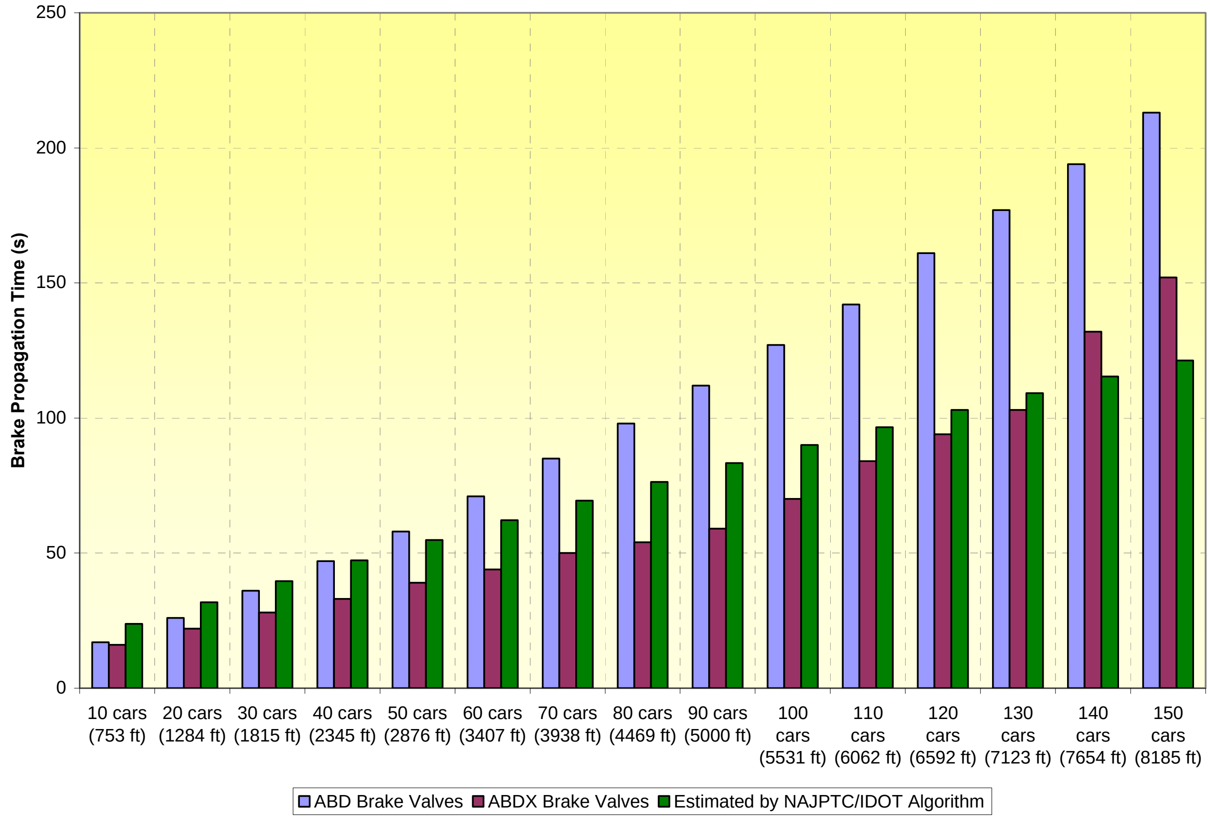

Figure 20. Comparison of Brake Pipe Propagation Time Determined by the NAJPTC/IDOT Algorithm and the TOES™ Model

A method for measuring the actual propagation time of any given train has the potential to significantly reduce the error between the propagation time used in the algorithm and the actual propagation time at the moment the penalty brake is applied. This section describes the development of the propagation time adaptive method, defines the algorithm, and discusses the testing process and results.

5.1 Development of the Propagation Time Adaptive Algorithm

The basic concept behind the propagation time adaptive algorithm is to measure the brake propagation time when the air brakes are applied during a normal initial terminal brake test and use this data to determine the propagation time for a penalty brake application. The general procedure for an initial terminal brake test is to charge the brake system to the required air pressure (typically 90 psi) and then make a service brake pipe reduction (typically a 15- or 20-psi reduction).

The propagation time must be measured using only the head-end and tail-end brake pipe pressure, as these are the only data sources available to the algorithm. Because the brake pipe propagation time is defined as the time between when the penalty brake is applied and when full brake cylinder pressure is reached on all cars in the train, the rear-end brake pipe pressure must be related to the brake cylinder pressure on the last car.

Figure 21 shows both the brake pipe and brake cylinder pressures for the last car in a 40-car unit freight train generated by the TOES™ model. This graph indicates that the brake cylinder on the last car reaches full pressure at approximately the same time that the brake pipe pressure begins to level off. This suggests that the time from the point of brake application to the time the brake pipe pressure levels off can be approximated as the train brake propagation time.

This approximation is valid for a service brake application, but not for a penalty application. This is because the brake pipe pressure for a penalty application does not level off until it reaches atmospheric pressure, while the brake cylinder pressure only increases until it equalizes with the pressure in the auxiliary reservoir. The brake pipe pressure does level off at this equalization pressure for a full-service application, and the brake cylinder pressure behaves exactly the same as for a penalty application. Therefore, for the purposes of the analysis and development of this algorithm, the penalty brake propagation time for a train was approximated as the time between when a full-service application is made to the time when the brake pipe levels off.

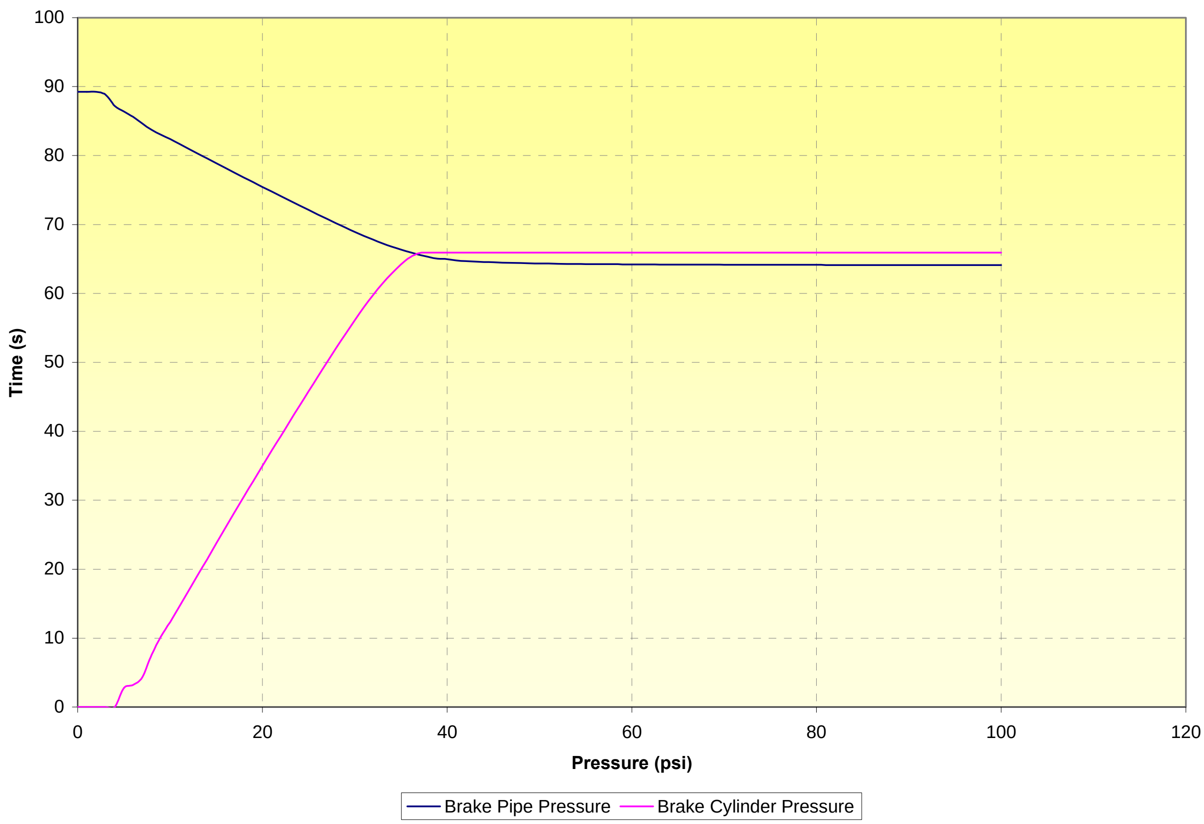

Figure 21. Brake Pipe and Brake Cylinder Pressures for a 40-car Unit Freight Train Generated by the TOES™ Model

To determine the penalty brake application propagation time, a relationship between the initial terminal brake test propagation time and the penalty brake application time must be established. Data from TOES™ simulations and field data collected during the evaluation of the base case algorithm were used to establish this relationship. Tests performed using the TOES™ model included brake tests and full-service brake applications for 10-car, 40-car, 75-car, 100-car, and

125-car unit and general freight trains. Tests performed in the field included brake tests and full-service brake applications for 10-car, 40-car, and 75-car unit freight trains.

Figure 22 shows the rear-end brake pipe pressure from the point of brake application for both a 15 psi brake test and a full-service brake application generated by the TOES™ model for a 40-car unit freight train. The figure shows that the brake pipe pressure remains constant for some time while the brake signal is propagated through the train for both the brake test and the full-service brake application. The brake pipe pressure then begins to decline, nearly linearly until a point near the ultimate brake pipe pressure, where it begins to level off. TOES™ data from other length and other type trains follow the same pattern.

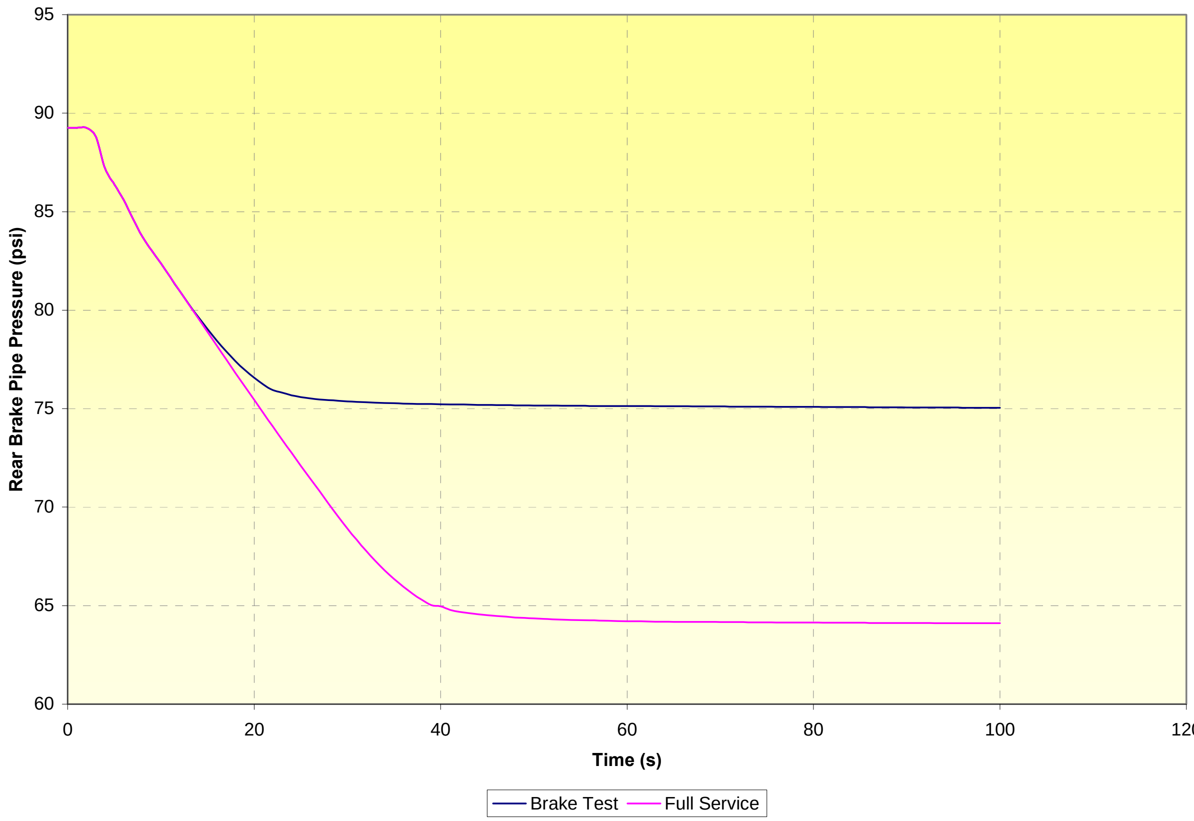

Figure 22. Brake Pipe Pressure during Brake Applications for a 40-car Unit Train Modeled by TOES™

This data suggests that:

- If the delay between the point of brake application and the point at which the rear end brake pipe pressure begins to decline is measured for a brake test, the same delay can be assumed for a full-service application, and
- If the slope between the point at which the rear end brake pipe pressure begins to decline and the point at which the rear-end brake pipe pressure begins to level off is measured, the same slope can be assumed for a full-service application.

Figure 23 shows EOT data from the base case enforcement algorithm field testing for several brake tests and several full-service applications for the same 40-car unit freight train. This chart shows that the data from the TOES™ model is consistent with data measured in the field, and thus validates the conclusions discussed above.

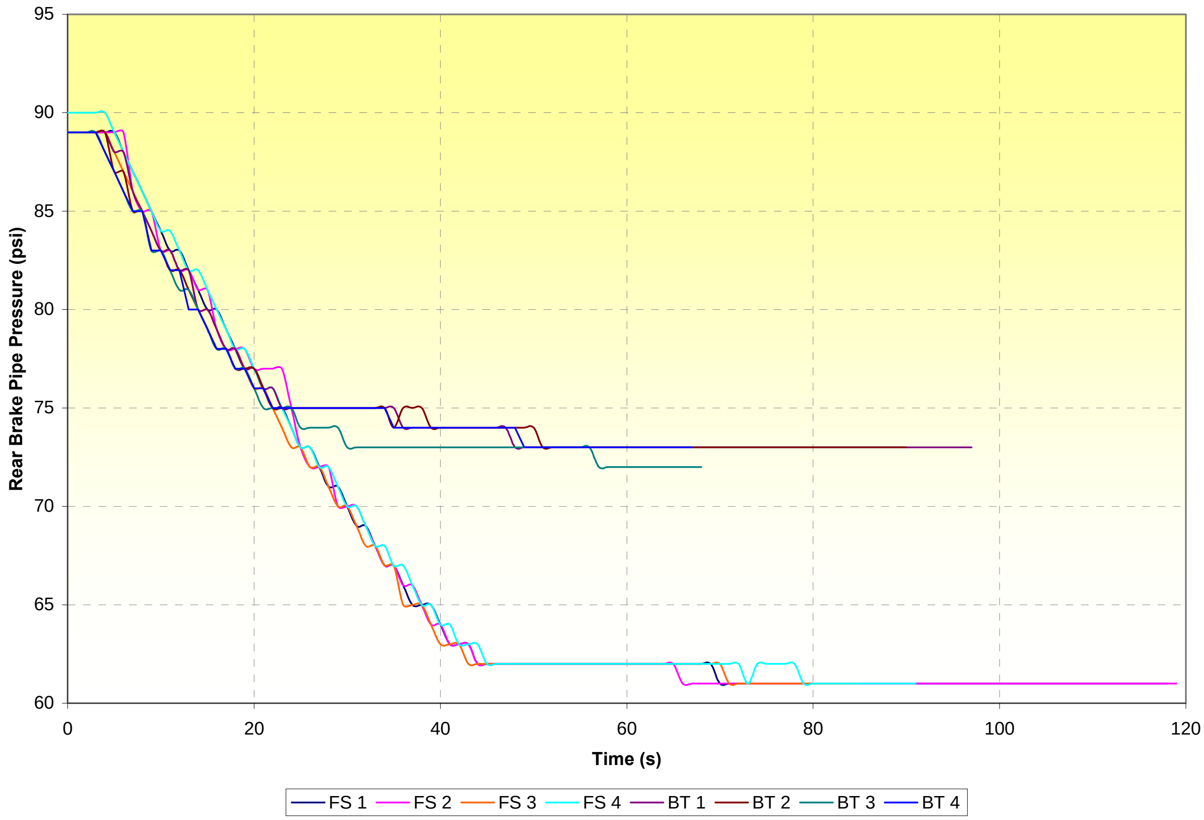

Figure 23. Brake Pipe Pressure during Brake Applications for a 40-car Unit Train from Field Tests

Figure 23 also shows that the rear-end brake pipe pressure levels off at the end of the linear decline and remains steady for approximately 10 to 30 seconds (s) before the pressure drops again. This observation was consistent for the other length trains tested in the field, as well. This suggests that this criterion can be used to determine the time at which the brake pipe pressure has leveled off.

By using the conclusions drawn from the data in Figures 21, 22, and 23 (and other similar graphs), it was possible to develop an algorithm that estimates the time from the point of brake application to the point at which the brake pipe pressure levels off for a full-service brake application, which can be used as an estimate of the train brake propagation time for a penalty application. This process is defined in the following section.

5.2 Propagation Time Adaptive Algorithm Definition

This algorithm assumes a brake pipe reduction (~15 psi) is made by the locomotive engineer after the locomotive onboard computer and EOT are set up and activated. Brake pipe pressure data at both the head end and rear end of the train are recorded by the onboard system and used to approximate the full-service brake pipe propagation time.

When the brake pipe reduction is first made, the onboard system will report a drop in head-end brake pipe pressure. The enforcement algorithm records the rear-end brake pipe pressure at this point as p_0, and also records the time as t_0, and starts a timer. After some delay, the onboard system will report a drop in rear-end brake pipe pressure. The enforcement algorithm records the time at this point as t_1, and the new rear-end brake pipe pressure as p_1.

The onboard computer will continue to send updates on the rear end brake pipe pressure as it drops. Each time a change in rear end brake pipe pressure is reported by the onboard system, the enforcement algorithm records the time and rear end brake pipe pressure, incrementing the subscripts (e.g., t_2, t_3, t_4,…,t_n). When no change occurs in rear-end brake pipe pressure for a period of 10 s, the timer is stopped.

At this point, the enforcement algorithm calculates the slope of the drop in rear end brake pipe pressure, m, as:

$$m = \frac{(p_n - p_0)}{(t_n - (t_1 - 1))} \tag{6}$$

The projected penalty brake pipe propagation time, t_{appl}, is then calculated, using the slope, m, and the full service brake pipe pressure reduction, which is 26psi:

$$t_{appl} = t_1 + \left(\frac{-26}{m}\right) \tag{7}$$

This value for t_{appl} replaces the default calculated value for t_{appl} in the enforcement algorithm.

5.3 Propagation Time Adaptive Algorithm Testing

There were two objectives of testing the propagation time adaptive algorithm. One objective was to evaluate the accuracy with which the algorithm estimates the actual propagation time of each of the test consists. The other objective was to determine the effect of the addition of the propagation time adaptive feature on the enforcement algorithm performance.

The propagation time adaptive algorithm was tested using the same methods as used for testing the base case enforcement algorithm, described in subsection 4.3.1.

5.3.1 Simulation Test Results

As with the base case enforcement algorithm simulation test results, discussed in subsection 4.3.2.1, the results from each test scenario were used to determine the mean and standard deviation of the stopping location, which were then used to generate the probability density curve for the particular test scenario. Figure 24 shows the probability distribution curve for the same 75-car loaded unit freight train traveling 60 mph on flat grade example used in the base case enforcement algorithm simulation test results section. The curve is overlaid on the curve from the base case enforcement algorithm simulation testing for this test scenario, to show how the two relate.

Figure 24 shows that the addition of the propagation time adaptive feature to the algorithm resulted in an improvement of the performance of the algorithm by bringing the mean stopping location closer to the target. It also shows that the standard deviation of the distribution was decreased, meaning that the enforcement algorithm more accurately predicted the stopping distance of each train for this test scenario.

As with the base case enforcement algorithm simulation testing, the measures of performance discussed at the beginning of section 4.3 were used to statistically describe the performance of the enforcement algorithm for each test scenario. The mean stopping location relative to the target for the example in Figure 24 was 2,508 ft, nearly 500 feet closer to the target than with the base case enforcement algorithm, which had a mean stopping location relative to the target of 2,006 ft. The standard deviation of this distance for the propagation time enforcement algorithm was 251 ft, as compared to the 303-foot standard deviation from the base case enforcement algorithm for this example. Despite these improvements, the percentage of trains that overshot the target was still 0 percent, while the percentage of trains that undershot the target by less than the specified 1,000 ft remained at 1 percent, the same as for the base case enforcement algorithm.

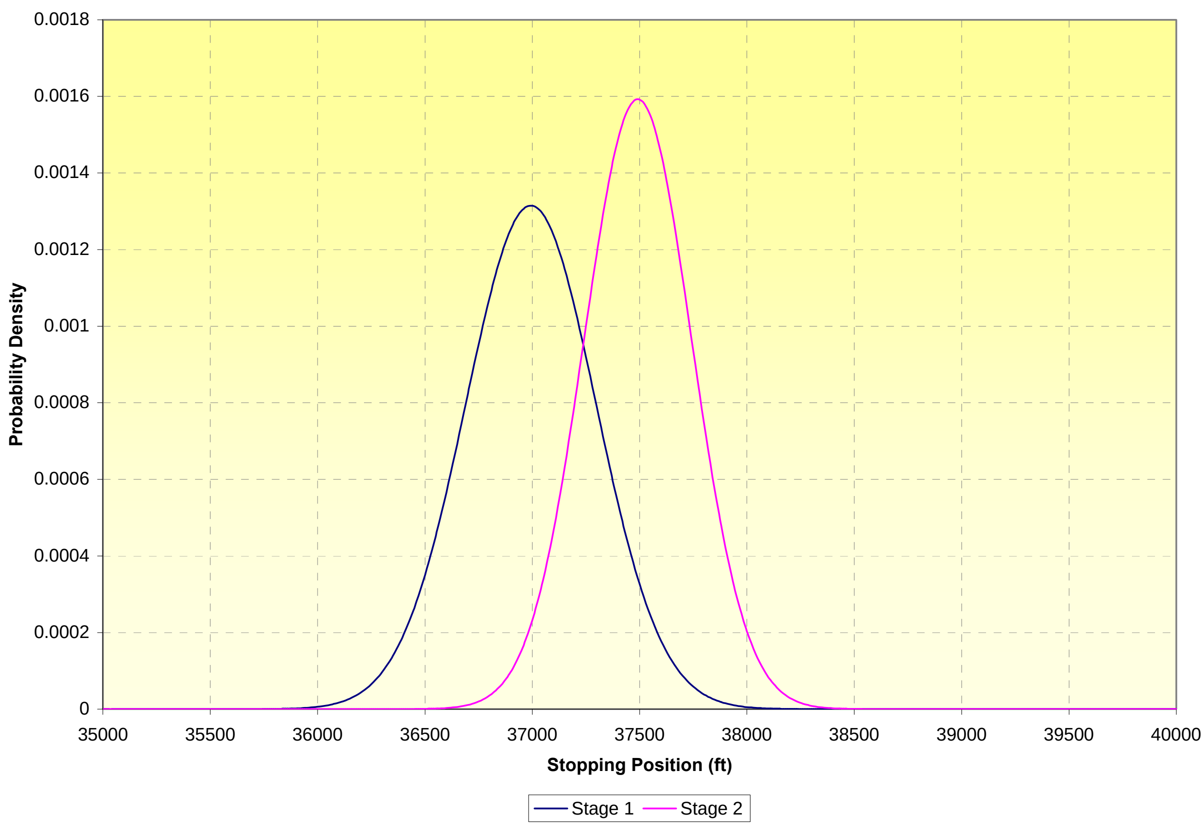

Figure 24. Stopping Location Probability Density Curves for 75-car Loaded Unit Freight Train Traveling 60 mph on Flat Grade

The probability density curves for all of the test scenarios are shown in Appendix F, and the statistical measures of performance for all test scenarios can be found in Appendix G. The data in these appendices shows that in every test scenario, the propagation time adaptive enforcement algorithm moved the mean stopping location closer to the target than the base case enforcement algorithm. In many cases, this had a positive effect on the performance of the enforcement algorithm as a whole, because enforcement started later, the trains stopped closer to the target, and still a very low percentage of trains overshot the targets.

However, in some cases, particularly the empty aluminum cases, this had the negative effect of causing more trains to overshoot the targets. The base case enforcement algorithm has several assumptions, as discussed earlier. Depending on the specific scenario, some of the assumptions are overly conservative, but in other scenarios, the same assumptions may be much less conservative. In the case of the empty aluminum trains, the base case algorithm was already stopping many of the trains close to the target. When the propagation time adaptive algorithm took those cases and removed the conservative propagation time estimation, the enforcement algorithm allowed more trains to overshoot, even though the propagation time was more correctly estimated. This result shows that other parameters need to be measured and adapted to, in addition to the propagation time.

5.3.2 Field Test Results

The propagation time adaptive enforcement algorithm was initially tested in the field during the week of September 28, 2008. During this field test period, the propagation time algorithm estimated the penalty brake propagation time from the brake tests performed before each test run. However, due to an error in the software implementation, the calculated value was not entered into the enforcement algorithm properly, and the default propagation time from the base case algorithm was instead used for each of the test runs. This error was not identified until after the field testing was completed. Therefore, the data from the brake tests was valid to determine how accurately the algorithm estimated propagation time, but the test runs could not be used to determine the effect that the correction had on the enforcement algorithm performance.

A correction was made in the software to allow for the calculated brake propagation time to be used in the enforcement algorithm tests. Because the test runs from the first field test period could not be used, the propagation time adaptive enforcement algorithm was retested, with the software correction for two of the field test scenarios on October 8, 2008. The two field test scenarios that were retested were test scenario 1 (40-car loaded train traveling 40 mph on flat grade) and test scenario 7 (75-car loaded train traveling 40 mph on -1.47% grade). Each of these test scenarios was repeated three times using the propagation time adaptive enforcement algorithm. To provide data for a more direct comparison between the base case enforcement algorithm and the propagation time adaptive algorithm under the same conditions, it was decided that one test run of the base case enforcement algorithm would also be run for each of the two test scenarios during this test period.

Table 9 shows how the propagation time estimated by the adaptive algorithm and how the propagation time estimated by the base case algorithm compare to the actual propagation time for the three different length test consists during both the September 2008 and October 2008 field test periods. The table shows the mean propagation time calculated by each of the algorithms for all the brake tests run, and the mean actual propagation time from all of the penalty applications made. As the table shows, the base case algorithm made a fair estimation of propagation time for the 40-car consist, but drastically overestimated the propagation time for the other two test consists. The propagation time adaptive algorithm estimated the propagation time reasonably accurately for all three test consists.

Table 9. Estimated and Actual Propagation Times from September 2008 and October 2008 Field Test Periods

		Stage 1 (Base Case Algorithm)			Stage 2 (Brake Propagation Time Adaptive Algorithm)		
Number of Cars	**Mean Brake Apply Time**	**Calculated Brake App Time**	**Error**	**Percent Error**	**Mean Calculated Brake Apply Time**	**Error**	**Percent Error**
40	43.36	45.89	2.53	5.83%	41.13	-2.23	-5.14%
75	58.6	75.46	16.86	28.77%	56.05	-2.55	-4.35%
10	15	21.92	6.92	46.13%	15.68	0.68	4.53%

The algorithm performance results from the retest of the propagation time adaptive enforcement algorithm are presented in Table 10. The results from the base case enforcement algorithm tests performed as part of this retest are presented in Table 11. As with the base case enforcement algorithm testing, the results were highly repeatable as indicated by the standard deviation of the distance to the target in Table 10. The standard deviations were not calculated for the base case runs in Table 11, because there was only one run for each test scenario.

Table 10. Propagation Time Algorithm Field Test Results from October 2008 Field Test

Test	Number of Cars	Mean Speed (mph)	Standard Deviation of Speed (mph)	Grade	Mean Distance to Target (ft)	Standard Deviation of Distance to Target (ft)
1	40	40.3	0.6	Flat	1,130	75
7	75	40.6	0.2	Decline	3,641	172

Table 11. Base Case Algorithm Field Test Results from October 2008 Field Test

Test	Number of Cars	Mean Speed (mph)	Standard Deviation of Speed (mph)	Grade	Mean Distance to Target (ft)	Standard Deviation of Distance to Target (ft)
1	40	40.2	N/A	Flat	1,310	N/A
7	75	39.4	N/A	Decline	4,205	N/A

If the mean distances to the targets from the propagation time adaptive algorithm tests in Table 10 are compared to the mean distances to the targets from the base case algorithm tests in Table 11, it is apparent that the propagation time algorithm had the effect of decreasing the distance to the target after stopping. This is consistent with the results from the simulation testing discussed in the previous section, and confirms the positive effect on the performance of the enforcement algorithm with the addition of the propagation time adaptive function.

To provide a more direct comparison between each of the enforcement algorithm developments, the propagation time adaptive algorithm was also tested during the testing of the train weight and braking efficiency adaptive algorithms. The train weight and braking efficiency adaptive algorithms were both field tested during the week of February 9, 2009. During this test period, the propagation time algorithm performed significantly worse than during the September 2008 and October 2008 test periods.

Table 12 shows the accuracy of the propagation time estimates for the February 2009 field test period. The table shows that the propagation time adaptive algorithm significantly overestimated the propagation time for both the 40-car and 75-car test consists. To understand the reason for the error during the February 2009 test period, examining the EOT data used by the algorithm to estimate the propagation time is necessary.

Table 12. Estimated and Actual Propagation Times from February 2009 Field Test Period

		Stage 1 (Base Case Algorithm)			Stage 2 (Brake Propagation Time Adaptive Algorithm)		
Number of Cars	**Mean Brake Apply Time**	**Calculated Brake Apply Time**	**Error**	**Percent Error**	**Mean Calculated Brake Apply Time**	**Error**	**Percent Error**
40	44.54	45.89	1.35	3.03%	57.87	13.3	29.93%
75	70.91	75.46	4.55	6.42%	88.47	17.6	24.76%
10	15.14	21.92	6.78	44.78%	14.95	-0.19	-1.25%

Figure 25 shows the EOT data for both the brake tests and the full-service applications for the 40-car tests from the September 2008 and October 2008 test periods. Figure 25 shows the same data for the February 2009 test period. In each of these charts, the brake test data is identified by the curves that level off around 75 psi, while the full-service applications level off at between 60 and 65 psi.

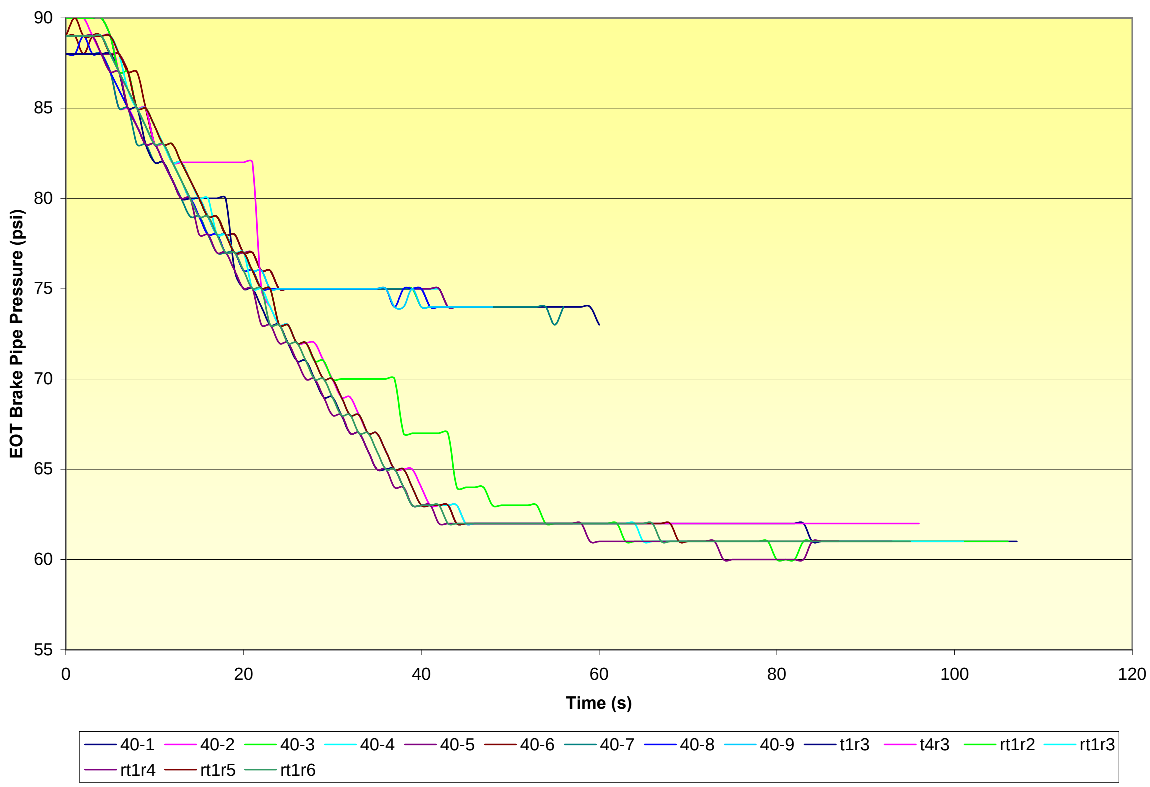

Figure 25. EOT Data from 40-car Tests from September 2008 and October 2008 Field Test Periods

Both Figure 25 and Figure 26 show that the slope of the EOT brake pipe pressure drop was approximately the same for the brake tests and for the full-service applications. However, in Figure 25 the EOT pressure levels off and remains constant for a relatively long period of time

(15–20 s). In Figure 26, the EOT pressure levels off for a relatively short period of time (<10 s) before dropping further. The propagation time adaptive algorithm uses a wait period of 10 s to identify the point at which the brake pipe pressure levels off and uses this point to determine the slope of the brake pipe pressure drop. In the case of the February 2009 test period, the point identified by this method is far past the actual level-off point.

The most likely reason for this change in behavior is varying environmental conditions. The air in the brake system acts differently when the ambient pressure and temperature are different. Therefore, this issue was not identified in the original test periods.

An alternate method for determining the slope of the brake pipe pressure drop is to calculate the slope between each data point and compare it to the slope calculated between the previous two data points. When the slope begins to level off dramatically, the brake pipe pressure has leveled. Because this issue was not identified until the final test period for the project, this method was not implemented and tested during this project, but it is recommended that this or another approach be implemented and tested in a variety of operating conditions in future work.

If this issue can be resolved, the propagation time adaptive algorithm shows promise for providing a more accurate stopping distance prediction calculation to be used in enforcement algorithms.

Figure 26. EOT Data from 40-car Tests from February 2009 Field Test Period

5.4 Operational Impact of Propagation Time Adaptive Enforcement Algorithm

The measurement of propagation time can be performed during the standard brake test that is required before the train leaves its initial terminal and again after cars are set out or picked up enroute. However, in come cases, the motive power and the EOT device have not yet been coupled to the train when the brake test is made. Instead, air pressure from the yard air supply is used to charge the train in these cases. The only negative impact on current railroad operations is that, for these cases, the locomotives and EOT devices will need to be coupled to the train and the PTC system activated before the brake test is performed.

Alternatively, the algorithm could use conservative estimates (e.g., from the base case algorithm) for propagation time until the first brake application is made on the road. This would allow yard air to be used for the initial brake pipe tests, but would eliminate the benefit of the propagation time adaptive algorithm until a brake application is made.

6 Train Weight Adaptive Algorithm Development and Testing

The second adaptive modification to the base case enforcement algorithm is to estimate the actual weight of the train on which the enforcement algorithm is running. The weight of the train is an essential parameter for the stopping distance prediction function of the enforcement algorithm. It is used to estimate the resistive forces acting on the train, to determine the grade and curve forces acting on the train, and to solve the equation of motion for the acceleration at each time step in the numerical integration process described in section 4.1.

The accuracy of the train weight provided to the enforcement algorithm can have a significant effect on the accuracy of the stopping distance prediction. The base case enforcement algorithm is given a train weight at initialization. The source of this train weight information may vary based on the railroad it is operating on, the train type, the commodity being transported, the location where the train is assembled, and possibly other factors. In some cases, the weight provided may be an agreed weight used to calculate shipping costs. In other cases, the weight may be assumed to be the rated GRL of the vehicle. Quite often, the shippers provide the lading weights, which are frequently only rough estimates. In any case, some error associated with the weight provided to the enforcement algorithm by the ground system is highly likely.

A method for measuring the actual weight of the train could significantly reduce the error in stopping distance prediction associated with the assumed weight provided to the enforcement algorithm. This section includes the development process, definition of, and testing of the train weight adaptive algorithm.

6.1 Development of the Train Weight Adaptive Algorithm

The train weight adaptive algorithm is based on the concept that the acceleration and forces acting on the train can be measured or estimated while the train is accelerating from its point of initiation and used in the equation of motion to solve for the actual weight of the train. Mathematically, this is expressed in the following equation:

$$\sum F = m \times a \quad , \tag{8}$$

where $\sum F$ is the sum of the forces acting on the train, m is the train mass, and a is the acceleration of the train. The mass in this equation is independent of the force due to the gravitational pull of the Earth. The weight of the train is related to the mass by this gravitational force, generally accepted as approximately 32.2 ft/s^2. The train mass, m, in pounds, is therefore related to the weight of the train, W, in tons, by the following relationship:

$$m = \frac{W \times 2000}{32.2} \tag{9}$$

Substituting for the mass in the first equation leaves the following equation:

$$\sum F = \frac{W \times 2000}{32.2} \times a \tag{10}$$

The forces acting on the train at any moment may include the tractive or dynamic brake effort produced by the locomotive(s), the bearing, rolling, and aerodynamic resistive forces acting on the train, the force due to the track grade, the resistance due to track curvature, and the force due to train braking. Assuming that no braking (dynamic or automatic air brakes) is underway at the time the weight calculation is performed, and substituting these forces into the previous equation, leaves the following:

$$F_{TE} - F_{RES} - F_{GRD} - F_{CRV} = \frac{W \times 2000}{32.2} \times a, \qquad (11)$$

where F_{TE} is the tractive effort, F_{RES} is the combined resistive forces acting on the train, F_{GRD} is the grade force, and F_{CRV} is the curving resistance.

The input data available to the algorithm consists of data from the onboard system including locomotive speed, throttle setting, and location; data input by the user including number and type of cars, number and type of locomotives, and total train length; and finally, data referenced from the track database. This data must be used to estimate all of the unknowns in the equation above to solve for train weight.

To estimate the acceleration of the train at each time step, the speed of the lead locomotive over multiple time steps is used (for this project, the time step used was one second). Specifically:

$$a_t = v_{t+1} - v_t, \qquad (12)$$

where a_t is the acceleration of the train at the given time step, v_t is the velocity of the train at the given time step, and v_{t+1} is the velocity of the train at the next time step. Several potential issues exist with this method of estimating train acceleration.

First, by using the speed of the lead locomotive as the train speed, the algorithm assumes the train to be a single mass, accelerating as one. In actuality, a train is a chain of masses with the potential for relative motion between each mass. Therefore, for this assumption to be accurate, the relative motion between each car in the train must be minimal. When the train begins accelerating from a stop, the slack is pulled out of each car one by one, which sends force waves through the train. Similarly, when the locomotive throttle setting is changed, it sends a force wave through the train, which results in relative motion between the cars for some period of time. Therefore, the best time to collect data for the train weight corrective algorithm is when the train has been accelerating in a constant notch long enough to allow for the force waves to settle.

Through both TOES™ simulation tests and instrumented coupler data from the base case enforcement algorithm field tests, it was determined that when the train is traveling at least 10 mph and has remained in a constant notch for 20 s, the force waves are generally minimal.

The second potential issue with this method of estimating train acceleration is the frequency of train speed measurement. In this implementation, the algorithm receives speed data from the onboard system once per second. Using speed data collected at 1 Hz results in very choppy acceleration data. This is illustrated in Figure 27, which shows the speed from a TOES™

simulation of a 40-car loaded unit train accelerating in a constant notch, and the acceleration of the train as calculated from the speed data once per second.

To provide more accurate train acceleration data, the acceleration must be filtered. Figure 27 shows the acceleration data with a simple Butterworth filter applied. As the figure shows, this acceleration data is much smoother, and provides a better estimate for the train weight calculation.

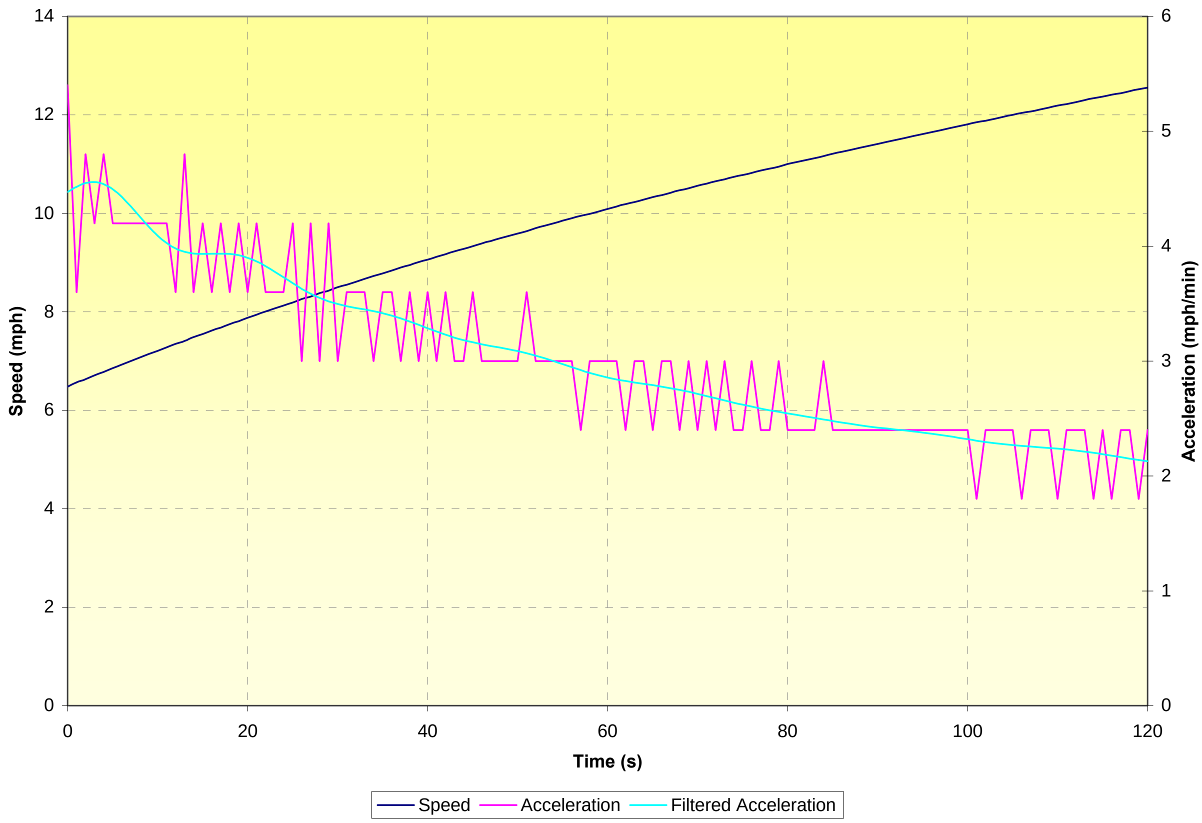

Figure 27. Speed and Acceleration for a 40-car Loaded Unit Train Modeled by TOES™

To estimate the tractive effort produced by the locomotives, several different techniques may be employed. The most accurate method is to measure the voltage and current on each of the traction motors on each locomotive in the consist, and use the data to calculate the tractive effort produced at the rail for each traction motor. A simpler version of this method is to measure the voltage and current on just the second traction motor of each locomotive, and assume the other traction motors on each locomotive produce the same amount of tractive effort. The second traction motor is used in this method because it is not uncommon to have wheel slip on the first axle of the locomotive, which can produce erroneous tractive effort results. The major drawback to using this method is that it requires additional instrumentation on every locomotive, and also requires that the data be passed from trailing locomotives up to the onboard system operating on the lead locomotive.

On many of the newer locomotives, the tractive effort is measured and displayed in the cab of the locomotive. It may be possible to tap into this measurement and provide the data to the enforcement algorithm. Also, this method may require additional instrumentation and a method for passing the data from trailing locomotives to the lead locomotive. This method was not investigated as part of this project, as the test locomotives available do not include this functionality.

The simplest method for estimating tractive effort is to use tractive effort tables. These tables (or their associated tractive effort curves) are generated by the locomotive manufacturers for every locomotive produced. Each tractive effort lookup table consists of a column of speeds from 0–70 mph in 1-mph increments and a column of tractive effort data for each of the eight throttle notches. The onboard system measures the speed and locomotive notch, which can be referenced to the tables to determine the tractive effort produced by each of the locomotives. The drawbacks to this method are that the tractive effort estimate is a theoretical tractive effort and does not take into account any degradation of the locomotive or if any of the traction motors are cut out. Additionally, tractive effort tables must be available for each of the locomotives in the test consist. Ultimately, for this project, this method of looking up tractive effort from available tractive effort tables was determined to be the most feasible method.

The remaining forces on the train are estimated using generally accepted methods.[5] The resistive forces are estimated using the modified Davis equation. The grade force is estimated by assuming 20lbf/lb/percent grade, and the curve resistance is estimated by assuming 0.8lbf/lb/degree of curvature. These methods are defined more explicitly in the following algorithm definition section. The methods for estimating grade and curve are designed with the assumption that the weight of the train is uniformly distributed throughout the length of the train. This method is sufficient for this study, as only unit train operations are considered, but a method for estimating these forces with a train of nonuniform mass distribution, such as the method defined in the base case enforcement algorithm definition document, would need to be applied to other train types.

Using the methods described in this section to estimate train acceleration and the forces acting on the train, it is possible to develop an algorithm capable of estimating train weight. The weight calculation can be performed once per second of data. By averaging the weight calculated at each time step for many time steps, the error in individual weight calculations can be minimized. Tests performed in the development of the algorithm suggest that averaging 20 independent weight calculations provides a reasonably accurate weight estimation.

6.2 Train Weight Adaptive Algorithm Definition

The first step in determining the train weight is collecting a usable data set from the onboard system. When the train has been traveling in excess of 10 mph in a constant notch for 20 s, the algorithm will begin collecting location, speed, and notch information from the onboard system once per second.

Once 20 samples have been collected, the algorithm calculates the train acceleration for each time step, using the following method:

$$a_t = v_{t+1} - v_t \,, \tag{13}$$

where a_t is the acceleration at the given time step, v_t is the velocity at the given time step, and v_{t+1} is the velocity at the next time step. The acceleration is then filtered using a fifth order low-pass Butterworth filter with a cutoff frequency of 1/16 Hz.

To solve for the train weight, the algorithm starts with the equation of motion, for each time step:

$$\sum F = m \times a \,, \tag{14}$$

where $\sum F$ is the sum of the forces acting on the train, m is the train mass, and a is the acceleration of the train, discussed above. The train mass, *m*, in pounds, is related to the weight of the train, *W*, in tons, by the following relationship:

$$m = \frac{W \times 2000}{32.2} \tag{15}$$

Substituting for the mass in the first equation leaves the following equation:

$$\sum F = \frac{W \times 2000}{32.2} \times a \tag{16}$$

The sum of the forces acting on the train include the tractive effort produced by the locomotive(s), F_{TE}; the resistive forces acting on the train, F_{RES}; the force due to the track grade, F_{GRD}; the force due to track curvature, F_{CRV}; and the force due to train braking, F_{BRK}. Assuming the brakes are not applied and substituting for $\sum F$ results in:

$$F_{TE} - F_{RES} - F_{GRD} - F_{CRV} = \frac{W \times 2000}{32.2} \times a \tag{17}$$

The tractive effort produced by the locomotive(s) is a function of the speed and throttle setting of the locomotive(s), and is independent of the weight of the train. This force is determined from tractive effort lookup tables for each of the locomotives.

For each time step, the algorithm looks up the tractive effort produced by each locomotive (using the speed and throttle setting at that time step and the tractive effort lookup table for that locomotive) and sums them to determine the force on the train due to tractive effort for that time step. If the speed is between two entries in the lookup table, the algorithm performs a linear interpolation between the two boundary entries to determine the tractive effort at that time step.

The resistive forces on the train are estimated using the modified Davis equation:

$$F_{RES} = (0.6 \times W) + (20 \times n) + (0.01 \times W \times v) + (0.07 \times N \times v^2) \,, \tag{18}$$

where *n* is the number of axles on the train, *v* is the velocity of the train, and *N* is the number of cars in the train.

The force due to track grade is determined from the following equation:

$$F_{GRD} = 20 \times W \times G \quad , \tag{19}$$

where G is the average percent grade under the train. The average percent grade under the train is determined by the following equation:

$$G = \frac{(E_{HE} - E_{TE})}{L} * 100 \quad , \tag{20}$$

Where E_{HE} is the elevation at the head end of the train, E_{TE} is the elevation at the tail end of the train, and L is the length of the train. The elevations are determined by referencing the head and tail-end positions with the data in the track database, where the tail-end position is the difference between the head-end position and the train length. It should be noted that this method of determining the resistance due to track grade is only accurate for trains with a uniform mass distribution, and therefore some error will be introduced by using this assumption.

The force due to track curvature is determined from the following equation:

$$F_{CRV} = 0.8 \times W \times C \quad , \tag{21}$$

where C is the average degree of curvature of the track under the train. To determine the average degree of curvature under the train, the algorithm looks at the track database between the head end and tail end of the train to determine the degree(s) of curvature under the train. The average degree of curvature is then determined from the following:

$$C = \left(C_1 \times \frac{L_1}{L_T} \right) + \left(C_2 \times \frac{L_2}{L_T} \right) + \cdots + \left(C_n \times \frac{L_n}{L_T} \right) , \tag{22}$$

where C_1, C_2, …, C_n are the various degrees of curvature under the length of the train, L_1, L_2, …, L_n are the length of the train that is on the corresponding degree of curvature, and L_T is the length of the entire train. If a portion of the train is on a spiral, the following formula is used to determine the value of C for the length of the train that is on the spiral:

$$C_{spiral} = C_{start} + \frac{\left(\frac{C_{end} - C_{start}}{L_{spiral}} \right)(D_2 + D_1)}{2} \quad , \tag{23}$$

where C_{start} is the degree of curvature at the start of the spiral, C_{end} is the degree of curvature at the end of the spiral, and L_{spiral} is the length of the spiral. D_1 is the distance from the beginning of the spiral to the head end of the train, if the head end of the train is on the spiral. If the head end of the train is beyond the spiral, then D_1 is equal to the length of the spiral. D_2 is the distance from the beginning of the spiral to the tail end of the train, if the tail end of the train is on the spiral. If the tail end of the train has not yet reached the spiral, then D_2 is equal to zero.

It should be noted that this method of determining resistance due to track curvature, like the method for determining resistance due to track grade, is only accurate for trains with uniform mass distribution, and therefore some error will be introduced by using this assumption.

Substituting the relationships discussed above in for F_{RES}, F_{GRD}, and F_{CRV}, results in the following:

$$F_{TE} - \left[(0.6\times W)+(20\times n)+(0.01\times W\times v)+\left(0.07\times N\times v^2\right)\right]-(20\times W\times G)-(0.8\times W\times C)=\frac{W\times 2000}{32.2}\times a \tag{24}$$

Solving for the train weight, W:

$$F_{TE} - (20\times n)-\left(0.07\times N\times v^2\right)=\left(\frac{W\times 2000}{32.2}\times a\right)+(0.6\times W)+(0.01\times W\times v)+(20\times W\times G)+(0.8\times W\times C)$$

$$F_{TE} - (20\times n)-\left(0.07\times N\times v^2\right)=W\times\left[\left(\frac{2000\times a}{32}\right)+0.6+(0.01\times v)+(20\times G)+(0.8\times C)\right]$$

$$W=\frac{\left[F_{TE}-(20\times n)-\left(0.07\times N\times v^2\right)\right]}{\left[\left(\frac{2000\times a}{32}\right)+0.6+(0.01\times v)+(20\times G)+(0.8\times C)\right]} \tag{25}$$

Once the weight is calculated for each time step, the mean and the standard deviation of the calculated weight are determined for all the time steps. If the standard deviation is within 5 percent of the mean value for calculated weight, then the mean is assumed to be the actual train weight and replaces the value entered by the ground system in the enforcement algorithm.

6.3 Train Weight Adaptive Algorithm Testing

The train weight adaptive enforcement algorithm was tested in the same manner as the previous two stages of enforcement algorithm testing.

6.3.1 Simulation Test Results

The simulation testing of the train weight adaptive algorithm resulted in the same type of results as for the simulation testing of the first two enforcement algorithms. Using the same example used in the previous simulation test results sections of a 75-car loaded unit freight train traveling 60 mph on flat grade, a comparison of the performance of the base case enforcement algorithm, the propagation time adaptive enforcement algorithm, and the train weight adaptive enforcement algorithm can be made. Figure 28 shows the probability density curves for all three enforcement algorithms for this example.

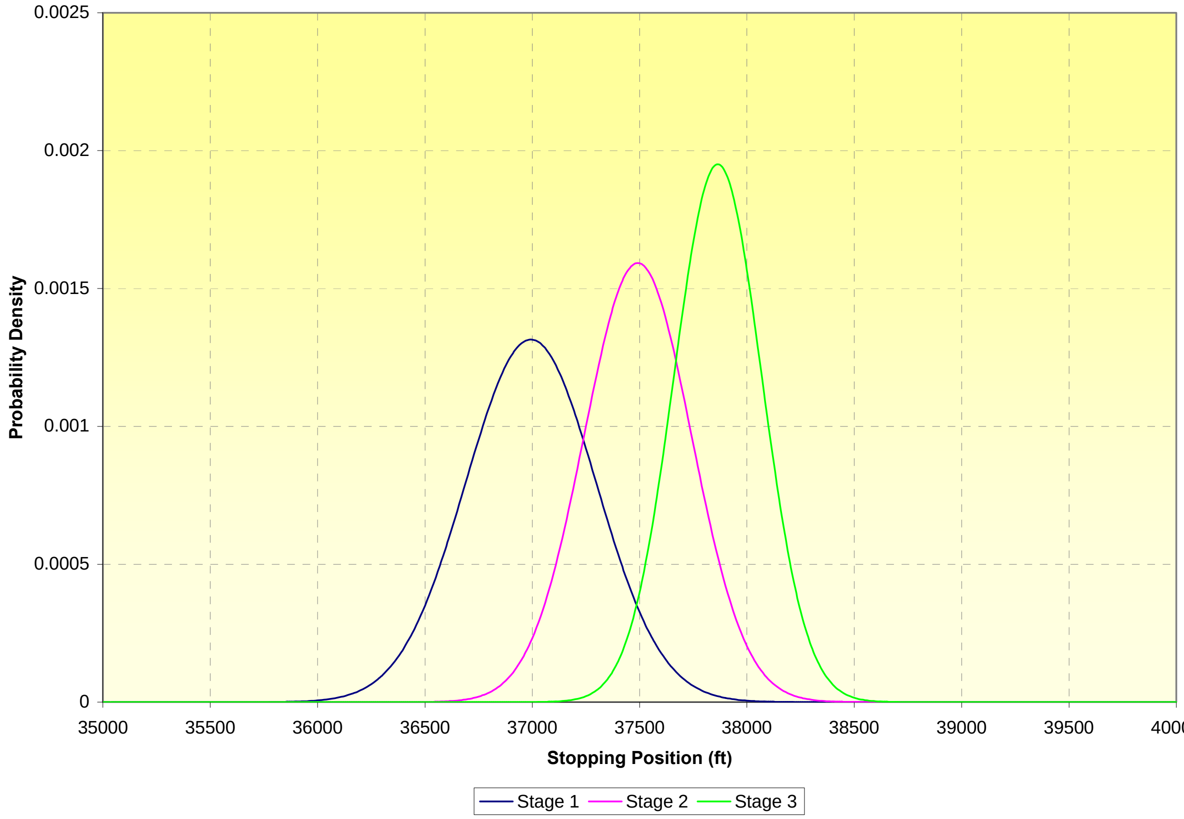

Figure 28. Stopping Location Probability Density Curves for a 75-car Unit Freight Train Traveling 60 mph on Flat Grade

The curves in Figure 28 indicate that the mean stopping location moved closer to the target with the addition of the train weight adaptive feature to the algorithm in this example. The standard deviation was also reduced, indicated by the tighter distribution. This example illustrates that the train weight adaptive feature had a positive effect on the performance of the enforcement algorithm.

The train weight adaptive enforcement algorithm distribution shown in the figure was statistically described as having a mean stopping location relative to the target of 2,136 ft, with a standard deviation of 205 ft. Compared to the mean of 3,006 ft for the base case enforcement algorithm and the mean of 2,508 ft for the propagation time adaptive algorithm, the train weight adaptive algorithm displayed considerably better performance for this example. However, the percent of trains that overshot the target was 0 percent, and the percent that undershot by less than the 1,000-foot specification was 1 percent, indicating no change from the previous two algorithms for this example.

The probability density curves for all of the test scenarios are shown in Appendix F, and the statistical measures of performance for all test scenarios can be found in Appendix G. Some general conclusions can be drawn from the data contained in these appendices. For the majority of the loaded train scenarios, the train weight adaptive enforcement algorithm moved the mean stopping location closer to the target without increasing the percent that overshot, indicating a general improvement in the performance of the enforcement algorithm.

For the empty test scenarios, however, the train weight adaptive enforcement algorithm moved the mean stopping location further from the target. This indicates that the assumption of the weight of an empty car made by the base case enforcement algorithm was generally lighter than the actual weight of the empty cars. Therefore, when the weight was corrected, the algorithm stopped the train sooner than when the assumed train weight was used.

6.3.2 Field Test Results

The train weight adaptive enforcement algorithm was field tested during the week of February 9, 2009. For this round of field testing, the base case enforcement algorithm and propagation time adaptive enforcement algorithm were each run once for each test scenario, to provide a more direct comparison to the train weight adaptive enforcement algorithm. The train weight enforcement algorithm was run twice for each test scenario to test the repeatability of the train weight algorithm under the same conditions.

The field test matrix was also modified for this test period. Field test scenarios 3 and 4 were removed from the test matrix. These test scenarios were proven to be the least difficult for the enforcement algorithm to predict the stopping distance for the previous field test periods. In fact, the base case enforcement algorithm met both the safety and performance specifications for each of these test scenarios. Therefore, the decision was to spend the limited field test time on testing the previous algorithms for a more direct comparison of the performance of the algorithms developed.

The actual weight of all of the cars in the test consist were measured on a scale for comparison against the weights measured by the train weight adaptive enforcement algorithm for each test consist. The train weight of each test consist was measured by the train weight adaptive algorithm before each test run. Therefore, the weight was measured by the algorithm for each test consist multiple times. Table 13 displays the mean, maximum, and minimum train weight measured by the train weight algorithm, along with the actual weight measured by the scale and the weight assumed by the base case enforcement algorithm, for each consist.

As the data in Table 13 indicates, the weights of the test consists were very close to the weights assumed by the base case enforcement algorithm, because the cars used in the test consists were loaded very closely to their rated GRL. This is less likely to be the case for trains in revenue service. The accuracy of the data given to the enforcement algorithm may vary widely based on a variety of factors, as discussed previously.

Table 13. Actual and Estimated Train Weights for February 2009 Field Test Period

	40-car Consist			75-car Consist			10-car Consist		
	Weight (tons)	Error	Percent Error	Weight (tons)	Error	Percent Error	Weight (tons)	Error	Percent Error
Actual	6,999	0	0%	12,532	0	0%	1,853	0	0%
Assumed (Base Case)	6,947	-52	-1%	12,460	-72	-1%	1,845	-8	0%
Mean (Calculated by Adaptive Algorithm)	7,864	865	12%	14,165	1,633	13%	1,751	-102	-6%
Maximum	9,447	2,447	35%	15,383	2,851	23%	2,339	486	26%
Minimum	6,390	-609	-9%	13,200	668	5%	1,364	-488	-26%

The data in Table 13 indicates that the train weight adaptive enforcement algorithm tended to overestimate the train weight for the longer consists. The short consist, however, had a mean train weight measurement that was closer to the actual weight with the minimum and maximum measurements equally spaced around the actual weight. This general difference in algorithm performance may be due to the locomotive consist, which was the same for both the 40-car and 75-car test consists, but was different for the 10-car consist. It is possible that the tractive effort curves used for the 10-car locomotive consist were more representative of their actual performance than the tractive effort curves used for the longer locomotive consists. In simulation testing, the theoretical and actual tractive effort produced by the locomotives are identical, which explains why the algorithm did not tend to overestimate the weight in the simulation testing as it did in the field test cases mentioned. This highlights the importance of developing an accurate method for estimating the tractive effort produced by the locomotive consists.

Table 13 also gives an indication of the range of weights estimated by the algorithm. This is likely not due to any one specific reason, but rather to a combination of errors in the estimation of each of the different forces acting on the train at different times. For this test, the 20 individual measurements were averaged to determine the train weight for each test. A method for collecting more data and performing some filtering on the output could provide more accurate measurements. Conceivably, the algorithm could make an initial estimate of train weight, but then continue to refine this measurement as more data is available as the train continues to travel. This concept was not explored further as part of this work scope, but the recommendation is that it be considered for future studies or for developing an implementation of this algorithm for revenue service.

Table 14 shows the results of the enforcement tests for the train weight adaptive enforcement algorithm. Table 15 shows the results of the propagation time adaptive enforcement algorithm test from this test period, and Table 16 shows the results of the base case enforcement algorithm test from this test period. Because each of these algorithms was only run once per test scenario, the standard deviation columns in Tables 15 and 16 display “N/A.”

Table 14. Train Weight Algorithm Field Test Results from February 2009 Field Test

Test	Number of Cars	Mean Speed (mph)	Standard Deviation of Speed (mph)	Grade	Mean Distance to Target (feet)	Standard Deviation of Distance to Target (feet)
1	40	40.2	0.4	Flat	1,695	777
2	40	59.7	2.3	Flat	2,150	260
5	10	40.1	0.1	Flat	1,224	863
6	75	10.0	0.1	Flat	240	9
7	75	40.1	0.0	Decline	5,387	56

Table 15. Propagation Time Algorithm Field Test Results from February 2009 Field Test

Test	Number of Cars	Mean Speed (mph)	Standard Deviation of Speed (mph)	Grade	Mean Distance to Target (feet)	Standard Deviation of Distance to Target (feet)
1	40	53.1	N/A	Flat	1,677	N/A
2	40	58.0	N/A	Flat	2,609	N/A
5	10	40.5	N/A	Flat	1,152	N/A
6	75	9.8	N/A	Flat	194	N/A
7	75	38.2	N/A	Decline	4,980	N/A

Table 16. Base Case Algorithm Field Test Results from February 2009 Field Test

Test	Number of Cars	Mean Speed (mph)	Standard Deviation of Speed (mph)	Grade	Mean Distance to Target (feet)	Standard Deviation of Distance to Target (feet)
1	40	40.1	N/A	Flat	1,047	N/A
2	40	56.1	N/A	Flat	2,425	N/A
5	10	40.0	N/A	Flat	1,297	N/A
6	75	10.1	N/A	Flat	142	N/A
7	75	38.0	N/A	Decline	4,100	N/A

If the mean distance to the target is compared for each of the three enforcement algorithms, from the data in Tables 14, 15, and 16, the base case enforcement algorithm was the closest to the target. During this test period, a flaw in the propagation time adaptive enforcement algorithm was identified that was causing the propagation time to be estimated much longer than the actual propagation time, which results in a negative impact on the performance of the enforcement algorithm, as discussed in subsection 5.3.2.

The train weight adaptive enforcement algorithm had a further negative impact on the enforcement algorithm performance due to the overestimation of the train weight discussed above. The one exception to this is for test scenario 2, which was closer to the target on average for the train weight adaptive algorithm than for the propagation time adaptive algorithm.

Although the specific reason for this is unknown, the fact that only one test run was performed for the propagation time algorithm suggests that this test run may not have been typical.

The data in Table 14 also indicates a large standard deviation of the distance to the target for most of the test scenarios. This is due to the wide variation in the estimation of train weight discussed above. This large variation for train weight measurements of the same test consist has a significant impact on the performance of the enforcement algorithm. As discussed earlier, a method for minimizing this variation by using more data points and some filtering routines may enable better performance from the train weight adaptive enforcement algorithm.

6.4 Operational Impact of the Train Weight Adaptive Enforcement Algorithm

The train weight adaptive enforcement algorithm was designed to function when the train is accelerating to track speed. It requires that the train be traveling over 10 mph with a constant throttle setting for some time. In many cases, the locomotive engineer will increase the throttle setting of the locomotive to a certain setting and leave it there while the train accelerates to track speed. There is no negative impact on operations from the use of the train weight adaptive algorithm in this case. However, in cases where the locomotive engineer would normally not hold the throttle setting constant, the algorithm may cause a minimal impact if the locomotive engineer is required to hold the throttle constant for a given period of time.

It may be possible, in future developments of the train weight adaptive algorithm, to make an accurate estimation of train weight without this requirement. Particularly, if the concept of constantly measuring and adapting the train weight throughout the trip is explored, the possibility exists of eliminating this requirement altogether, meaning there would be no negative operational impact.

7 Braking Efficiency Adaptive Algorithm Development and Testing

The final adaptive improvement to the base case algorithm adapts to the actual braking efficiency of the train. Braking efficiency is a term that refers generally to the braking capability of the train. It is related to the brake ratio, which is defined by the AAR standards as the net brake shoe force with a 30-psi reduction from a 90-psi brake pipe divided by the GRL.[3]

The braking efficiency of the train is an important parameter when performing stopping distance prediction calculations. During a penalty brake application, the largest two forces acting on the train are the force due to grade and the force due to train braking. A significant error in the estimation of braking force can result in a large error in stopping distance prediction.

The base case enforcement algorithm estimates braking efficiency by assuming a certain amount of brake shoe force, defined as “braking power” in the algorithm definition document, with 50 psi brake cylinder pressure, per car, based on the GRL of the car. Because the base case enforcement algorithm safety objective is of greatest importance, the brake shoe forces assumed by the algorithm are worst case. This assumption has a major impact on the performance of the enforcement algorithm.

An algorithm capable of measuring the actual brake force produced by a given train has the potential to minimize the negative operational impact of the enforcement algorithm significantly, without negatively affecting the safety objective. The development of this algorithm is discussed in this section, followed by the algorithm definition and the testing of the algorithm.

7.1 Development of the Braking Efficiency Adaptive Algorithm

The braking efficiency adaptive algorithm concept is similar to that used by the train weight adaptive algorithm. In the case of the braking efficiency algorithm, however, the weight is assumed to be accurate, and the equation of motion is solved for the braking force acting on the train during a service brake application. This brake force can then be used to estimate what the braking force would be for a full-service or penalty brake application.

The base case enforcement algorithm determines the nominal brake shoe force for the train, F_{B-NOM} by summing the assumed brake shoe force, or braking power, for all cars in the train. This nominal brake shoe force is used to determine the maximum available brake shoe force, F_{B-MAX}, through the following relationship:

$$F_{B-MAX} = \left(\frac{P_{equ}}{50}\right) F_{B-NOM}\,, \tag{26}$$

where P_{equ} is the maximum available brake cylinder pressure for full service braking, determined from the monitor brake system function, discussed in section 4.1. The maximum available brake shoe force, F_{B-MAX}, is used to determine the total brake shoe force for the entire train at any moment in the braking distance prediction. At each moment, the total braking force is equal to the brake shoe force at that moment multiplied by the coefficient of friction between the brake shoes and the wheels:

$$F_{B,BCP} = F_{SHOE,BCP} \times COF_{SHOE,WHEEL} \tag{27}$$

The coefficient of friction is a function of the velocity of the train, and therefore the actual braking force must be calculated using the brake shoe force at each time step of the prediction loop. The maximum brake shoe force is a function of the current state of the brake system, meaning that if the brake system is not fully charged due to a previous brake application, the maximum available brake shoe force will be less. The state of the brake system is determined at the moment the stopping distance calculation is made. Therefore, the most logical parameter to estimate for the braking efficiency algorithm is the nominal brake shoe force of the train with 50 psi brake cylinder pressure, $F_{B\text{-}NOM}$.

The algorithm is designed to operate whenever a service brake application is made. The equation of motion relates the sum of the forces acting on the train to the acceleration of the train during the service brake application:

$$F_{TE} - F_{DB} - F_{RES} - F_{GRD} - F_{CRV} - F_{B,BCP} = \frac{W \times 2000}{32.2} \times a\,, \tag{28}$$

where F_{TE} is the tractive effort produced by the locomotive(s), F_{DB} is the dynamic brake effort produced by the locomotive(s), F_{RES} is the combined resistive forces acting on the train, F_{GRD} is the force due to track grade, F_{CRV} is the resistance due to track curvature, and $F_{B,BCP}$ is the resistance due to the train air brakes at the brake cylinder pressure resulting from the service brake application, which is defined as P_{BC}.

Solving this equation for the braking force at P_{BC}, $F_{B,BCP}$, results in the following relationship:

$$F_{B,BCP} = F_{TE} - F_{DB} - F_{RES} - F_{GRD} - F_{CRV} - \frac{W \times 2000}{32.2} \times a \tag{29}$$

The acceleration of the train and the forces in this equation are all estimated in the same manner as in the train weight adaptive algorithm, discussed in section 6.1.

Once the braking force at P_{BC} is solved for, the brake shoe force at P_{BC}, $F_{SHOE,BCP}$, can be estimated through the following relationship:

$$F_{SHOE,BCP} = \frac{F_{B,BCP}}{COF_{SHOE,WHEEL}}\,, \tag{30}$$

where $F_{SHOE,BCP}$ is the force the brake shoe force at P_{BC} and $COF_{SHOE,WHEEL}$ is the coefficient of friction between the brake shoes and the wheels. Field tests have been used to empirically derive the relationship between this coefficient of friction and the velocity of the train. A variety of different equations have been used to fit the data from these field tests. The following equation, used by the base case enforcement algorithm to determine the braking force for stopping distance prediction, is a reasonable estimation for coefficient of friction:

$$COF_{SHOE,WHEEL} = (0.0092v + 1) \times \left(\frac{1.023 + 0.0031v}{2.5 + 0.0833v} \right) \tag{31}$$

where v is the velocity of the train, in mph. To determine the brake shoe force at 50 psi brake cylinder pressure, $F_{B\text{-}NOM}$, from the brake shoe force at P_{BC}, $F_{SHOE,BCP}$, an equation must be developed to relate the two. To develop this relationship, it is necessary to understand the operation of the brake system. When air pressure builds in the brake cylinder, it pushes a piston out that drives the brake shoes against the wheels. When the pressure is released from the brake cylinder, a spring forces the piston back, which pulls the brake shoes away from the wheels. For the brakes to apply, enough pressure must build in the brake cylinder to overcome the force of this return spring. It takes approximately 10 psi brake cylinder pressure to overcome this force and drive the brake shoes against the wheels.

At this point, the force from the brake cylinder pressure is enough to hold the brake shoes against the wheels, but not enough to generate any force against the wheel. As more brake cylinder pressure builds, the force against the wheels begins to increase and braking occurs. If it is assumed that after the brake cylinder pressure reaches 10 psi, the brake shoe force increases linearly as brake cylinder pressure increases, it is possible to relate the brake shoe force at any brake cylinder pressure, $F_{SHOE,BCP}$, to the brake shoe force at 50 psi, $F_{B\text{-}NOM}$, as a two-piece linear function. Figure 29 shows this relationship, which is expressed mathematically as:

$$F_{SHOE,BCP} = \begin{cases} 0,\ if\ \ BCP \le 10\,psi \\ (0.025 \times P_{BC} - 0.25) \times F_{SHOE,50\,psi},\ if\ \ BCP > 10\,psi \end{cases} \tag{32}$$

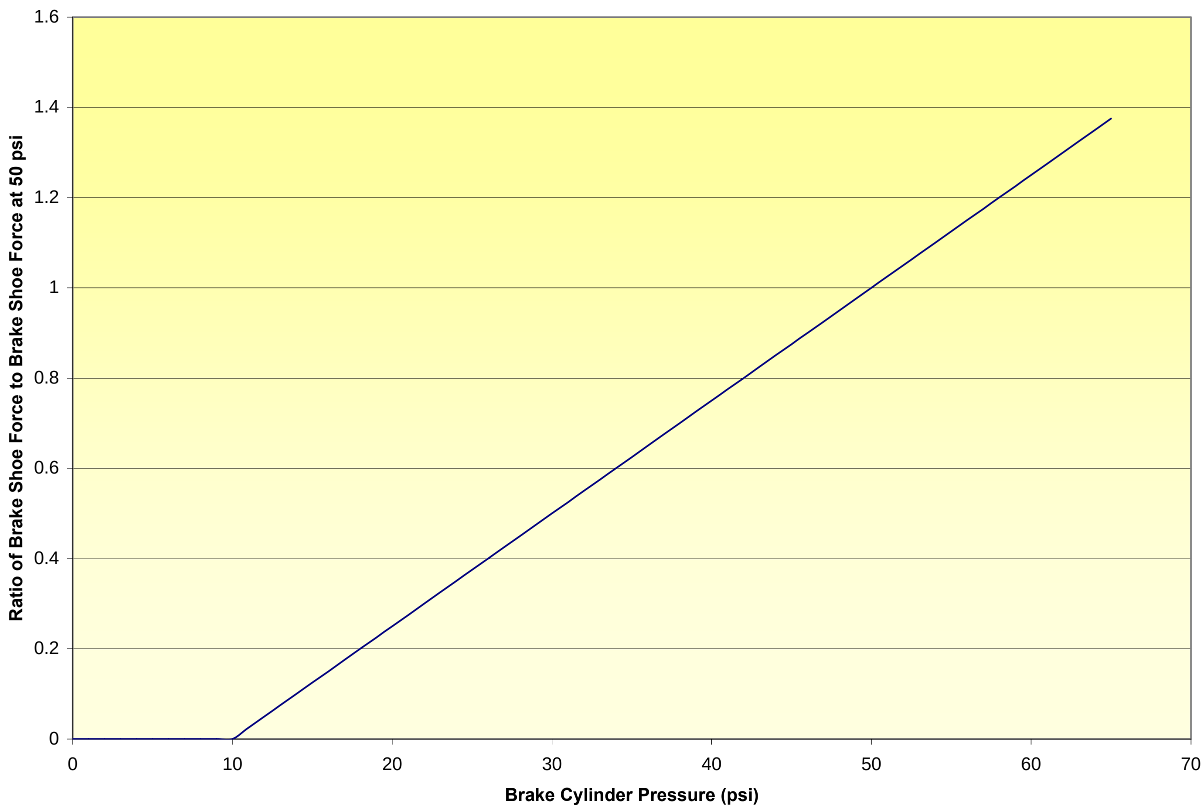

Figure 29. Brake Shoe Force as a Function of Brake Cylinder Pressure

It can be seen from this relationship that to estimate the brake shoe force at 50 psi, $F_{B\text{-}NOM}$, the brake cylinder pressure, P_{BC}, must be known. The brake cylinder pressure can be estimated from the brake pipe pressure reduction. When the brake pipe pressure is reduced, air in the auxiliary reservoir is allowed to move into the brake cylinder until the auxiliary reservoir pressure equals the pressure of the brake pipe. However, because the volume of the auxiliary reservoir is two and half times the volume of the brake cylinder, the air that is allowed to move from the auxiliary reservoir to the brake cylinder generates two and a half times the amount of pressure as it did in the auxiliary reservoir. The brake cylinder pressure can therefore be estimated as follows:

$$P_{BC} = 2.5 \times P_{RED}, \tag{33}$$

where P_{BC} is the pressure in the brake cylinder and P_{RED} is the amount of brake pipe pressure reduction for the current service application, which is determined by subtracting the current head-end brake pipe pressure from the initially charged brake pipe operating pressure.

To accurately estimate the braking efficiency of the entire train, the algorithm must collect data from a brake application that has had enough time to propagate through the entire train. This ensures that the train is bunched and in-train forces are minimal, as well as ensuring that the brakes have had time to apply on all of the cars.

The algorithm can determine when a brake application has been made and propagated through the train by monitoring the brake pipe pressures at the head and tail end of the train. When the head-end brake pipe pressure begins to drop, a brake application has been made. When the tail end-brake pipe pressure begins to drop, the brake signal has propagated through the train. When both head and tail-end brake pipe pressure remain constant for a period of 10 s, the brake application is assumed to be complete.

The brake application must also be sufficiently large to ensure that the brakes will apply on all of the cars. If the brake application is not large enough, the pressure in the brake cylinder may not be enough to overcome the return spring and force the brake shoes against the wheels. A 10 psi brake pipe reduction is generally considered to be sufficient for applying the brakes on all the cars.

The logic and equations described in this section were used to develop an algorithm capable of estimating the brake shoe force generated by the cars with 50 psi in each of the brake cylinders, which represents the braking efficiency of the train. This value is estimated at each time step that the brakes remain applied on all the cars in the train. These values are then averaged to minimize the error associated with any one individual measurement—similar to the averaging performed in the train weight adaptive algorithm.

7.2 Braking Efficiency Adaptive Algorithm Definition

The algorithm begins by monitoring the head-end brake pipe pressure to identify when a brake pipe pressure reduction of at least 10 psi has been made. If the head-end brake pipe pressure reaches a value that is at least 10 psi less than the initially charged brake pipe operating pressure, the algorithm will begin monitoring the tail-end brake pipe pressure. When both the tail-end brake pipe pressure and the head-end brake pipe pressure remain constant (within +/- 1 psi) for 10 s, the propagation of the brake signal will be considered complete, and the algorithm will begin sampling data to determine the force due to this brake application.

The period of data sampling will last for 20 s. If, however, at any point during the data sampling period, the head-end brake pipe pressure changes by more than 1psi, the sampling will stop. At this point, if at least five samples exist, the algorithm will proceed with estimating the braking efficiency. This is to ensure that a brake release or a deeper brake pipe reduction has not been made by the locomotive engineer.

Once the algorithm has a data set of at least five samples, it will estimate the brake cylinder pressure for the data collected by using the following equation:

$$P_{BC} = 2.5 \times P_{RED} \,, \tag{34}$$

where P_{BC} is the pressure in the brake cylinder and P_{RED} is the amount of brake pipe pressure reduction for the current application, determined by subtracting the current head-end brake pipe pressure from the initially charged brake pipe operating pressure.

The algorithm then calculates the train acceleration for each time step (for this project, a time step of one second was used), using the following method:

$$a_t = v_{t+1} - v_t \,, \tag{35}$$

where a_t is the acceleration at the given time step, v_t is the velocity at the given time step, and v_{t+1} is the velocity at the next time step. The acceleration data is then filtered using a fifth order low-pass Butterworth filter with a cutoff frequency of 1/16 Hz.

The algorithm uses the filtered acceleration in the following equation to estimate the brake force generated by the current brake application for each time step:

$$F_{B,BCP} = F_{TE} - F_{DB} - F_{RES} - F_{GRD} - F_{CRV} - \frac{W \times 2000}{32.2} \times a \,, \tag{36}$$

where F_{TE} is the tractive effort produced by the locomotive(s), F_{DB} is the dynamic brake effort produced by the locomotive(s), F_{RES} is the combined resistive forces acting on the train, F_{GRD} is the force due to track grade, F_{CRV} is the resistance due to track curvature, and $F_{B,BCP}$ is the resistance due to the train air brakes at each time step.

The tractive effort produced by the locomotive(s) is a function of the speed and throttle setting of the locomotive(s), and is independent of the weight of the train. This force is determined from tractive effort lookup tables for each of the locomotives.

For each time step, the algorithm looks up the tractive effort produced by each locomotive (using the speed and throttle setting at that time step and the tractive effort lookup table for that locomotive) and sums them to determine the force on the train due to tractive effort for that time step. If the speed is between two entries in the lookup table, the algorithm performs a linear interpolation between the two boundary entries to determine the tractive effort at that time step.

The resistive forces on the train are estimated using the modified Davis equation:

$$F_{RES} = (0.6 \times W) + (20 \times n) + (0.01 \times W \times v) + (0.07 \times N \times v^2) \,, \tag{37}$$

where n is the number of axles on the train, v is the velocity of the train, and N is the number of cars in the train.

The force due to track grade is determined from the following equation:

$$F_{GRD} = 20 \times W \times G \quad , \tag{38}$$

where G is the average percent grade under the train. The average percent grade under the train is determined by the following equation:

$$G = \frac{(E_{HE} - E_{TE})}{L} * 100 \quad , \tag{39}$$

Where E_{HE} is the elevation at the head end of the train, E_{TE} is the elevation at the tail end of the train, and L is the length of the train. The elevations are determined by referencing the head and tail-end positions with the data in the track database, where the tail-end position is the difference between the head-end position and the train length. It should be noted that this method of determining the resistance due to track grade is only accurate for trains with a uniform mass distribution, and therefore some error will be introduced by using this assumption.

The force due to track curvature is determined from the following equation:

$$F_{CRV} = 0.8 \times W \times C \quad , \tag{40}$$

where C is the average degree of curvature of the track under the train. To determine the average degree of curvature under the train, the algorithm looks at the track database between the head end and tail end of the train to determine the degree(s) of curvature under the train. The average degree of curvature is then determined from the following:

$$C = \left(C_1 \times \frac{L_1}{L_T} \right) + \left(C_2 \times \frac{L_2}{L_T} \right) + \cdots + \left(C_n \times \frac{L_n}{L_T} \right) , \tag{41}$$

where C_1, C_2, …, C_n are the various degrees of curvature under the length of the train, L_1, L_2, …, L_n are the length of the train that is on the corresponding degree of curvature, and L_T is the length of the entire train. If a portion of the train is on a spiral, the following formula is used to determine the value of C for the length of the train that is on the spiral:

$$C_{spiral} = C_{start} + \frac{\left(\frac{C_{end} - C_{start}}{L_{spiral}} \right)(D_2 + D_1)}{2} \quad , \tag{42}$$

where C_{start} is the degree of curvature at the start of the spiral, C_{end} is the degree of curvature at the end of the spiral, and L_{spiral} is the length of the spiral. D_1 is the distance from the beginning of the spiral to the head end of the train, if the head end of the train is on the spiral. If the head end of the train is beyond the spiral, then D_1 is equal to the length of the spiral. D_2 is the distance from the beginning of the spiral to the tail end of the train, if the tail end of the train is on the spiral. If the tail end of the train has not yet reached the spiral, then D_2 is equal to zero.

It should be noted that this method of determining resistance due to track curvature, similar to the method for determining resistance due to track grade, is only accurate for trains with uniform mass distribution, and therefore some error will be introduced by using this assumption.

The brake force determined above is used to estimate the brake shoe force at each time step, from the following equation:

$$F_{SHOE,BCP} = \frac{F_{B,BCP}}{(0.0092v+1)\times\left(\frac{1.023+0.0031v}{2.5+0.0833v}\right)} \tag{43}$$

The brake shoe force at 50 psi is then estimated using the following equation:

$$F_{SHOE,50\,psi} = \frac{F_{SHOE,BCP}}{(0.025\times P_{BC} - 0.25)} \tag{44}$$

where P_{BC} is the brake cylinder pressure determined earlier, and $F_{SHOE,50\,psi}$ is the brake shoe force at a brake cylinder pressure of 50 psi. Once $F_{SHOE,50\,psi}$ is determined for each time step, the mean and the standard deviation will be determined for all the time steps in the data set. If the standard deviation is within 5 percent of the mean value, then the mean will be substituted in for $F_{B\text{-}NOM}$ in the enforcement algorithm.

7.3 Braking Efficiency Adaptive Algorithm Testing

The braking efficiency adaptive algorithm was tested using a combination of simulation testing and field testing as described in the test methodology section for the base case enforcement algorithm, subsection 4.3.1.

7.3.1 Simulation Test Results

The stopping location results for each simulation of each test scenario were used to generate a stopping location probability density curve in the same manner as the previous simulation tests. The simulation test results for each test scenario of the braking efficient adaptive enforcement algorithm test can be compared graphically to the results from the base case, propagation time adaptive, and train weight adaptive enforcement algorithms. Appendix F shows these graphical comparisons for each of the test scenarios.

From the example used in the previous simulation test results sections, Figure 30 shows the probability density stopping location curves for each of the four stages of enforcement algorithm development for a 75-car loaded unit freight train traveling 60 mph on flat grade with a target stopping location of 40,000 ft.

The figure shows that, with each added adaptive feature, the stopping location distribution was tighter and the mean stopping location was closer to the target. This indicates a general positive effect on the performance of the enforcement algorithm for each of the adaptive enforcement algorithm developments.

The mean stopping location for the braking efficient adaptive enforcement algorithm was 1,465 ft short of the target in this example, compared with 2,136 ft for the train weight adaptive enforcement algorithm, 2,508 ft for the propagation time adaptive enforcement algorithm, and 3,006 ft for the base case enforcement algorithm. While 0 percent of the trains overshot the target in this case, still only 1 percent undershot the target by less than the specified 1,000 ft in this example. Appendix G contains the statistics for all of the test scenarios.

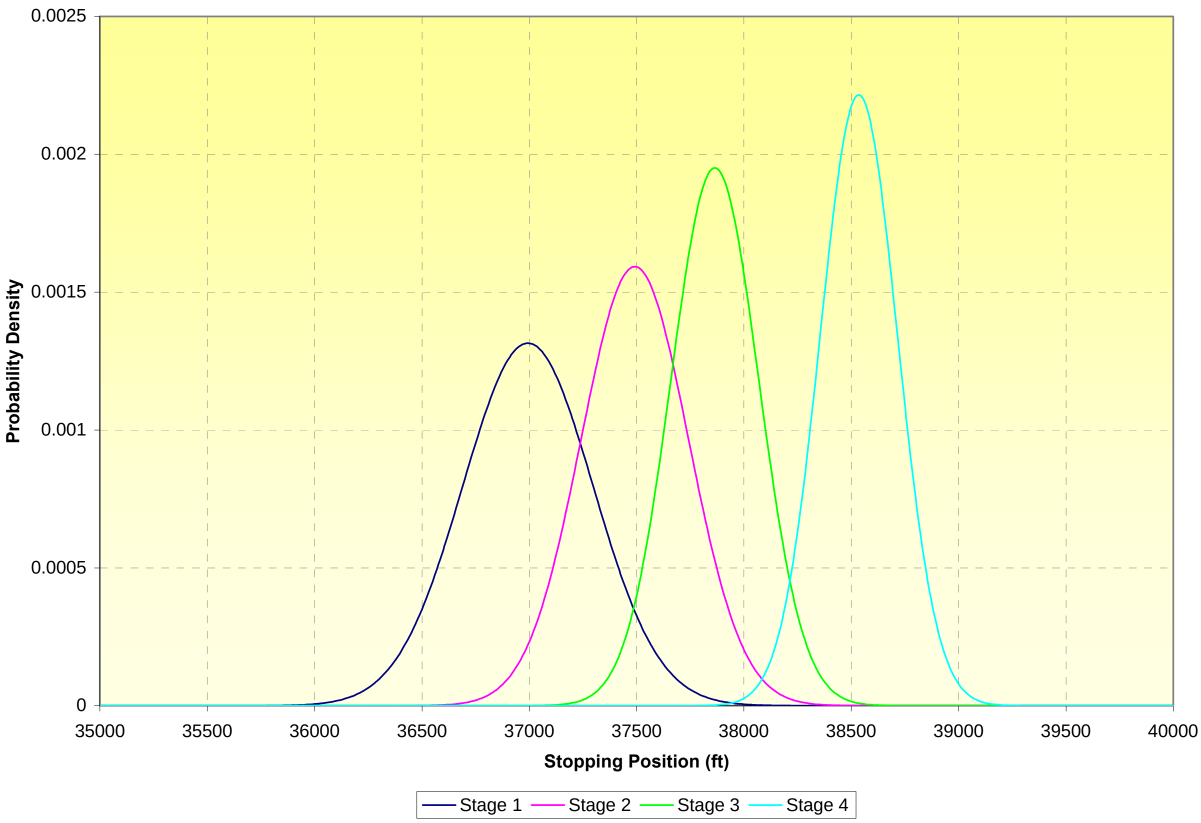

Figure 30. Stopping Location Probability Density Curves for a 75-car Loaded Unit Freight Train Traveling 60 mph on Flat Grade

The data in these appendices make it apparent that the braking efficiency generally has a significantly positive effect on the performance of the enforcement algorithm. In most cases, the braking efficiency algorithm moved the mean stopping location closer to the target and increased the percent of trains that undershot the target by less than the specified distance without increasing the percent of trains that overshot the target. In other cases, the braking efficiency algorithm moved the mean stopping location further from the target, but in doing so, the percent of trains that overshot the target decreased.

7.3.2 Field Test Results

During the week of February 9, 2009, the braking efficiency adaptive enforcement algorithm and the train weight adaptive enforcement algorithm were both tested. Field testing included test runs with all four of the enforcement algorithms, in five of the original seven test scenarios. At least two test runs were completed for each test scenario for the braking efficiency adaptive enforcement algorithm to provide an indication of the repeatability of the algorithm stopping location.

The braking efficiency adaptive enforcement algorithm estimates the total train brake shoe force with 50 psi brake cylinder pressure. Ideally, the test results would provide an indication of the accuracy of the estimation of this braking force. However, to test this would require that the brake shoe force be measured for every vehicle in the test consist. To measure the brake shoe force with 50 psi in the brake cylinder on a single car, load cells are placed between each brake shoe and wheel on the car. The brake system is then charged to 70 psi, and a 20 psi brake pipe reduction is made to generate 50 psi in the brake cylinder. The forces on the load cells are summed to determine the total brake shoe force for the car. This is an expensive and time consuming process, and outside of the scope of this project. Therefore, the performance of the braking efficiency adaptive algorithm was measured based solely on the stopping locations from the enforcement tests.

Table 17 shows the results from the enforcement tests for the braking efficiency adaptive algorithm test runs. Tables 18, 19, and 20 show the results for, respectively, the train weight adaptive, propagation time adaptive, and base case enforcement algorithms for this test period. These tables are identical to Tables 14, 15 and 16 from subsection 6.3.2, but are repeated here for easier comparison.

Table 17. Braking Efficiency Algorithm Field Test Results from February 2009 Field Test

Test	Number of Cars	Mean Speed (mph)	Standard Deviation of Speed (mph)	Grade	Mean Distance to Target (feet)	Standard Deviation of Distance to Target (feet)
1	40	41.2	1.1	Flat	516	9
2	40	62.8	0.2	Flat	175	121
5	10	40.0	0.2	Flat	194	52
6	75	10.0	0.1	Flat	89	19
7	75	44.0	1.0	Decline	682	232

Table 18. Train Weight Algorithm Field Test Results from February 2009 Field Test

Test	Number of Cars	Mean Speed (mph)	Standard Deviation of Speed (mph)	Grade	Mean Distance to Target (feet)	Standard Deviation of Distance to Target (feet)
1	40	40.2	0.4	Flat	1,695	777
2	40	59.7	2.3	Flat	2,150	260
5	10	40.1	0.1	Flat	1,224	863
6	75	10.0	0.1	Flat	240	9
7	75	40.1	0.0	Decline	5,387	56

Table 19. Propagation Time Algorithm Field Test Results from February 2009 Field Test

Test	Number of Cars	Mean Speed (mph)	Standard Deviation of Speed (mph)	Grade	Mean Distance to Target (feet)	Standard Deviation of Distance to Target (feet)
1	40	53.1	N/A	Flat	1,677	N/A
2	40	58.0	N/A	Flat	2,609	N/A
5	10	40.5	N/A	Flat	1,152	N/A
6	75	9.8	N/A	Flat	194	N/A
7	75	38.2	N/A	Decline	4,980	N/A

Table 20. Base Case Algorithm Field Test Results from February 2009 Field Test

Test	Number of Cars	Mean Speed (mph)	Standard Deviation of Speed (mph)	Grade	Mean Distance to Target (feet)	Standard Deviation of Distance to Target (feet)
1	40	40.1	N/A	Flat	1,047	N/A
2	40	56.1	N/A	Flat	2,425	N/A
5	10	40.0	N/A	Flat	1,297	N/A
6	75	10.1	N/A	Flat	142	N/A
7	75	38.0	N/A	Decline	4,100	N/A

The data in Table 17 indicates a major improvement in the performance of the enforcement algorithm with the addition of the braking efficiency adaptive functionality. The mean distance to the target was within the specified distance for all test scenarios. The standard deviation of the stopping distance to the target was also significantly lower for most of the test scenarios, due to the improved stopping distance prediction.

An additional benefit realized by the braking efficiency adaptive enforcement algorithm is that it compensates for any error in train weight, either from the ground system or from the train weight adaptive enforcement algorithm. In some cases, the train weight adaptive algorithm overestimated the weight for one test run and underestimated the weight for another, and the stopping location remained consistent. This is because the train weight is used in the estimation of the braking efficiency. If the train weight is overestimated, the braking efficiency will also be overestimated and the net effect will be minimal.

7.4 Operational Impact of the Braking Efficiency Adaptive Enforcement Algorithm

The braking efficiency adaptive enforcement algorithm requires a service brake application to be made while the train is moving and held long enough to allow for the brakes to apply on all cars in the train to get a good set of data for measuring the braking force. Traditionally, railroads required that a running brake test be performed after leaving the initial terminal. This practice has gone away in recent history due to primarily to the unnecessary fuel cost. Use of the air brakes to control train speed has also been significantly reduced and replaced by the use of dynamic brakes. Because of this, it is very rare that service brake applications are made enroute. Therefore, a brake test may need to be required to realize the benefits of the braking efficiency adaptive algorithm. This will have a negative impact on operations that will manifest itself in additional trip time and fuel costs.

8 Conclusions

This study researched, developed, and tested proof-of-concept methods for converting a static enforcement algorithm into one which can adapt to the specific characteristics of a train. The concept was to identify and to prove the feasibility of these techniques. In general, the techniques developed during this project have proven that the concept of measuring the characteristics of the train can have an appreciable effect on the performance of the enforcement algorithm. Three adaptive routines were developed and tested in this project.

The propagation time adaptive routine initially proved to be very accurate for estimating the actual penalty or full-service brake propagation time. However, as detailed in subsection 5.3.2, later field testing proved that some minor enhancements are needed to allow the algorithm to be as accurate in all operating conditions. Although the concept for how this enhancement might be implemented was discussed, no actual implementation or testing was performed as part of this study. For future work in this area, the recommendation is for this concept to be implemented and tested to prove the concept in all operating conditions. In addition, tests using EOTs with ranging ages and from various manufacturers should be performed to determine the effect they may have on the algorithm performance. Overall, the propagation time adaptive routine proved to have a significant effect on the performance of the base case enforcement algorithm used in this study as detailed in section 5.3.

The train weight adaptive routine proved to be very accurate at predicting train weight for simulation tests, but this accuracy did not follow for the field testing. This is likely due to the large number of additional variables that are present in the field. For instance, the TOES™ model uses the same tractive effort tables as the enforcement algorithm uses, which means the tractive effort estimation was quite accurate in the simulation environment. In the field, however, the method of using tractive effort tables proved to be somewhat insufficient and inaccurate. Another issue in the field testing of this algorithm was the large variance in calculated train weight. As discussed in subsection 6.3.2, by using a limited number of independent measurements to determine the train weight, wide variations can occur. A method for continually refining the train weight measurement through more data and filtering could have a significant impact on both the accuracy and variance of the train weight measurement. Future work should include researching this concept.

The impact of the train weight adaptive routine on the performance of the enforcement algorithm is largely dependent on the accuracy of the train weight provided to the enforcement algorithm. For instance, unit train operations may provide more accurate weights than can be determined by the adaptive routine, while the accuracy of container weights on an intermodal train may vary widely in comparison to the accuracy provided by the train weight adaptive routine. Other options for determining more accurate train weight, such as transmitting vehicle weights in real time from data collected from WILD, could prove useful as well. Ultimately, the best method for determining an accurate train weight will likely be a combination of techniques. A method for determining the confidence in the train weight data could also be implemented and the enforcement algorithm safety offset could be a function of this confidence. While the concept of measuring train weight has been proven to be possible through this project, more research still needs to be performed in this area, and future studies should consider these concepts.

The braking efficiency adaptive routine proved to have the most significant impact on the performance of the enforcement algorithm. As discussed in section 7.3, the braking efficiency enforcement algorithm had the lowest percentage of trains that overshot the target and also the lowest percentage of trains that undershot the target by more than the specified distance. Because the adaptive routines were built progressively, this impact is due to all three of the adaptive routines, but the performance was improved significantly between stage 3 (train weight) and stage 4 (braking efficiency) of the development process. The magnitude of the improvement due to the braking efficiency routine is likely due to the worst case assumptions of braking efficiency used by the base case enforcement algorithm.

The assumptions on braking efficiency may also be improved without the use of the adaptive routine. For instance, if the enforcement algorithm were to have knowledge of the build dates of the cars in the consist, or the types of cars in the consist, less conservative assumptions on braking efficiency could likely be made. As with the train weight enforcement algorithm, a combination of these techniques will likely prove to be the best method, although perhaps not the most practical.

Although the concept of measuring the characteristics of a train and using the data to improve the enforcement algorithm has been shown to be feasible in this project, continued research in this area is recommended. A more indepth parametric study could be performed to identify the impact of all the parameters that can affect stopping distance. This parametric study should also include more detailed research and input from the railroads to determine the most realistic values for the variability of each parameter.

Development and testing of the enforcement algorithms developed in this project were focused on unit train operations. Research needs to be performed on other train types, because braking characteristics can vary based on different car types, particularly articulated intermodal cars. Although it is possible that no modifications are needed for these techniques to work on these train types, testing is needed to confirm this.

Numerous other techniques, in addition to the adaptive techniques developed for this project, have been identified as having potential for improving enforcement algorithm performance. These techniques include using less conservative assumptions with an emergency brake backup in addition to consideration of dynamic brake and independent brake use. Finally, modifications to the enforcement algorithm to take into consideration train characteristics such as distributed power, empty/load devices, and electronically controlled pneumatic brakes could drastically improve the performance of the enforcement algorithm.

Through the combination of improved adaptive techniques and these other techniques, the viability of developing an enforcement algorithm capable of meeting both the safety objective and performance objectives demanded by PTC systems in use today looks promising. At a minimum, these techniques will identify the enforcement algorithm performance level possible for these systems and will likely provide a performance level that will minimize the negative impact on the railroad operation while still meeting the safety objectives of a PTC system.

9 References

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Appendix A.

Test Controller/Logger
Enforcement Algorithm Communications Specification

Enforcement Algorithm Evaluation

Test Controller/Logger – Enforcement Algorithm Communications Specification

v3.2

October 13, 2008

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

REVISION RECORD

REV	DESCRIPTION OF CHANGE	DATE
V1.0	Initial Release	April 25, 2008
V2.0	J. Bilodeau, changed data type integer to unsigned shorts, added enumeration to STATUS field of EA/TCL message	June 23, 2008
V3.0	J. Brosseau, added communication description section, added 02-complete field to STATUS enumeration.	August 28, 2008
V3.1	J. Bilodeau, expanded document with system description section	Sept 29, 2008
V3.2	J. Brosseau, general edits to document	October 13, 2008

1. Introduction

The purpose of this document is to define the communication specification between the Test Controller/Logger (TCL) application and a braking Enforcement Algorithm (EA) application.

The purpose of this system is to test and evaluate braking enforcement algorithms using simulated trains. The trains are simulated by the Train Operations and Energy Simulator (TOES™) application. The TCL application acts as bridge between the braking enforcement algorithm and TOES™.

2. System Description and Definitions

The following figure is a schematic representation of the applications.

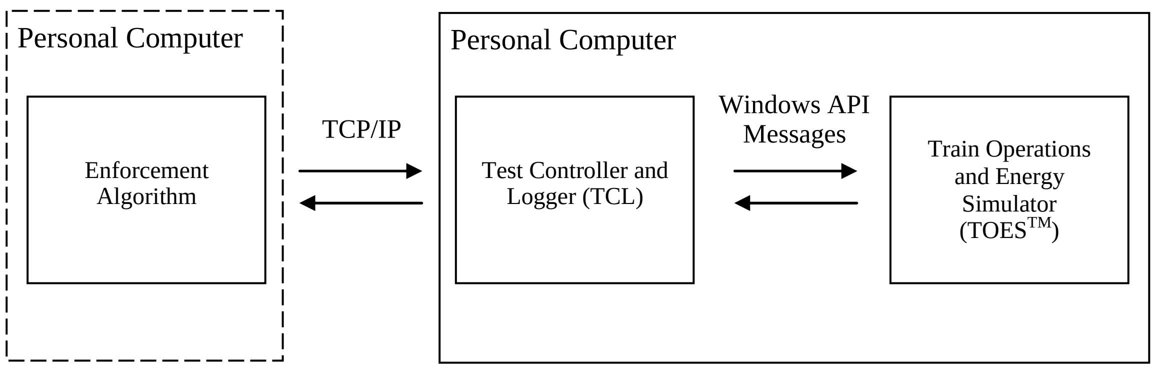

Figure 1 – Application Diagram

The TCL application and the TOES™ application must be run on the same computer. The EA can run either on the same computer running TCL and TOES™ or on a separate computer connected to the TCL/TOES™ computer by an Ethernet connection.

2.1 Application Descriptions

Train Operations and Energy Simulator (TOES™) – TOES™ is a train action simulator developed by TTCI in Pueblo, CO. TOES™ uses inputs that define the train consist and track conditions to model the response of the train to different operational inputs. The TOES™ model simulates the response of the train to a full service brake enforcement command from the enforcement algorithm. The results from the TOES™ simulations are written to text files which are read to determine stopping distance, among other things.

Test Controller/Logger (TCL) – This application is used to control the simulation process. It has the capability to generate and execute batches of enforcement algorithm evaluation simulations. The TCL application generates consist definitions and other inputs required by TOES™ and opens the TOES™ and EA applications to start each simulation. It then acts as a gateway between the two applications during each simulation. It receives messages containing train parameters such as location and velocity at one second (simulation time) intervals from TOES™ and forwards them onto the enforcement algorithm, and receives status and brake application messages from the enforcement algorithm and forwards them to the TOES™ simulator.

Enforcement Algorithm (EA) – This can be any braking enforcement algorithm that communicates with the TCL application via this communications specification. It receives TCP/IP packets from the TCL containing current train parameters (received from TOES™) such as velocity and location. It also sends TCP/IP packets to the TCL application instructing the TCL when to command TOES™ to apply the brakes.

3. Communications Overview

The TCL and EA communicate using TCP/IP, running either on separate computers over a standard Ethernet connection or running on a single machine. In either case a client/server configuration is used. The TCL is the server and the EA is the client. The simulation process begins with the TCL waiting or listening for the EA to make a connection.

9.1 IP Configuration

The EA must have its own IP address if operating on a separate computer. This IP address must use the same subnet mask as the computer running the TCL application.

The port must also be defined. This is a user configurable parameter in the TCL application, the default value is currently port 2525.

3.2 EA Pre-Simulation Configuration

It is assumed that any initialization data the algorithm uses (e.g. number of locos, number of cars, train weight, length, etc.) is loaded into the EA before starting the simulation (in the case of the TTCI AEA, this data is entered in an initialization file that is read by the EA upon starting).

3.3 Starting Simulations

The TCL application must be started before the EA. This ensures that the TCL (server) is up and waiting for an EA (client) connection.

Once the EA makes a connection to the TCL, it sends a status message (MSG0002) to the TCL and waits for the first data message to be sent back. The simulation proceeds from this point until the train has stopped.

The TCL has the ability to start the EA application, if it is running on the same computer. This feature enables automated running of large batches of simulations. If this feature is not used, the user must manually start the EA between every simulation.

3.4 Normal Simulation Operation

During normal simulation operation, the TCL sends a MSG0001 message to the EA once every second (simulation time) and then waits for the EA to send back a MSG0002 message. The TCL then takes the information in the MSG0002 message, forwards it on to the TOES™ application and waits for the TOES™ application to respond. The parameters given in the TOES™ response will be delivered to the EA in the next MSG0001 message. This process continues until the train comes to a stop. During normal operation, the STATUS field of the MSG0002 will be 00 indicating normal operation. If an error has occurred in the EA, the status field should contain a 01 (see MSG0002 format, below).

The first time a MSG0002 message containing a command to initiate a brake application is sent by the EA, the TCL will initiate the brake application in TOES. ™ Once the brake application is initiated, further commands by the EA will have no effect on the simulation (i.e. it is not necessary for the EA to continue sending brake application commands in the MSG0002 messages after this point).

When the EA has completed (train velocity is less then 0.5 mph) a MSG0002 will be sent to the TCL with the STATUS field set to 02 indicating the EA has completed.

4. Message Formats

4.1 TCL to EA message

MSG0001 - TCL TO EA MESSAGE

FIELD NAME	DESCRIPTION	DATA LENGTH	DATA TYPE	LIMITS
TRN_LOC	Current Train Location (footage)	4 bytes	Double	2.3E-308 to 1.E307
TRN_SPD	Current Train Speed (mph)	4 bytes	Double	2.3E-308 to 1.E307
BPP_HEAD	Current Brake Pipe Pressure at Head of train (psi)	4 bytes	Double	2.3E-308 to 1.E307
BPP_END	Current Brake Pipe Pressure at End of Train (psi)	4 bytes	Double	2.3E-308 to 1.E307
NOTCH	Current locomotive throttle position	4 bytes	Double	0-8

4.2 EA to TCL message

MSG0002 - EA TO TCL MESSAGE

FIELD NAME	DESCRIPTION	DATA LENGTH	DATA TYPE	LIMITS
STATUS	Health Status 00 – OK 01 – Error 02 – Complete	2 bytes	short	0-65536
APPLY_BR	Apply service brake	1 bit	Boolean	0 or 1
APPLY_EB	Apply emergency brake	1 bit	Boolean	0 or 1

Appendix B.
Parametric Study Simulation Test Matrix

Sim Set ID	Type of Train	Train Length	Train Load	Train Speed	Track Grade	Train Power	Test Variable
000	Manifest Freight	Short	Loaded	Fast	Flat	N/A	Weight
001	Manifest Freight	Short	Loaded	Fast	Flat	N/A	Brake Valve
002	Manifest Freight	Short	Loaded	Fast	Flat	N/A	Piston Stroke
003	Manifest Freight	Short	Loaded	Fast	Flat	N/A	Net Brake Force
004	Manifest Freight	Short	Loaded	Fast	Incline	N/A	Weight
005	Manifest Freight	Short	Loaded	Fast	Incline	N/A	Brake Valve
006	Manifest Freight	Short	Loaded	Fast	Incline	N/A	Piston Stroke
007	Manifest Freight	Short	Loaded	Fast	Incline	N/A	Net Brake Force
008	Manifest Freight	Short	Loaded	Fast	Decline	N/A	Weight
009	Manifest Freight	Short	Loaded	Fast	Decline	N/A	Brake Valve
010	Manifest Freight	Short	Loaded	Fast	Decline	N/A	Piston Stroke
011	Manifest Freight	Short	Loaded	Fast	Decline	N/A	Net Brake Force
012	Manifest Freight	Short	Loaded	Fast	Crest	N/A	Weight
013	Manifest Freight	Short	Loaded	Fast	Crest	N/A	Brake Valve
014	Manifest Freight	Short	Loaded	Fast	Crest	N/A	Piston Stroke
015	Manifest Freight	Short	Loaded	Fast	Crest	N/A	Net Brake Force
016	Manifest Freight	Short	Loaded	Fast	Trough	N/A	Weight
017	Manifest Freight	Short	Loaded	Fast	Trough	N/A	Brake Valve
018	Manifest Freight	Short	Loaded	Fast	Trough	N/A	Piston Stroke
019	Manifest Freight	Short	Loaded	Fast	Trough	N/A	Net Brake Force
020	Manifest Freight	Short	Loaded	Slow	Flat	N/A	Weight
021	Manifest Freight	Short	Loaded	Slow	Flat	N/A	Brake Valve
022	Manifest Freight	Short	Loaded	Slow	Flat	N/A	Piston Stroke
023	Manifest Freight	Short	Loaded	Slow	Flat	N/A	Net Brake Force
024	Manifest Freight	Short	Loaded	Slow	Incline	N/A	Weight
025	Manifest Freight	Short	Loaded	Slow	Incline	N/A	Brake Valve
026	Manifest Freight	Short	Loaded	Slow	Incline	N/A	Piston Stroke
027	Manifest Freight	Short	Loaded	Slow	Incline	N/A	Net Brake Force
028	Manifest Freight	Short	Loaded	Slow	Decline	N/A	Weight
029	Manifest Freight	Short	Loaded	Slow	Decline	N/A	Brake Valve
030	Manifest Freight	Short	Loaded	Slow	Decline	N/A	Piston Stroke
031	Manifest Freight	Short	Loaded	Slow	Decline	N/A	Net Brake Force

Sim Set ID	Type of Train	Train Length	Train Load	Train Speed	Track Grade	Train Power	Test Variable
032	Manifest Freight	Short	Loaded	Slow	Crest	N/A	Weight
033	Manifest Freight	Short	Loaded	Slow	Crest	N/A	Brake Valve
034	Manifest Freight	Short	Loaded	Slow	Crest	N/A	Piston Stroke
035	Manifest Freight	Short	Loaded	Slow	Crest	N/A	Net Brake Force
036	Manifest Freight	Short	Loaded	Slow	Trough	N/A	Weight
037	Manifest Freight	Short	Loaded	Slow	Trough	N/A	Brake Valve
038	Manifest Freight	Short	Loaded	Slow	Trough	N/A	Piston Stroke
039	Manifest Freight	Short	Loaded	Slow	Trough	N/A	Net Brake Force
040	Manifest Freight	Short	Empty	Fast	Flat	N/A	Weight
041	Manifest Freight	Short	Empty	Fast	Flat	N/A	Brake Valve
042	Manifest Freight	Short	Empty	Fast	Flat	N/A	Piston Stroke
043	Manifest Freight	Short	Empty	Fast	Flat	N/A	Net Brake Force
044	Manifest Freight	Short	Empty	Fast	Incline	N/A	Weight
045	Manifest Freight	Short	Empty	Fast	Incline	N/A	Brake Valve
046	Manifest Freight	Short	Empty	Fast	Incline	N/A	Piston Stroke
047	Manifest Freight	Short	Empty	Fast	Incline	N/A	Net Brake Force
048	Manifest Freight	Short	Empty	Fast	Decline	N/A	Weight
049	Manifest Freight	Short	Empty	Fast	Decline	N/A	Brake Valve
050	Manifest Freight	Short	Empty	Fast	Decline	N/A	Piston Stroke
051	Manifest Freight	Short	Empty	Fast	Decline	N/A	Net Brake Force
052	Manifest Freight	Short	Empty	Fast	Crest	N/A	Weight
053	Manifest Freight	Short	Empty	Fast	Crest	N/A	Brake Valve
054	Manifest Freight	Short	Empty	Fast	Crest	N/A	Piston Stroke
055	Manifest Freight	Short	Empty	Fast	Crest	N/A	Net Brake Force
056	Manifest Freight	Short	Empty	Fast	Trough	N/A	Weight
057	Manifest Freight	Short	Empty	Fast	Trough	N/A	Brake Valve
058	Manifest Freight	Short	Empty	Fast	Trough	N/A	Piston Stroke
059	Manifest Freight	Short	Empty	Fast	Trough	N/A	Net Brake Force
060	Manifest Freight	Short	Empty	Slow	Flat	N/A	Weight
061	Manifest Freight	Short	Empty	Slow	Flat	N/A	Brake Valve
062	Manifest Freight	Short	Empty	Slow	Flat	N/A	Piston Stroke
063	Manifest Freight	Short	Empty	Slow	Flat	N/A	Net Brake Force
064	Manifest Freight	Short	Empty	Slow	Incline	N/A	Weight

Sim Set ID	Type of Train	Train Length	Train Load	Train Speed	Track Grade	Train Power	Test Variable
065	Manifest Freight	Short	Empty	Slow	Incline	N/A	Brake Valve
066	Manifest Freight	Short	Empty	Slow	Incline	N/A	Piston Stroke
067	Manifest Freight	Short	Empty	Slow	Incline	N/A	Net Brake Force
068	Manifest Freight	Short	Empty	Slow	Decline	N/A	Weight
069	Manifest Freight	Short	Empty	Slow	Decline	N/A	Brake Valve
070	Manifest Freight	Short	Empty	Slow	Decline	N/A	Piston Stroke
071	Manifest Freight	Short	Empty	Slow	Decline	N/A	Net Brake Force
072	Manifest Freight	Short	Empty	Slow	Crest	N/A	Weight
073	Manifest Freight	Short	Empty	Slow	Crest	N/A	Brake Valve
074	Manifest Freight	Short	Empty	Slow	Crest	N/A	Piston Stroke
075	Manifest Freight	Short	Empty	Slow	Crest	N/A	Net Brake Force
076	Manifest Freight	Short	Empty	Slow	Trough	N/A	Weight
077	Manifest Freight	Short	Empty	Slow	Trough	N/A	Brake Valve
078	Manifest Freight	Short	Empty	Slow	Trough	N/A	Piston Stroke
079	Manifest Freight	Short	Empty	Slow	Trough	N/A	Net Brake Force
080	Manifest Freight	Short	Partial Uniform	Fast	Flat	N/A	Weight
081	Manifest Freight	Short	Partial Uniform	Fast	Flat	N/A	Brake Valve
082	Manifest Freight	Short	Partial Uniform	Fast	Flat	N/A	Piston Stroke
083	Manifest Freight	Short	Partial Uniform	Fast	Flat	N/A	Net Brake Force
084	Manifest Freight	Short	Partial Uniform	Fast	Incline	N/A	Weight
085	Manifest Freight	Short	Partial Uniform	Fast	Incline	N/A	Brake Valve
086	Manifest Freight	Short	Partial Uniform	Fast	Incline	N/A	Piston Stroke
087	Manifest Freight	Short	Partial Uniform	Fast	Incline	N/A	Net Brake Force
088	Manifest Freight	Short	Partial Uniform	Fast	Decline	N/A	Weight
089	Manifest Freight	Short	Partial Uniform	Fast	Decline	N/A	Brake Valve
090	Manifest Freight	Short	Partial Uniform	Fast	Decline	N/A	Piston Stroke
091	Manifest Freight	Short	Partial Uniform	Fast	Decline	N/A	Net Brake Force
092	Manifest Freight	Short	Partial Uniform	Fast	Crest	N/A	Weight
093	Manifest Freight	Short	Partial Uniform	Fast	Crest	N/A	Brake Valve
094	Manifest Freight	Short	Partial Uniform	Fast	Crest	N/A	Piston Stroke
095	Manifest Freight	Short	Partial Uniform	Fast	Crest	N/A	Net Brake Force
096	Manifest Freight	Short	Partial Uniform	Fast	Trough	N/A	Weight
097	Manifest Freight	Short	Partial Uniform	Fast	Trough	N/A	Brake Valve

Sim Set ID	Type of Train	Train Length	Train Load	Train Speed	Track Grade	Train Power	Test Variable
098	Manifest Freight	Short	Partial Uniform	Fast	Trough	N/A	Piston Stroke
099	Manifest Freight	Short	Partial Uniform	Fast	Trough	N/A	Net Brake Force
100	Manifest Freight	Short	Partial Uniform	Slow	Flat	N/A	Weight
101	Manifest Freight	Short	Partial Uniform	Slow	Flat	N/A	Brake Valve
102	Manifest Freight	Short	Partial Uniform	Slow	Flat	N/A	Piston Stroke
103	Manifest Freight	Short	Partial Uniform	Slow	Flat	N/A	Net Brake Force
104	Manifest Freight	Short	Partial Uniform	Slow	Incline	N/A	Weight
105	Manifest Freight	Short	Partial Uniform	Slow	Incline	N/A	Brake Valve
106	Manifest Freight	Short	Partial Uniform	Slow	Incline	N/A	Piston Stroke
107	Manifest Freight	Short	Partial Uniform	Slow	Incline	N/A	Net Brake Force
108	Manifest Freight	Short	Partial Uniform	Slow	Decline	N/A	Weight
109	Manifest Freight	Short	Partial Uniform	Slow	Decline	N/A	Brake Valve
110	Manifest Freight	Short	Partial Uniform	Slow	Decline	N/A	Piston Stroke
111	Manifest Freight	Short	Partial Uniform	Slow	Decline	N/A	Net Brake Force
112	Manifest Freight	Short	Partial Uniform	Slow	Crest	N/A	Weight
113	Manifest Freight	Short	Partial Uniform	Slow	Crest	N/A	Brake Valve
114	Manifest Freight	Short	Partial Uniform	Slow	Crest	N/A	Piston Stroke
115	Manifest Freight	Short	Partial Uniform	Slow	Crest	N/A	Net Brake Force
116	Manifest Freight	Short	Partial Uniform	Slow	Trough	N/A	Weight
117	Manifest Freight	Short	Partial Uniform	Slow	Trough	N/A	Brake Valve
118	Manifest Freight	Short	Partial Uniform	Slow	Trough	N/A	Piston Stroke
119	Manifest Freight	Short	Partial Uniform	Slow	Trough	N/A	Net Brake Force
120	Manifest Freight	Short	Partial Non-uniform	Fast	Flat	N/A	Weight
121	Manifest Freight	Short	Partial Non-uniform	Fast	Flat	N/A	Brake Valve
122	Manifest Freight	Short	Partial Non-uniform	Fast	Flat	N/A	Piston Stroke
123	Manifest Freight	Short	Partial Non-uniform	Fast	Flat	N/A	Net Brake Force
124	Manifest Freight	Short	Partial Non-uniform	Fast	Incline	N/A	Weight
125	Manifest Freight	Short	Partial Non-uniform	Fast	Incline	N/A	Brake Valve
126	Manifest Freight	Short	Partial Non-uniform	Fast	Incline	N/A	Piston Stroke
127	Manifest Freight	Short	Partial Non-uniform	Fast	Incline	N/A	Net Brake Force
128	Manifest Freight	Short	Partial Non-uniform	Fast	Decline	N/A	Weight
129	Manifest Freight	Short	Partial Non-uniform	Fast	Decline	N/A	Brake Valve
130	Manifest Freight	Short	Partial Non-uniform	Fast	Decline	N/A	Piston Stroke

Sim Set ID	Type of Train	Train Length	Train Load	Train Speed	Track Grade	Train Power	Test Variable
131	Manifest Freight	Short	Partial Non-uniform	Fast	Decline	N/A	Net Brake Force
132	Manifest Freight	Short	Partial Non-uniform	Fast	Crest	N/A	Weight
133	Manifest Freight	Short	Partial Non-uniform	Fast	Crest	N/A	Brake Valve
134	Manifest Freight	Short	Partial Non-uniform	Fast	Crest	N/A	Piston Stroke
135	Manifest Freight	Short	Partial Non-uniform	Fast	Crest	N/A	Net Brake Force
136	Manifest Freight	Short	Partial Non-uniform	Fast	Trough	N/A	Weight
137	Manifest Freight	Short	Partial Non-uniform	Fast	Trough	N/A	Brake Valve
138	Manifest Freight	Short	Partial Non-uniform	Fast	Trough	N/A	Piston Stroke
139	Manifest Freight	Short	Partial Non-uniform	Fast	Trough	N/A	Net Brake Force
140	Manifest Freight	Short	Partial Non-uniform	Slow	Flat	N/A	Weight
141	Manifest Freight	Short	Partial Non-uniform	Slow	Flat	N/A	Brake Valve
142	Manifest Freight	Short	Partial Non-uniform	Slow	Flat	N/A	Piston Stroke
143	Manifest Freight	Short	Partial Non-uniform	Slow	Flat	N/A	Net Brake Force
144	Manifest Freight	Short	Partial Non-uniform	Slow	Incline	N/A	Weight
145	Manifest Freight	Short	Partial Non-uniform	Slow	Incline	N/A	Brake Valve
146	Manifest Freight	Short	Partial Non-uniform	Slow	Incline	N/A	Piston Stroke
147	Manifest Freight	Short	Partial Non-uniform	Slow	Incline	N/A	Net Brake Force
148	Manifest Freight	Short	Partial Non-uniform	Slow	Decline	N/A	Weight
149	Manifest Freight	Short	Partial Non-uniform	Slow	Decline	N/A	Brake Valve
150	Manifest Freight	Short	Partial Non-uniform	Slow	Decline	N/A	Piston Stroke
151	Manifest Freight	Short	Partial Non-uniform	Slow	Decline	N/A	Net Brake Force
152	Manifest Freight	Short	Partial Non-uniform	Slow	Crest	N/A	Weight
153	Manifest Freight	Short	Partial Non-uniform	Slow	Crest	N/A	Brake Valve
154	Manifest Freight	Short	Partial Non-uniform	Slow	Crest	N/A	Piston Stroke
155	Manifest Freight	Short	Partial Non-uniform	Slow	Crest	N/A	Net Brake Force
156	Manifest Freight	Short	Partial Non-uniform	Slow	Trough	N/A	Weight
157	Manifest Freight	Short	Partial Non-uniform	Slow	Trough	N/A	Brake Valve
158	Manifest Freight	Short	Partial Non-uniform	Slow	Trough	N/A	Piston Stroke
159	Manifest Freight	Short	Partial Non-uniform	Slow	Trough	N/A	Net Brake Force
160	Manifest Freight	Medium	Loaded	Fast	Flat	N/A	Weight
161	Manifest Freight	Medium	Loaded	Fast	Flat	N/A	Brake Valve
162	Manifest Freight	Medium	Loaded	Fast	Flat	N/A	Piston Stroke
163	Manifest Freight	Medium	Loaded	Fast	Flat	N/A	Net Brake Force

Sim Set ID	Type of Train	Train Length	Train Load	Train Speed	Track Grade	Train Power	Test Variable
164	Manifest Freight	Medium	Loaded	Fast	Incline	N/A	Weight
165	Manifest Freight	Medium	Loaded	Fast	Incline	N/A	Brake Valve
166	Manifest Freight	Medium	Loaded	Fast	Incline	N/A	Piston Stroke
167	Manifest Freight	Medium	Loaded	Fast	Incline	N/A	Net Brake Force
168	Manifest Freight	Medium	Loaded	Fast	Decline	N/A	Weight
169	Manifest Freight	Medium	Loaded	Fast	Decline	N/A	Brake Valve
170	Manifest Freight	Medium	Loaded	Fast	Decline	N/A	Piston Stroke
171	Manifest Freight	Medium	Loaded	Fast	Decline	N/A	Net Brake Force
172	Manifest Freight	Medium	Loaded	Fast	Crest	N/A	Weight
173	Manifest Freight	Medium	Loaded	Fast	Crest	N/A	Brake Valve
174	Manifest Freight	Medium	Loaded	Fast	Crest	N/A	Piston Stroke
175	Manifest Freight	Medium	Loaded	Fast	Crest	N/A	Net Brake Force
176	Manifest Freight	Medium	Loaded	Fast	Trough	N/A	Weight
177	Manifest Freight	Medium	Loaded	Fast	Trough	N/A	Brake Valve
178	Manifest Freight	Medium	Loaded	Fast	Trough	N/A	Piston Stroke
179	Manifest Freight	Medium	Loaded	Fast	Trough	N/A	Net Brake Force
180	Manifest Freight	Medium	Loaded	Slow	Flat	N/A	Weight
181	Manifest Freight	Medium	Loaded	Slow	Flat	N/A	Brake Valve
182	Manifest Freight	Medium	Loaded	Slow	Flat	N/A	Piston Stroke
183	Manifest Freight	Medium	Loaded	Slow	Flat	N/A	Net Brake Force
184	Manifest Freight	Medium	Loaded	Slow	Incline	N/A	Weight
185	Manifest Freight	Medium	Loaded	Slow	Incline	N/A	Brake Valve
186	Manifest Freight	Medium	Loaded	Slow	Incline	N/A	Piston Stroke
187	Manifest Freight	Medium	Loaded	Slow	Incline	N/A	Net Brake Force
188	Manifest Freight	Medium	Loaded	Slow	Decline	N/A	Weight
189	Manifest Freight	Medium	Loaded	Slow	Decline	N/A	Brake Valve
190	Manifest Freight	Medium	Loaded	Slow	Decline	N/A	Piston Stroke
191	Manifest Freight	Medium	Loaded	Slow	Decline	N/A	Net Brake Force
192	Manifest Freight	Medium	Loaded	Slow	Crest	N/A	Weight
193	Manifest Freight	Medium	Loaded	Slow	Crest	N/A	Brake Valve
194	Manifest Freight	Medium	Loaded	Slow	Crest	N/A	Piston Stroke
195	Manifest Freight	Medium	Loaded	Slow	Crest	N/A	Net Brake Force
196	Manifest Freight	Medium	Loaded	Slow	Trough	N/A	Weight

Sim Set ID	Type of Train	Train Length	Train Load	Train Speed	Track Grade	Train Power	Test Variable
197	Manifest Freight	Medium	Loaded	Slow	Trough	N/A	Brake Valve
198	Manifest Freight	Medium	Loaded	Slow	Trough	N/A	Piston Stroke
199	Manifest Freight	Medium	Loaded	Slow	Trough	N/A	Net Brake Force
200	Manifest Freight	Medium	Empty	Fast	Flat	N/A	Weight
201	Manifest Freight	Medium	Empty	Fast	Flat	N/A	Brake Valve
202	Manifest Freight	Medium	Empty	Fast	Flat	N/A	Piston Stroke
203	Manifest Freight	Medium	Empty	Fast	Flat	N/A	Net Brake Force
204	Manifest Freight	Medium	Empty	Fast	Incline	N/A	Weight
205	Manifest Freight	Medium	Empty	Fast	Incline	N/A	Brake Valve
206	Manifest Freight	Medium	Empty	Fast	Incline	N/A	Piston Stroke
207	Manifest Freight	Medium	Empty	Fast	Incline	N/A	Net Brake Force
208	Manifest Freight	Medium	Empty	Fast	Decline	N/A	Weight
209	Manifest Freight	Medium	Empty	Fast	Decline	N/A	Brake Valve
210	Manifest Freight	Medium	Empty	Fast	Decline	N/A	Piston Stroke
211	Manifest Freight	Medium	Empty	Fast	Decline	N/A	Net Brake Force
212	Manifest Freight	Medium	Empty	Fast	Crest	N/A	Weight
213	Manifest Freight	Medium	Empty	Fast	Crest	N/A	Brake Valve
214	Manifest Freight	Medium	Empty	Fast	Crest	N/A	Piston Stroke
215	Manifest Freight	Medium	Empty	Fast	Crest	N/A	Net Brake Force
216	Manifest Freight	Medium	Empty	Fast	Trough	N/A	Weight
217	Manifest Freight	Medium	Empty	Fast	Trough	N/A	Brake Valve
218	Manifest Freight	Medium	Empty	Fast	Trough	N/A	Piston Stroke
219	Manifest Freight	Medium	Empty	Fast	Trough	N/A	Net Brake Force
220	Manifest Freight	Medium	Empty	Slow	Flat	N/A	Weight
221	Manifest Freight	Medium	Empty	Slow	Flat	N/A	Brake Valve
222	Manifest Freight	Medium	Empty	Slow	Flat	N/A	Piston Stroke
223	Manifest Freight	Medium	Empty	Slow	Flat	N/A	Net Brake Force
224	Manifest Freight	Medium	Empty	Slow	Incline	N/A	Weight
225	Manifest Freight	Medium	Empty	Slow	Incline	N/A	Brake Valve
226	Manifest Freight	Medium	Empty	Slow	Incline	N/A	Piston Stroke
227	Manifest Freight	Medium	Empty	Slow	Incline	N/A	Net Brake Force
228	Manifest Freight	Medium	Empty	Slow	Decline	N/A	Weight
229	Manifest Freight	Medium	Empty	Slow	Decline	N/A	Brake Valve

Sim Set ID	Type of Train	Train Length	Train Load	Train Speed	Track Grade	Train Power	Test Variable
230	Manifest Freight	Medium	Empty	Slow	Decline	N/A	Piston Stroke
231	Manifest Freight	Medium	Empty	Slow	Decline	N/A	Net Brake Force
232	Manifest Freight	Medium	Empty	Slow	Crest	N/A	Weight
233	Manifest Freight	Medium	Empty	Slow	Crest	N/A	Brake Valve
234	Manifest Freight	Medium	Empty	Slow	Crest	N/A	Piston Stroke
235	Manifest Freight	Medium	Empty	Slow	Crest	N/A	Net Brake Force
236	Manifest Freight	Medium	Empty	Slow	Trough	N/A	Weight
237	Manifest Freight	Medium	Empty	Slow	Trough	N/A	Brake Valve
238	Manifest Freight	Medium	Empty	Slow	Trough	N/A	Piston Stroke
239	Manifest Freight	Medium	Empty	Slow	Trough	N/A	Net Brake Force
240	Manifest Freight	Medium	Partial Uniform	Fast	Flat	N/A	Weight
241	Manifest Freight	Medium	Partial Uniform	Fast	Flat	N/A	Brake Valve
242	Manifest Freight	Medium	Partial Uniform	Fast	Flat	N/A	Piston Stroke
243	Manifest Freight	Medium	Partial Uniform	Fast	Flat	N/A	Net Brake Force
244	Manifest Freight	Medium	Partial Uniform	Fast	Incline	N/A	Weight
245	Manifest Freight	Medium	Partial Uniform	Fast	Incline	N/A	Brake Valve
246	Manifest Freight	Medium	Partial Uniform	Fast	Incline	N/A	Piston Stroke
247	Manifest Freight	Medium	Partial Uniform	Fast	Incline	N/A	Net Brake Force
248	Manifest Freight	Medium	Partial Uniform	Fast	Decline	N/A	Weight
249	Manifest Freight	Medium	Partial Uniform	Fast	Decline	N/A	Brake Valve
250	Manifest Freight	Medium	Partial Uniform	Fast	Decline	N/A	Piston Stroke
251	Manifest Freight	Medium	Partial Uniform	Fast	Decline	N/A	Net Brake Force
252	Manifest Freight	Medium	Partial Uniform	Fast	Crest	N/A	Weight
253	Manifest Freight	Medium	Partial Uniform	Fast	Crest	N/A	Brake Valve
254	Manifest Freight	Medium	Partial Uniform	Fast	Crest	N/A	Piston Stroke
255	Manifest Freight	Medium	Partial Uniform	Fast	Crest	N/A	Net Brake Force
256	Manifest Freight	Medium	Partial Uniform	Fast	Trough	N/A	Weight
257	Manifest Freight	Medium	Partial Uniform	Fast	Trough	N/A	Brake Valve
258	Manifest Freight	Medium	Partial Uniform	Fast	Trough	N/A	Piston Stroke
259	Manifest Freight	Medium	Partial Uniform	Fast	Trough	N/A	Net Brake Force
260	Manifest Freight	Medium	Partial Uniform	Slow	Flat	N/A	Weight
261	Manifest Freight	Medium	Partial Uniform	Slow	Flat	N/A	Brake Valve
262	Manifest Freight	Medium	Partial Uniform	Slow	Flat	N/A	Piston Stroke

Sim Set ID	Type of Train	Train Length	Train Load	Train Speed	Track Grade	Train Power	Test Variable
263	Manifest Freight	Medium	Partial Uniform	Slow	Flat	N/A	Net Brake Force
264	Manifest Freight	Medium	Partial Uniform	Slow	Incline	N/A	Weight
265	Manifest Freight	Medium	Partial Uniform	Slow	Incline	N/A	Brake Valve
266	Manifest Freight	Medium	Partial Uniform	Slow	Incline	N/A	Piston Stroke
267	Manifest Freight	Medium	Partial Uniform	Slow	Incline	N/A	Net Brake Force
268	Manifest Freight	Medium	Partial Uniform	Slow	Decline	N/A	Weight
269	Manifest Freight	Medium	Partial Uniform	Slow	Decline	N/A	Brake Valve
270	Manifest Freight	Medium	Partial Uniform	Slow	Decline	N/A	Piston Stroke
271	Manifest Freight	Medium	Partial Uniform	Slow	Decline	N/A	Net Brake Force
272	Manifest Freight	Medium	Partial Uniform	Slow	Crest	N/A	Weight
273	Manifest Freight	Medium	Partial Uniform	Slow	Crest	N/A	Brake Valve
274	Manifest Freight	Medium	Partial Uniform	Slow	Crest	N/A	Piston Stroke
275	Manifest Freight	Medium	Partial Uniform	Slow	Crest	N/A	Net Brake Force
276	Manifest Freight	Medium	Partial Uniform	Slow	Trough	N/A	Weight
277	Manifest Freight	Medium	Partial Uniform	Slow	Trough	N/A	Brake Valve
278	Manifest Freight	Medium	Partial Uniform	Slow	Trough	N/A	Piston Stroke
279	Manifest Freight	Medium	Partial Uniform	Slow	Trough	N/A	Net Brake Force
280	Manifest Freight	Medium	Partial Non-uniform	Fast	Flat	N/A	Weight
281	Manifest Freight	Medium	Partial Non-uniform	Fast	Flat	N/A	Brake Valve
282	Manifest Freight	Medium	Partial Non-uniform	Fast	Flat	N/A	Piston Stroke
283	Manifest Freight	Medium	Partial Non-uniform	Fast	Flat	N/A	Net Brake Force
284	Manifest Freight	Medium	Partial Non-uniform	Fast	Incline	N/A	Weight
285	Manifest Freight	Medium	Partial Non-uniform	Fast	Incline	N/A	Brake Valve
286	Manifest Freight	Medium	Partial Non-uniform	Fast	Incline	N/A	Piston Stroke
287	Manifest Freight	Medium	Partial Non-uniform	Fast	Incline	N/A	Net Brake Force
288	Manifest Freight	Medium	Partial Non-uniform	Fast	Decline	N/A	Weight
289	Manifest Freight	Medium	Partial Non-uniform	Fast	Decline	N/A	Brake Valve
290	Manifest Freight	Medium	Partial Non-uniform	Fast	Decline	N/A	Piston Stroke
291	Manifest Freight	Medium	Partial Non-uniform	Fast	Decline	N/A	Net Brake Force
292	Manifest Freight	Medium	Partial Non-uniform	Fast	Crest	N/A	Weight
293	Manifest Freight	Medium	Partial Non-uniform	Fast	Crest	N/A	Brake Valve
294	Manifest Freight	Medium	Partial Non-uniform	Fast	Crest	N/A	Piston Stroke
295	Manifest Freight	Medium	Partial Non-uniform	Fast	Crest	N/A	Net Brake Force

Sim Set ID	Type of Train	Train Length	Train Load	Train Speed	Track Grade	Train Power	Test Variable
296	Manifest Freight	Medium	Partial Non-uniform	Fast	Trough	N/A	Weight
297	Manifest Freight	Medium	Partial Non-uniform	Fast	Trough	N/A	Brake Valve
298	Manifest Freight	Medium	Partial Non-uniform	Fast	Trough	N/A	Piston Stroke
299	Manifest Freight	Medium	Partial Non-uniform	Fast	Trough	N/A	Net Brake Force
300	Manifest Freight	Medium	Partial Non-uniform	Slow	Flat	N/A	Weight
301	Manifest Freight	Medium	Partial Non-uniform	Slow	Flat	N/A	Brake Valve
302	Manifest Freight	Medium	Partial Non-uniform	Slow	Flat	N/A	Piston Stroke
303	Manifest Freight	Medium	Partial Non-uniform	Slow	Flat	N/A	Net Brake Force
304	Manifest Freight	Medium	Partial Non-uniform	Slow	Incline	N/A	Weight
305	Manifest Freight	Medium	Partial Non-uniform	Slow	Incline	N/A	Brake Valve
306	Manifest Freight	Medium	Partial Non-uniform	Slow	Incline	N/A	Piston Stroke
307	Manifest Freight	Medium	Partial Non-uniform	Slow	Incline	N/A	Net Brake Force
308	Manifest Freight	Medium	Partial Non-uniform	Slow	Decline	N/A	Weight
309	Manifest Freight	Medium	Partial Non-uniform	Slow	Decline	N/A	Brake Valve
310	Manifest Freight	Medium	Partial Non-uniform	Slow	Decline	N/A	Piston Stroke
311	Manifest Freight	Medium	Partial Non-uniform	Slow	Decline	N/A	Net Brake Force
312	Manifest Freight	Medium	Partial Non-uniform	Slow	Crest	N/A	Weight
313	Manifest Freight	Medium	Partial Non-uniform	Slow	Crest	N/A	Brake Valve
314	Manifest Freight	Medium	Partial Non-uniform	Slow	Crest	N/A	Piston Stroke
315	Manifest Freight	Medium	Partial Non-uniform	Slow	Crest	N/A	Net Brake Force
316	Manifest Freight	Medium	Partial Non-uniform	Slow	Trough	N/A	Weight
317	Manifest Freight	Medium	Partial Non-uniform	Slow	Trough	N/A	Brake Valve
318	Manifest Freight	Medium	Partial Non-uniform	Slow	Trough	N/A	Piston Stroke
319	Manifest Freight	Medium	Partial Non-uniform	Slow	Trough	N/A	Net Brake Force
320	Manifest Freight	Long	Loaded	Fast	Flat	N/A	Weight
321	Manifest Freight	Long	Loaded	Fast	Flat	N/A	Brake Valve
322	Manifest Freight	Long	Loaded	Fast	Flat	N/A	Piston Stroke
323	Manifest Freight	Long	Loaded	Fast	Flat	N/A	Net Brake Force
324	Manifest Freight	Long	Loaded	Fast	Incline	N/A	Weight
325	Manifest Freight	Long	Loaded	Fast	Incline	N/A	Brake Valve
326	Manifest Freight	Long	Loaded	Fast	Incline	N/A	Piston Stroke
327	Manifest Freight	Long	Loaded	Fast	Incline	N/A	Net Brake Force
328	Manifest Freight	Long	Loaded	Fast	Decline	N/A	Weight

Sim Set ID	Type of Train	Train Length	Train Load	Train Speed	Track Grade	Train Power	Test Variable
329	Manifest Freight	Long	Loaded	Fast	Decline	N/A	Brake Valve
330	Manifest Freight	Long	Loaded	Fast	Decline	N/A	Piston Stroke
331	Manifest Freight	Long	Loaded	Fast	Decline	N/A	Net Brake Force
332	Manifest Freight	Long	Loaded	Fast	Crest	N/A	Weight
333	Manifest Freight	Long	Loaded	Fast	Crest	N/A	Brake Valve
334	Manifest Freight	Long	Loaded	Fast	Crest	N/A	Piston Stroke
335	Manifest Freight	Long	Loaded	Fast	Crest	N/A	Net Brake Force
336	Manifest Freight	Long	Loaded	Fast	Trough	N/A	Weight
337	Manifest Freight	Long	Loaded	Fast	Trough	N/A	Brake Valve
338	Manifest Freight	Long	Loaded	Fast	Trough	N/A	Piston Stroke
339	Manifest Freight	Long	Loaded	Fast	Trough	N/A	Net Brake Force
340	Manifest Freight	Long	Loaded	Slow	Flat	N/A	Weight
341	Manifest Freight	Long	Loaded	Slow	Flat	N/A	Brake Valve
342	Manifest Freight	Long	Loaded	Slow	Flat	N/A	Piston Stroke
343	Manifest Freight	Long	Loaded	Slow	Flat	N/A	Net Brake Force
344	Manifest Freight	Long	Loaded	Slow	Incline	N/A	Weight
345	Manifest Freight	Long	Loaded	Slow	Incline	N/A	Brake Valve
346	Manifest Freight	Long	Loaded	Slow	Incline	N/A	Piston Stroke
347	Manifest Freight	Long	Loaded	Slow	Incline	N/A	Net Brake Force
348	Manifest Freight	Long	Loaded	Slow	Decline	N/A	Weight
349	Manifest Freight	Long	Loaded	Slow	Decline	N/A	Brake Valve
350	Manifest Freight	Long	Loaded	Slow	Decline	N/A	Piston Stroke
351	Manifest Freight	Long	Loaded	Slow	Decline	N/A	Net Brake Force
352	Manifest Freight	Long	Loaded	Slow	Crest	N/A	Weight
353	Manifest Freight	Long	Loaded	Slow	Crest	N/A	Brake Valve
354	Manifest Freight	Long	Loaded	Slow	Crest	N/A	Piston Stroke
355	Manifest Freight	Long	Loaded	Slow	Crest	N/A	Net Brake Force
356	Manifest Freight	Long	Loaded	Slow	Trough	N/A	Weight
357	Manifest Freight	Long	Loaded	Slow	Trough	N/A	Brake Valve
358	Manifest Freight	Long	Loaded	Slow	Trough	N/A	Piston Stroke
359	Manifest Freight	Long	Loaded	Slow	Trough	N/A	Net Brake Force
360	Manifest Freight	Long	Empty	Fast	Flat	N/A	Weight
361	Manifest Freight	Long	Empty	Fast	Flat	N/A	Brake Valve

Sim Set ID	Type of Train	Train Length	Train Load	Train Speed	Track Grade	Train Power	Test Variable
362	Manifest Freight	Long	Empty	Fast	Flat	N/A	Piston Stroke
363	Manifest Freight	Long	Empty	Fast	Flat	N/A	Net Brake Force
364	Manifest Freight	Long	Empty	Fast	Incline	N/A	Weight
365	Manifest Freight	Long	Empty	Fast	Incline	N/A	Brake Valve
366	Manifest Freight	Long	Empty	Fast	Incline	N/A	Piston Stroke
367	Manifest Freight	Long	Empty	Fast	Incline	N/A	Net Brake Force
368	Manifest Freight	Long	Empty	Fast	Decline	N/A	Weight
369	Manifest Freight	Long	Empty	Fast	Decline	N/A	Brake Valve
370	Manifest Freight	Long	Empty	Fast	Decline	N/A	Piston Stroke
371	Manifest Freight	Long	Empty	Fast	Decline	N/A	Net Brake Force
372	Manifest Freight	Long	Empty	Fast	Crest	N/A	Weight
373	Manifest Freight	Long	Empty	Fast	Crest	N/A	Brake Valve
374	Manifest Freight	Long	Empty	Fast	Crest	N/A	Piston Stroke
375	Manifest Freight	Long	Empty	Fast	Crest	N/A	Net Brake Force
376	Manifest Freight	Long	Empty	Fast	Trough	N/A	Weight
377	Manifest Freight	Long	Empty	Fast	Trough	N/A	Brake Valve
378	Manifest Freight	Long	Empty	Fast	Trough	N/A	Piston Stroke
379	Manifest Freight	Long	Empty	Fast	Trough	N/A	Net Brake Force
380	Manifest Freight	Long	Empty	Slow	Flat	N/A	Weight
381	Manifest Freight	Long	Empty	Slow	Flat	N/A	Brake Valve
382	Manifest Freight	Long	Empty	Slow	Flat	N/A	Piston Stroke
383	Manifest Freight	Long	Empty	Slow	Flat	N/A	Net Brake Force
384	Manifest Freight	Long	Empty	Slow	Incline	N/A	Weight
385	Manifest Freight	Long	Empty	Slow	Incline	N/A	Brake Valve
386	Manifest Freight	Long	Empty	Slow	Incline	N/A	Piston Stroke
387	Manifest Freight	Long	Empty	Slow	Incline	N/A	Net Brake Force
388	Manifest Freight	Long	Empty	Slow	Decline	N/A	Weight
389	Manifest Freight	Long	Empty	Slow	Decline	N/A	Brake Valve
390	Manifest Freight	Long	Empty	Slow	Decline	N/A	Piston Stroke
391	Manifest Freight	Long	Empty	Slow	Decline	N/A	Net Brake Force
392	Manifest Freight	Long	Empty	Slow	Crest	N/A	Weight
393	Manifest Freight	Long	Empty	Slow	Crest	N/A	Brake Valve
394	Manifest Freight	Long	Empty	Slow	Crest	N/A	Piston Stroke

Sim Set ID	Type of Train	Train Length	Train Load	Train Speed	Track Grade	Train Power	Test Variable
395	Manifest Freight	Long	Empty	Slow	Crest	N/A	Net Brake Force
396	Manifest Freight	Long	Empty	Slow	Trough	N/A	Weight
397	Manifest Freight	Long	Empty	Slow	Trough	N/A	Brake Valve
398	Manifest Freight	Long	Empty	Slow	Trough	N/A	Piston Stroke
399	Manifest Freight	Long	Empty	Slow	Trough	N/A	Net Brake Force
400	Manifest Freight	Long	Partial Uniform	Fast	Flat	N/A	Weight
401	Manifest Freight	Long	Partial Uniform	Fast	Flat	N/A	Brake Valve
402	Manifest Freight	Long	Partial Uniform	Fast	Flat	N/A	Piston Stroke
403	Manifest Freight	Long	Partial Uniform	Fast	Flat	N/A	Net Brake Force
404	Manifest Freight	Long	Partial Uniform	Fast	Incline	N/A	Weight
405	Manifest Freight	Long	Partial Uniform	Fast	Incline	N/A	Brake Valve
406	Manifest Freight	Long	Partial Uniform	Fast	Incline	N/A	Piston Stroke
407	Manifest Freight	Long	Partial Uniform	Fast	Incline	N/A	Net Brake Force
408	Manifest Freight	Long	Partial Uniform	Fast	Decline	N/A	Weight
409	Manifest Freight	Long	Partial Uniform	Fast	Decline	N/A	Brake Valve
410	Manifest Freight	Long	Partial Uniform	Fast	Decline	N/A	Piston Stroke
411	Manifest Freight	Long	Partial Uniform	Fast	Decline	N/A	Net Brake Force
412	Manifest Freight	Long	Partial Uniform	Fast	Crest	N/A	Weight
413	Manifest Freight	Long	Partial Uniform	Fast	Crest	N/A	Brake Valve
414	Manifest Freight	Long	Partial Uniform	Fast	Crest	N/A	Piston Stroke
415	Manifest Freight	Long	Partial Uniform	Fast	Crest	N/A	Net Brake Force
416	Manifest Freight	Long	Partial Uniform	Fast	Trough	N/A	Weight
417	Manifest Freight	Long	Partial Uniform	Fast	Trough	N/A	Brake Valve
418	Manifest Freight	Long	Partial Uniform	Fast	Trough	N/A	Piston Stroke
419	Manifest Freight	Long	Partial Uniform	Fast	Trough	N/A	Net Brake Force
420	Manifest Freight	Long	Partial Uniform	Slow	Flat	N/A	Weight
421	Manifest Freight	Long	Partial Uniform	Slow	Flat	N/A	Brake Valve
422	Manifest Freight	Long	Partial Uniform	Slow	Flat	N/A	Piston Stroke
423	Manifest Freight	Long	Partial Uniform	Slow	Flat	N/A	Net Brake Force
424	Manifest Freight	Long	Partial Uniform	Slow	Incline	N/A	Weight
425	Manifest Freight	Long	Partial Uniform	Slow	Incline	N/A	Brake Valve
426	Manifest Freight	Long	Partial Uniform	Slow	Incline	N/A	Piston Stroke
427	Manifest Freight	Long	Partial Uniform	Slow	Incline	N/A	Net Brake Force

Sim Set ID	Type of Train	Train Length	Train Load	Train Speed	Track Grade	Train Power	Test Variable
428	Manifest Freight	Long	Partial Uniform	Slow	Decline	N/A	Weight
429	Manifest Freight	Long	Partial Uniform	Slow	Decline	N/A	Brake Valve
430	Manifest Freight	Long	Partial Uniform	Slow	Decline	N/A	Piston Stroke
431	Manifest Freight	Long	Partial Uniform	Slow	Decline	N/A	Net Brake Force
432	Manifest Freight	Long	Partial Uniform	Slow	Crest	N/A	Weight
433	Manifest Freight	Long	Partial Uniform	Slow	Crest	N/A	Brake Valve
434	Manifest Freight	Long	Partial Uniform	Slow	Crest	N/A	Piston Stroke
435	Manifest Freight	Long	Partial Uniform	Slow	Crest	N/A	Net Brake Force
436	Manifest Freight	Long	Partial Uniform	Slow	Trough	N/A	Weight
437	Manifest Freight	Long	Partial Uniform	Slow	Trough	N/A	Brake Valve
438	Manifest Freight	Long	Partial Uniform	Slow	Trough	N/A	Piston Stroke
439	Manifest Freight	Long	Partial Uniform	Slow	Trough	N/A	Net Brake Force
440	Manifest Freight	Long	Partial Non-uniform	Fast	Flat	N/A	Weight
441	Manifest Freight	Long	Partial Non-uniform	Fast	Flat	N/A	Brake Valve
442	Manifest Freight	Long	Partial Non-uniform	Fast	Flat	N/A	Piston Stroke
443	Manifest Freight	Long	Partial Non-uniform	Fast	Flat	N/A	Net Brake Force
444	Manifest Freight	Long	Partial Non-uniform	Fast	Incline	N/A	Weight
445	Manifest Freight	Long	Partial Non-uniform	Fast	Incline	N/A	Brake Valve
446	Manifest Freight	Long	Partial Non-uniform	Fast	Incline	N/A	Piston Stroke
447	Manifest Freight	Long	Partial Non-uniform	Fast	Incline	N/A	Net Brake Force
448	Manifest Freight	Long	Partial Non-uniform	Fast	Decline	N/A	Weight
449	Manifest Freight	Long	Partial Non-uniform	Fast	Decline	N/A	Brake Valve
450	Manifest Freight	Long	Partial Non-uniform	Fast	Decline	N/A	Piston Stroke
451	Manifest Freight	Long	Partial Non-uniform	Fast	Decline	N/A	Net Brake Force
452	Manifest Freight	Long	Partial Non-uniform	Fast	Crest	N/A	Weight
453	Manifest Freight	Long	Partial Non-uniform	Fast	Crest	N/A	Brake Valve
454	Manifest Freight	Long	Partial Non-uniform	Fast	Crest	N/A	Piston Stroke
455	Manifest Freight	Long	Partial Non-uniform	Fast	Crest	N/A	Net Brake Force
456	Manifest Freight	Long	Partial Non-uniform	Fast	Trough	N/A	Weight
457	Manifest Freight	Long	Partial Non-uniform	Fast	Trough	N/A	Brake Valve
458	Manifest Freight	Long	Partial Non-uniform	Fast	Trough	N/A	Piston Stroke
459	Manifest Freight	Long	Partial Non-uniform	Fast	Trough	N/A	Net Brake Force
460	Manifest Freight	Long	Partial Non-uniform	Slow	Flat	N/A	Weight

Sim Set ID	Type of Train	Train Length	Train Load	Train Speed	Track Grade	Train Power	Test Variable
461	Manifest Freight	Long	Partial Non-uniform	Slow	Flat	N/A	Brake Valve
462	Manifest Freight	Long	Partial Non-uniform	Slow	Flat	N/A	Piston Stroke
463	Manifest Freight	Long	Partial Non-uniform	Slow	Flat	N/A	Net Brake Force
464	Manifest Freight	Long	Partial Non-uniform	Slow	Incline	N/A	Weight
465	Manifest Freight	Long	Partial Non-uniform	Slow	Incline	N/A	Brake Valve
466	Manifest Freight	Long	Partial Non-uniform	Slow	Incline	N/A	Piston Stroke
467	Manifest Freight	Long	Partial Non-uniform	Slow	Incline	N/A	Net Brake Force
468	Manifest Freight	Long	Partial Non-uniform	Slow	Decline	N/A	Weight
469	Manifest Freight	Long	Partial Non-uniform	Slow	Decline	N/A	Brake Valve
470	Manifest Freight	Long	Partial Non-uniform	Slow	Decline	N/A	Piston Stroke
471	Manifest Freight	Long	Partial Non-uniform	Slow	Decline	N/A	Net Brake Force
472	Manifest Freight	Long	Partial Non-uniform	Slow	Crest	N/A	Weight
473	Manifest Freight	Long	Partial Non-uniform	Slow	Crest	N/A	Brake Valve
474	Manifest Freight	Long	Partial Non-uniform	Slow	Crest	N/A	Piston Stroke
475	Manifest Freight	Long	Partial Non-uniform	Slow	Crest	N/A	Net Brake Force
476	Manifest Freight	Long	Partial Non-uniform	Slow	Trough	N/A	Weight
477	Manifest Freight	Long	Partial Non-uniform	Slow	Trough	N/A	Brake Valve
478	Manifest Freight	Long	Partial Non-uniform	Slow	Trough	N/A	Piston Stroke
479	Manifest Freight	Long	Partial Non-uniform	Slow	Trough	N/A	Net Brake Force
480	Unit Train	N/A	Loaded	Fast	Flat	Head End	Weight
481	Unit Train	N/A	Loaded	Fast	Flat	Head End	Brake Valve
482	Unit Train	N/A	Loaded	Fast	Flat	Head End	Piston Stroke
483	Unit Train	N/A	Loaded	Fast	Flat	Head End	Net Brake Force
484	Unit Train	N/A	Loaded	Fast	Flat	Distributed	Weight
485	Unit Train	N/A	Loaded	Fast	Flat	Distributed	Brake Valve
486	Unit Train	N/A	Loaded	Fast	Flat	Distributed	Piston Stroke
487	Unit Train	N/A	Loaded	Fast	Flat	Distributed	Net Brake Force
488	Unit Train	N/A	Loaded	Fast	Decline	Head End	Weight
489	Unit Train	N/A	Loaded	Fast	Decline	Head End	Brake Valve
490	Unit Train	N/A	Loaded	Fast	Decline	Head End	Piston Stroke
491	Unit Train	N/A	Loaded	Fast	Decline	Head End	Net Brake Force
492	Unit Train	N/A	Loaded	Fast	Decline	Distributed	Weight
493	Unit Train	N/A	Loaded	Fast	Decline	Distributed	Brake Valve

Sim Set ID	Type of Train	Train Length	Train Load	Train Speed	Track Grade	Train Power	Test Variable
494	Unit Train	N/A	Loaded	Fast	Decline	Distributed	Piston Stroke
495	Unit Train	N/A	Loaded	Fast	Decline	Distributed	Net Brake Force
496	Unit Train	N/A	Loaded	Fast	Crest	Head End	Weight
497	Unit Train	N/A	Loaded	Fast	Crest	Head End	Brake Valve
498	Unit Train	N/A	Loaded	Fast	Crest	Head End	Piston Stroke
499	Unit Train	N/A	Loaded	Fast	Crest	Head End	Net Brake Force
500	Unit Train	N/A	Loaded	Fast	Crest	Distributed	Weight
501	Unit Train	N/A	Loaded	Fast	Crest	Distributed	Brake Valve
502	Unit Train	N/A	Loaded	Fast	Crest	Distributed	Piston Stroke
503	Unit Train	N/A	Loaded	Fast	Crest	Distributed	Net Brake Force
504	Unit Train	N/A	Loaded	Fast	Trough	Head End	Weight
505	Unit Train	N/A	Loaded	Fast	Trough	Head End	Brake Valve
506	Unit Train	N/A	Loaded	Fast	Trough	Head End	Piston Stroke
507	Unit Train	N/A	Loaded	Fast	Trough	Head End	Net Brake Force
508	Unit Train	N/A	Loaded	Fast	Trough	Distributed	Weight
509	Unit Train	N/A	Loaded	Fast	Trough	Distributed	Brake Valve
510	Unit Train	N/A	Loaded	Fast	Trough	Distributed	Piston Stroke
511	Unit Train	N/A	Loaded	Fast	Trough	Distributed	Net Brake Force
512	Unit Train	N/A	Loaded	Slow	Flat	Head End	Weight
513	Unit Train	N/A	Loaded	Slow	Flat	Head End	Brake Valve
514	Unit Train	N/A	Loaded	Slow	Flat	Head End	Piston Stroke
515	Unit Train	N/A	Loaded	Slow	Flat	Head End	Net Brake Force
516	Unit Train	N/A	Loaded	Slow	Flat	Distributed	Weight
517	Unit Train	N/A	Loaded	Slow	Flat	Distributed	Brake Valve
518	Unit Train	N/A	Loaded	Slow	Flat	Distributed	Piston Stroke
519	Unit Train	N/A	Loaded	Slow	Flat	Distributed	Net Brake Force
520	Unit Train	N/A	Loaded	Slow	Incline	Head End	Weight
521	Unit Train	N/A	Loaded	Slow	Incline	Head End	Brake Valve
522	Unit Train	N/A	Loaded	Slow	Incline	Head End	Piston Stroke
523	Unit Train	N/A	Loaded	Slow	Incline	Head End	Net Brake Force
524	Unit Train	N/A	Loaded	Slow	Incline	Distributed	Weight
525	Unit Train	N/A	Loaded	Slow	Incline	Distributed	Brake Valve
526	Unit Train	N/A	Loaded	Slow	Incline	Distributed	Piston Stroke

Sim Set ID	Type of Train	Train Length	Train Load	Train Speed	Track Grade	Train Power	Test Variable
527	Unit Train	N/A	Loaded	Slow	Incline	Distributed	Net Brake Force
528	Unit Train	N/A	Loaded	Slow	Decline	Head End	Weight
529	Unit Train	N/A	Loaded	Slow	Decline	Head End	Brake Valve
530	Unit Train	N/A	Loaded	Slow	Decline	Head End	Piston Stroke
531	Unit Train	N/A	Loaded	Slow	Decline	Head End	Net Brake Force
532	Unit Train	N/A	Loaded	Slow	Decline	Distributed	Weight
533	Unit Train	N/A	Loaded	Slow	Decline	Distributed	Brake Valve
534	Unit Train	N/A	Loaded	Slow	Decline	Distributed	Piston Stroke
535	Unit Train	N/A	Loaded	Slow	Decline	Distributed	Net Brake Force
536	Unit Train	N/A	Loaded	Slow	Crest	Head End	Weight
537	Unit Train	N/A	Loaded	Slow	Crest	Head End	Brake Valve
538	Unit Train	N/A	Loaded	Slow	Crest	Head End	Piston Stroke
539	Unit Train	N/A	Loaded	Slow	Crest	Head End	Net Brake Force
540	Unit Train	N/A	Loaded	Slow	Crest	Distributed	Weight
541	Unit Train	N/A	Loaded	Slow	Crest	Distributed	Brake Valve
542	Unit Train	N/A	Loaded	Slow	Crest	Distributed	Piston Stroke
543	Unit Train	N/A	Loaded	Slow	Crest	Distributed	Net Brake Force
544	Unit Train	N/A	Loaded	Slow	Trough	Head End	Weight
545	Unit Train	N/A	Loaded	Slow	Trough	Head End	Brake Valve
546	Unit Train	N/A	Loaded	Slow	Trough	Head End	Piston Stroke
547	Unit Train	N/A	Loaded	Slow	Trough	Head End	Net Brake Force
548	Unit Train	N/A	Loaded	Slow	Trough	Distributed	Weight
549	Unit Train	N/A	Loaded	Slow	Trough	Distributed	Brake Valve
550	Unit Train	N/A	Loaded	Slow	Trough	Distributed	Piston Stroke
551	Unit Train	N/A	Loaded	Slow	Trough	Distributed	Net Brake Force
552	Unit Train	N/A	Empty	Fast	Flat	Head End	Weight
553	Unit Train	N/A	Empty	Fast	Flat	Head End	Brake Valve
554	Unit Train	N/A	Empty	Fast	Flat	Head End	Piston Stroke
555	Unit Train	N/A	Empty	Fast	Flat	Head End	Net Brake Force
556	Unit Train	N/A	Empty	Fast	Flat	Distributed	Weight
557	Unit Train	N/A	Empty	Fast	Flat	Distributed	Brake Valve
558	Unit Train	N/A	Empty	Fast	Flat	Distributed	Piston Stroke
559	Unit Train	N/A	Empty	Fast	Flat	Distributed	Net Brake Force

Sim Set ID	Type of Train	Train Length	Train Load	Train Speed	Track Grade	Train Power	Test Variable
560	Unit Train	N/A	Empty	Fast	Decline	Head End	Weight
561	Unit Train	N/A	Empty	Fast	Decline	Head End	Brake Valve
562	Unit Train	N/A	Empty	Fast	Decline	Head End	Piston Stroke
563	Unit Train	N/A	Empty	Fast	Decline	Head End	Net Brake Force
564	Unit Train	N/A	Empty	Fast	Decline	Distributed	Weight
565	Unit Train	N/A	Empty	Fast	Decline	Distributed	Brake Valve
566	Unit Train	N/A	Empty	Fast	Decline	Distributed	Piston Stroke
567	Unit Train	N/A	Empty	Fast	Decline	Distributed	Net Brake Force
568	Unit Train	N/A	Empty	Fast	Crest	Head End	Weight
569	Unit Train	N/A	Empty	Fast	Crest	Head End	Brake Valve
570	Unit Train	N/A	Empty	Fast	Crest	Head End	Piston Stroke
571	Unit Train	N/A	Empty	Fast	Crest	Head End	Net Brake Force
572	Unit Train	N/A	Empty	Fast	Crest	Distributed	Weight
573	Unit Train	N/A	Empty	Fast	Crest	Distributed	Brake Valve
574	Unit Train	N/A	Empty	Fast	Crest	Distributed	Piston Stroke
575	Unit Train	N/A	Empty	Fast	Crest	Distributed	Net Brake Force
576	Unit Train	N/A	Empty	Fast	Trough	Head End	Weight
577	Unit Train	N/A	Empty	Fast	Trough	Head End	Brake Valve
578	Unit Train	N/A	Empty	Fast	Trough	Head End	Piston Stroke
579	Unit Train	N/A	Empty	Fast	Trough	Head End	Net Brake Force
580	Unit Train	N/A	Empty	Fast	Trough	Distributed	Weight
581	Unit Train	N/A	Empty	Fast	Trough	Distributed	Brake Valve
582	Unit Train	N/A	Empty	Fast	Trough	Distributed	Piston Stroke
583	Unit Train	N/A	Empty	Fast	Trough	Distributed	Net Brake Force
584	Unit Train	N/A	Empty	Slow	Flat	Head End	Weight
585	Unit Train	N/A	Empty	Slow	Flat	Head End	Brake Valve
586	Unit Train	N/A	Empty	Slow	Flat	Head End	Piston Stroke
587	Unit Train	N/A	Empty	Slow	Flat	Head End	Net Brake Force
588	Unit Train	N/A	Empty	Slow	Flat	Distributed	Weight
589	Unit Train	N/A	Empty	Slow	Flat	Distributed	Brake Valve
590	Unit Train	N/A	Empty	Slow	Flat	Distributed	Piston Stroke
591	Unit Train	N/A	Empty	Slow	Flat	Distributed	Net Brake Force
592	Unit Train	N/A	Empty	Slow	Incline	Head End	Weight

Sim Set ID	Type of Train	Train Length	Train Load	Train Speed	Track Grade	Train Power	Test Variable
593	Unit Train	N/A	Empty	Slow	Incline	Head End	Brake Valve
594	Unit Train	N/A	Empty	Slow	Incline	Head End	Piston Stroke
595	Unit Train	N/A	Empty	Slow	Incline	Head End	Net Brake Force
596	Unit Train	N/A	Empty	Slow	Incline	Distributed	Weight
597	Unit Train	N/A	Empty	Slow	Incline	Distributed	Brake Valve
598	Unit Train	N/A	Empty	Slow	Incline	Distributed	Piston Stroke
599	Unit Train	N/A	Empty	Slow	Incline	Distributed	Net Brake Force
600	Unit Train	N/A	Empty	Slow	Decline	Head End	Weight
601	Unit Train	N/A	Empty	Slow	Decline	Head End	Brake Valve
602	Unit Train	N/A	Empty	Slow	Decline	Head End	Piston Stroke
603	Unit Train	N/A	Empty	Slow	Decline	Head End	Net Brake Force
604	Unit Train	N/A	Empty	Slow	Decline	Distributed	Weight
605	Unit Train	N/A	Empty	Slow	Decline	Distributed	Brake Valve
606	Unit Train	N/A	Empty	Slow	Decline	Distributed	Piston Stroke
607	Unit Train	N/A	Empty	Slow	Decline	Distributed	Net Brake Force
608	Unit Train	N/A	Empty	Slow	Crest	Head End	Weight
609	Unit Train	N/A	Empty	Slow	Crest	Head End	Brake Valve
610	Unit Train	N/A	Empty	Slow	Crest	Head End	Piston Stroke
611	Unit Train	N/A	Empty	Slow	Crest	Head End	Net Brake Force
612	Unit Train	N/A	Empty	Slow	Crest	Distributed	Weight
613	Unit Train	N/A	Empty	Slow	Crest	Distributed	Brake Valve
614	Unit Train	N/A	Empty	Slow	Crest	Distributed	Piston Stroke
615	Unit Train	N/A	Empty	Slow	Crest	Distributed	Net Brake Force
616	Unit Train	N/A	Empty	Slow	Trough	Head End	Weight
617	Unit Train	N/A	Empty	Slow	Trough	Head End	Brake Valve
618	Unit Train	N/A	Empty	Slow	Trough	Head End	Piston Stroke
619	Unit Train	N/A	Empty	Slow	Trough	Head End	Net Brake Force
620	Unit Train	N/A	Empty	Slow	Trough	Distributed	Weight
621	Unit Train	N/A	Empty	Slow	Trough	Distributed	Brake Valve
622	Unit Train	N/A	Empty	Slow	Trough	Distributed	Piston Stroke
623	Unit Train	N/A	Empty	Slow	Trough	Distributed	Net Brake Force

Appendix C.
Parametric Study Probability Density Curves

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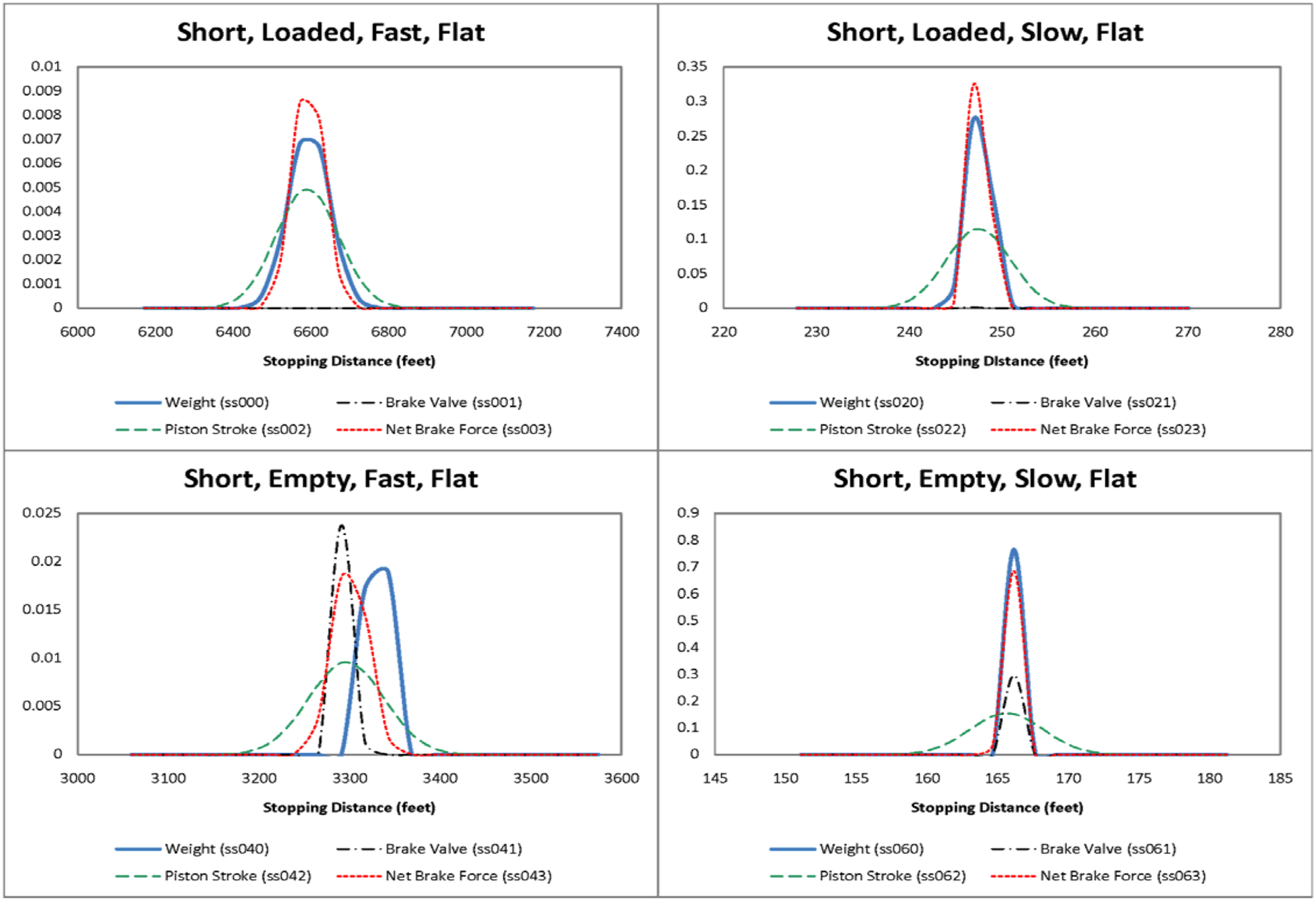
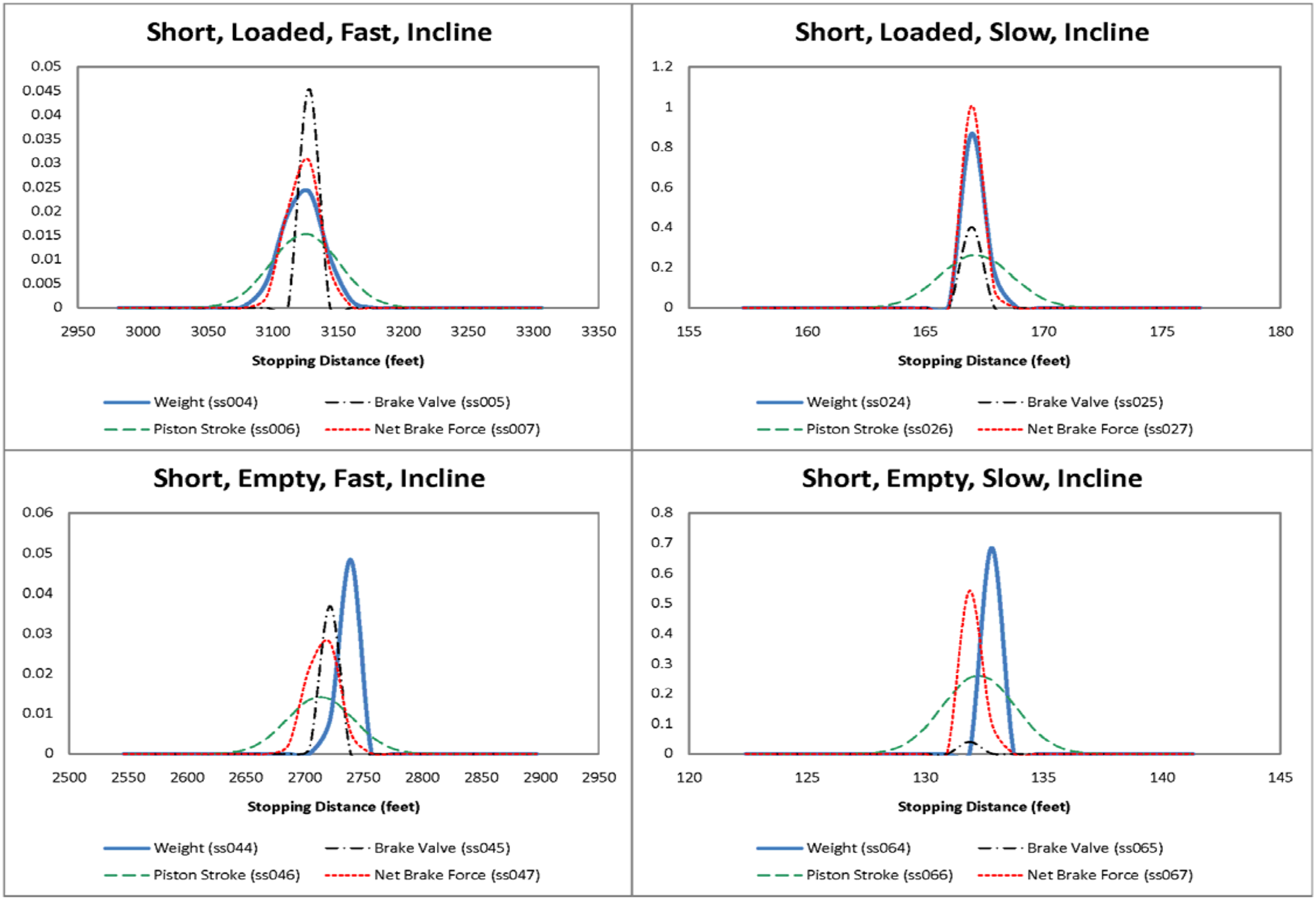
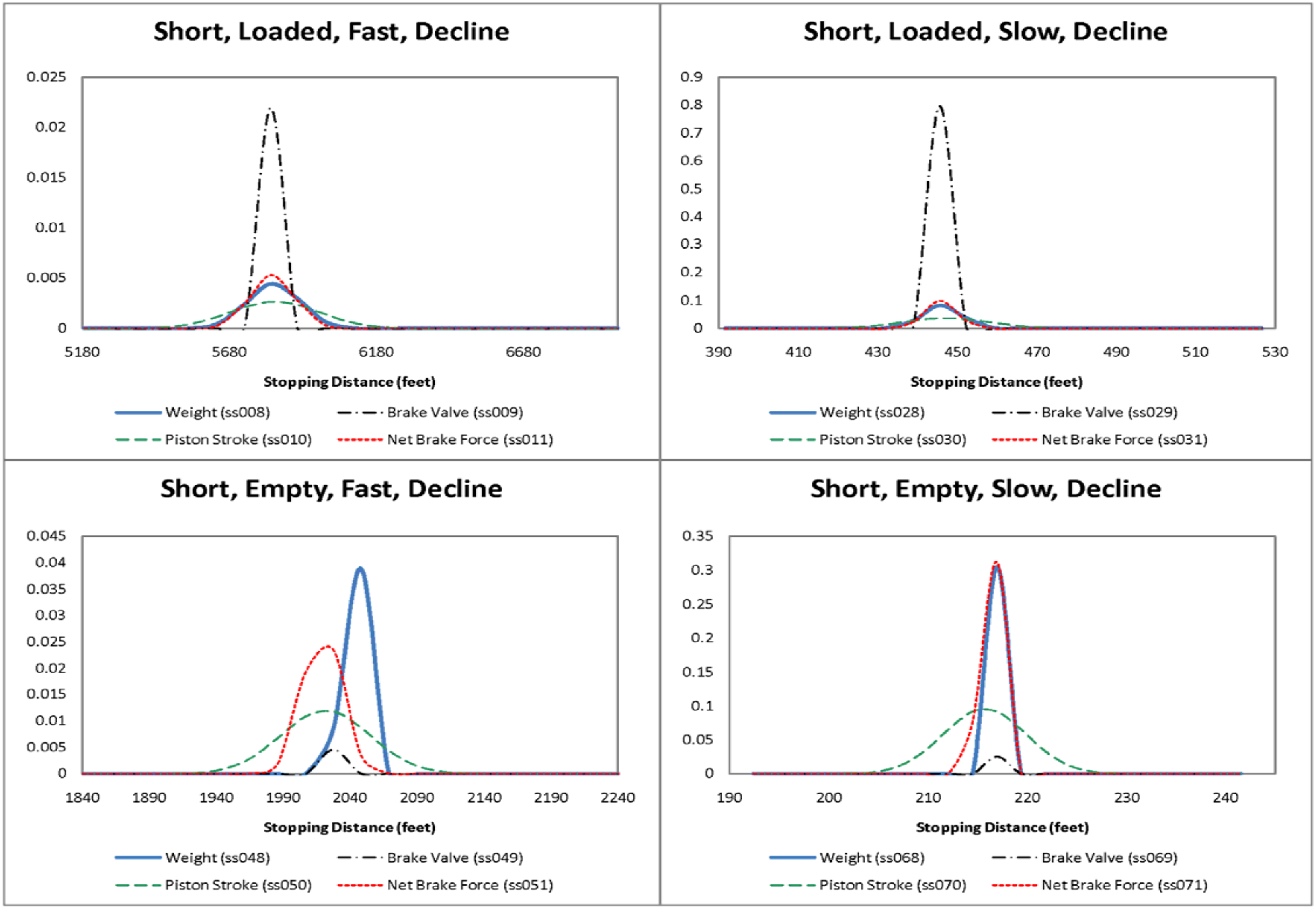


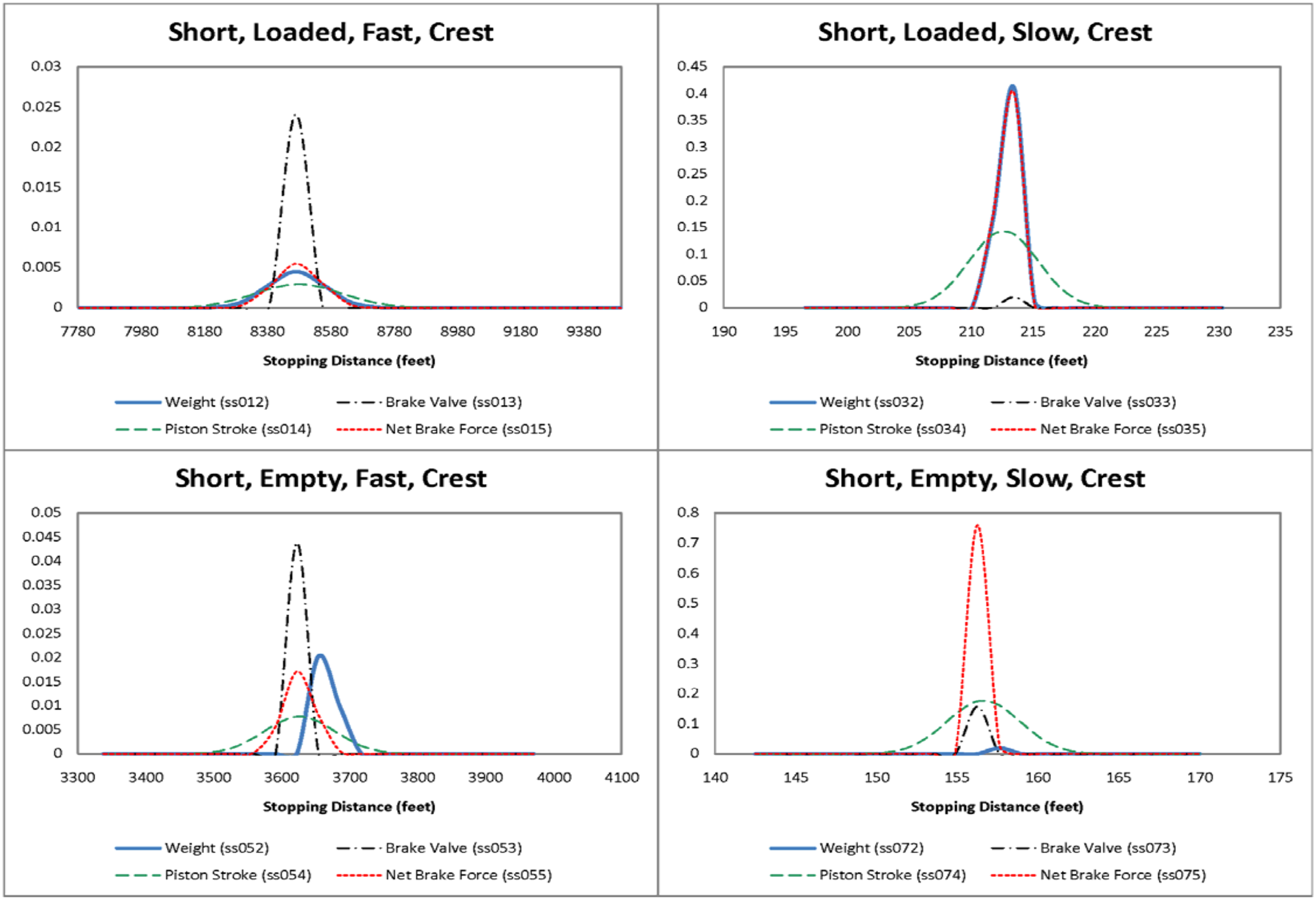
Short, Loaded, Fast, Flat
0.01
0.009
0.008
0.007
0.006
0.005
0.004
0.003
0.002
0.001
0
6000
6200
6400
6600
6800
7000
7200
7400
Stopping Distance (feet)
Weight (ss000)
Brake Valve (ss001)
Piston Stroke (ss002)
Net Brake Force (ss003)
Short, Loaded, Slow, Flat
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
220
230
240
250
260
270
280
Stopping DIstance (feet)
Weight (ss020)
Brake Valve (ss021)
Piston Stroke (ss022)
Net Brake Force (ss023)
Short, Empty, Fast, Flat
0.025
0.02
0.015
0.01
0.005
0
3000
3100
3200
3300
3400
3500
3600
Stopping Distance (feet)
Weight (ss040)
Brake Valve (ss041)
Piston Stroke (ss042)
Net Brake Force (ss043)
Short, Empty, Slow, Flat
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
145
150
155
160
165
170
175
180
185
Stopping Distance (feet)
Weight (ss060)
Brake Valve (ss061)
Piston Stroke (ss062)
Net Brake Force (ss063)

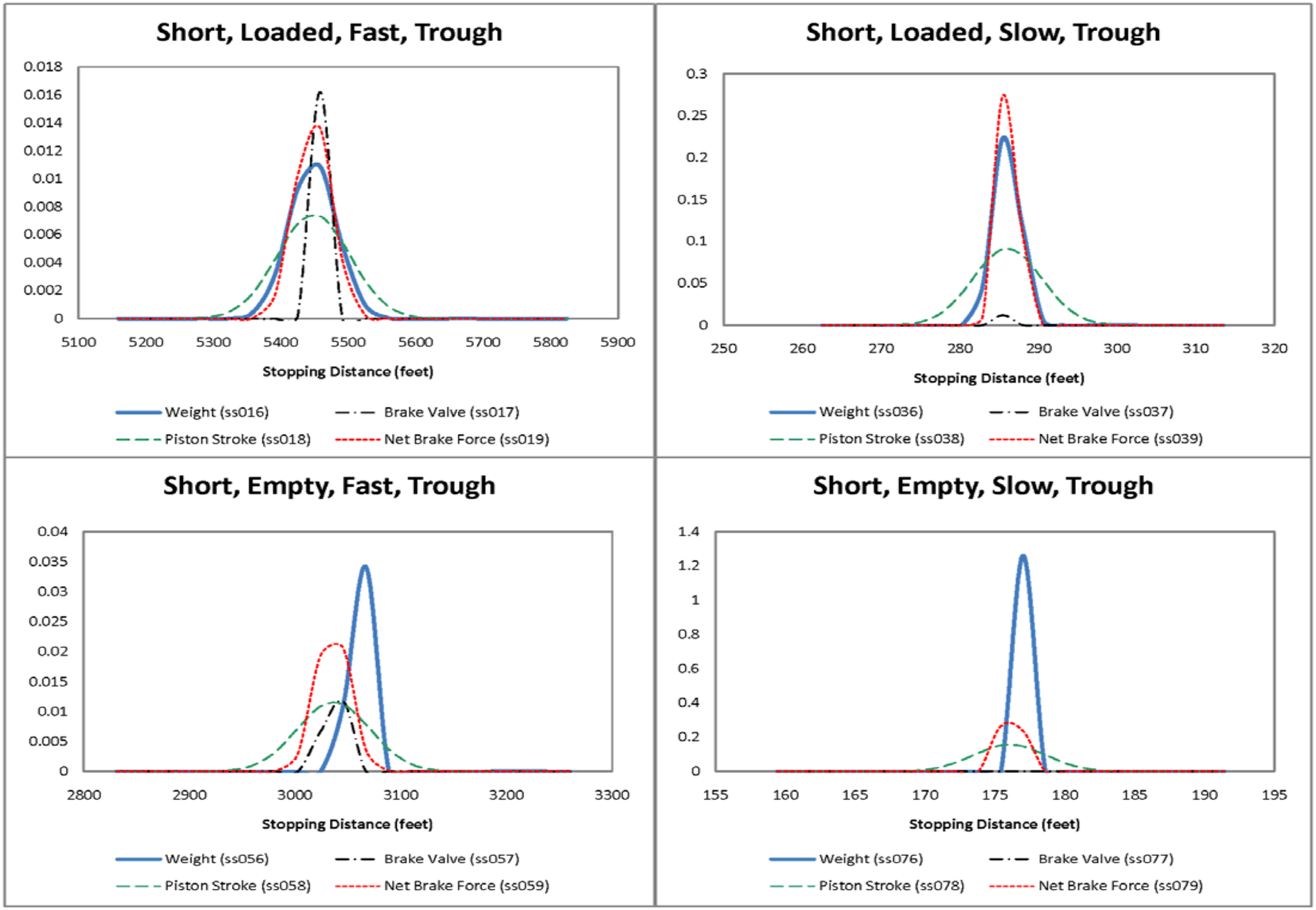


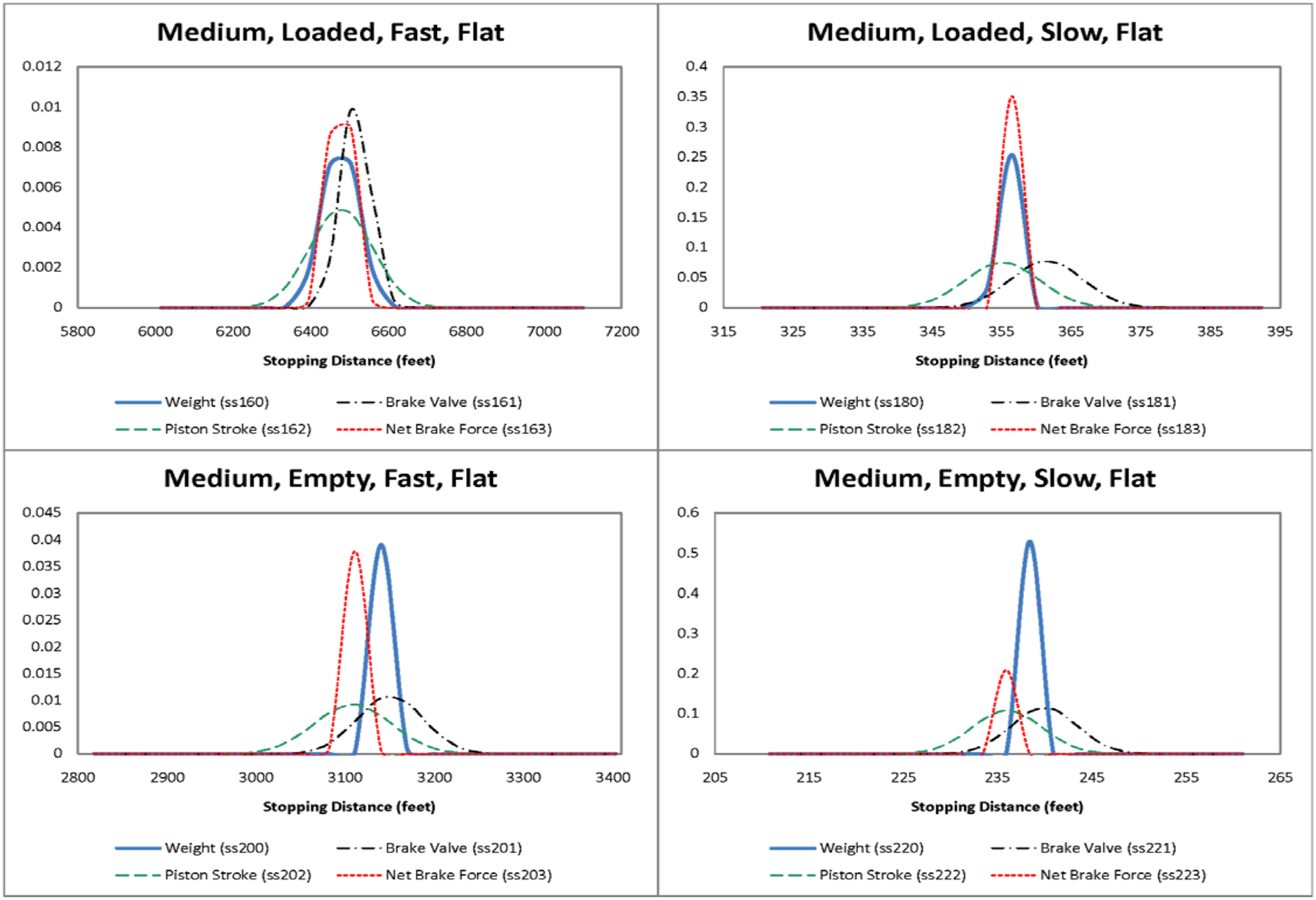
Short, Loaded, Fast, Incline
0.05
0.045
0.04
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
2950 3000 3050 3100 3150 3200 3250 3300 3350
Stopping Distance (feet)
Weight (ss004)
Brake Valve (ss005)
Piston Stroke (ss006)
Net Brake Force (ss007)
Short, Loaded, Slow, Incline
1.2
1
0.8
0.6
0.4
0.2
0
155 160 165 170 175 180
Stopping Distance (feet)
Weight (ss024)
Brake Valve (ss025)
Piston Stroke (ss026)
Net Brake Force (ss027)
Short, Empty, Fast, Incline
0.06
0.05
0.04
0.03
0.02
0.01
0
2500 2550 2600 2650 2700 2750 2800 2850 2900 2950
Stopping Distance (feet)
Weight (ss044)
Brake Valve (ss045)
Piston Stroke (ss046)
Net Brake Force (ss047)
Short, Empty, Slow, Incline
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
120 125 130 135 140 145
Stopping Distance (feet)
Weight (ss064)
Brake Valve (ss065)
Piston Stroke (ss066)
Net Brake Force (ss067)

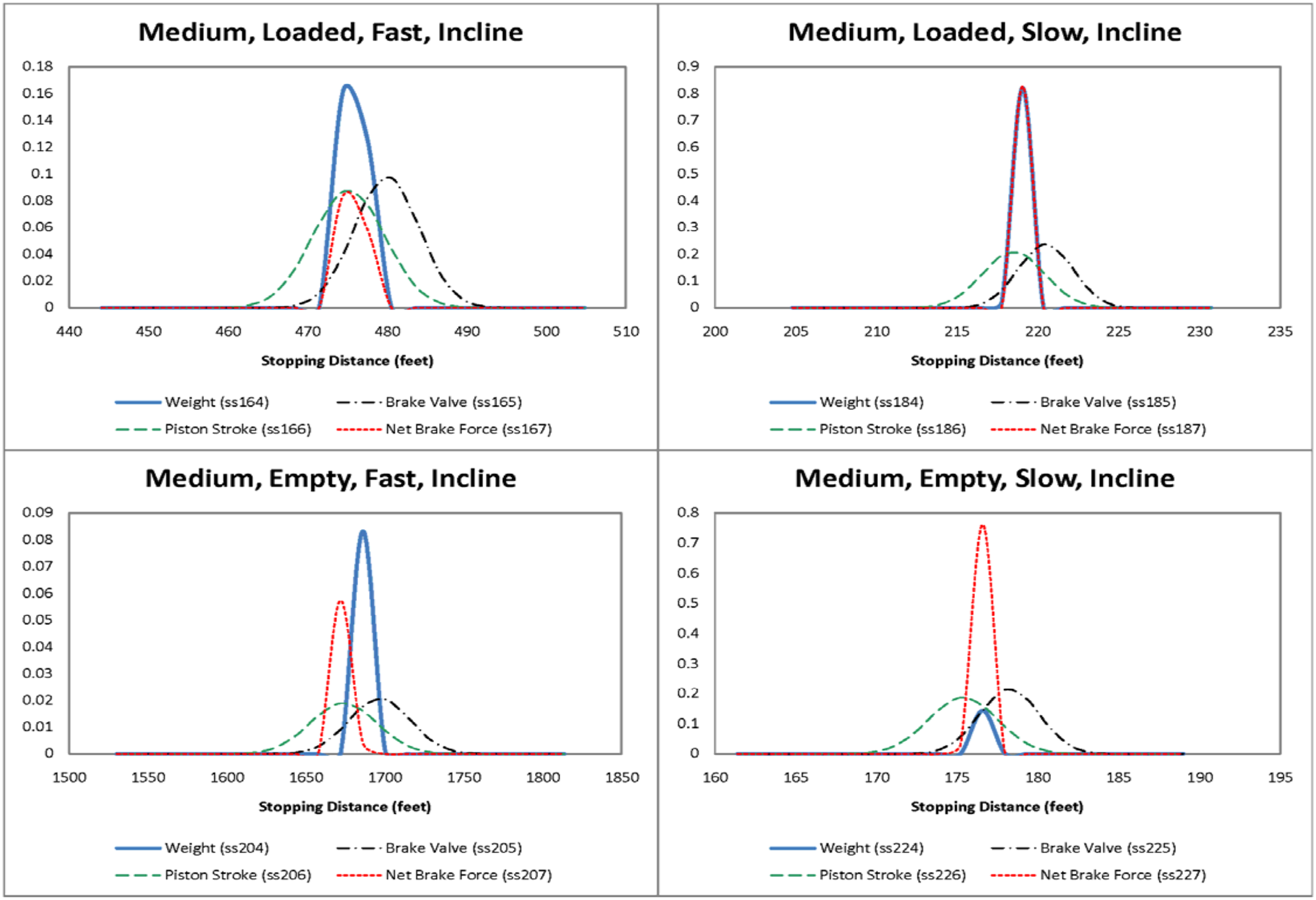


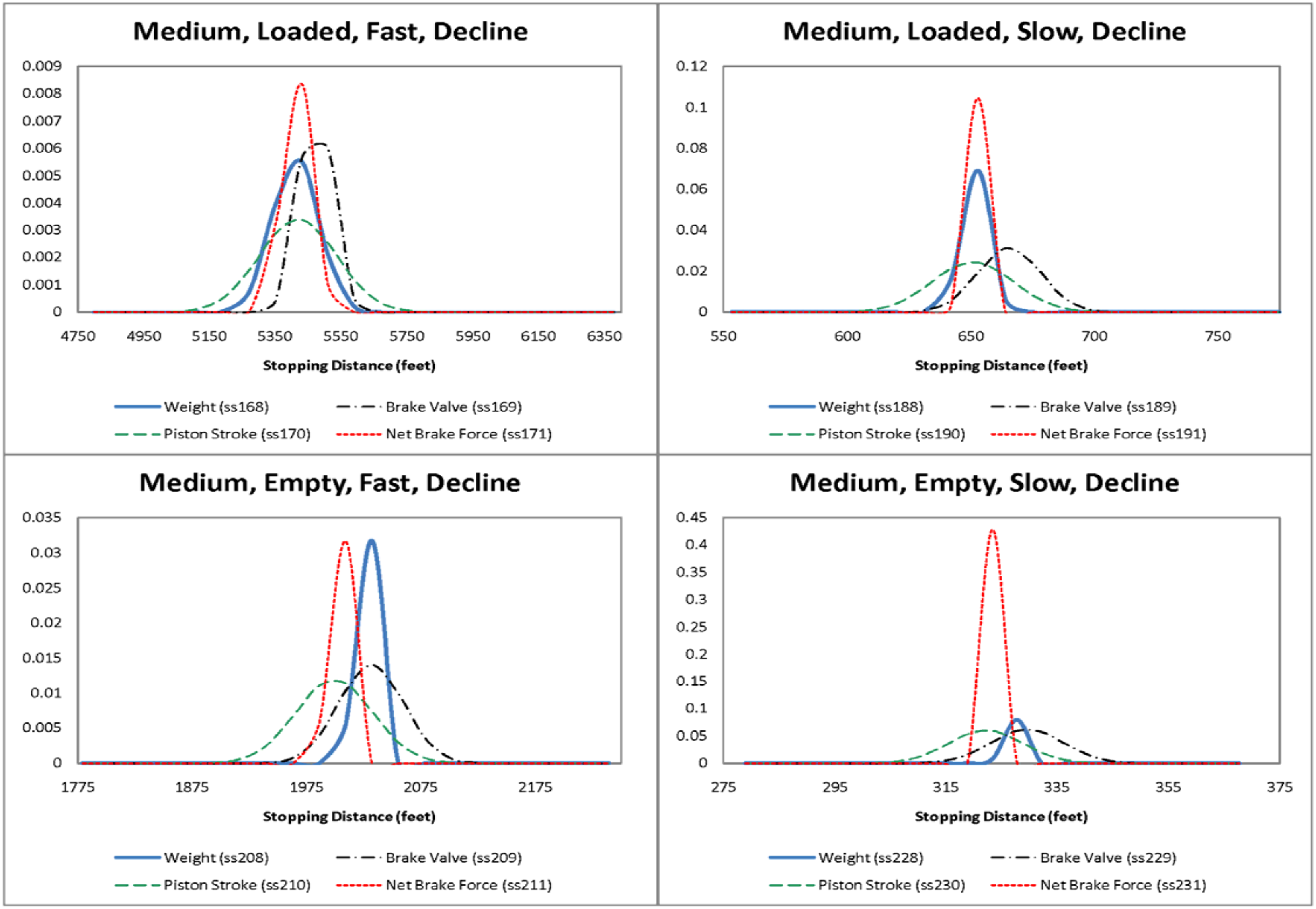
Short, Loaded, Fast, Decline
0.025
0.02
0.015
0.01
0.005
0
5180
5680
6180
6680
Stopping Distance (feet)
Weight (ss008)
Brake Valve (ss009)
Piston Stroke (ss010)
Net Brake Force (ss011)
Short, Loaded, Slow, Decline
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
390
410
430
450
470
490
510
530
Stopping Distance (feet)
Weight (ss028)
Brake Valve (ss029)
Piston Stroke (ss030)
Net Brake Force (ss031)
Short, Empty, Fast, Decline
0.045
0.04
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
1840
1890
1940
1990
2040
2090
2140
2190
2240
Stopping Distance (feet)
Weight (ss048)
Brake Valve (ss049)
Piston Stroke (ss050)
Net Brake Force (ss051)
Short, Empty, Slow, Decline
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
190
200
210
220
230
240
Stopping Distance (feet)
Weight (ss068)
Brake Valve (ss069)
Piston Stroke (ss070)
Net Brake Force (ss071)

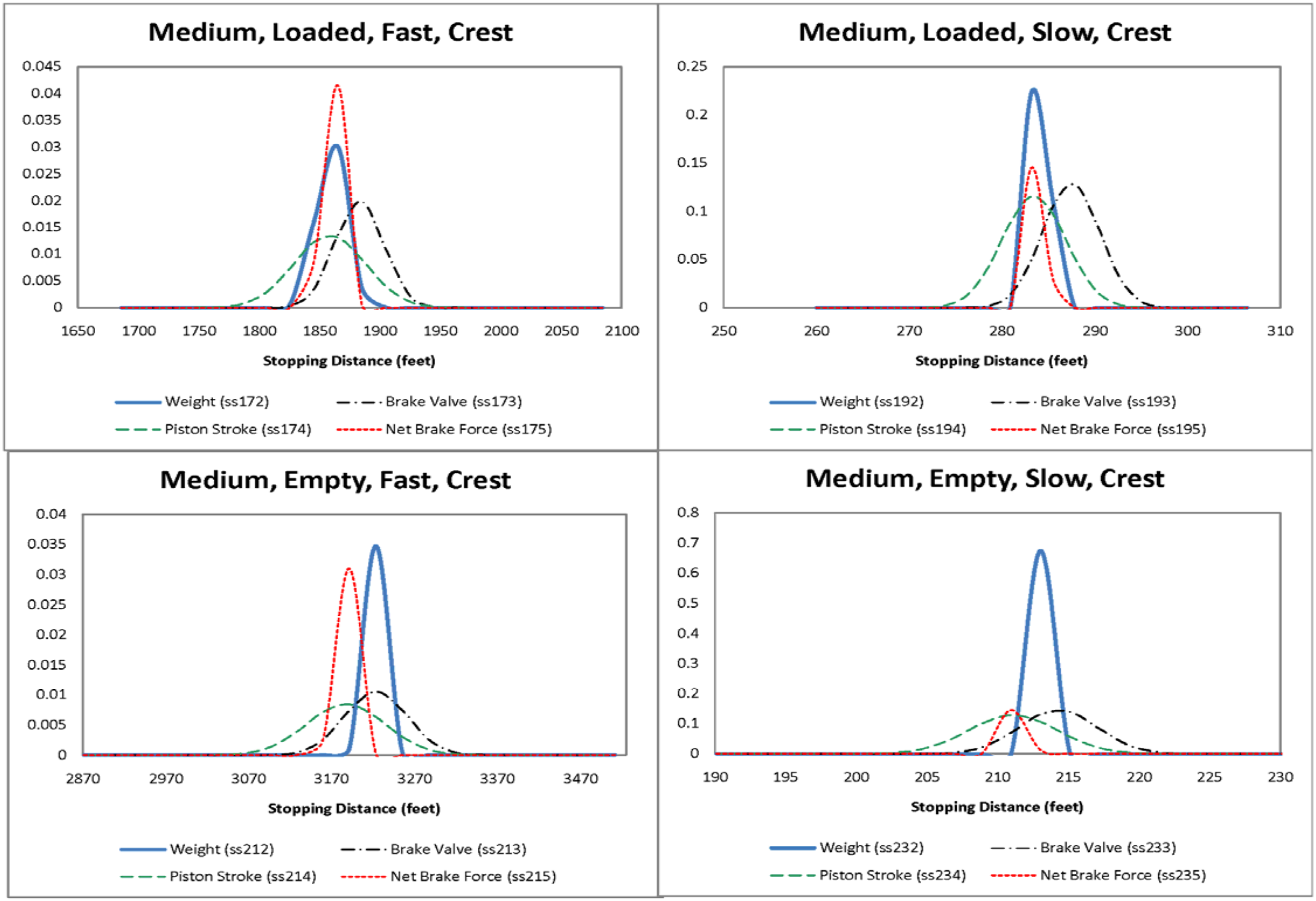

Short, Loaded, Fast, Crest
0.03
0.025
0.02
0.015
0.01
0.005
0
7780
7980
8180
8380
8580
8780
8980
9180
9380
Stopping Distance (feet)
Weight (ss012)
Brake Valve (ss013)
Piston Stroke (ss014)
Net Brake Force (ss015)
Short, Loaded, Slow, Crest
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
190
195
200
205
210
215
220
225
230
235
Stopping Distance (feet)
Weight (ss032)
Brake Valve (ss033)
Piston Stroke (ss034)
Net Brake Force (ss035)
Short, Empty, Fast, Crest
0.05
0.045
0.04
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
3300
3400
3500
3600
3700
3800
3900
4000
4100
Stopping Distance (feet)
Weight (ss052)
Brake Valve (ss053)
Piston Stroke (ss054)
Net Brake Force (ss055)
Short, Empty, Slow, Crest
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
140
145
150
155
160
165
170
175
Stopping Distance (feet)
Weight (ss072)
Brake Valve (ss073)
Piston Stroke (ss074)
Net Brake Force (ss075)

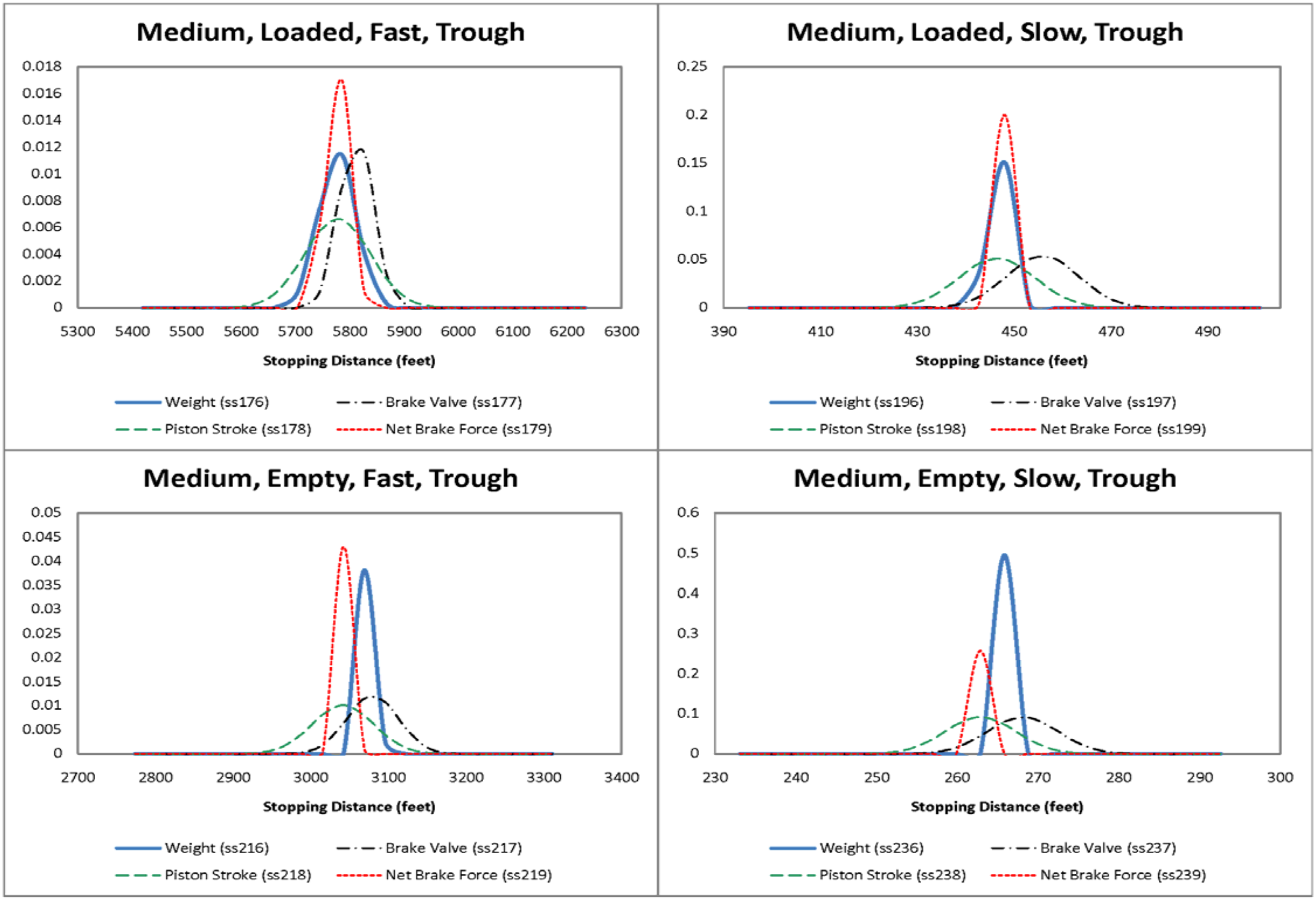

Short, Loaded, Fast, Trough
Stopping Distance (feet)
Weight (ss016)
Brake Valve (ss017)
Piston Stroke (ss018)
Net Brake Force (ss019)
Short, Loaded, Slow, Trough
Stopping Distance (feet)
Weight (ss036)
Brake Valve (ss037)
Piston Stroke (ss038)
Net Brake Force (ss039)
Short, Empty, Fast, Trough
Stopping Distance (feet)
Weight (ss056)
Brake Valve (ss057)
Piston Stroke (ss058)
Net Brake Force (ss059)
Short, Empty, Slow, Trough
Stopping Distance (feet)
Weight (ss076)
Brake Valve (ss077)
Piston Stroke (ss078)
Net Brake Force (ss079)

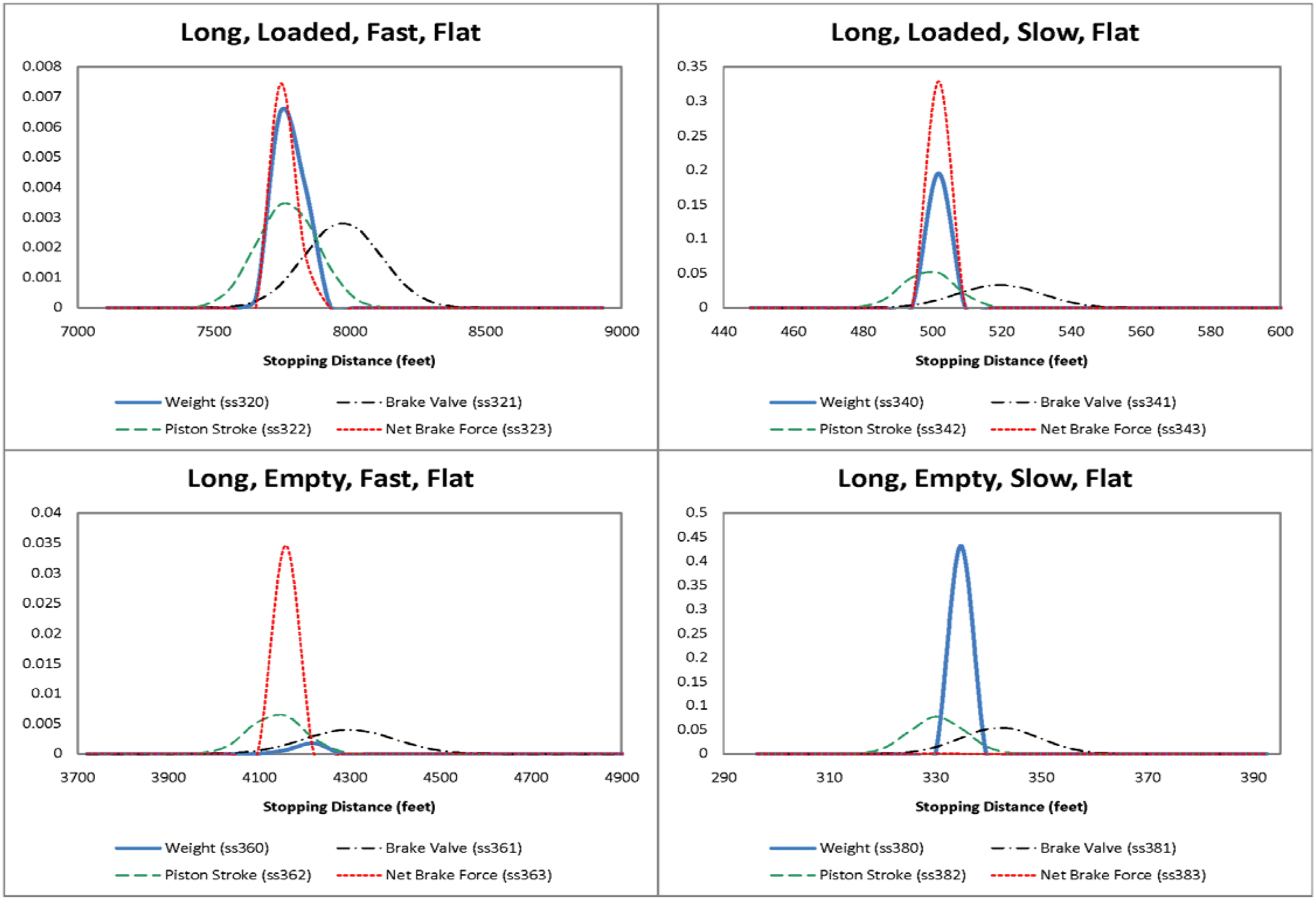

Medium, Loaded, Fast, Flat
Stopping Distance (feet)
Weight (ss160)
Brake Valve (ss161)
Piston Stroke (ss162)
Net Brake Force (ss163)
Medium, Loaded, Slow, Flat
Stopping Distance (feet)
Weight (ss180)
Brake Valve (ss181)
Piston Stroke (ss182)
Net Brake Force (ss183)
Medium, Empty, Fast, Flat
Stopping Distance (feet)
Weight (ss200)
Brake Valve (ss201)
Piston Stroke (ss202)
Net Brake Force (ss203)
Medium, Empty, Slow, Flat
Stopping Distance (feet)
Weight (ss220)
Brake Valve (ss221)
Piston Stroke (ss222)
Net Brake Force (ss223)

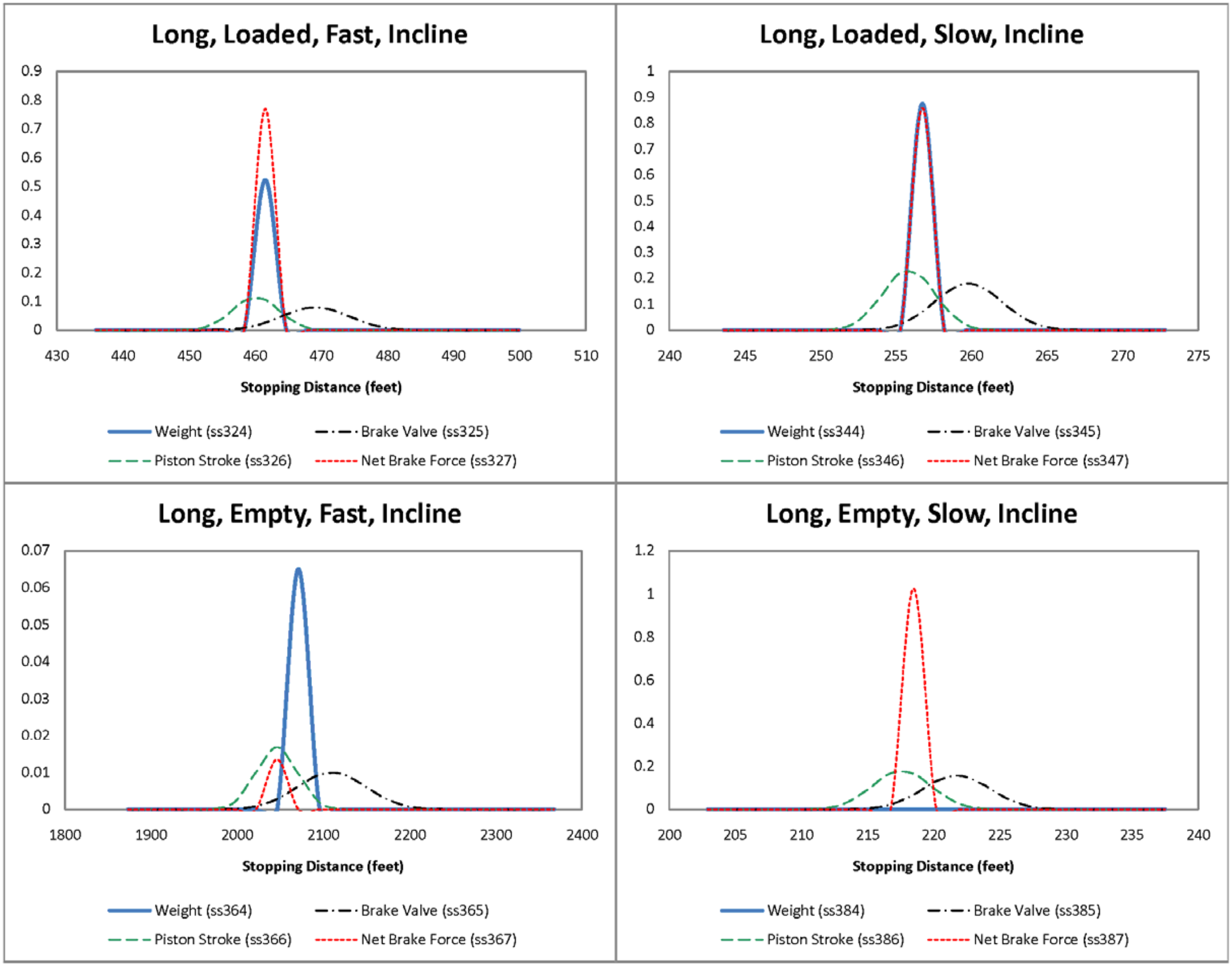

Medium, Loaded, Fast, Incline
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
440
450
460
470
480
490
500
510
Stopping Distance (feet)
Weight (ss164)
Brake Valve (ss165)
Piston Stroke (ss166)
Net Brake Force (ss167)
Medium, Loaded, Slow, Incline
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
200
205
210
215
220
225
230
235
Stopping Distance (feet)
Weight (ss184)
Brake Valve (ss185)
Piston Stroke (ss186)
Net Brake Force (ss187)
Medium, Empty, Fast, Incline
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
1500
1550
1600
1650
1700
1750
1800
1850
Stopping Distance (feet)
Weight (ss204)
Brake Valve (ss205)
Piston Stroke (ss206)
Net Brake Force (ss207)
Medium, Empty, Slow, Incline
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
160
165
170
175
180
185
190
195
Stopping Distance (feet)
Weight (ss224)
Brake Valve (ss225)
Piston Stroke (ss226)
Net Brake Force (ss227)


Medium, Loaded, Fast, Decline
0.009
0.008
0.007
0.006
0.005
0.004
0.003
0.002
0.001
0
4750
4950
5150
5350
5550
5750
5950
6150
6350
Stopping Distance (feet)
Weight (ss168)
Brake Valve (ss169)
Piston Stroke (ss170)
Net Brake Force (ss171)
Medium, Loaded, Slow, Decline
0.12
0.1
0.08
0.06
0.04
0.02
0
550
600
650
700
750
Stopping Distance (feet)
Weight (ss188)
Brake Valve (ss189)
Piston Stroke (ss190)
Net Brake Force (ss191)
Medium, Empty, Fast, Decline
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
1775
1875
1975
2075
2175
Stopping Distance (feet)
Weight (ss208)
Brake Valve (ss209)
Piston Stroke (ss210)
Net Brake Force (ss211)
Medium, Empty, Slow, Decline
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
275
295
315
335
355
375
Stopping Distance (feet)
Weight (ss228)
Brake Valve (ss229)
Piston Stroke (ss230)
Net Brake Force (ss231)

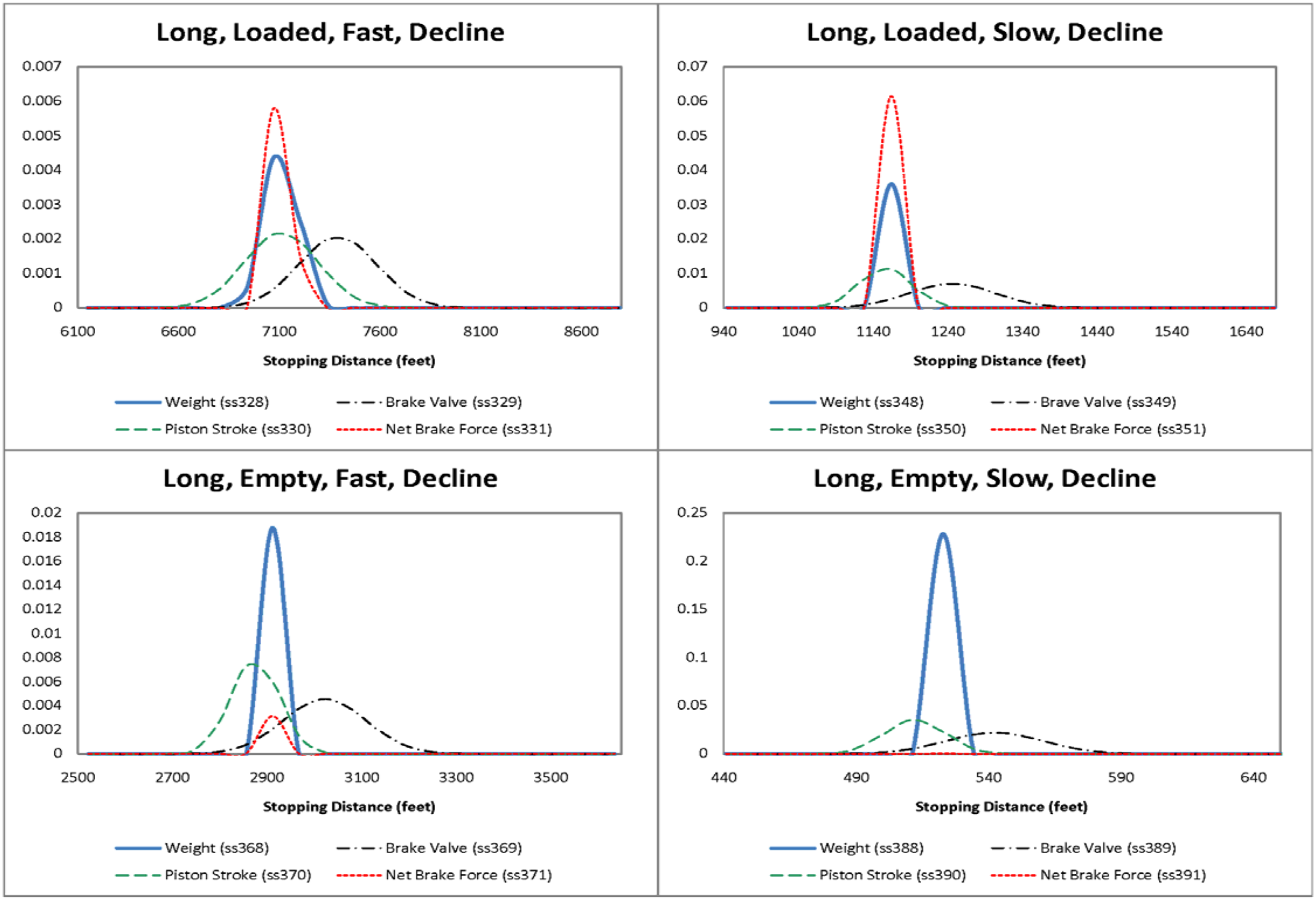

Medium, Loaded, Fast, Crest
0.045
0.04
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
1650
1700
1750
1800
1850
1900
1950
2000
2050
2100
Stopping Distance (feet)
Weight (ss172)
Brake Valve (ss173)
Piston Stroke (ss174)
Net Brake Force (ss175)
Medium, Loaded, Slow, Crest
0.25
0.2
0.15
0.1
0.05
0
250
260
270
280
290
300
310
Stopping Distance (feet)
Weight (ss192)
Brake Valve (ss193)
Piston Stroke (ss194)
Net Brake Force (ss195)
Medium, Empty, Fast, Crest
0.04
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
2870
2970
3070
3170
3270
3370
3470
Stopping Distance (feet)
Weight (ss212)
Brake Valve (ss213)
Piston Stroke (ss214)
Net Brake Force (ss215)
Medium, Empty, Slow, Crest
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
190
195
200
205
210
215
220
225
230
Stopping Distance (feet)
Weight (ss232)
Brake Valve (ss233)
Piston Stroke (ss234)
Net Brake Force (ss235)

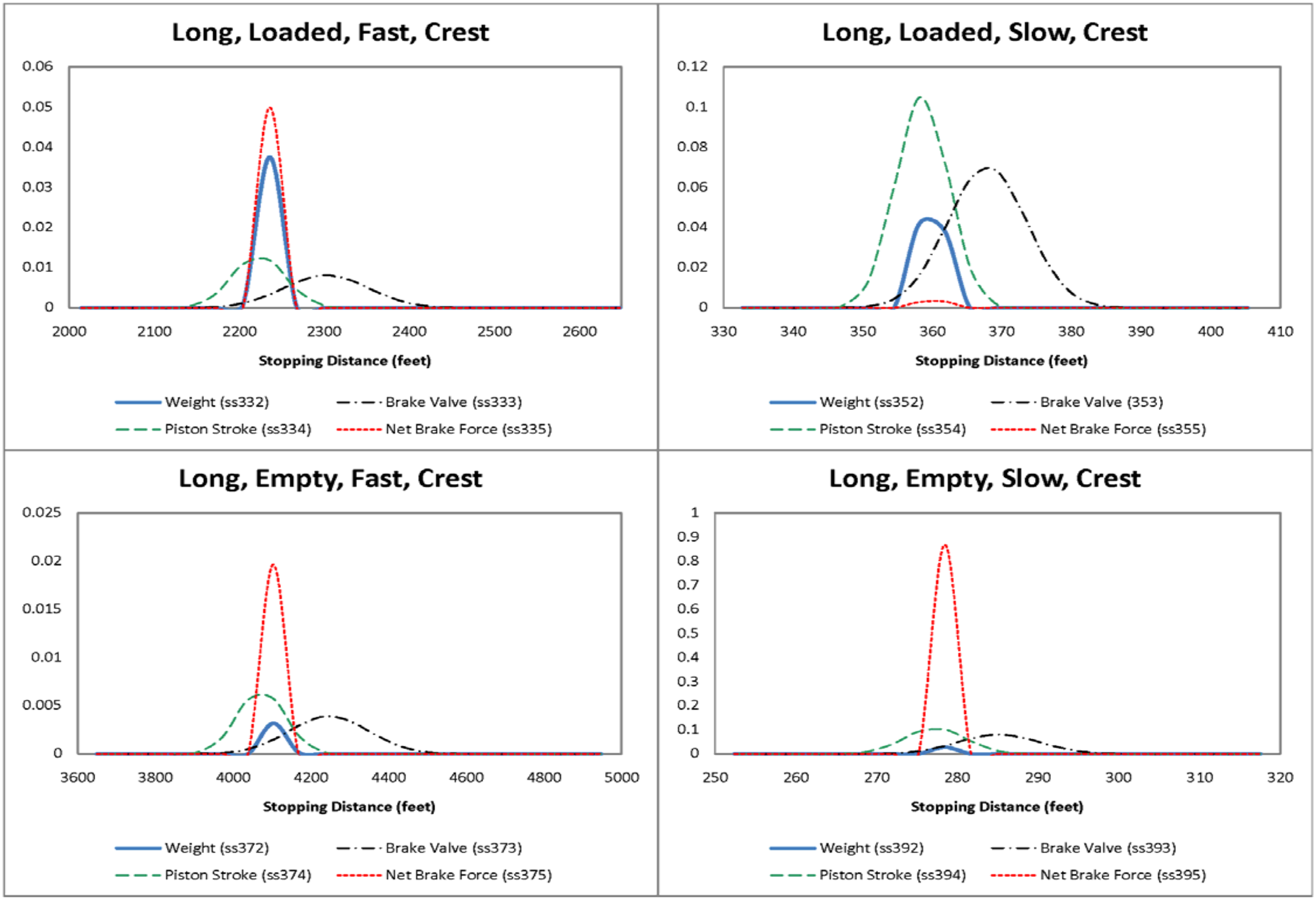

Medium, Loaded, Fast, Trough
Stopping Distance (feet)
Weight (ss176)
Brake Valve (ss177)
Piston Stroke (ss178)
Net Brake Force (ss179)
Medium, Loaded, Slow, Trough
Stopping Distance (feet)
Weight (ss196)
Brake Valve (ss197)
Piston Stroke (ss198)
Net Brake Force (ss199)
Medium, Empty, Fast, Trough
Stopping Distance (feet)
Weight (ss216)
Brake Valve (ss217)
Piston Stroke (ss218)
Net Brake Force (ss219)
Medium, Empty, Slow, Trough
Stopping Distance (feet)
Weight (ss236)
Brake Valve (ss237)
Piston Stroke (ss238)
Net Brake Force (ss239)


Long, Loaded, Fast, Flat
Stopping Distance (feet)
Weight (ss320)
Brake Valve (ss321)
Piston Stroke (ss322)
Net Brake Force (ss323)
Long, Loaded, Slow, Flat
Stopping Distance (feet)
Weight (ss340)
Brake Valve (ss341)
Piston Stroke (ss342)
Net Brake Force (ss343)
Long, Empty, Fast, Flat
Stopping Distance (feet)
Weight (ss360)
Brake Valve (ss361)
Piston Stroke (ss362)
Net Brake Force (ss363)
Long, Empty, Slow, Flat
Stopping Distance (feet)
Weight (ss380)
Brake Valve (ss381)
Piston Stroke (ss382)
Net Brake Force (ss383)

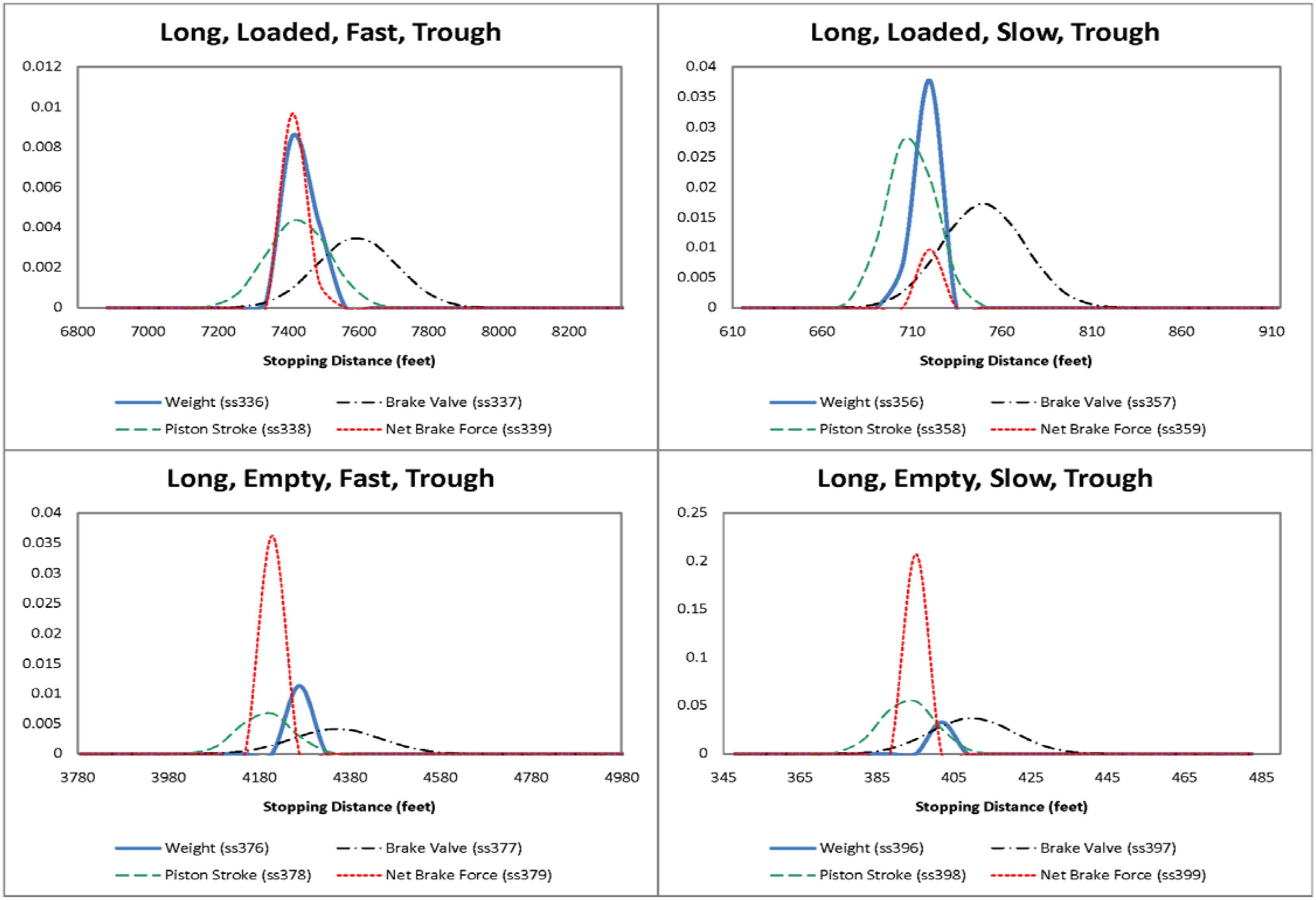


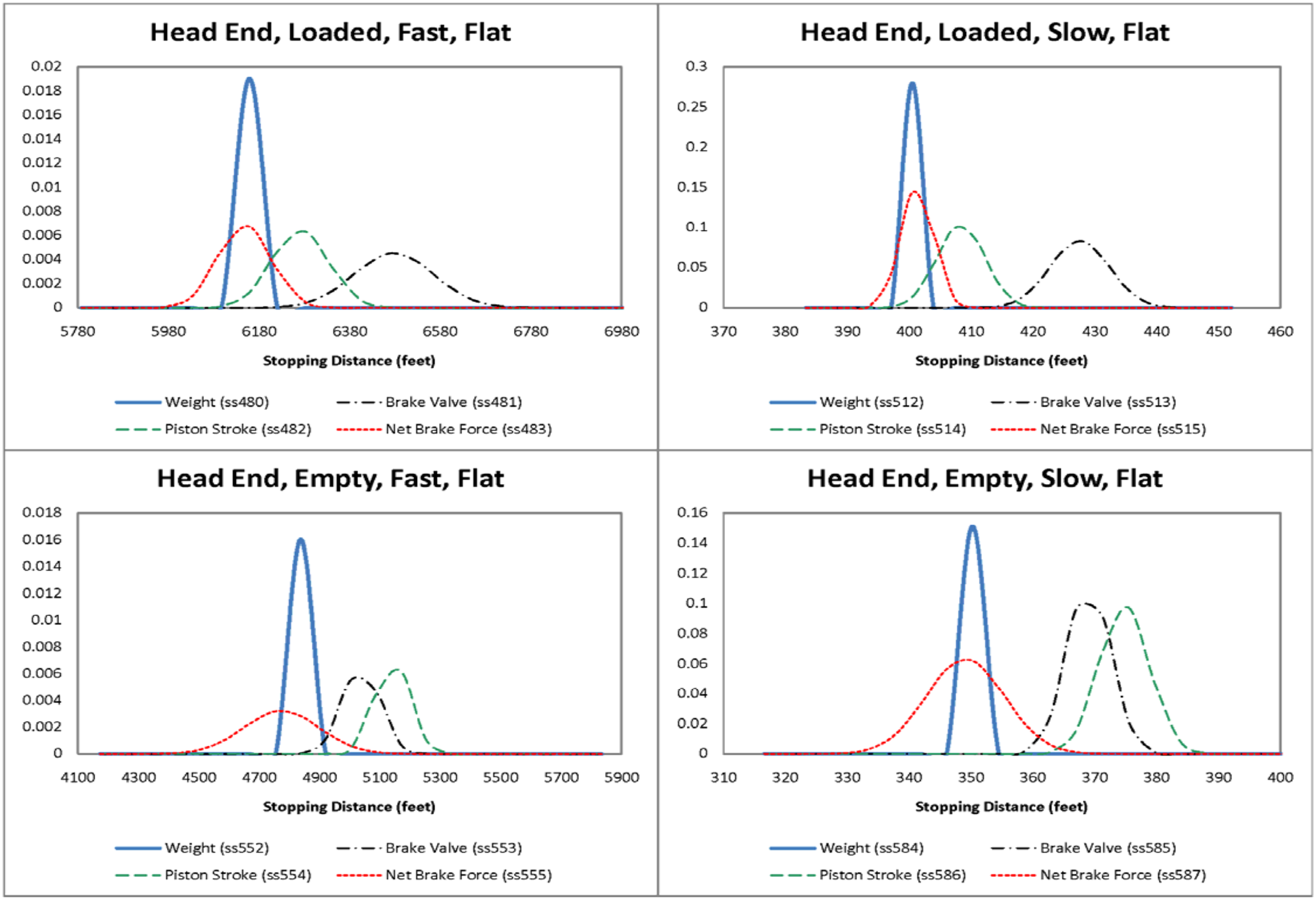
Long, Loaded, Fast, Incline
Stopping Distance (feet)
Weight (ss324)
Brake Valve (ss325)
Piston Stroke (ss326)
Net Brake Force (ss327)
Long, Loaded, Slow, Incline
Stopping Distance (feet)
Weight (ss344)
Brake Valve (ss345)
Piston Stroke (ss346)
Net Brake Force (ss347)
Long, Empty, Fast, Incline
Stopping Distance (feet)
Weight (ss364)
Brake Valve (ss365)
Piston Stroke (ss366)
Net Brake Force (ss367)
Long, Empty, Slow, Incline
Stopping Distance (feet)
Weight (ss384)
Brake Valve (ss385)
Piston Stroke (ss386)
Net Brake Force (ss387)

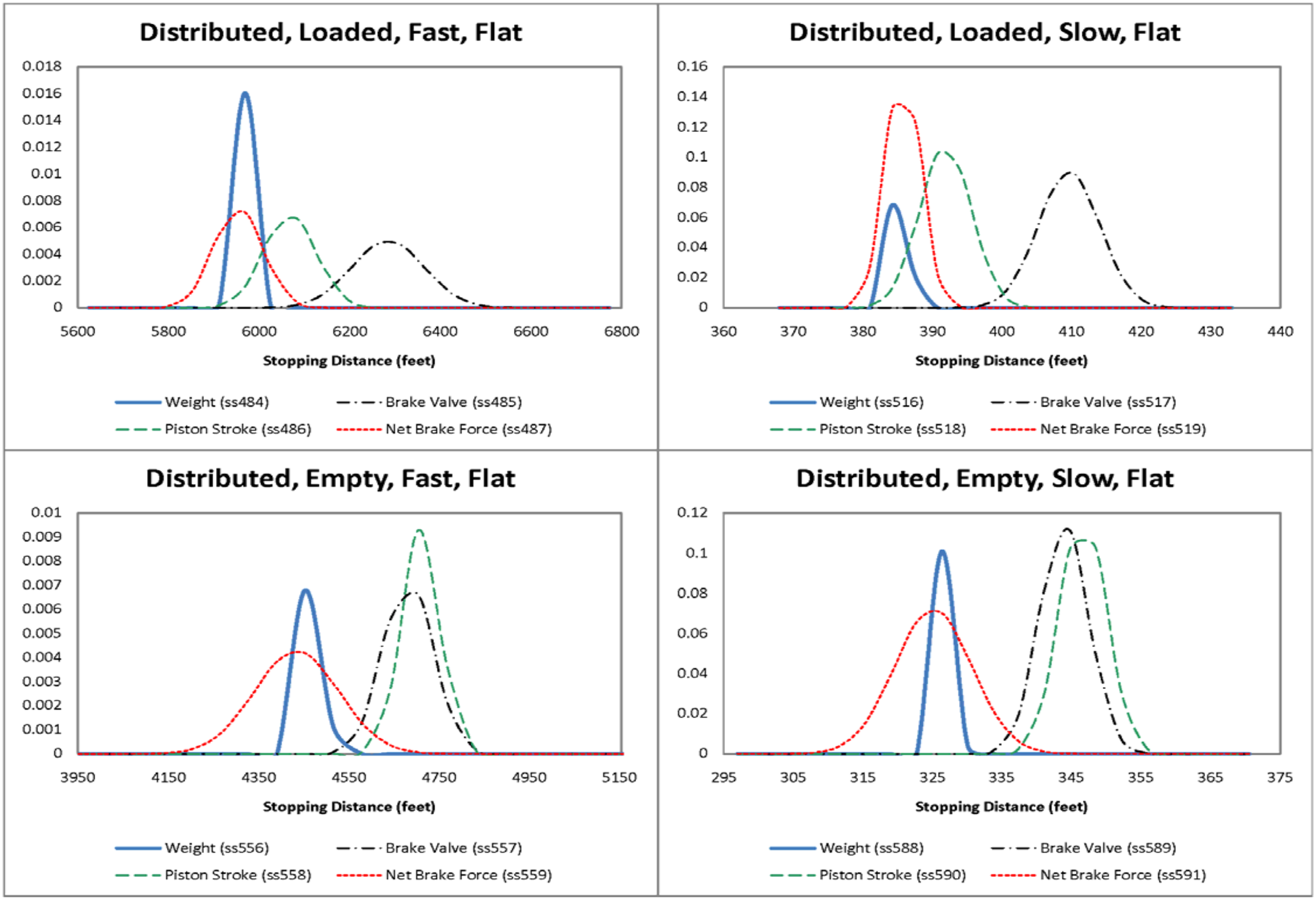

Long, Loaded, Fast, Decline
0.007
0.006
0.005
0.004
0.003
0.002
0.001
0
6100
6600
7100
7600
8100
8600
Stopping Distance (feet)
Weight (ss328)
Brake Valve (ss329)
Piston Stroke (ss330)
Net Brake Force (ss331)
Long, Loaded, Slow, Decline
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
940
1040
1140
1240
1340
1440
1540
1640
Stopping Distance (feet)
Weight (ss348)
Brave Valve (ss349)
Piston Stroke (ss350)
Net Brake Force (ss351)
Long, Empty, Fast, Decline
0.02
0.018
0.016
0.014
0.012
0.01
0.008
0.006
0.004
0.002
0
2500
2700
2900
3100
3300
3500
Stopping Distance (feet)
Weight (ss368)
Brake Valve (ss369)
Piston Stroke (ss370)
Net Brake Force (ss371)
Long, Empty, Slow, Decline
0.25
0.2
0.15
0.1
0.05
0
440
490
540
590
640
Stopping Distance (feet)
Weight (ss388)
Brake Valve (ss389)
Piston Stroke (ss390)
Net Brake Force (ss391)

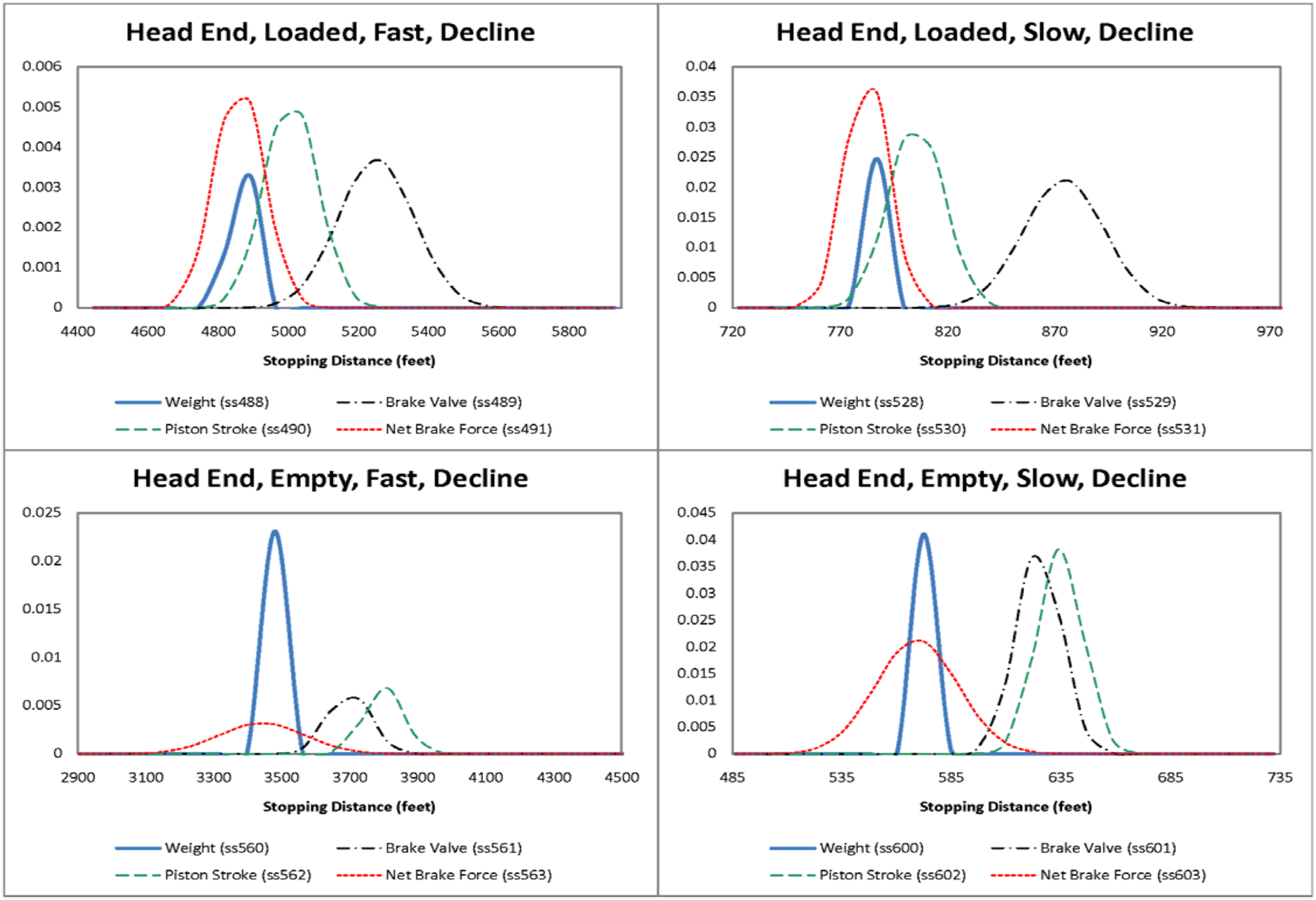


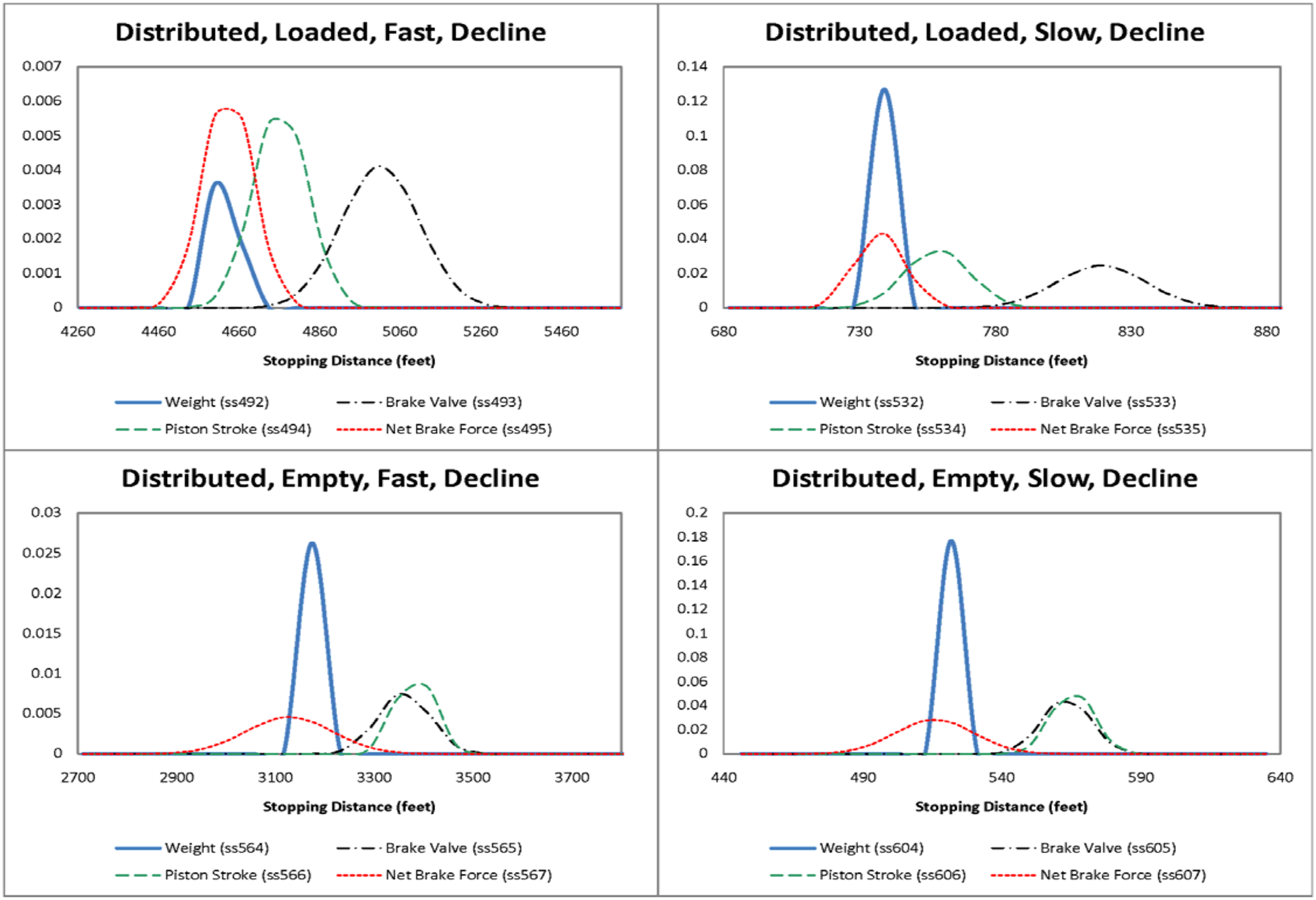
Long, Loaded, Fast, Crest
0.06
0.05
0.04
0.03
0.02
0.01
0
2000
2100
2200
2300
2400
2500
2600
Stopping Distance (feet)
Weight (ss332)
Brake Valve (ss333)
Piston Stroke (ss334)
Net Brake Force (ss335)
Long, Loaded, Slow, Crest
0.12
0.1
0.08
0.06
0.04
0.02
0
330
340
350
360
370
380
390
400
410
Stopping Distance (feet)
Weight (ss352)
Brake Valve (353)
Piston Stroke (ss354)
Net Brake Force (ss355)
Long, Empty, Fast, Crest
0.025
0.02
0.015
0.01
0.005
0
3600
3800
4000
4200
4400
4600
4800
5000
Stopping Distance (feet)
Weight (ss372)
Brake Valve (ss373)
Piston Stroke (ss374)
Net Brake Force (ss375)
Long, Empty, Slow, Crest
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
250
260
270
280
290
300
310
320
Stopping Distance (feet)
Weight (ss392)
Brake Valve (ss393)
Piston Stroke (ss394)
Net Brake Force (ss395)


Long, Loaded, Fast, Trough
0.012
0.01
0.008
0.006
0.004
0.002
0
6800
7000
7200
7400
7600
7800
8000
8200
Stopping Distance (feet)
Weight (ss336)
Brake Valve (ss337)
Piston Stroke (ss338)
Net Brake Force (ss339)
Long, Loaded, Slow, Trough
0.04
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
610
660
710
760
810
860
910
Stopping Distance (feet)
Weight (ss356)
Brake Valve (ss357)
Piston Stroke (ss358)
Net Brake Force (ss359)
Long, Empty, Fast, Trough
0.04
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
3780
3980
4180
4380
4580
4780
4980
Stopping Distance (feet)
Weight (ss376)
Brake Valve (ss377)
Piston Stroke (ss378)
Net Brake Force (ss379)
Long, Empty, Slow, Trough
0.25
0.2
0.15
0.1
0.05
0
345
365
385
405
425
445
465
485
Stopping Distance (feet)
Weight (ss396)
Brake Valve (ss397)
Piston Stroke (ss398)
Net Brake Force (ss399)

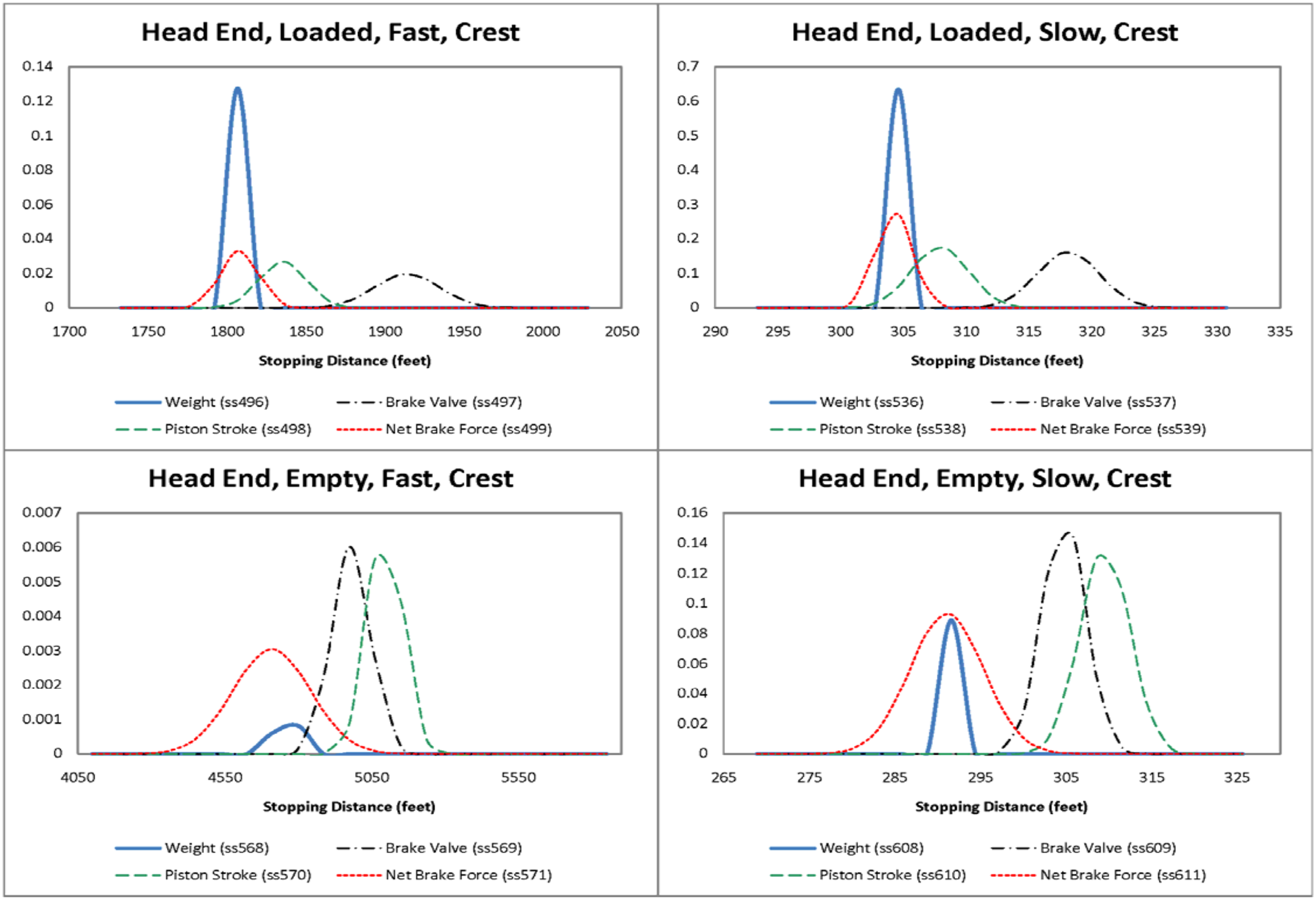

Head End, Loaded, Fast, Flat
0.02
0.018
0.016
0.014
0.012
0.01
0.008
0.006
0.004
0.002
0
5780
5980
6180
6380
6580
6780
6980
Stopping Distance (feet)
Weight (ss480)
Brake Valve (ss481)
Piston Stroke (ss482)
Net Brake Force (ss483)
Head End, Loaded, Slow, Flat
0.3
0.25
0.2
0.15
0.1
0.05
0
370
380
390
400
410
420
430
440
450
460
Stopping Distance (feet)
Weight (ss512)
Brake Valve (ss513)
Piston Stroke (ss514)
Net Brake Force (ss515)
Head End, Empty, Fast, Flat
0.018
0.016
0.014
0.012
0.01
0.008
0.006
0.004
0.002
0
4100
4300
4500
4700
4900
5100
5300
5500
5700
5900
Stopping Distance (feet)
Weight (ss552)
Brake Valve (ss553)
Piston Stroke (ss554)
Net Brake Force (ss555)
Head End, Empty, Slow, Flat
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
310
320
330
340
350
360
370
380
390
400
Stopping Distance (feet)
Weight (ss584)
Brake Valve (ss585)
Piston Stroke (ss586)
Net Brake Force (ss587)


Distributed, Loaded, Fast, Flat
0.018
0.016
0.014
0.012
0.01
0.008
0.006
0.004
0.002
0
5600
5800
6000
6200
6400
6600
6800
Stopping Distance (feet)
Weight (ss484)
Brake Valve (ss485)
Piston Stroke (ss486)
Net Brake Force (ss487)
Distributed, Loaded, Slow, Flat
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
360
370
380
390
400
410
420
430
440
Stopping Distance (feet)
Weight (ss516)
Brake Valve (ss517)
Piston Stroke (ss518)
Net Brake Force (ss519)
Distributed, Empty, Fast, Flat
0.01
0.009
0.008
0.007
0.006
0.005
0.004
0.003
0.002
0.001
0
3950
4150
4350
4550
4750
4950
5150
Stopping Distance (feet)
Weight (ss556)
Brake Valve (ss557)
Piston Stroke (ss558)
Net Brake Force (ss559)
Distributed, Empty, Slow, Flat
0.12
0.1
0.08
0.06
0.04
0.02
0
295
305
315
325
335
345
355
365
375
Stopping Distance (feet)
Weight (ss588)
Brake Valve (ss589)
Piston Stroke (ss590)
Net Brake Force (ss591)

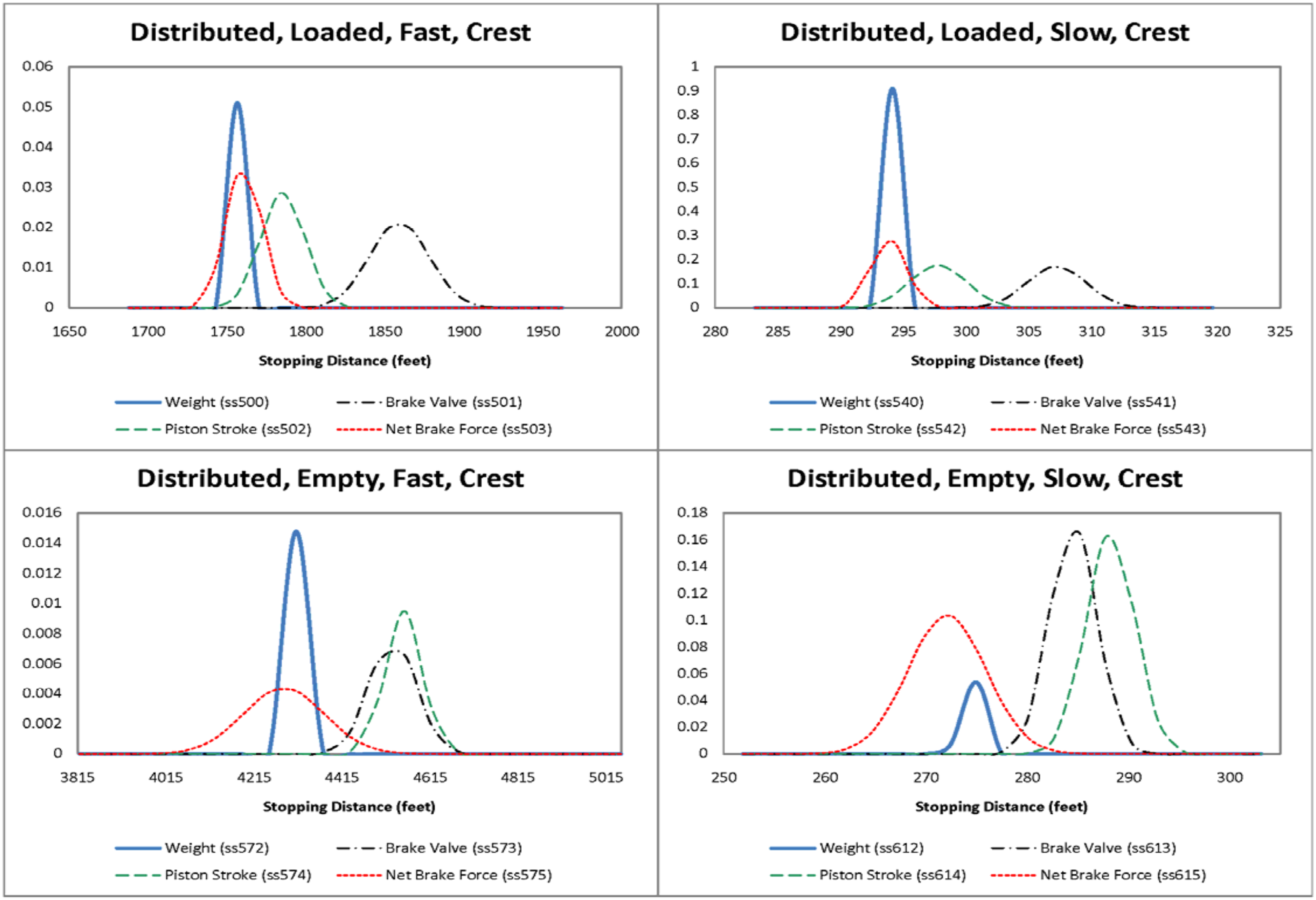

Head End, Loaded, Fast, Decline
0.006
0.005
0.004
0.003
0.002
0.001
0
4400 4600 4800 5000 5200 5400 5600 5800
Stopping Distance (feet)
Weight (ss488)
Brake Valve (ss489)
Piston Stroke (ss490)
Net Brake Force (ss491)
Head End, Loaded, Slow, Decline
0.04
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
720 770 820 870 920 970
Stopping Distance (feet)
Weight (ss528)
Brake Valve (ss529)
Piston Stroke (ss530)
Net Brake Force (ss531)
Head End, Empty, Fast, Decline
0.025
0.02
0.015
0.01
0.005
0
2900 3100 3300 3500 3700 3900 4100 4300 4500
Stopping Distance (feet)
Weight (ss560)
Brake Valve (ss561)
Piston Stroke (ss562)
Net Brake Force (ss563)
Head End, Empty, Slow, Decline
0.045
0.04
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
485 535 585 635 685 735
Stopping Distance (feet)
Weight (ss600)
Brake Valve (ss601)
Piston Stroke (ss602)
Net Brake Force (ss603)



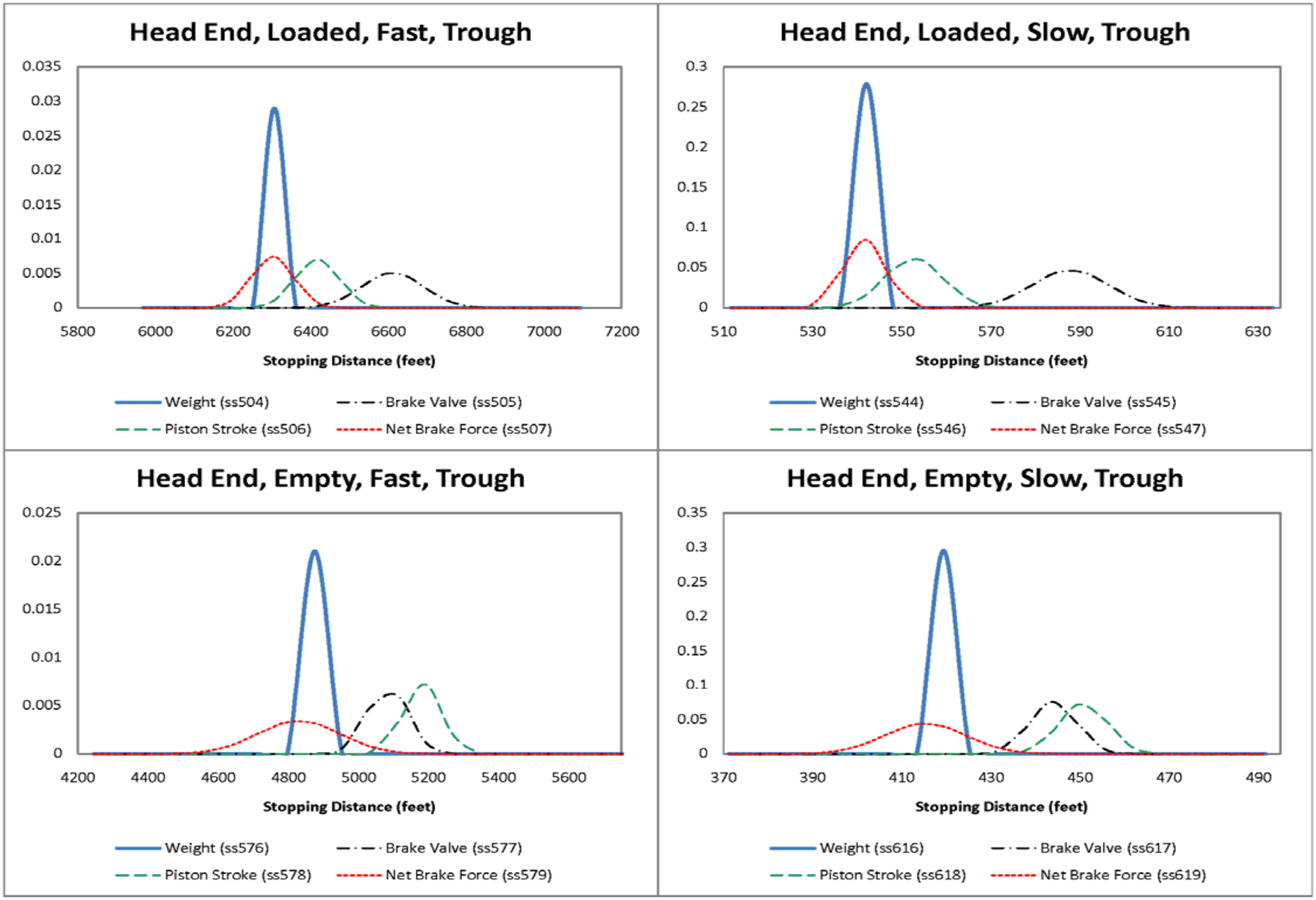
Distributed, Loaded, Fast, Decline
0.007
0.006
0.005
0.004
0.003
0.002
0.001
0
4260
4460
4660
4860
5060
5260
5460
Stopping Distance (feet)
Weight (ss492)
Brake Valve (ss493)
Piston Stroke (ss494)
Net Brake Force (ss495)
Distributed, Loaded, Slow, Decline
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
680
730
780
830
880
Stopping Distance (feet)
Weight (ss532)
Brake Valve (ss533)
Piston Stroke (ss534)
Net Brake Force (ss535)
Distributed, Empty, Fast, Decline
0.03
0.025
0.02
0.015
0.01
0.005
0
2700
2900
3100
3300
3500
3700
Stopping Distance (feet)
Weight (ss564)
Brake Valve (ss565)
Piston Stroke (ss566)
Net Brake Force (ss567)
Distributed, Empty, Slow, Decline
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
440
490
540
590
640
Stopping Distance (feet)
Weight (ss604)
Brake Valve (ss605)
Piston Stroke (ss606)
Net Brake Force (ss607)

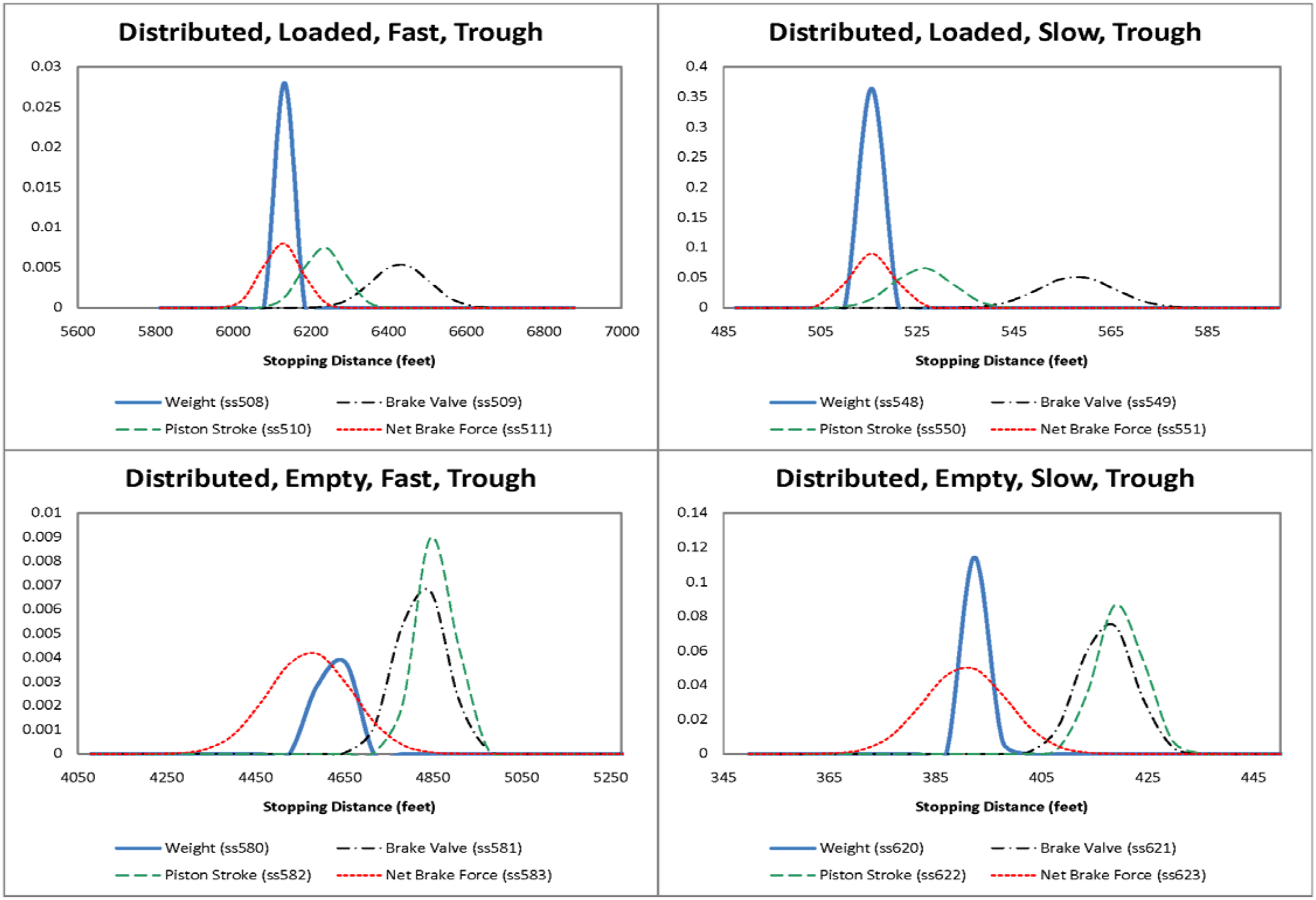


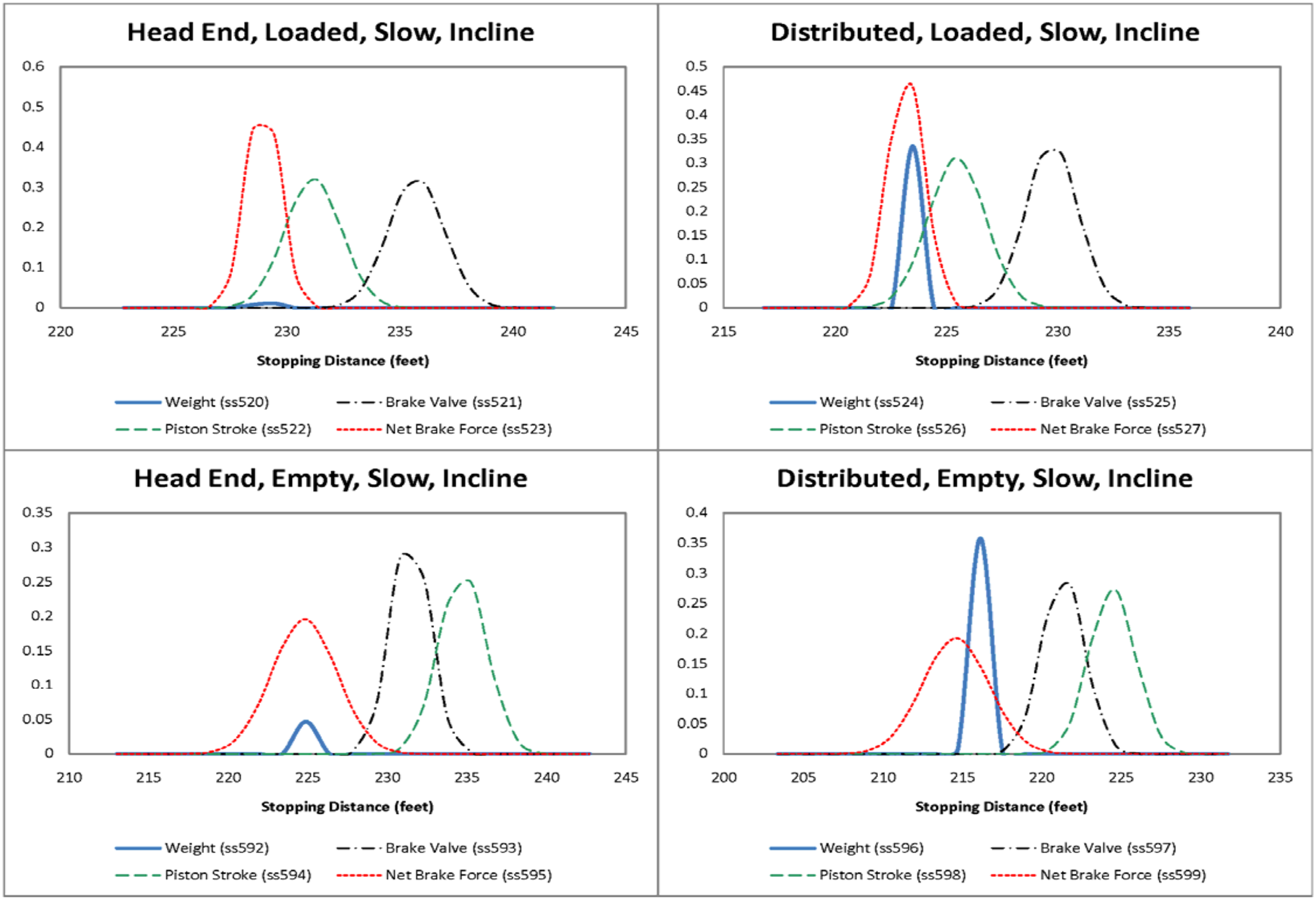
Head End, Loaded, Fast, Crest
Stopping Distance (feet)
Weight (ss496)
Brake Valve (ss497)
Piston Stroke (ss498)
Net Brake Force (ss499)
Head End, Loaded, Slow, Crest
Stopping Distance (feet)
Weight (ss536)
Brake Valve (ss537)
Piston Stroke (ss538)
Net Brake Force (ss539)
Head End, Empty, Fast, Crest
Stopping Distance (feet)
Weight (ss568)
Brake Valve (ss569)
Piston Stroke (ss570)
Net Brake Force (ss571)
Head End, Empty, Slow, Crest
Stopping Distance (feet)
Weight (ss608)
Brake Valve (ss609)
Piston Stroke (ss610)
Net Brake Force (ss611)



Distributed, Loaded, Fast, Crest
Stopping Distance (feet)
Weight (ss500)
Brake Valve (ss501)
Piston Stroke (ss502)
Net Brake Force (ss503)
Distributed, Loaded, Slow, Crest
Stopping Distance (feet)
Weight (ss540)
Brake Valve (ss541)
Piston Stroke (ss542)
Net Brake Force (ss543)
Distributed, Empty, Fast, Crest
Stopping Distance (feet)
Weight (ss572)
Brake Valve (ss573)
Piston Stroke (ss574)
Net Brake Force (ss575)
Distributed, Empty, Slow, Crest
Stopping Distance (feet)
Weight (ss612)
Brake Valve (ss613)
Piston Stroke (ss614)
Net Brake Force (ss615)

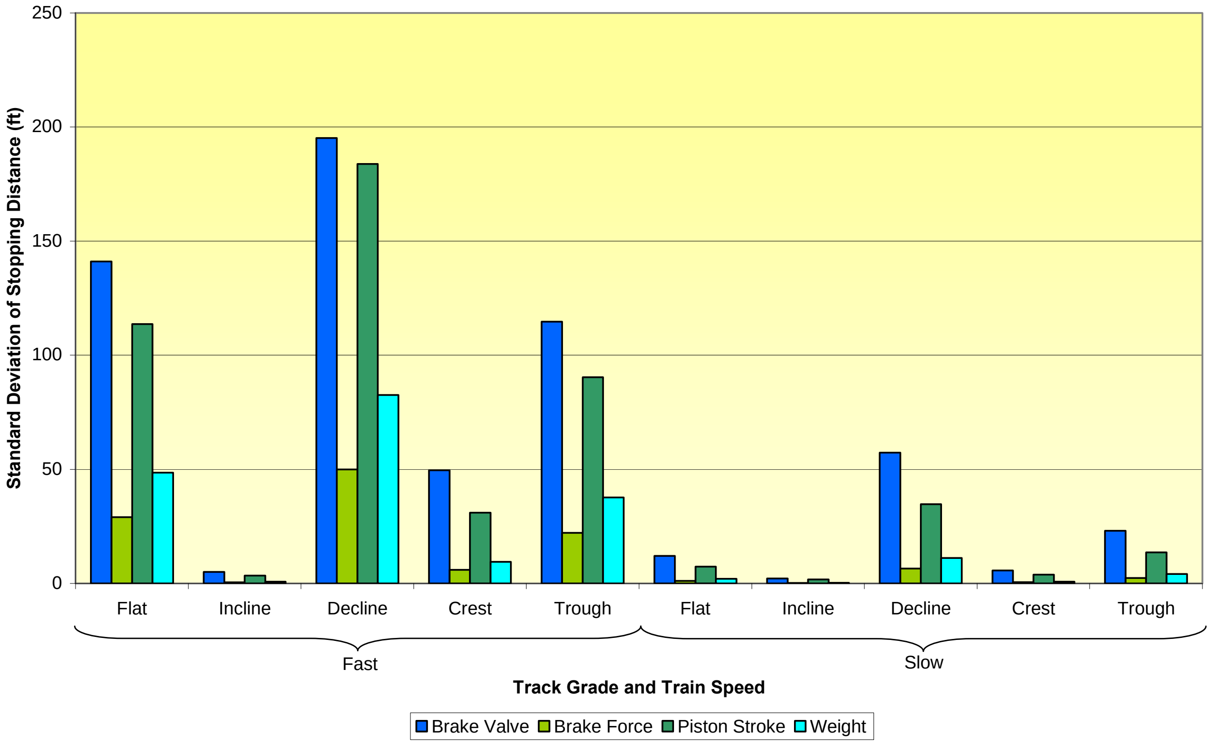

Head End, Loaded, Fast, Trough
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
5800
6000
6200
6400
6600
6800
7000
7200
Stopping Distance (feet)
Weight (ss504)
Brake Valve (ss505)
Piston Stroke (ss506)
Net Brake Force (ss507)
Head End, Loaded, Slow, Trough
0.3
0.25
0.2
0.15
0.1
0.05
0
510
530
550
570
590
610
630
Stopping Distance (feet)
Weight (ss544)
Brake Valve (ss545)
Piston Stroke (ss546)
Net Brake Force (ss547)
Head End, Empty, Fast, Trough
0.025
0.02
0.015
0.01
0.005
0
4200
4400
4600
4800
5000
5200
5400
5600
Stopping Distance (feet)
Weight (ss576)
Brake Valve (ss577)
Piston Stroke (ss578)
Net Brake Force (ss579)
Head End, Empty, Slow, Trough
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
370
390
410
430
450
470
490
Stopping Distance (feet)
Weight (ss616)
Brake Valve (ss617)
Piston Stroke (ss618)
Net Brake Force (ss619)


Distributed, Loaded, Fast, Trough
Stopping Distance (feet)
Weight (ss508)
Brake Valve (ss509)
Piston Stroke (ss510)
Net Brake Force (ss511)
Distributed, Loaded, Slow, Trough
Stopping Distance (feet)
Weight (ss548)
Brake Valve (ss549)
Piston Stroke (ss550)
Net Brake Force (ss551)
Distributed, Empty, Fast, Trough
Stopping Distance (feet)
Weight (ss580)
Brake Valve (ss581)
Piston Stroke (ss582)
Net Brake Force (ss583)
Distributed, Empty, Slow, Trough
Stopping Distance (feet)
Weight (ss620)
Brake Valve (ss621)
Piston Stroke (ss622)
Net Brake Force (ss623)

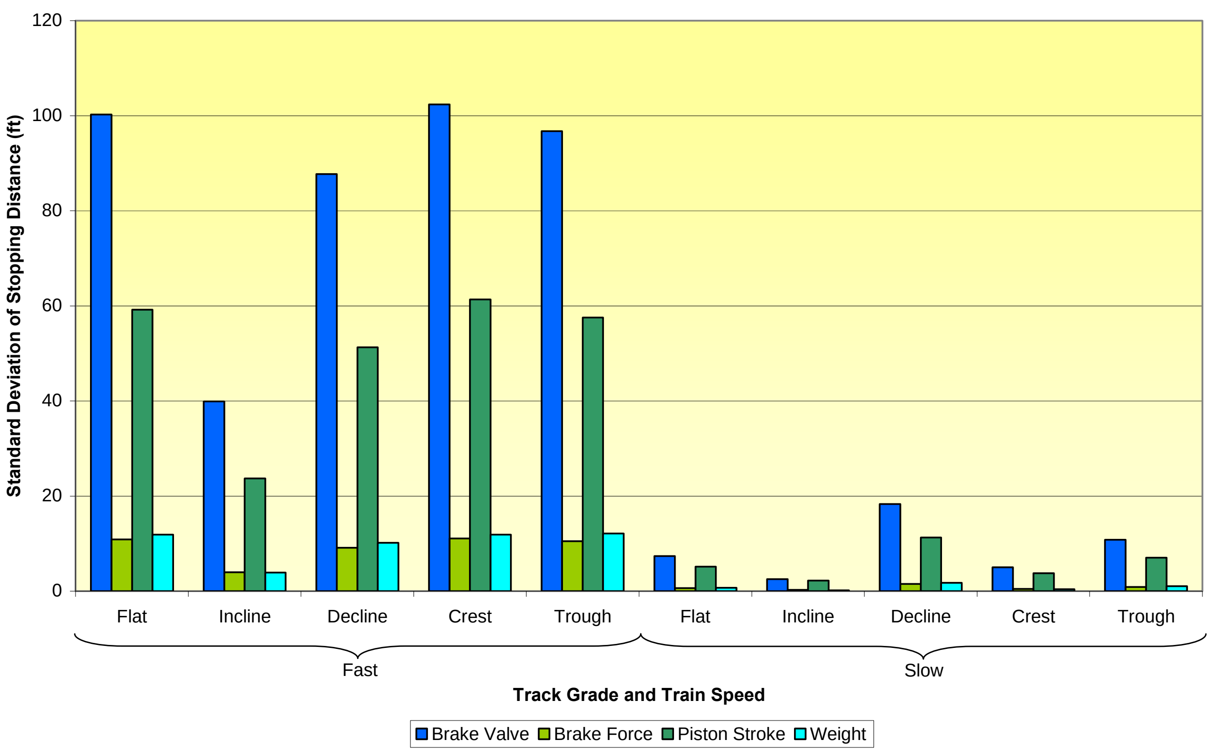

Head End, Loaded, Slow, Incline
0.6
0.5
0.4
0.3
0.2
0.1
0
220
225
230
235
240
245
Stopping Distance (feet)
Weight (ss520)
Brake Valve (ss521)
Piston Stroke (ss522)
Net Brake Force (ss523)
Distributed, Loaded, Slow, Incline
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
215
220
225
230
235
240
Stopping Distance (feet)
Weight (ss524)
Brake Valve (ss525)
Piston Stroke (ss526)
Net Brake Force (ss527)
Head End, Empty, Slow, Incline
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
210
215
220
225
230
235
240
245
Stopping Distance (feet)
Weight (ss592)
Brake Valve (ss593)
Piston Stroke (ss594)
Net Brake Force (ss595)
Distributed, Empty, Slow, Incline
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
200
205
210
215
220
225
230
235
Stopping Distance (feet)
Weight (ss596)
Brake Valve (ss597)
Piston Stroke (ss598)
Net Brake Force (ss599)

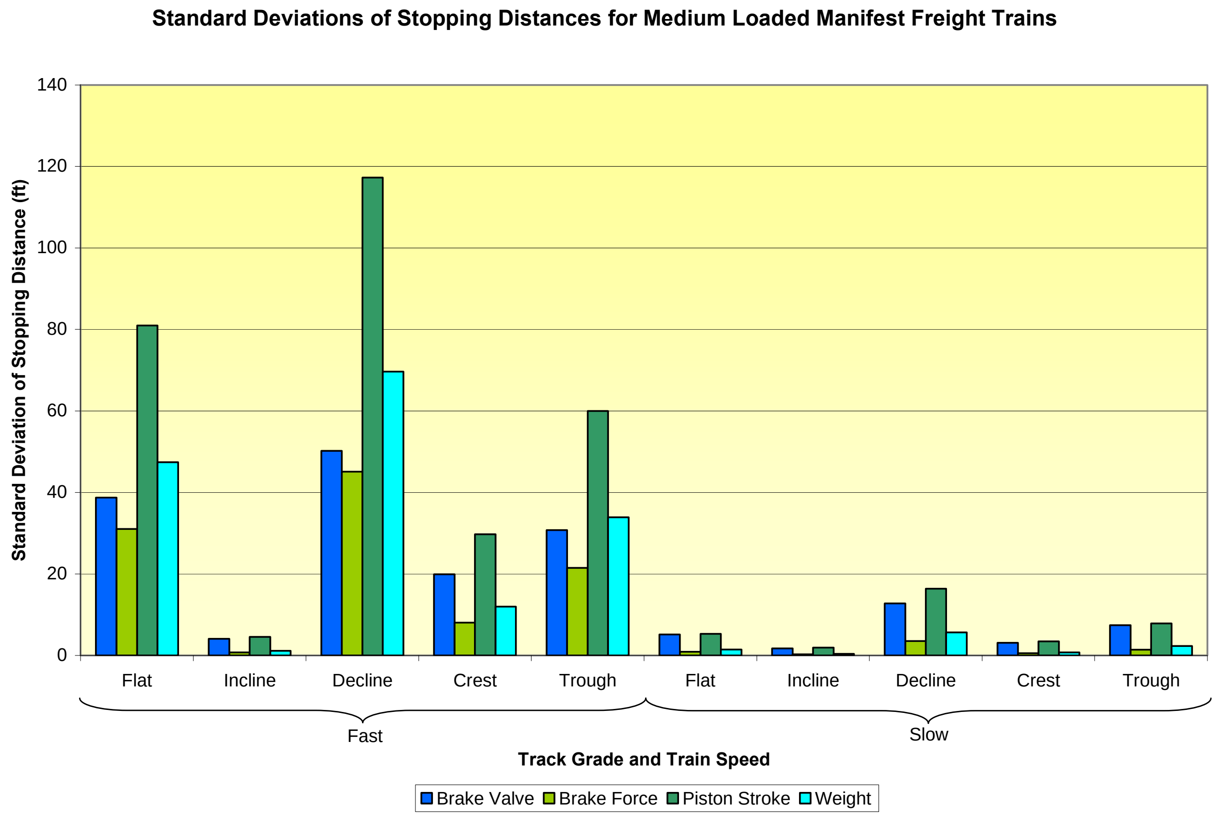
Appendix D.
Parametric Study Standard Deviation Charts

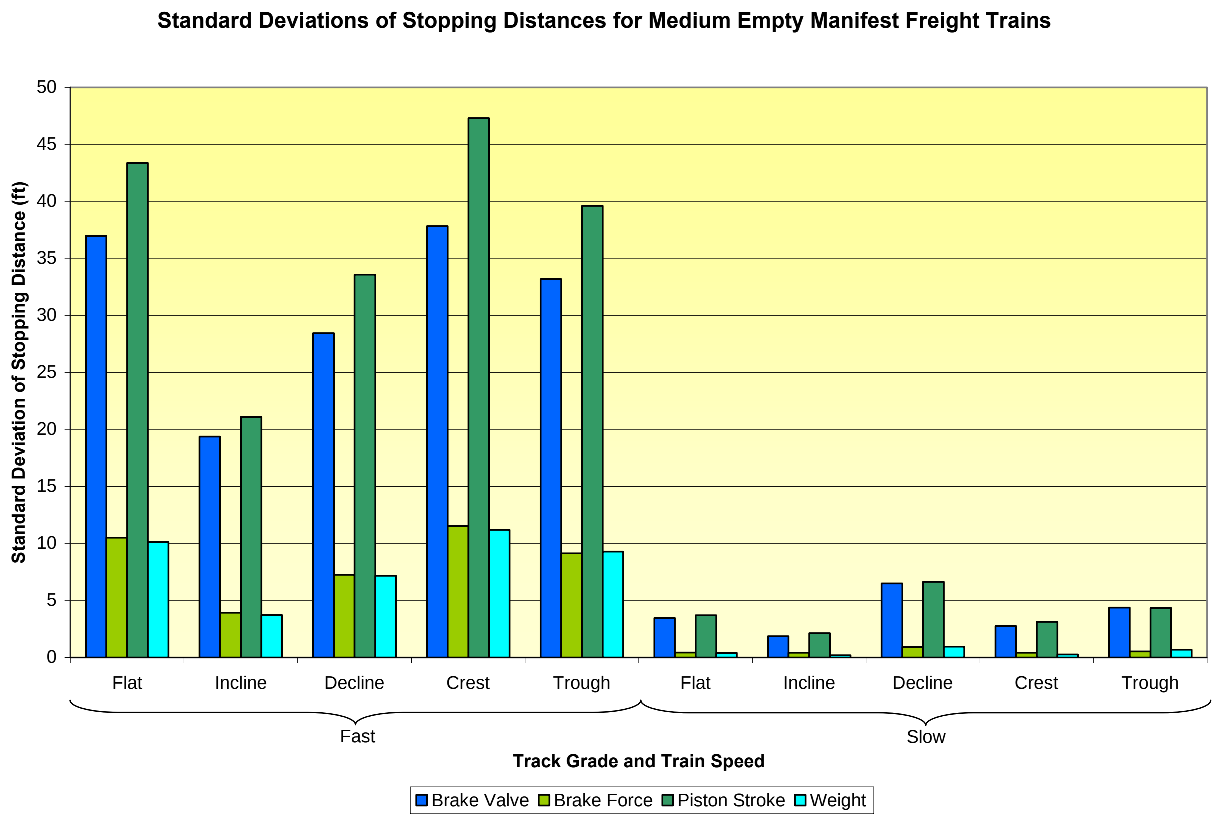
Standard Deviations of Stopping Distances for Long Loaded Manifest Freight Trains



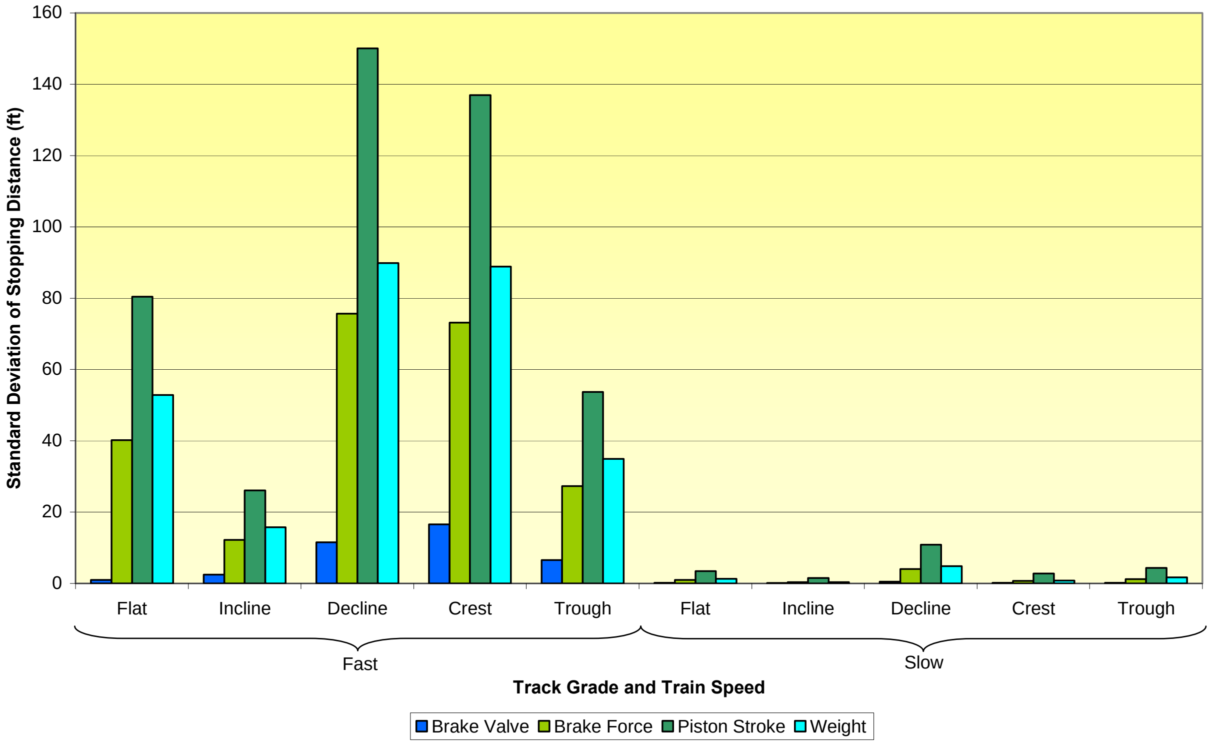
Standard Deviations of Stopping Distances for Long Empty Manifest Freight Trains



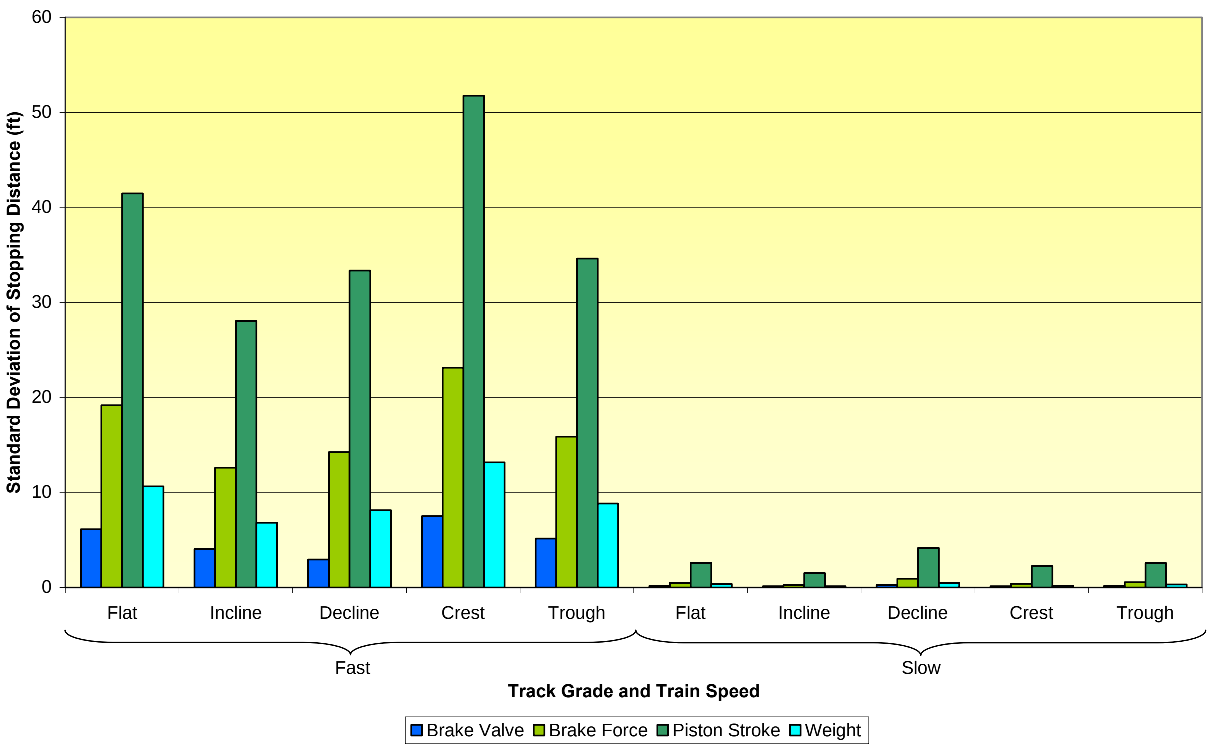

Standard Deviations of Stopping Distances for Medium Loaded Manifest Freight Trains
Standard Deviation of Stopping Distance (ft)
0
20
40
60
80
100
120
140
Flat
Incline
Decline
Crest
Trough
Flat
Incline
Decline
Crest
Trough
Fast
Slow
Track Grade and Train Speed
Brake Valve
Brake Force
Piston Stroke
Weight

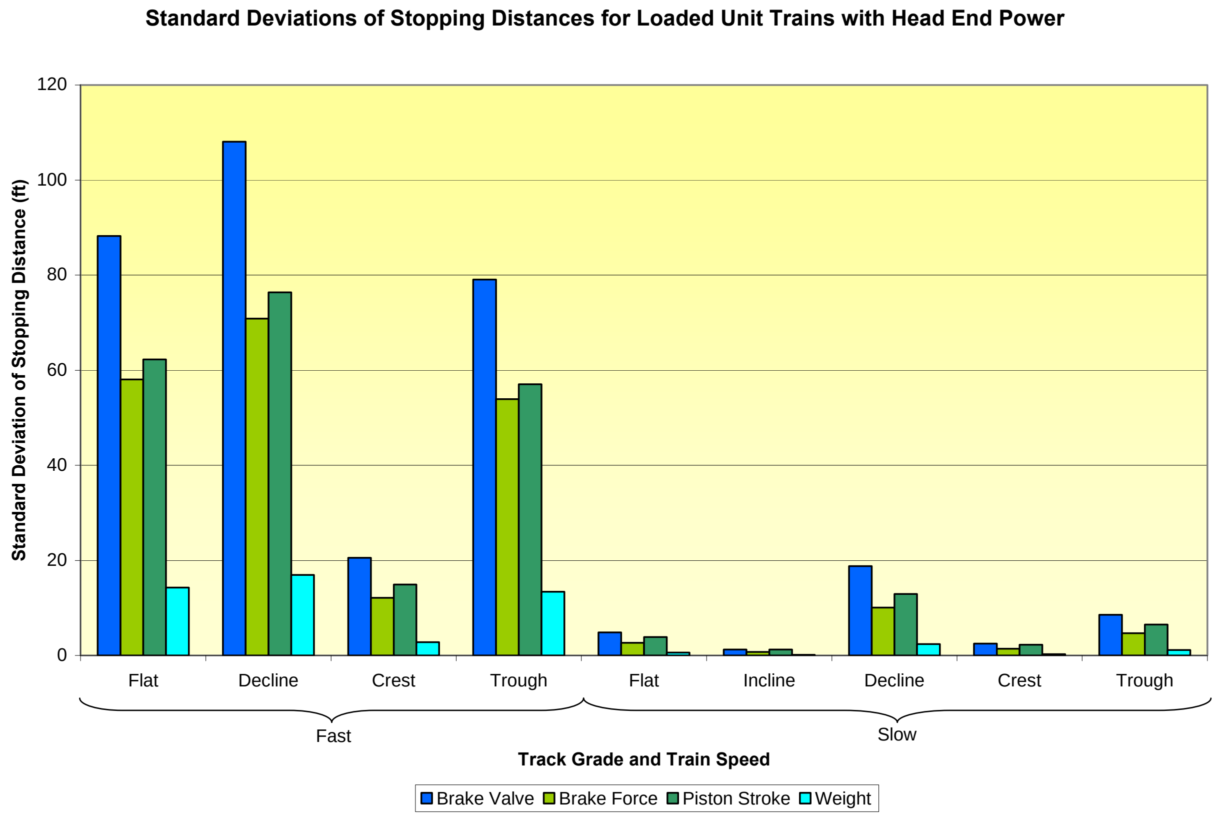

Standard Deviations of Stopping Distances for Medium Empty Manifest Freight Trains
Standard Deviation of Stopping Distance (ft)
0
5
10
15
20
25
30
35
40
45
50
Flat
Incline
Decline
Crest
Trough
Flat
Incline
Decline
Crest
Trough
Fast
Slow
Track Grade and Train Speed
Brake Valve
Brake Force
Piston Stroke
Weight

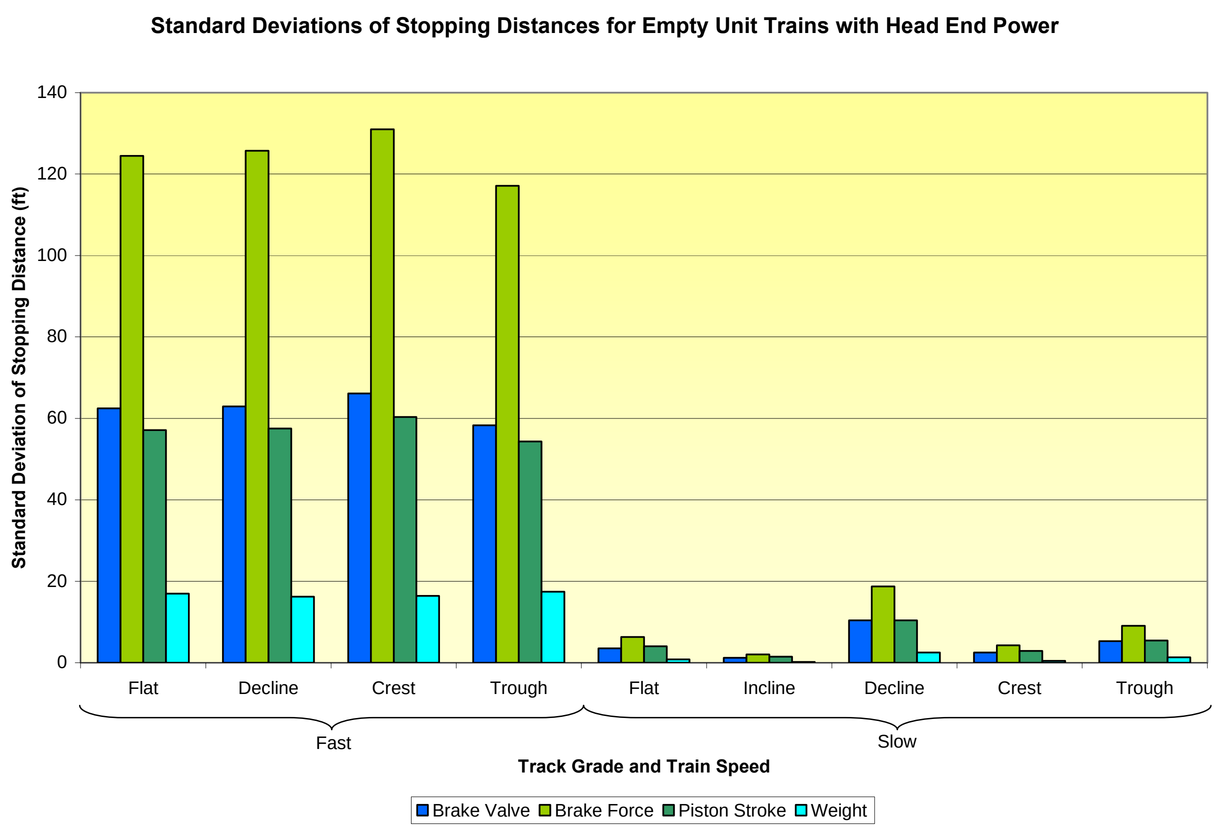
Standard Deviations of Stopping Distances for Short Loaded Manifest Freight Trains



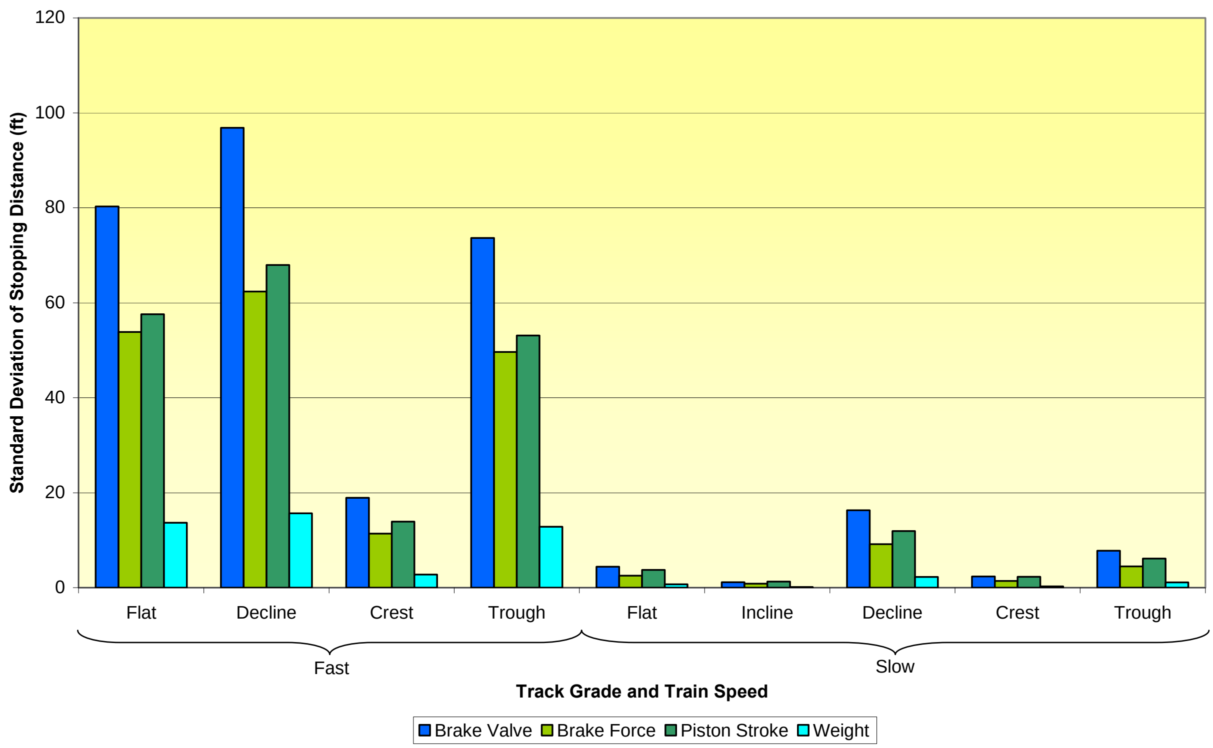
Standard Deviations of Stopping Distances for Short Empty Manifest Freight Trains



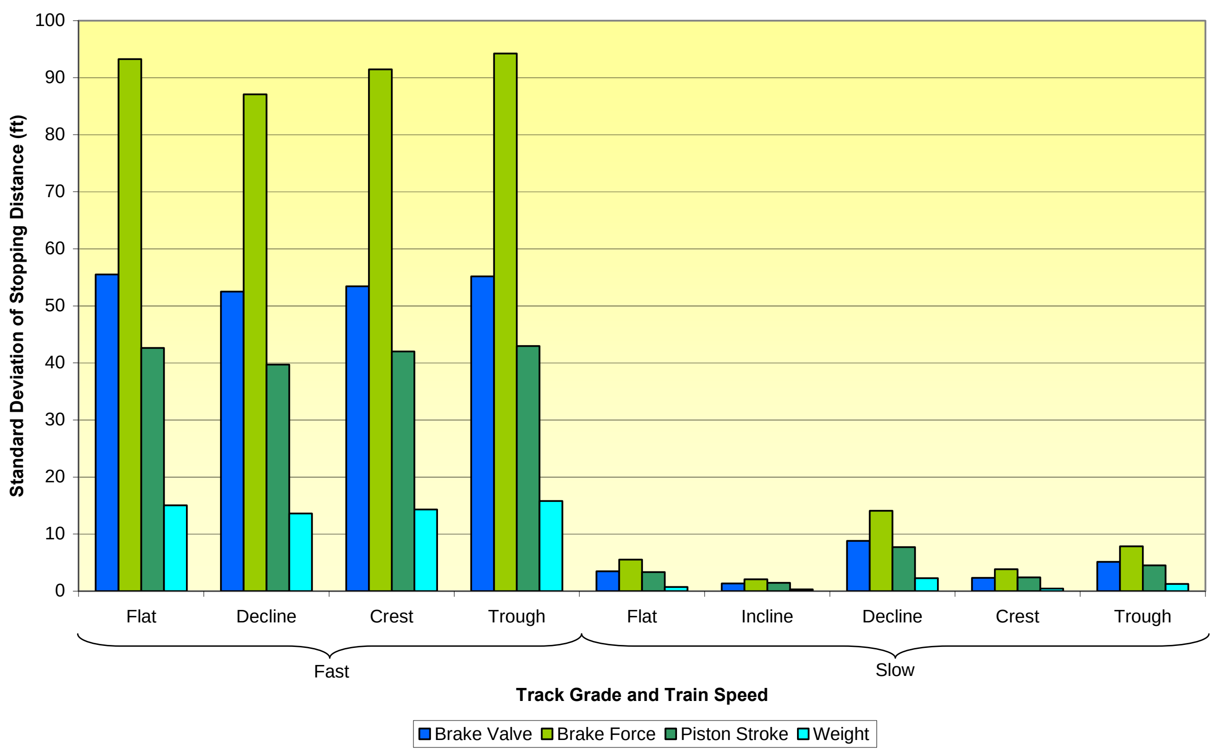

Standard Deviations of Stopping Distances for Loaded Unit Trains with Head End Power
120
100
80
60
40
20
0
Standard Deviation of Stopping Distance (ft)
Flat
Decline
Crest
Trough
Flat
Incline
Decline
Crest
Trough
Fast
Slow
Track Grade and Train Speed
Brake Valve
Brake Force
Piston Stroke
Weight


Standard Deviations of Stopping Distances for Empty Unit Trains with Head End Power
140
120
100
80
60
40
20
0
Standard Deviation of Stopping Distance (ft)
Flat
Decline
Crest
Trough
Flat
Incline
Decline
Crest
Trough
Fast
Slow
Track Grade and Train Speed
Brake Valve
Brake Force
Piston Stroke
Weight

Standard Deviations of Stopping Distances for Loaded Unit Trains with Distributed Power



Standard Deviations of Stopping Distances for Empty Unit Trains with Distributed Power



Appendix E.
Enforcement Algorithm Evaluation Simulation Test Matrix

Sim Set ID	Train Length	Train Load	Train Speed	Track Grade
0	Short	Loaded	Fast	Flat
1	Short	Loaded	Fast	1% Decline
2	Short	Loaded	Fast	0.5% Decline
3	Short	Loaded	Fast	Crest
4	Short	Loaded	Fast	Trough
5	Short	Loaded	Slow	Flat
6	Short	Loaded	Slow	1% Incline
7	Short	Loaded	Slow	1% Decline
8	Short	Loaded	Slow	0.5% Decline
9	Short	Loaded	Slow	Crest
10	Short	Loaded	Slow	Trough
11	Short	Empty Steel	Fast	Flat
12	Short	Empty Steel	Fast	1% Incline
13	Short	Empty Steel	Fast	1% Decline
14	Short	Empty Steel	Fast	0.5% Decline
15	Short	Empty Steel	Fast	Crest
16	Short	Empty Steel	Fast	Trough
17	Short	Empty Steel	Slow	Flat
18	Short	Empty Steel	Slow	1% Incline
19	Short	Empty Steel	Slow	1% Decline
20	Short	Empty Steel	Slow	0.5% Decline
21	Short	Empty Steel	Slow	Crest
22	Short	Empty Steel	Slow	Trough
23	Short	Empty Aluminum	Fast	Flat
24	Short	Empty Aluminum	Fast	1% Incline
25	Short	Empty Aluminum	Fast	1% Decline
26	Short	Empty Aluminum	Fast	0.5% Decline
27	Short	Empty Aluminum	Fast	Crest
28	Short	Empty Aluminum	Fast	Trough
29	Short	Empty Aluminum	Slow	Flat
30	Short	Empty Aluminum	Slow	1% Incline
31	Short	Empty Aluminum	Slow	1% Decline
32	Short	Empty Aluminum	Slow	0.5% Decline
33	Short	Empty Aluminum	Slow	Crest
34	Short	Empty Aluminum	Slow	Trough
35	Long	Loaded	Fast	Flat
36	Long	Loaded	Fast	1% Decline
37	Long	Loaded	Fast	0.5% Decline
38	Long	Loaded	Fast	Crest
39	Long	Loaded	Fast	Trough
40	Long	Loaded	Slow	Flat
41	Long	Loaded	Slow	1% Incline
42	Long	Loaded	Slow	1% Decline

Sim Set ID	Train Length	Train Load	Train Speed	Track Grade
43	Long	Loaded	Slow	0.5% Decline
44	Long	Loaded	Slow	Crest
45	Long	Loaded	Slow	Trough
46	Long	Empty Steel	Fast	Flat
47	Long	Empty Steel	Fast	1% Incline
48	Long	Empty Steel	Fast	1% Decline
49	Long	Empty Steel	Fast	0.5% Decline
50	Long	Empty Steel	Fast	Crest
51	Long	Empty Steel	Fast	Trough
52	Long	Empty Steel	Slow	Flat
53	Long	Empty Steel	Slow	1% Incline
54	Long	Empty Steel	Slow	1% Decline
55	Long	Empty Steel	Slow	0.5% Decline
56	Long	Empty Steel	Slow	Crest
57	Long	Empty Steel	Slow	Trough
58	Long	Empty Aluminum	Fast	Flat
59	Long	Empty Aluminum	Fast	1% Incline
60	Long	Empty Aluminum	Fast	1% Decline
61	Long	Empty Aluminum	Fast	0.5% Decline
62	Long	Empty Aluminum	Fast	Crest
63	Long	Empty Aluminum	Fast	Trough
64	Long	Empty Aluminum	Slow	Flat
65	Long	Empty Aluminum	Slow	1% Incline
66	Long	Empty Aluminum	Slow	1% Decline
67	Long	Empty Aluminum	Slow	0.5% Decline
68	Long	Empty Aluminum	Slow	Crest
69	Long	Empty Aluminum	Slow	Trough
T1	40-car	Loaded	40 mph	Flat
T2	40-car	Loaded	60 mph	Flat
T3	40-car	Loaded	40 mph	Incline
T4	40-car	Loaded	40 mph	Crest
T5	10-car	Loaded	40 mph	Flat
T6	75-car	Loaded	10 mph	Flat
T7	75-car	Loaded	40 mph	Decline

Appendix F.
Enforcement Algorithm Evaluation Simulation Probability Density Curves

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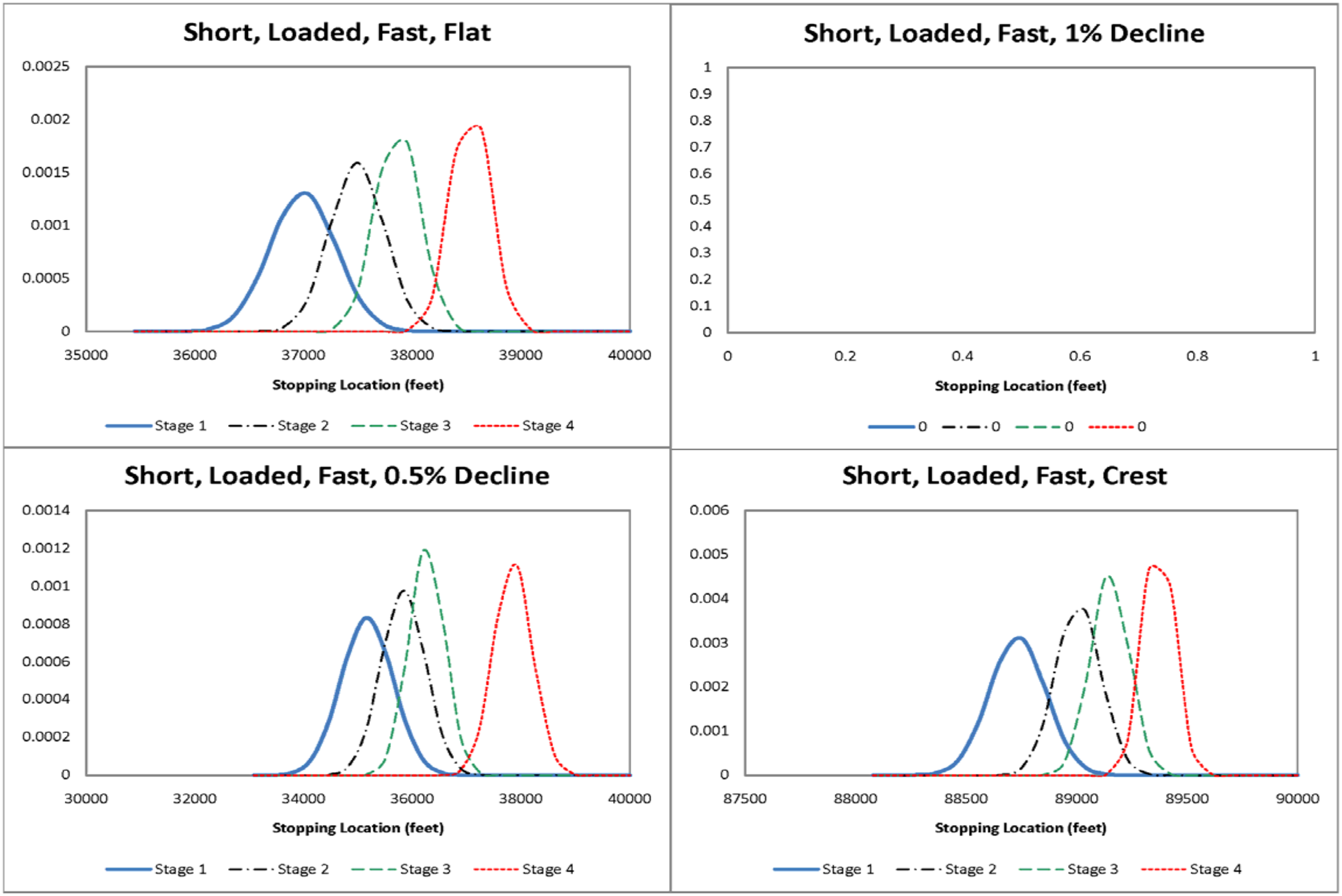
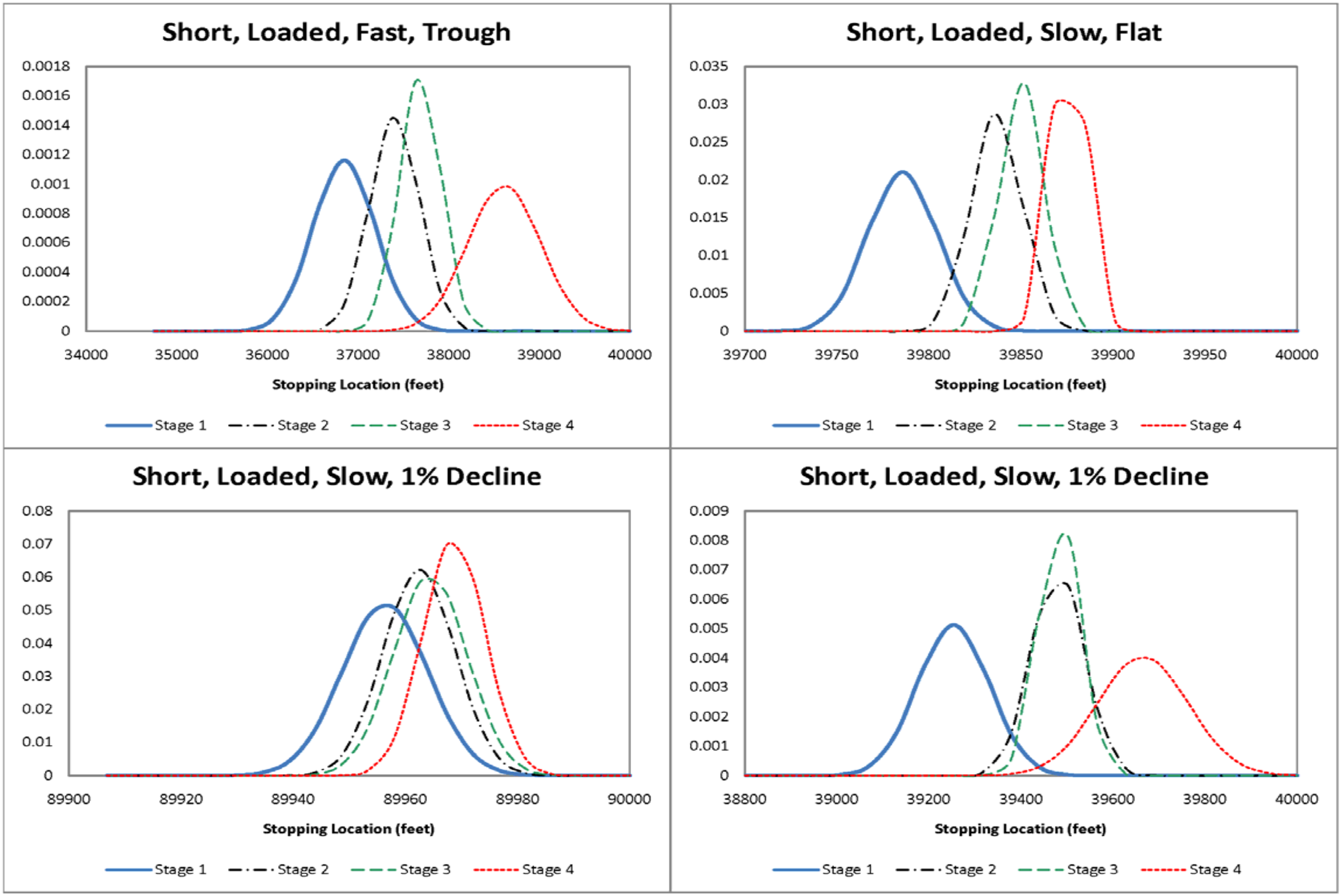
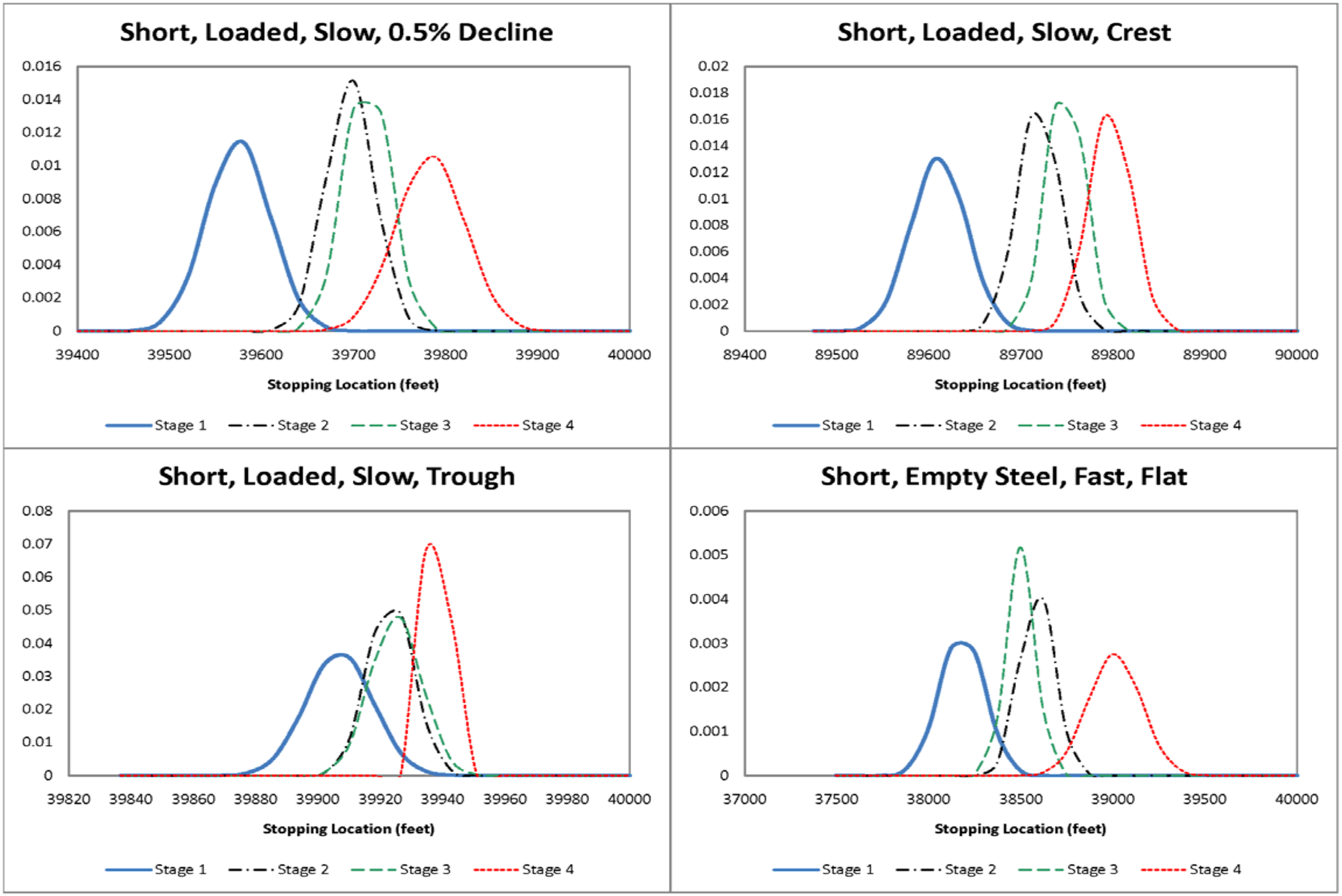
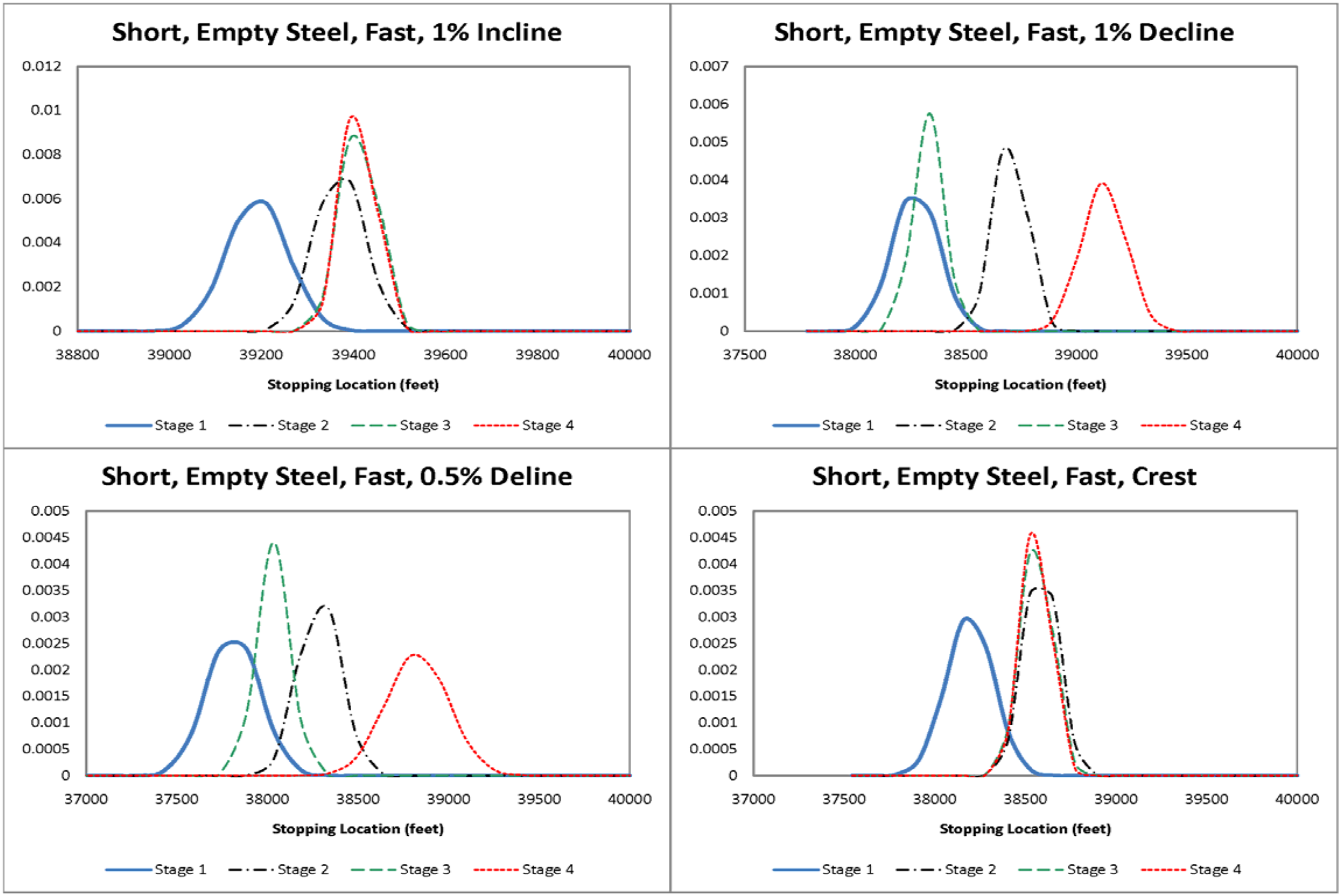
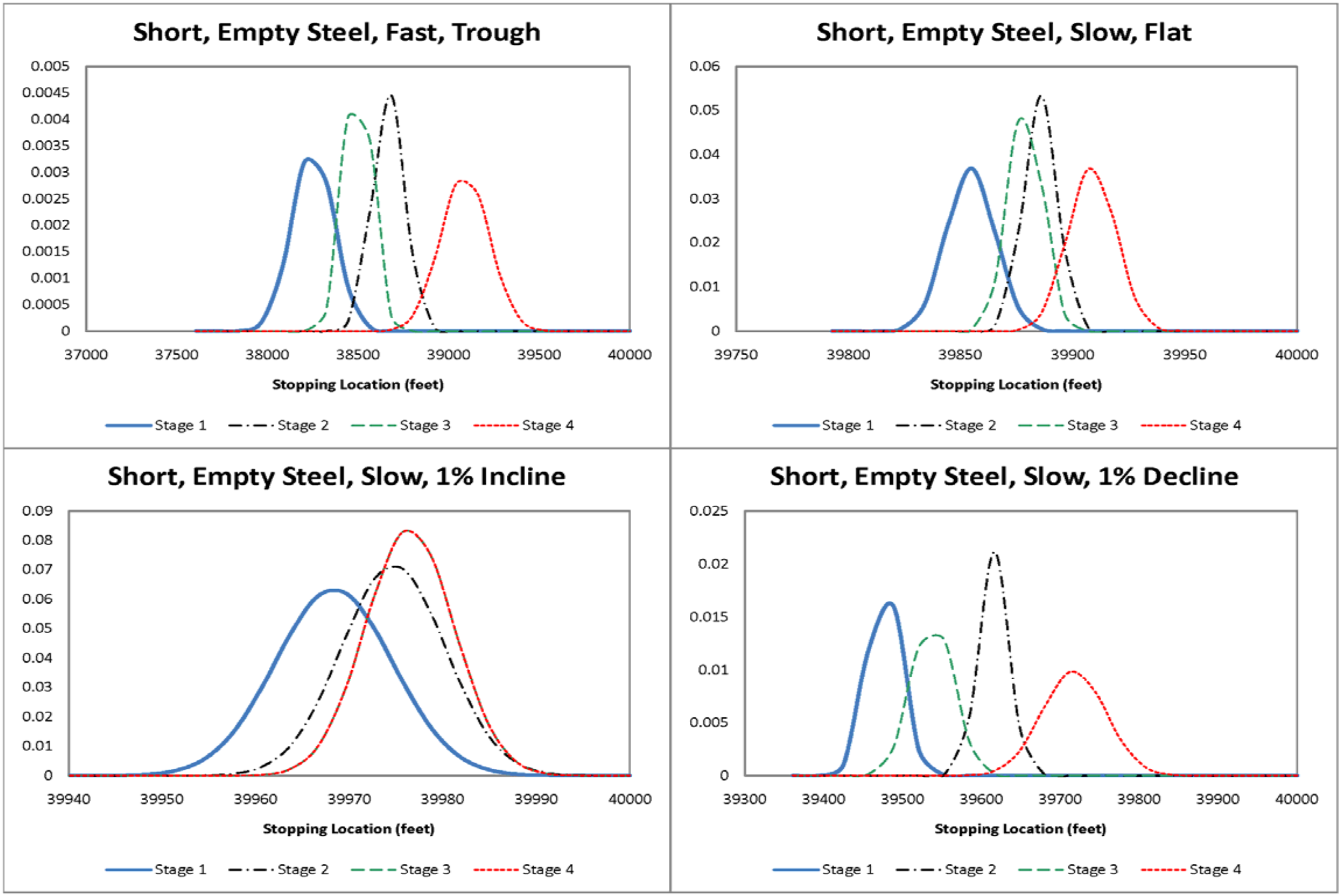
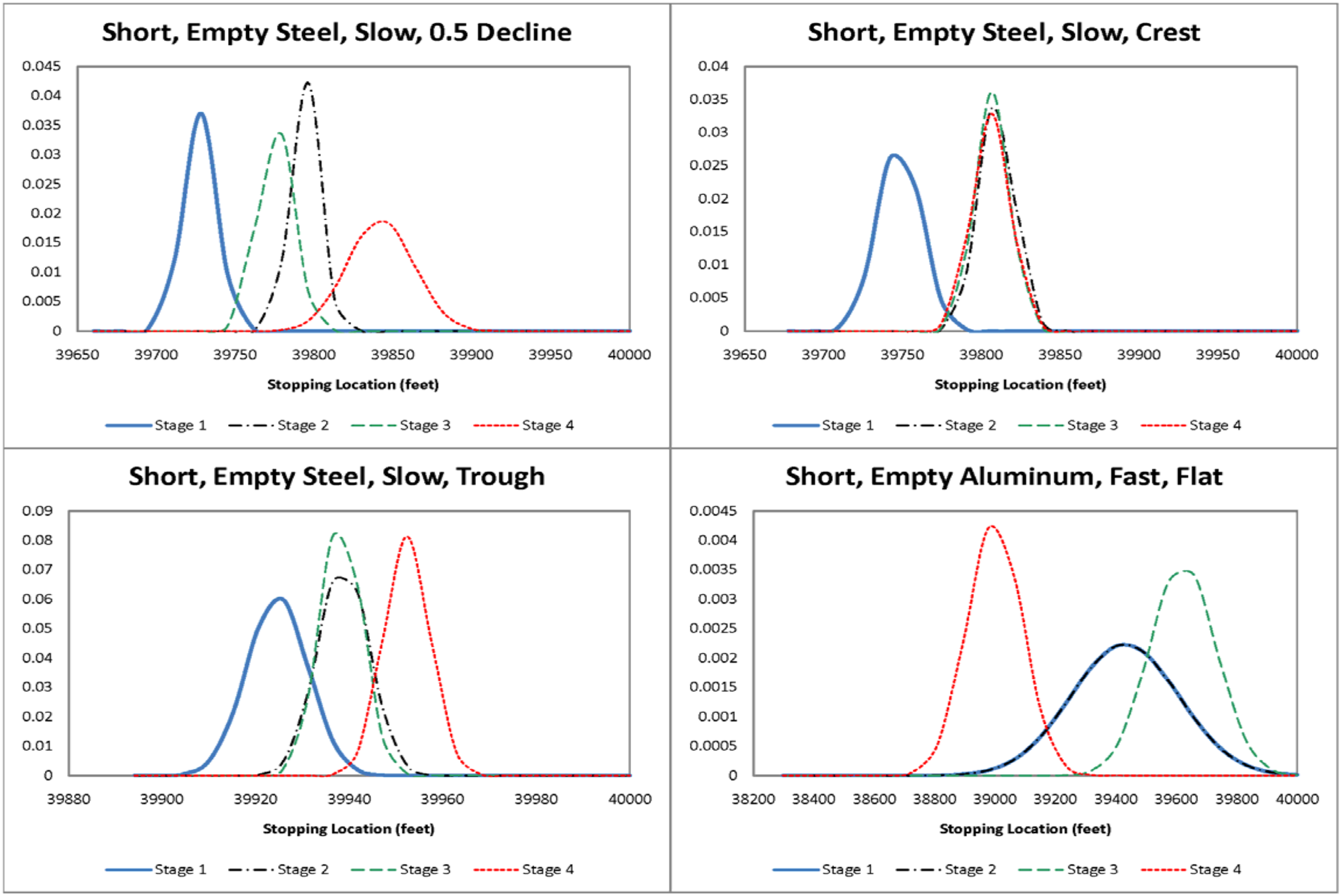

Short, Loaded, Fast, Flat
0.0025
0.002
0.0015
0.001
0.0005
0
35000
36000
37000
38000
39000
40000
Stopping Location (feet)
Stage 1
Stage 2
Stage 3
Stage 4
Short, Loaded, Fast, 1% Decline
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
0.2
0.4
0.6
0.8
1
Stopping Location (feet)
0
0
0
0
Short, Loaded, Fast, 0.5% Decline
0.0014
0.0012
0.001
0.0008
0.0006
0.0004
0.0002
0
30000
32000
34000
36000
38000
40000
Stopping Location (feet)
Stage 1
Stage 2
Stage 3
Stage 4
Short, Loaded, Fast, Crest
0.006
0.005
0.004
0.003
0.002
0.001
0
87500
88000
88500
89000
89500
90000
Stopping Location (feet)
Stage 1
Stage 2
Stage 3
Stage 4

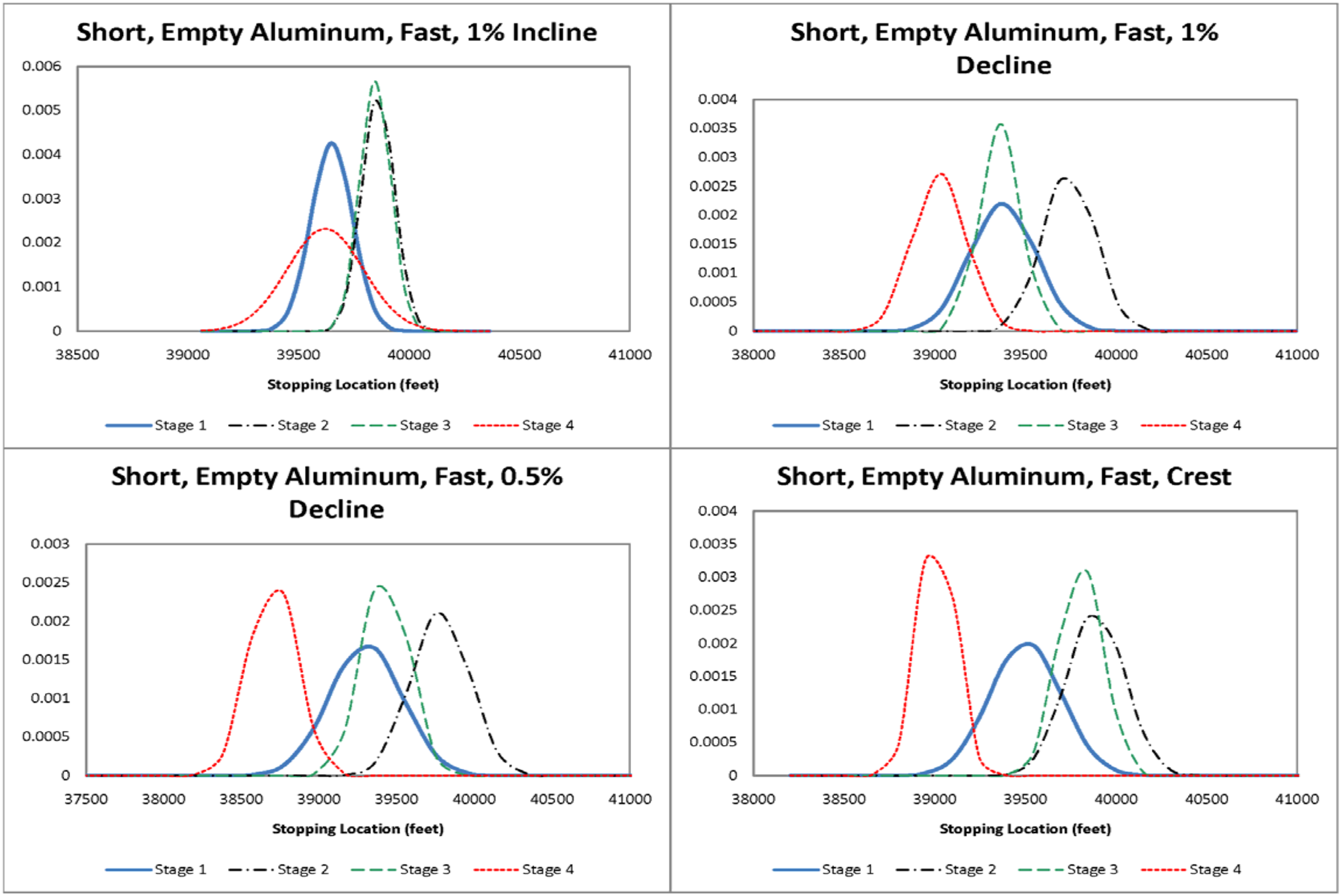

Short, Loaded, Fast, Trough
0.0018
0.0016
0.0014
0.0012
0.001
0.0008
0.0006
0.0004
0.0002
0
34000
35000
36000
37000
38000
39000
40000
Stopping Location (feet)
Stage 1
Stage 2
Stage 3
Stage 4
Short, Loaded, Slow, Flat
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
39700
39750
39800
39850
39900
39950
40000
Stopping Location (feet)
Stage 1
Stage 2
Stage 3
Stage 4
Short, Loaded, Slow, 1% Decline
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
89900
89920
89940
89960
89980
90000
Stopping Location (feet)
Stage 1
Stage 2
Stage 3
Stage 4
Short, Loaded, Slow, 1% Decline
0.009
0.008
0.007
0.006
0.005
0.004
0.003
0.002
0.001
0
38800
39000
39200
39400
39600
39800
40000
Stopping Location (feet)
Stage 1
Stage 2
Stage 3
Stage 4

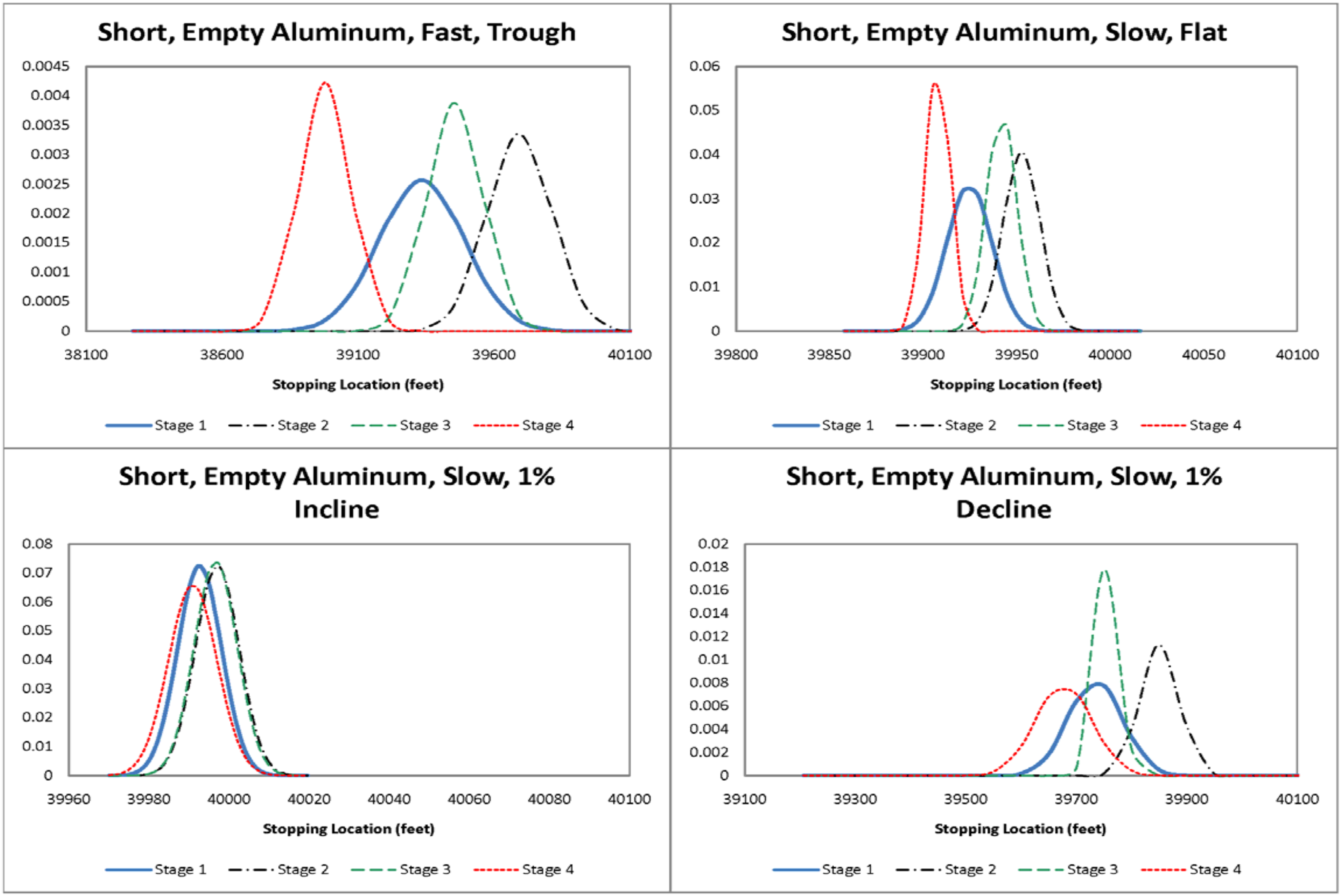

Short, Loaded, Slow, 0.5% Decline
0.016
0.014
0.012
0.01
0.008
0.006
0.004
0.002
0
39400
39500
39600
39700
39800
39900
40000
Stopping Location (feet)
Stage 1
Stage 2
Stage 3
Stage 4
Short, Loaded, Slow, Crest
0.02
0.018
0.016
0.014
0.012
0.01
0.008
0.006
0.004
0.002
0
89400
89500
89600
89700
89800
89900
90000
Stopping Location (feet)
Stage 1
Stage 2
Stage 3
Stage 4
Short, Loaded, Slow, Trough
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
39820
39840
39860
39880
39900
39920
39940
39960
39980
40000
Stopping Location (feet)
Stage 1
Stage 2
Stage 3
Stage 4
Short, Empty Steel, Fast, Flat
0.006
0.005
0.004
0.003
0.002
0.001
0
37000
37500
38000
38500
39000
39500
40000
Stopping Location (feet)
Stage 1
Stage 2
Stage 3
Stage 4


Short, Empty Steel, Fast, 1% Incline
Stopping Location (feet)
Stage 1
Stage 2
Stage 3
Stage 4
Short, Empty Steel, Fast, 1% Decline
Stopping Location (feet)
Stage 1
Stage 2
Stage 3
Stage 4
Short, Empty Steel, Fast, 0.5% Deline
Stopping Location (feet)
Stage 1
Stage 2
Stage 3
Stage 4
Short, Empty Steel, Fast, Crest
Stopping Location (feet)
Stage 1
Stage 2
Stage 3
Stage 4

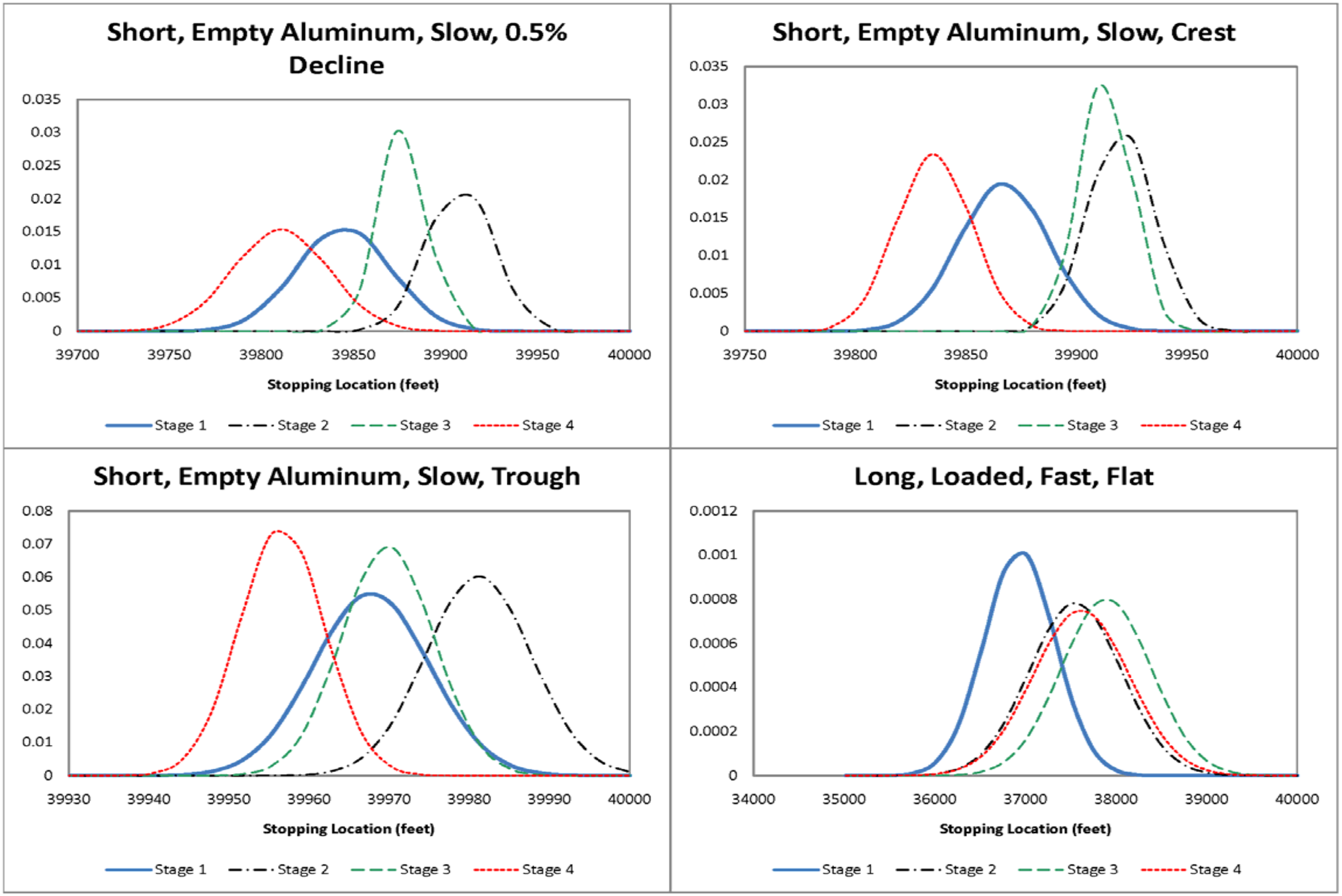

Short, Empty Steel, Fast, Trough
0.005
0.0045
0.004
0.0035
0.003
0.0025
0.002
0.0015
0.001
0.0005
0
37000
37500
38000
38500
39000
39500
40000
Stopping Location (feet)
Stage 1
Stage 2
Stage 3
Stage 4
Short, Empty Steel, Slow, Flat
0.06
0.05
0.04
0.03
0.02
0.01
0
39750
39800
39850
39900
39950
40000
Stopping Location (feet)
Stage 1
Stage 2
Stage 3
Stage 4
Short, Empty Steel, Slow, 1% Incline
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
39940
39950
39960
39970
39980
39990
40000
Stopping Location (feet)
Stage 1
Stage 2
Stage 3
Stage 4
Short, Empty Steel, Slow, 1% Decline
0.025
0.02
0.015
0.01
0.005
0
39300
39400
39500
39600
39700
39800
39900
40000
Stopping Location (feet)
Stage 1
Stage 2
Stage 3
Stage 4

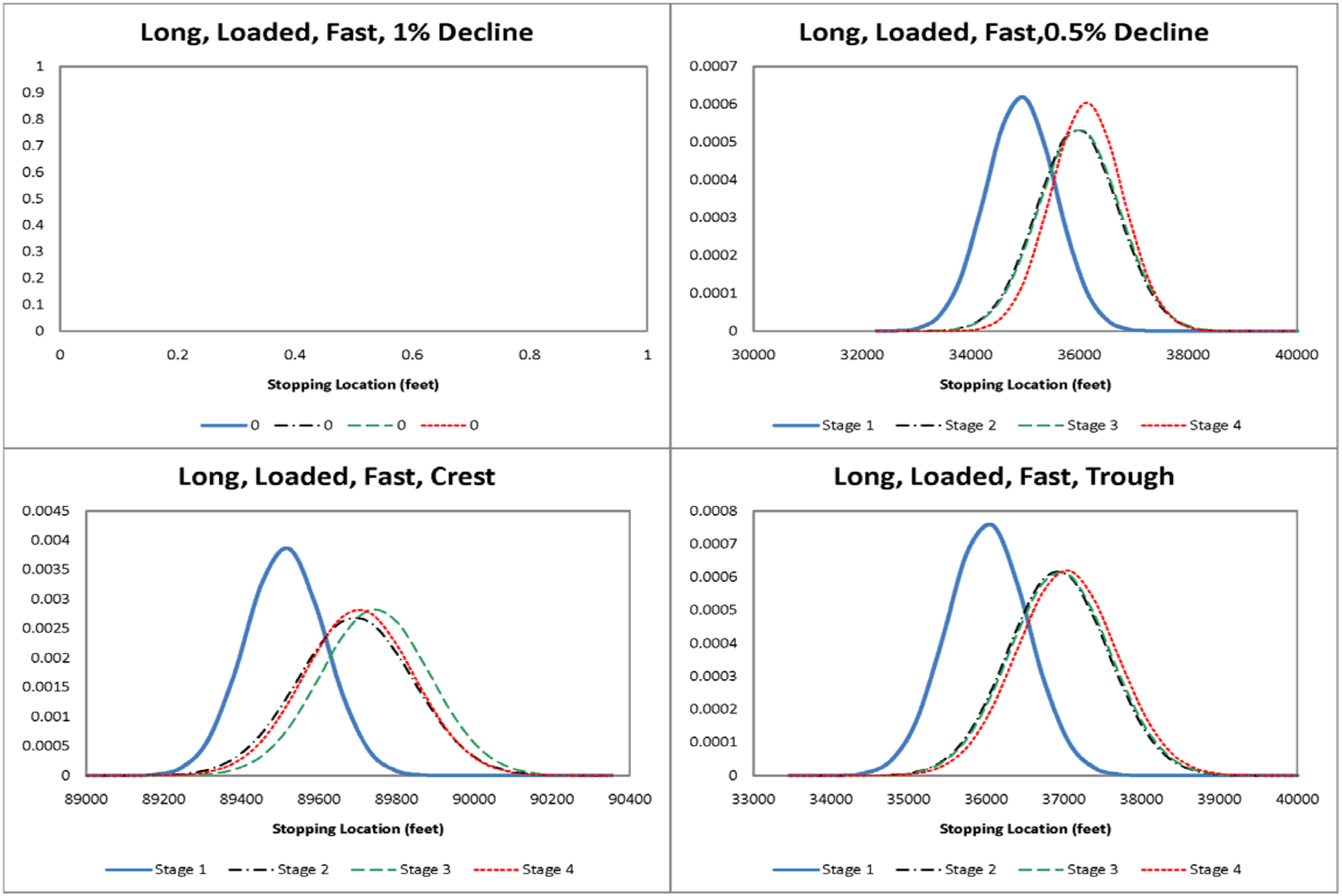

Short, Empty Steel, Slow, 0.5 Decline
0.045
0.04
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
39650 39700 39750 39800 39850 39900 39950 40000
Stopping Location (feet)
Stage 1 Stage 2 Stage 3 Stage 4
Short, Empty Steel, Slow, Crest
0.04
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
39650 39700 39750 39800 39850 39900 39950 40000
Stopping Location (feet)
Stage 1 Stage 2 Stage 3 Stage 4
Short, Empty Steel, Slow, Trough
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
39880 39900 39920 39940 39960 39980 40000
Stopping Location (feet)
Stage 1 Stage 2 Stage 3 Stage 4
Short, Empty Aluminum, Fast, Flat
0.0045
0.004
0.0035
0.003
0.0025
0.002
0.0015
0.001
0.0005
0
38200 38400 38600 38800 39000 39200 39400 39600 39800 40000
Stopping Location (feet)
Stage 1 Stage 2 Stage 3 Stage 4

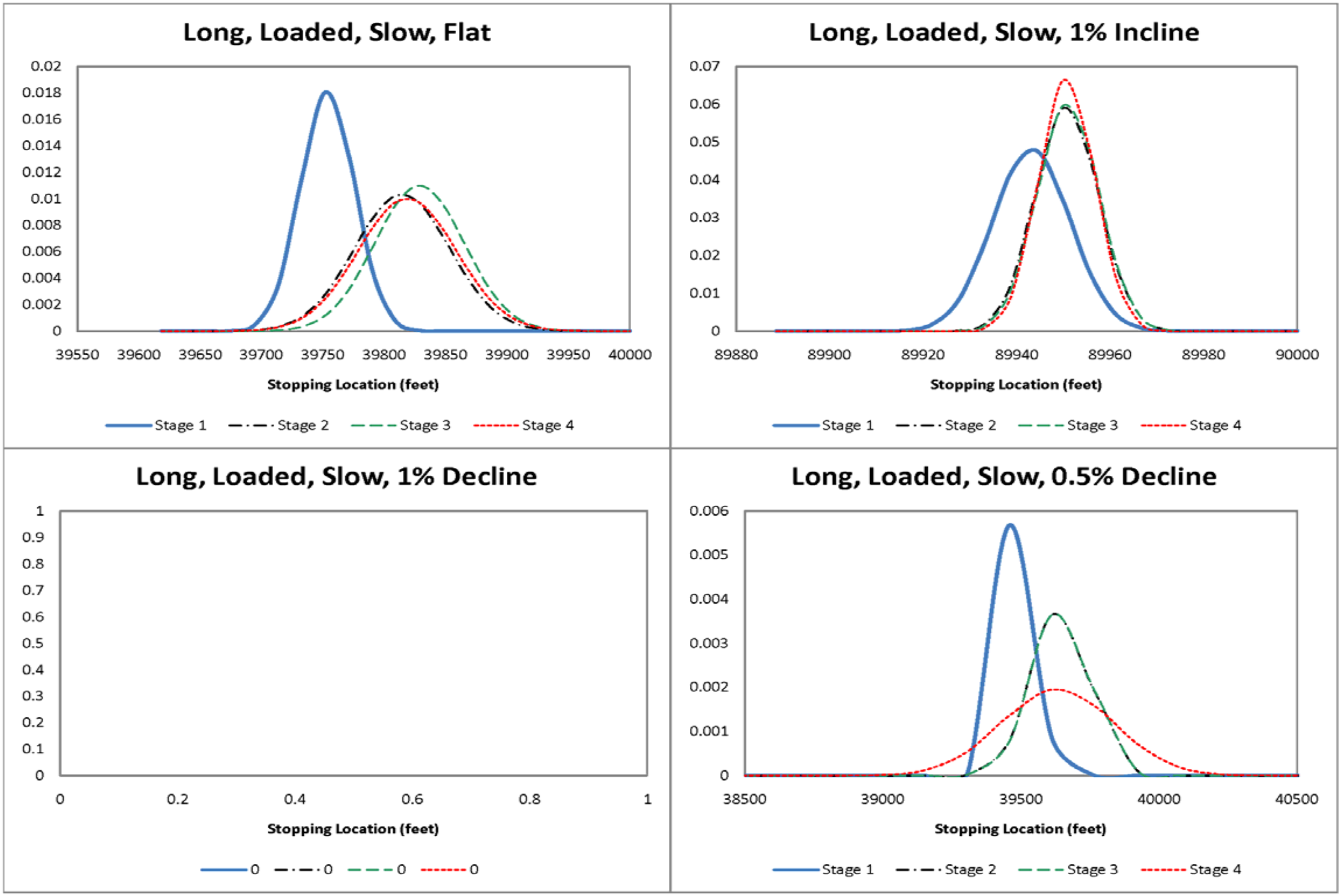

Short, Empty Aluminum, Fast, 1% Incline
0.006
0.005
0.004
0.003
0.002
0.001
0
38500
39000
39500
40000
40500
41000
Stopping Location (feet)
Stage 1
Stage 2
Stage 3
Stage 4
Short, Empty Aluminum, Fast, 1% Decline
0.004
0.0035
0.003
0.0025
0.002
0.0015
0.001
0.0005
0
38000
38500
39000
39500
40000
40500
41000
Stopping Location (feet)
Stage 1
Stage 2
Stage 3
Stage 4
Short, Empty Aluminum, Fast, 0.5% Decline
0.003
0.0025
0.002
0.0015
0.001
0.0005
0
37500
38000
38500
39000
39500
40000
40500
41000
Stopping Location (feet)
Stage 1
Stage 2
Stage 3
Stage 4
Short, Empty Aluminum, Fast, Crest
0.004
0.0035
0.003
0.0025
0.002
0.0015
0.001
0.0005
0
38000
38500
39000
39500
40000
40500
41000
Stopping Location (feet)
Stage 1
Stage 2
Stage 3
Stage 4

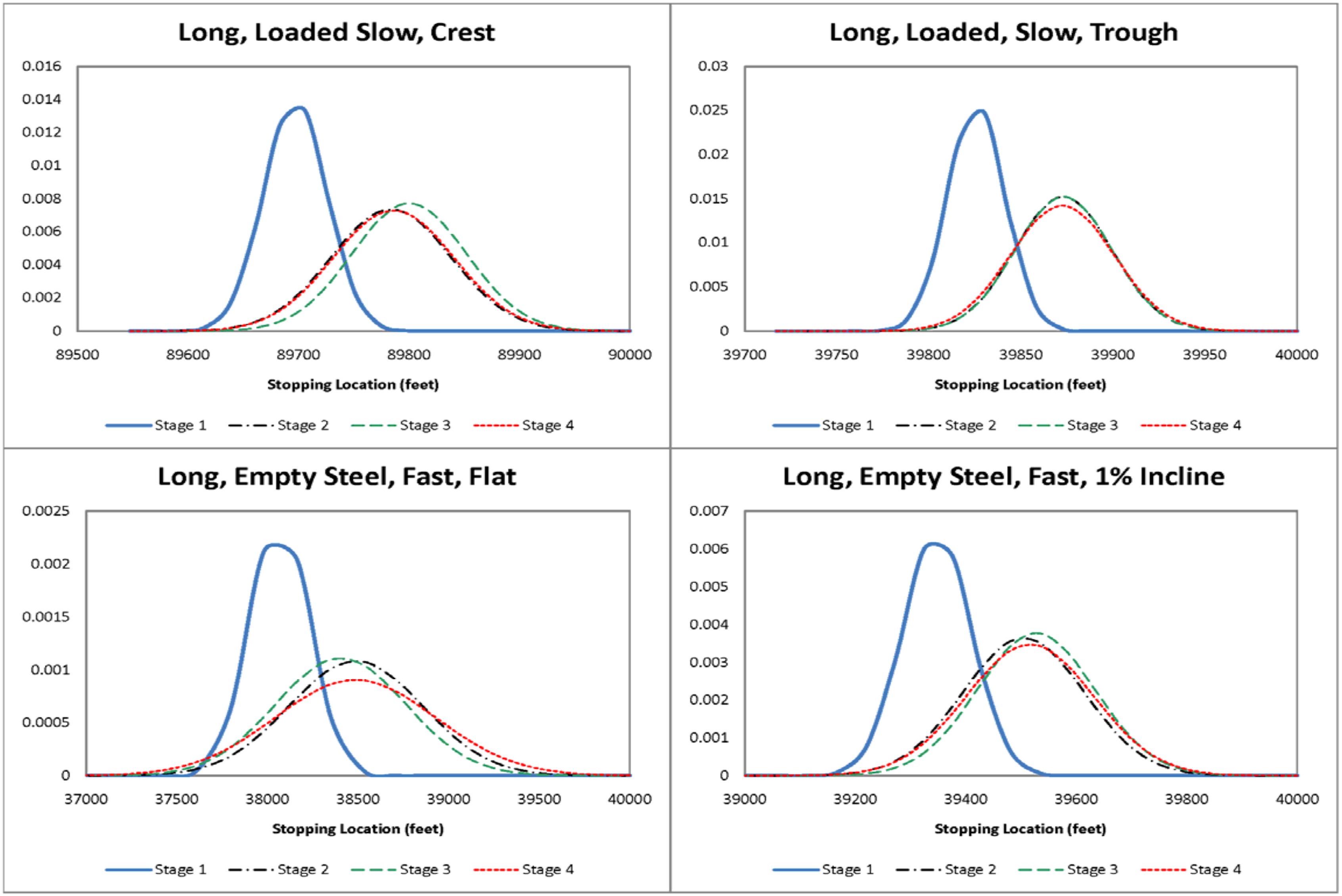


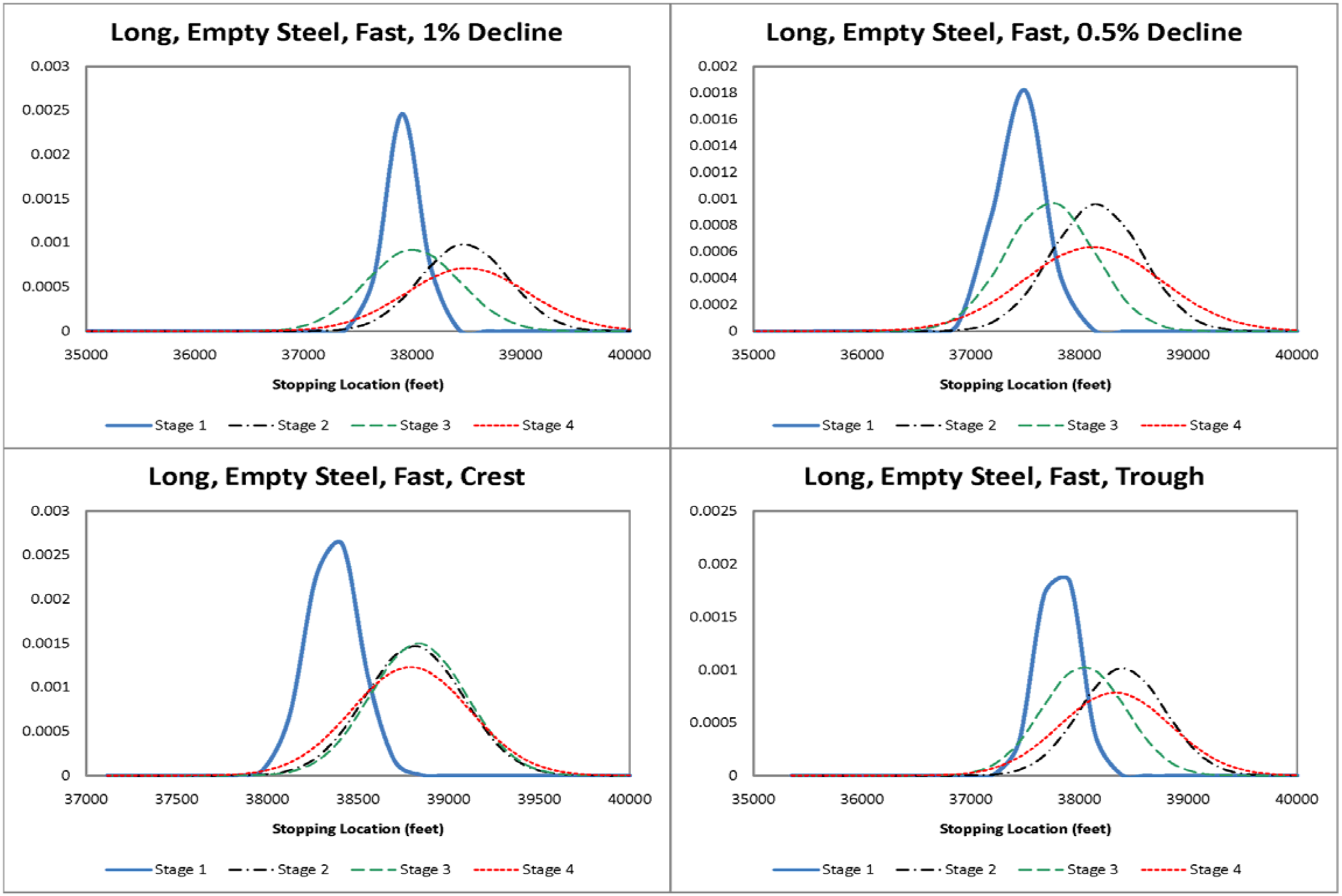
Short, Empty Aluminum, Fast, Trough
0.0045
0.004
0.0035
0.003
0.0025
0.002
0.0015
0.001
0.0005
0
38100
38600
39100
39600
40100
Stopping Location (feet)
Stage 1
Stage 2
Stage 3
Stage 4
Short, Empty Aluminum, Slow, Flat
0.06
0.05
0.04
0.03
0.02
0.01
0
39800
39850
39900
39950
40000
40050
40100
Stopping Location (feet)
Stage 1
Stage 2
Stage 3
Stage 4
Short, Empty Aluminum, Slow, 1% Incline
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
39960
39980
40000
40020
40040
40060
40080
40100
Stopping Location (feet)
Stage 1
Stage 2
Stage 3
Stage 4
Short, Empty Aluminum, Slow, 1% Decline
0.02
0.018
0.016
0.014
0.012
0.01
0.008
0.006
0.004
0.002
0
39100
39300
39500
39700
39900
40100
Stopping Location (feet)
Stage 1
Stage 2
Stage 3
Stage 4


Short, Empty Aluminum, Slow, 0.5% Decline
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
39700
39750
39800
39850
39900
39950
40000
Stopping Location (feet)
Stage 1
Stage 2
Stage 3
Stage 4
Short, Empty Aluminum, Slow, Crest
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
39750
39800
39850
39900
39950
40000
Stopping Location (feet)
Stage 1
Stage 2
Stage 3
Stage 4
Short, Empty Aluminum, Slow, Trough
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
39930
39940
39950
39960
39970
39980
39990
40000
Stopping Location (feet)
Stage 1
Stage 2
Stage 3
Stage 4
Long, Loaded, Fast, Flat
0.0012
0.001
0.0008
0.0006
0.0004
0.0002
0
34000
35000
36000
37000
38000
39000
40000
Stopping Location (feet)
Stage 1
Stage 2
Stage 3
Stage 4

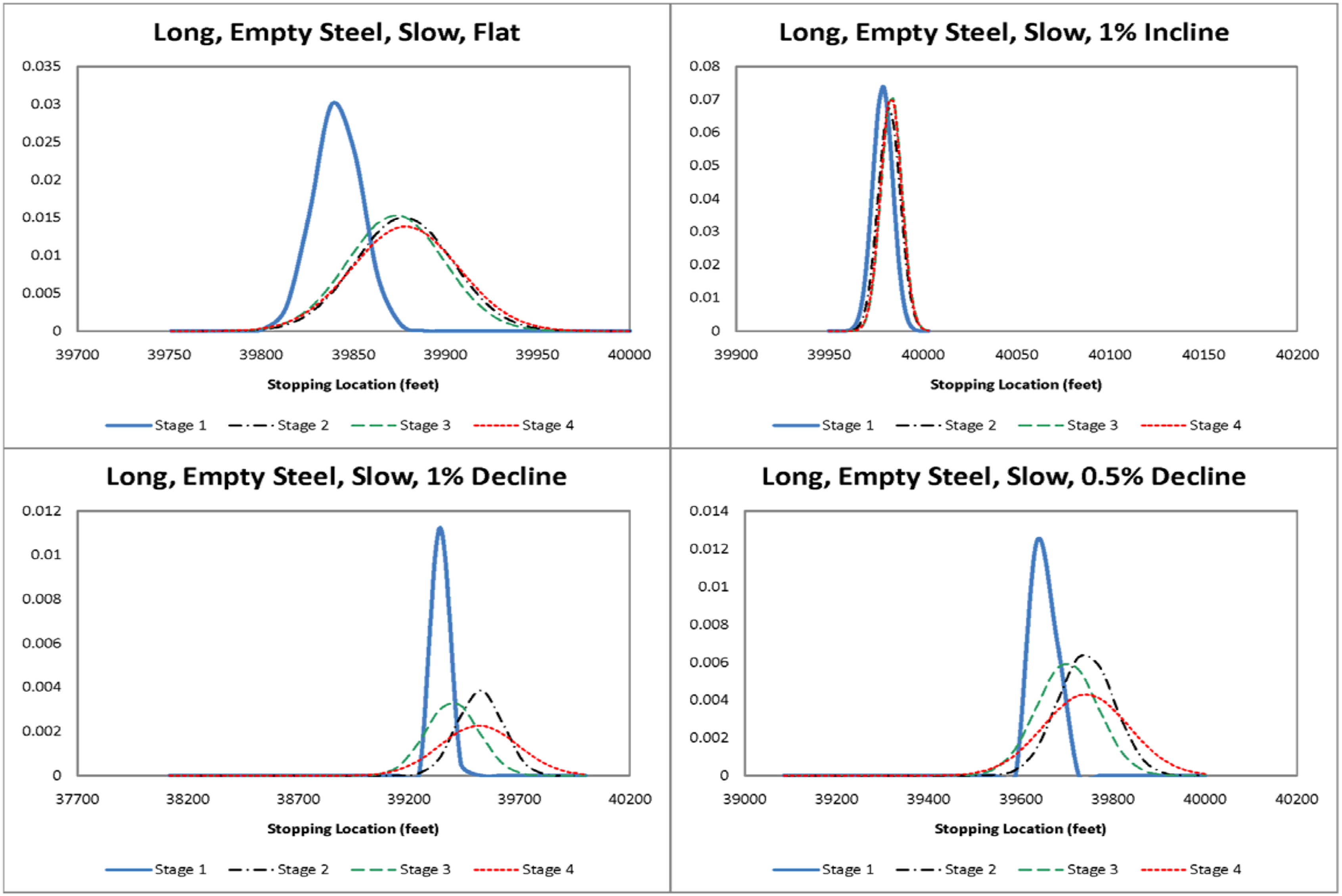

Long, Loaded, Fast, 1% Decline
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
0.2
0.4
0.6
0.8
1
Stopping Location (feet)
0 0 0 0
Long, Loaded, Fast,0.5% Decline
0.0007
0.0006
0.0005
0.0004
0.0003
0.0002
0.0001
0
30000
32000
34000
36000
38000
40000
Stopping Location (feet)
Stage 1 Stage 2 Stage 3 Stage 4
Long, Loaded, Fast, Crest
0.0045
0.004
0.0035
0.003
0.0025
0.002
0.0015
0.001
0.0005
0
89000
89200
89400
89600
89800
90000
90200
90400
Stopping Location (feet)
Stage 1 Stage 2 Stage 3 Stage 4
Long, Loaded, Fast, Trough
0.0008
0.0007
0.0006
0.0005
0.0004
0.0003
0.0002
0.0001
0
33000
34000
35000
36000
37000
38000
39000
40000
Stopping Location (feet)
Stage 1 Stage 2 Stage 3 Stage 4


Long, Loaded, Slow, Flat
0.02
0.018
0.016
0.014
0.012
0.01
0.008
0.006
0.004
0.002
0
39550
39600
39650
39700
39750
39800
39850
39900
39950
40000
Stopping Location (feet)
Stage 1
Stage 2
Stage 3
Stage 4
Long, Loaded, Slow, 1% Incline
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
89880
89900
89920
89940
89960
89980
90000
Stopping Location (feet)
Stage 1
Stage 2
Stage 3
Stage 4
Long, Loaded, Slow, 1% Decline
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
0.2
0.4
0.6
0.8
1
Stopping Location (feet)
0
0
0
0
Long, Loaded, Slow, 0.5% Decline
0.006
0.005
0.004
0.003
0.002
0.001
0
38500
39000
39500
40000
40500
Stopping Location (feet)
Stage 1
Stage 2
Stage 3
Stage 4

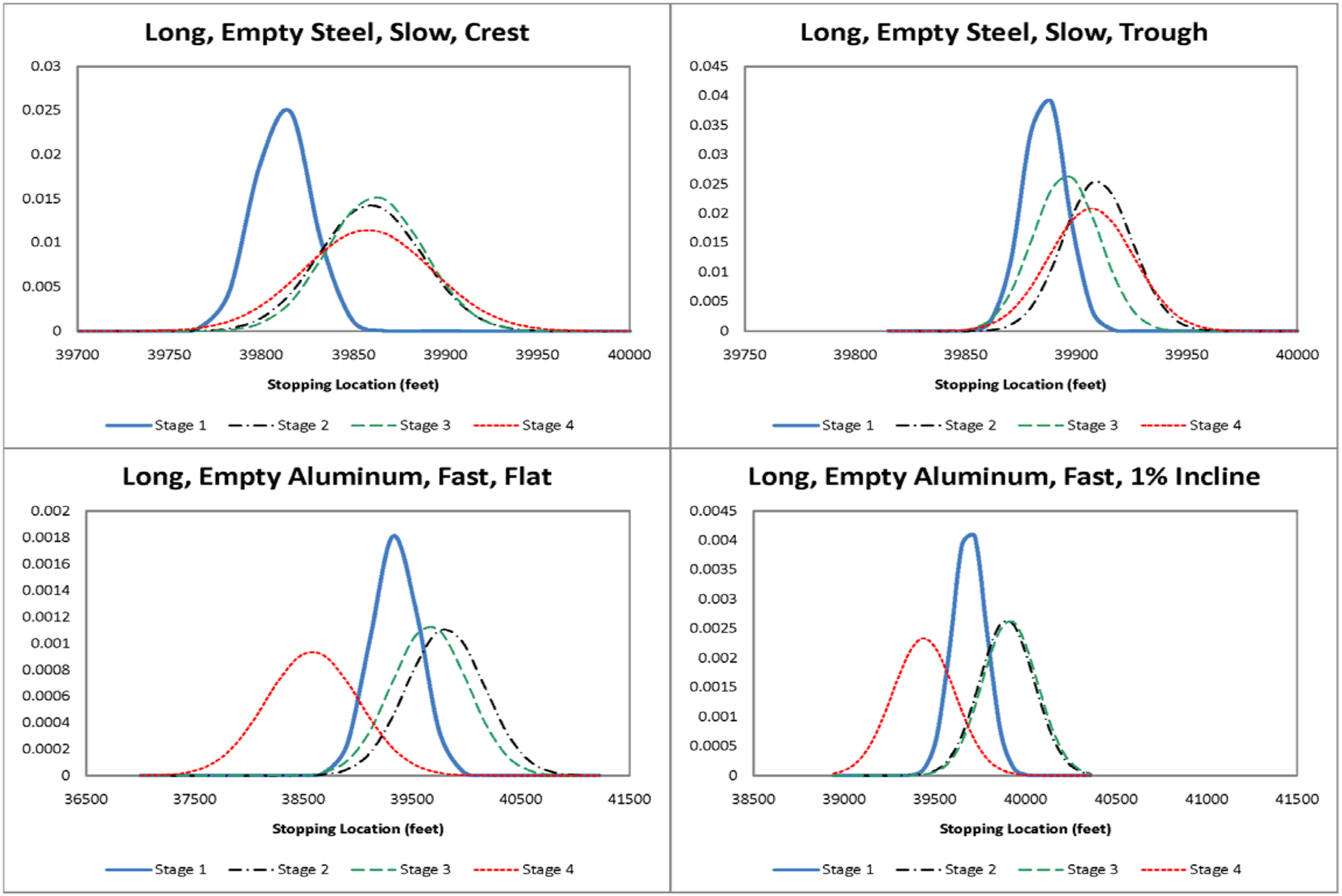

Long, Loaded Slow, Crest
0.016
0.014
0.012
0.01
0.008
0.006
0.004
0.002
0
89500
89600
89700
89800
89900
90000
Stopping Location (feet)
Stage 1
Stage 2
Stage 3
Stage 4
Long, Loaded, Slow, Trough
0.03
0.025
0.02
0.015
0.01
0.005
0
39700
39750
39800
39850
39900
39950
40000
Stopping Location (feet)
Stage 1
Stage 2
Stage 3
Stage 4
Long, Empty Steel, Fast, Flat
0.0025
0.002
0.0015
0.001
0.0005
0
37000
37500
38000
38500
39000
39500
40000
Stopping Location (feet)
Stage 1
Stage 2
Stage 3
Stage 4
Long, Empty Steel, Fast, 1% Incline
0.007
0.006
0.005
0.004
0.003
0.002
0.001
0
39000
39200
39400
39600
39800
40000
Stopping Location (feet)
Stage 1
Stage 2
Stage 3
Stage 4

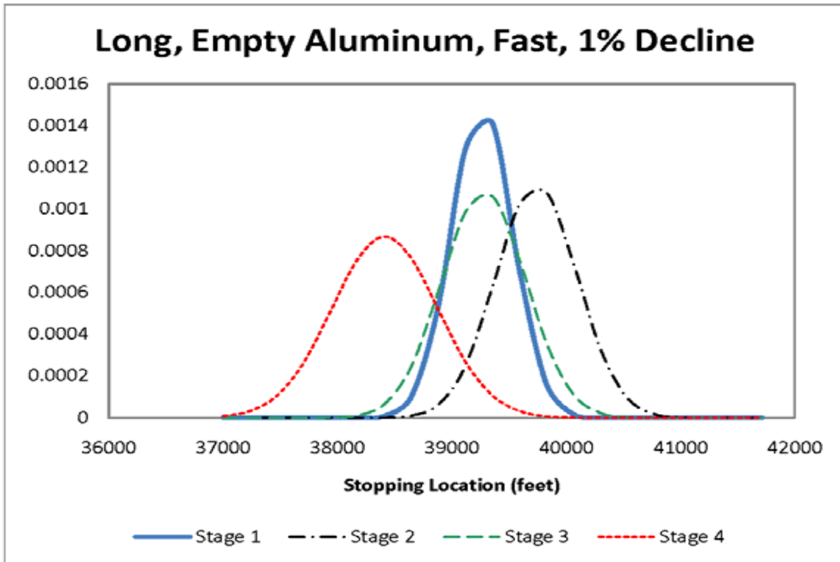


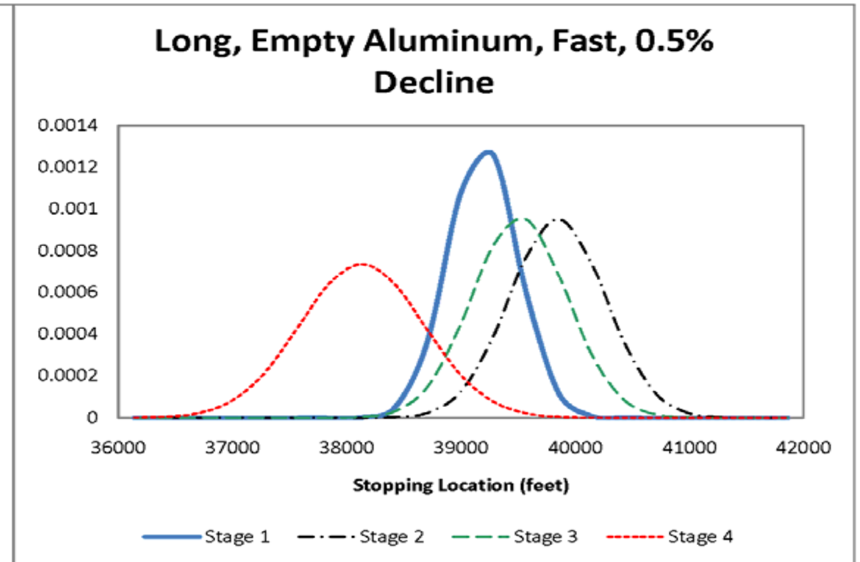
Long, Empty Steel, Fast, 1% Decline
0.003
0.0025
0.002
0.0015
0.001
0.0005
0
35000
36000
37000
38000
39000
40000
Stopping Location (feet)
Stage 1
Stage 2
Stage 3
Stage 4
Long, Empty Steel, Fast, 0.5% Decline
0.002
0.0018
0.0016
0.0014
0.0012
0.001
0.0008
0.0006
0.0004
0.0002
0
35000
36000
37000
38000
39000
40000
Stopping Location (feet)
Stage 1
Stage 2
Stage 3
Stage 4
Long, Empty Steel, Fast, Crest
0.003
0.0025
0.002
0.0015
0.001
0.0005
0
37000
37500
38000
38500
39000
39500
40000
Stopping Location (feet)
Stage 1
Stage 2
Stage 3
Stage 4
Long, Empty Steel, Fast, Trough
0.0025
0.002
0.0015
0.001
0.0005
0
35000
36000
37000
38000
39000
40000
Stopping Location (feet)
Stage 1
Stage 2
Stage 3
Stage 4

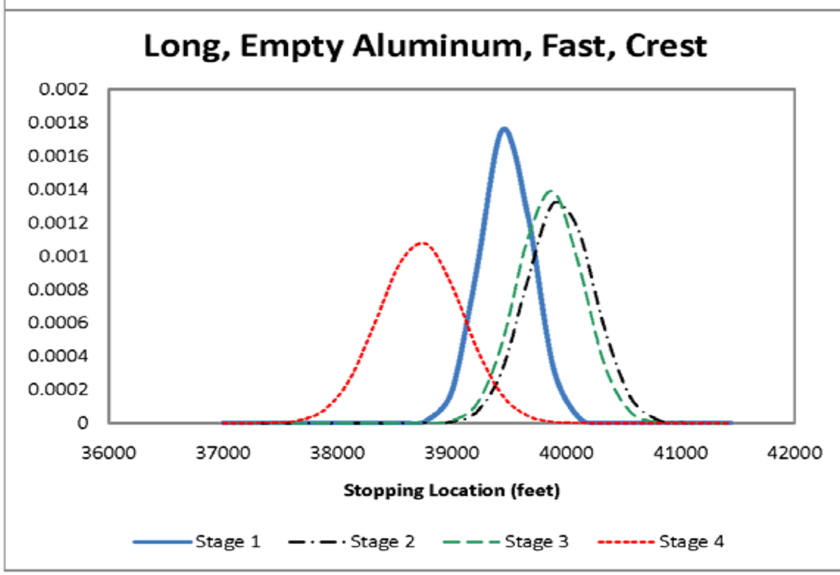


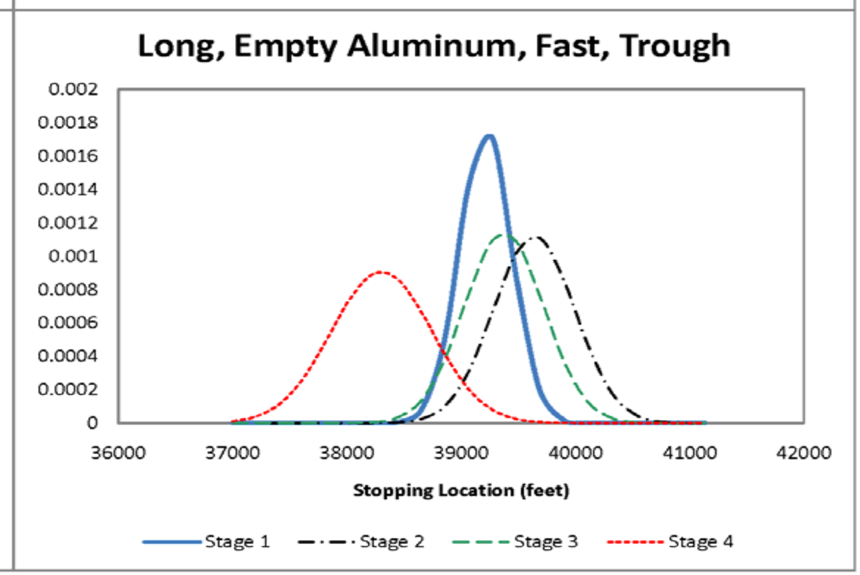
Long, Empty Steel, Slow, Flat
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
39700
39750
39800
39850
39900
39950
40000
Stopping Location (feet)
Stage 1
Stage 2
Stage 3
Stage 4
Long, Empty Steel, Slow, 1% Incline
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
39900
39950
40000
40050
40100
40150
40200
Stopping Location (feet)
Stage 1
Stage 2
Stage 3
Stage 4
Long, Empty Steel, Slow, 1% Decline
0.012
0.01
0.008
0.006
0.004
0.002
0
37700
38200
38700
39200
39700
40200
Stopping Location (feet)
Stage 1
Stage 2
Stage 3
Stage 4
Long, Empty Steel, Slow, 0.5% Decline
0.014
0.012
0.01
0.008
0.006
0.004
0.002
0
39000
39200
39400
39600
39800
40000
40200
Stopping Location (feet)
Stage 1
Stage 2
Stage 3
Stage 4

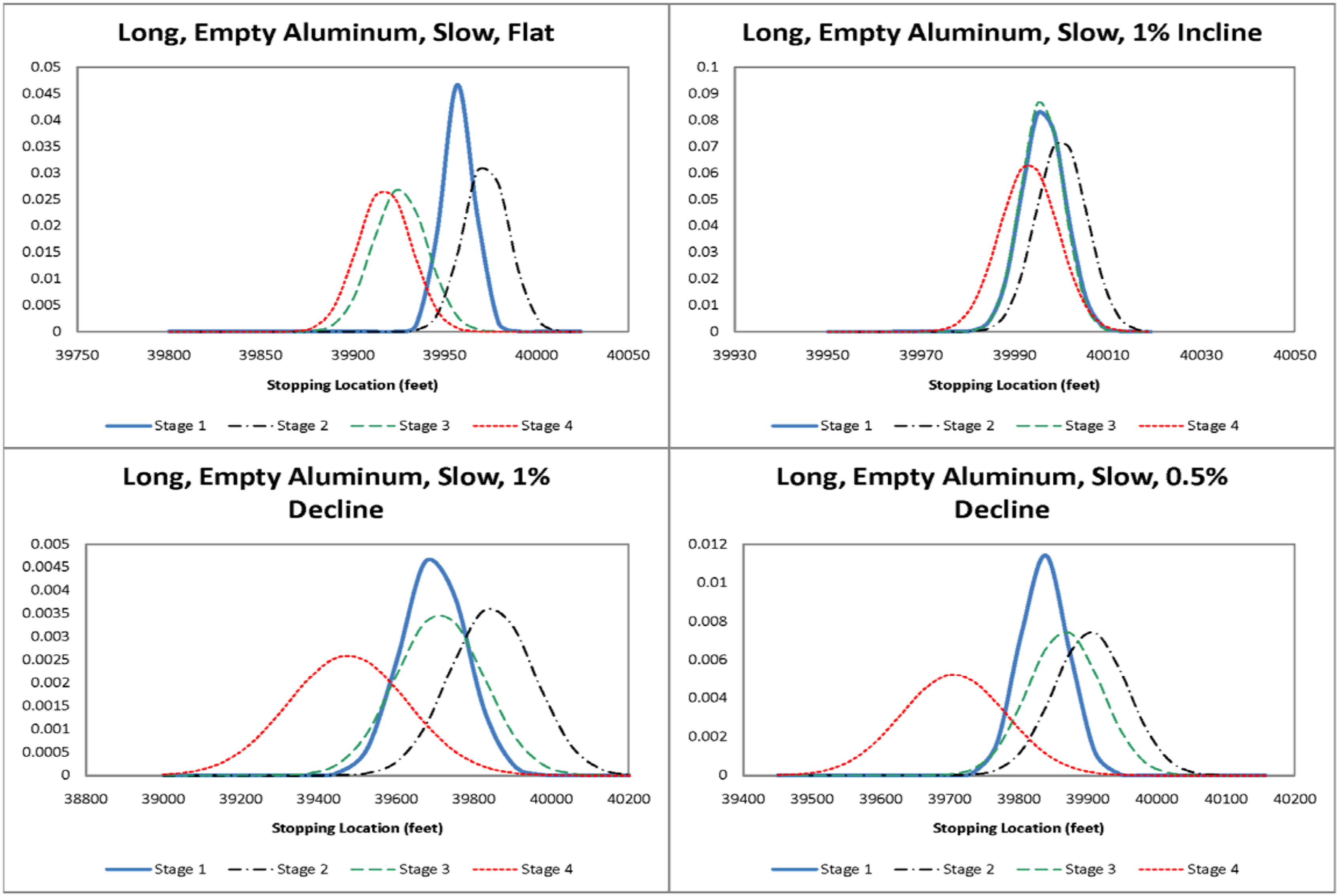

Long, Empty Steel, Slow, Crest
0.03
0.025
0.02
0.015
0.01
0.005
0
39700
39750
39800
39850
39900
39950
40000
Stopping Location (feet)
Stage 1
Stage 2
Stage 3
Stage 4
Long, Empty Steel, Slow, Trough
0.045
0.04
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
39750
39800
39850
39900
39950
40000
Stopping Location (feet)
Stage 1
Stage 2
Stage 3
Stage 4
Long, Empty Aluminum, Fast, Flat
0.002
0.0018
0.0016
0.0014
0.0012
0.001
0.0008
0.0006
0.0004
0.0002
0
36500
37500
38500
39500
40500
41500
Stopping Location (feet)
Stage 1
Stage 2
Stage 3
Stage 4
Long, Empty Aluminum, Fast, 1% Incline
0.0045
0.004
0.0035
0.003
0.0025
0.002
0.0015
0.001
0.0005
0
38500
39000
39500
40000
40500
41000
41500
Stopping Location (feet)
Stage 1
Stage 2
Stage 3
Stage 4

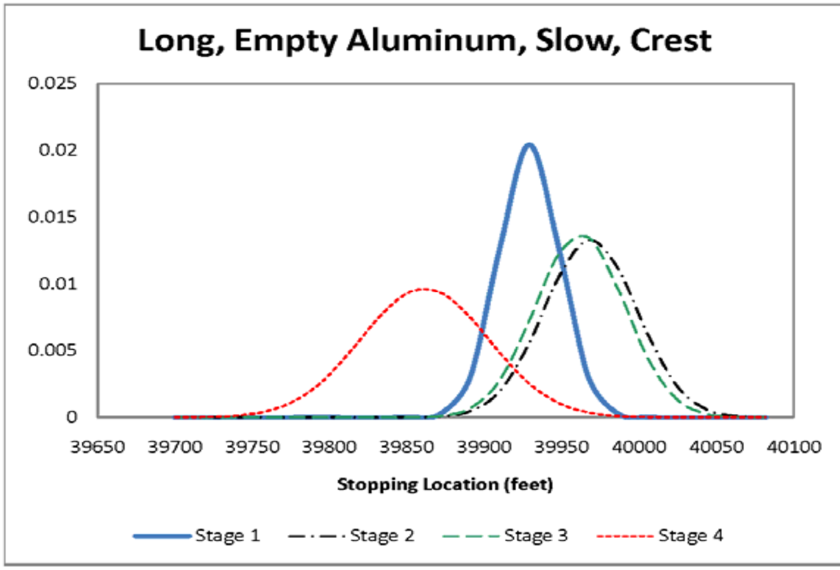

Long, Empty Aluminum, Fast, 1% Decline
0.0016
0.0014
0.0012
0.001
0.0008
0.0006
0.0004
0.0002
0
36000
37000
38000
39000
40000
41000
42000
Stopping Location (feet)
Stage 1
Stage 2
Stage 3
Stage 4

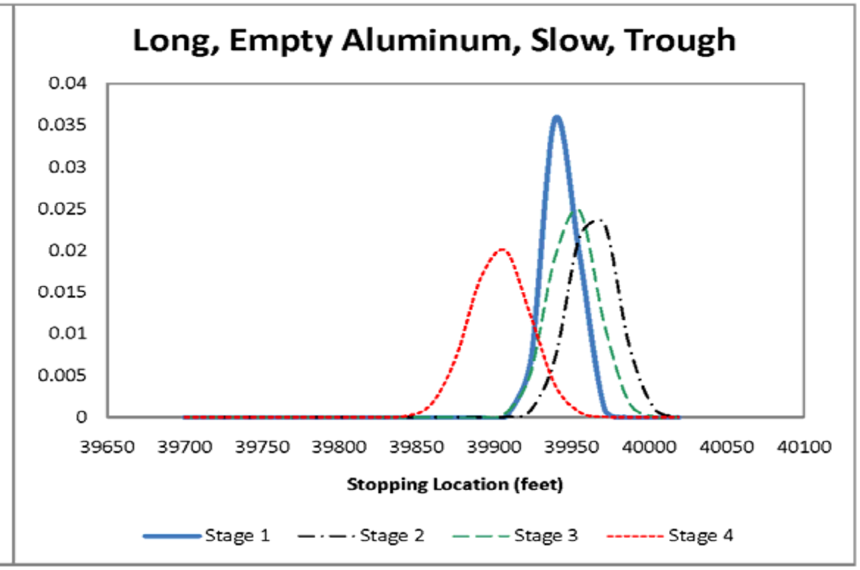

Long, Empty Aluminum, Fast, 0.5% Decline
0.0014
0.0012
0.001
0.0008
0.0006
0.0004
0.0002
0
36000
37000
38000
39000
40000
41000
42000
Stopping Location (feet)
Stage 1
Stage 2
Stage 3
Stage 4

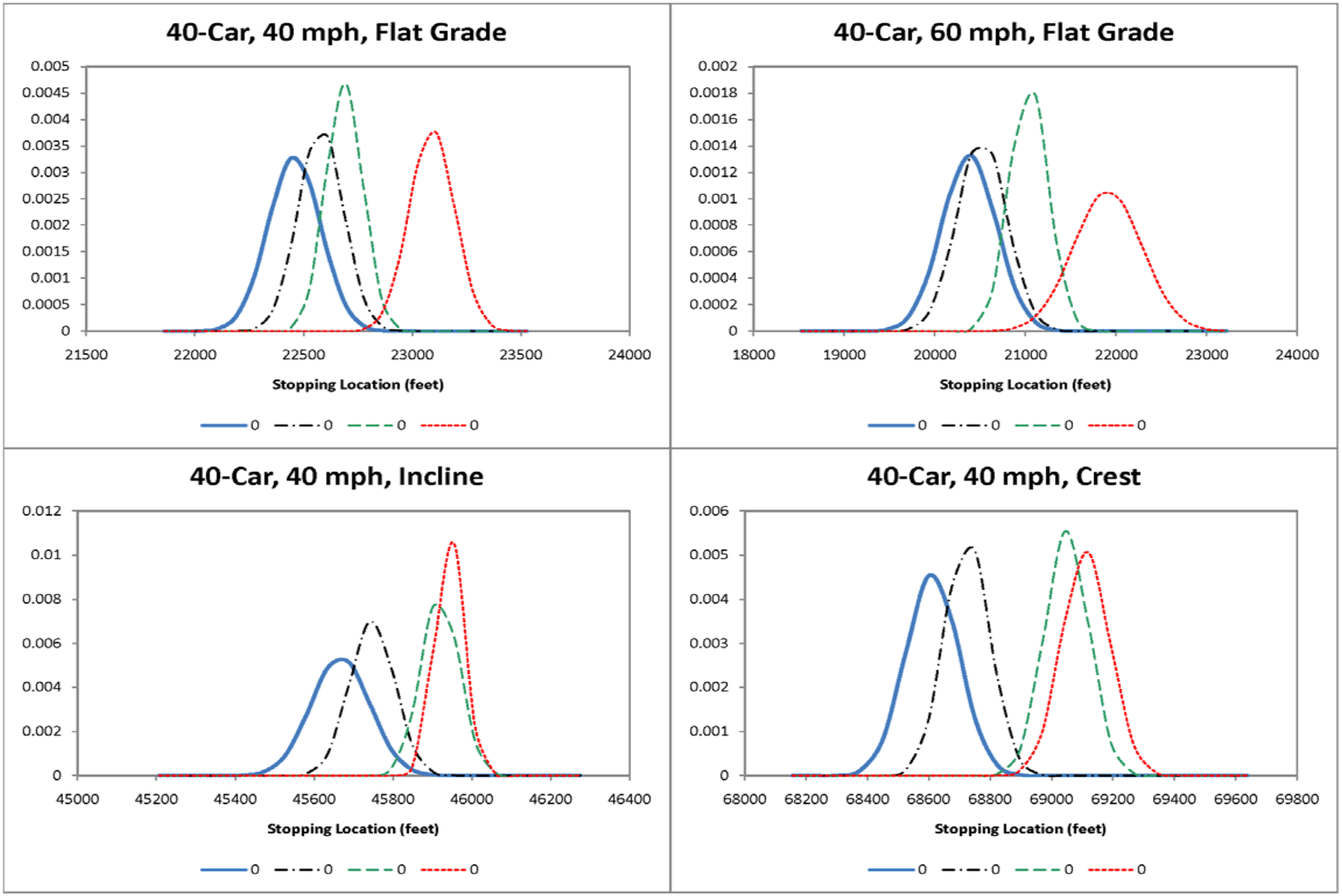

Long, Empty Aluminum, Fast, Crest
0.002
0.0018
0.0016
0.0014
0.0012
0.001
0.0008
0.0006
0.0004
0.0002
0
36000
37000
38000
39000
40000
41000
42000
Stopping Location (feet)
Stage 1
Stage 2
Stage 3
Stage 4

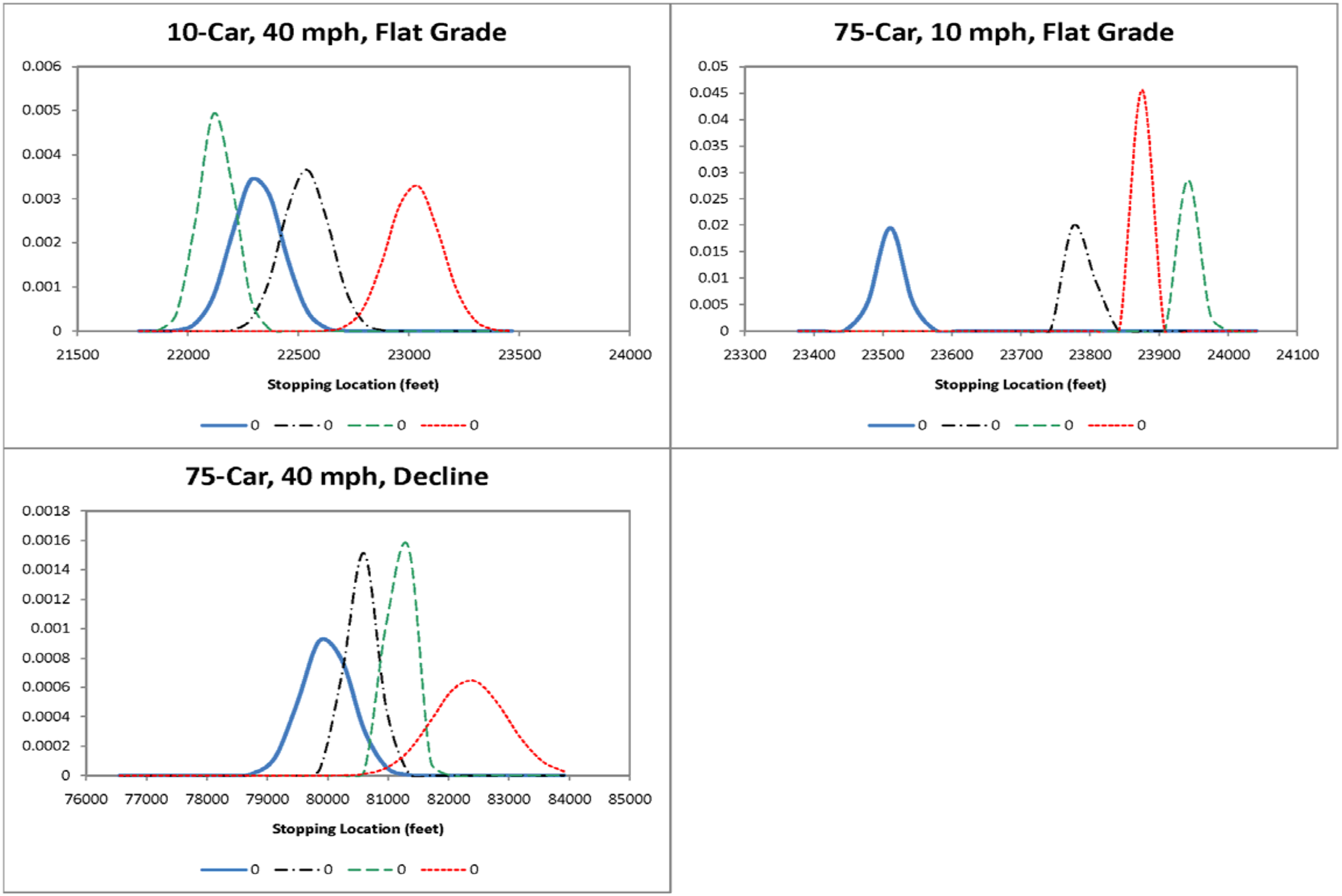

Long, Empty Aluminum, Fast, Trough
0.002
0.0018
0.0016
0.0014
0.0012
0.001
0.0008
0.0006
0.0004
0.0002
0
36000
37000
38000
39000
40000
41000
42000
Stopping Location (feet)
Stage 1
Stage 2
Stage 3
Stage 4


Long, Empty Aluminum, Slow, Flat
Long, Empty Aluminum, Slow, 1% Incline
Long, Empty Aluminum, Slow, 1% Decline
Long, Empty Aluminum, Slow, 0.5% Decline
Stopping Location (feet)
Stage 1
Stage 2
Stage 3
Stage 4


Long, Empty Aluminum, Slow, Crest
0.025
0.02
0.015
0.01
0.005
0
39650
39700
39750
39800
39850
39900
39950
40000
40050
40100
Stopping Location (feet)
Stage 1
Stage 2
Stage 3
Stage 4


Long, Empty Aluminum, Slow, Trough
0.04
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
39650
39700
39750
39800
39850
39900
39950
40000
40050
40100
Stopping Location (feet)
Stage 1
Stage 2
Stage 3
Stage 4


40-Car, 40 mph, Flat Grade
0.005
0.0045
0.004
0.0035
0.003
0.0025
0.002
0.0015
0.001
0.0005
0
21500
22000
22500
23000
23500
24000
Stopping Location (feet)
0
0
0
0
40-Car, 60 mph, Flat Grade
0.002
0.0018
0.0016
0.0014
0.0012
0.001
0.0008
0.0006
0.0004
0.0002
0
18000
19000
20000
21000
22000
23000
24000
Stopping Location (feet)
0
0
0
0
40-Car, 40 mph, Incline
0.012
0.01
0.008
0.006
0.004
0.002
0
45000
45200
45400
45600
45800
46000
46200
46400
Stopping Location (feet)
0
0
0
0
40-Car, 40 mph, Crest
0.006
0.005
0.004
0.003
0.002
0.001
0
68000
68200
68400
68600
68800
69000
69200
69400
69600
69800
Stopping Location (feet)
0
0
0
0


10-Car, 40 mph, Flat Grade
0.006
0.005
0.004
0.003
0.002
0.001
0
21500
22000
22500
23000
23500
24000
Stopping Location (feet)
0
0
0
0
75-Car, 10 mph, Flat Grade
0.05
0.045
0.04
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
23300
23400
23500
23600
23700
23800
23900
24000
24100
Stopping Location (feet)
0
0
0
0
75-Car, 40 mph, Decline
0.0018
0.0016
0.0014
0.0012
0.001
0.0008
0.0006
0.0004
0.0002
0
76000
77000
78000
79000
80000
81000
82000
83000
84000
85000
Stopping Location (feet)
0
0
0
0

Appendix G.
Simulation Test Results for Enforcement Algorithm Evaluation

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Stage	Sim Set ID	Train Length	Train Load	Train Speed	Track Grade	Mean Distance to Target (ft)	Standard Deviation of Distance to Target (ft)	Maximum Deviation from Mean Distance to Target (ft)	Percent Overshoot	Percent Undershoot
1	000	Short	Loaded	Fast	Flat	3006	303	2565	0%	99%
2	000	Short	Loaded	Fast	Flat	2508	251	1980	0%	99%
3	000	Short	Loaded	Fast	Flat	2136	205	1607	0%	99%
4	000	Short	Loaded	Fast	Flat	1465	180	1520	0%	99%
1	001	Short	Loaded	Fast	1% Decline	N/A	N/A	N/A	N/A	N/A
2	001	Short	Loaded	Fast	1% Decline	N/A	N/A	N/A	N/A	N/A
3	001	Short	Loaded	Fast	1% Decline	N/A	N/A	N/A	N/A	N/A
4	001	Short	Loaded	Fast	1% Decline	N/A	N/A	N/A	N/A	N/A
1	002	Short	Loaded	Fast	0.5% Decline	4836	479	4247	0%	99%
2	002	Short	Loaded	Fast	0.5% Decline	4167	409	3488	0%	99%
3	002	Short	Loaded	Fast	0.5% Decline	3740	330	2789	0%	99%
4	002	Short	Loaded	Fast	0.5% Decline	2152	352	3097	0%	100%
1	003	Short	Loaded	Fast	Crest	1267	127	1064	0%	99%
2	003	Short	Loaded	Fast	Crest	993	102	731	0%	40%
3	003	Short	Loaded	Fast	Crest	850	87	588	0%	2%
4	003	Short	Loaded	Fast	Crest	629	71	536	0%	1%
1	004	Short	Loaded	Fast	Trough	3154	343	2820	0%	99%
2	004	Short	Loaded	Fast	Trough	2595	274	2152	0%	99%
3	004	Short	Loaded	Fast	Trough	2315	230	1762	0%	99%
4	004	Short	Loaded	Fast	Trough	1388	402	3862	0%	99%
1	005	Short	Loaded	Slow	Flat	214	19	141	0%	0%
2	005	Short	Loaded	Slow	Flat	163	14	75	0%	0%
3	005	Short	Loaded	Slow	Flat	150	12	61	0%	0%
4	005	Short	Loaded	Slow	Flat	124	10	52	0%	0%
1	006	Short	Loaded	Slow	1% Incline	44	8	50	0%	0%
2	006	Short	Loaded	Slow	1% Incline	38	6	39	0%	0%
3	006	Short	Loaded	Slow	1% Incline	36	7	41	0%	0%
4	006	Short	Loaded	Slow	1% Incline	31	6	28	0%	0%
1	007	Short	Loaded	Slow	1% Decline	747	78	704	0%	98%
2	007	Short	Loaded	Slow	1% Decline	520	57	371	0%	87%

Stage	Sim Set ID	Train Length	Train Load	Train Speed	Track Grade	Mean Distance to Target (ft)	Standard Deviation of Distance to Target (ft)	Maximum Deviation from Mean Distance to Target (ft)	Percent Overshoot	Percent Undershoot
3	007	Short	Loaded	Slow	1% Decline	516	45	285	0%	75%
4	007	Short	Loaded	Slow	1% Decline	335	98	907	0%	2%
1	008	Short	Loaded	Slow	0.5% Decline	425	35	272	0%	0%
2	008	Short	Loaded	Slow	0.5% Decline	304	26	149	0%	0%
3	008	Short	Loaded	Slow	0.5% Decline	285	25	152	0%	0%
4	008	Short	Loaded	Slow	0.5% Decline	216	37	299	0%	1%
1	009	Short	Loaded	Slow	Crest	389	30	264	0%	1%
2	009	Short	Loaded	Slow	Crest	281	23	132	0%	0%
3	009	Short	Loaded	Slow	Crest	252	20	131	0%	0%
4	009	Short	Loaded	Slow	Crest	203	24	181	0%	0%
1	010	Short	Loaded	Slow	Trough	93	11	70	0%	0%
2	010	Short	Loaded	Slow	Trough	77	7	55	0%	0%
3	010	Short	Loaded	Slow	Trough	75	8	57	0%	0%
4	010	Short	Loaded	Slow	Trough	62	3	18	0%	0%
1	011	Short	Empty Steel	Fast	Flat	1820	123	991	0%	99%
2	011	Short	Empty Steel	Fast	Flat	1412	94	496	0%	99%
3	011	Short	Empty Steel	Fast	Flat	1501	77	397	0%	100%
4	011	Short	Empty Steel	Fast	Flat	991	144	907	0%	19%
1	012	Short	Empty Steel	Fast	1% Incline	809	66	461	0%	1%
2	012	Short	Empty Steel	Fast	1% Incline	630	54	299	0%	0%
3	012	Short	Empty Steel	Fast	1% Incline	589	41	269	0%	0%
4	012	Short	Empty Steel	Fast	1% Incline	591	37	267	0%	0%
1	013	Short	Empty Steel	Fast	1% Decline	1727	105	876	0%	99%
2	013	Short	Empty Steel	Fast	1% Decline	1299	76	487	0%	99%
3	013	Short	Empty Steel	Fast	1% Decline	1669	69	461	0%	100%
4	013	Short	Empty Steel	Fast	1% Decline	876	101	817	0%	3%
1	014	Short	Empty Steel	Fast	0.5% Decline	2189	147	1179	0%	100%
2	014	Short	Empty Steel	Fast	0.5% Decline	1711	116	643	0%	100%
3	014	Short	Empty Steel	Fast	0.5% Decline	1968	90	556	0%	100%
4	014	Short	Empty Steel	Fast	0.5% Decline	1173	172	1254	0%	100%

Stage	Sim Set ID	Train Length	Train Load	Train Speed	Track Grade	Mean Distance to Target (ft)	Standard Deviation of Distance to Target (ft)	Maximum Deviation from Mean Distance to Target (ft)	Percent Overshoot	Percent Undershoot
1	015	Short	Empty Steel	Fast	Crest	1806	131	1106	0%	99%
2	015	Short	Empty Steel	Fast	Crest	1414	95	608	0%	99%
3	015	Short	Empty Steel	Fast	Crest	1439	88	447	0%	100%
4	015	Short	Empty Steel	Fast	Crest	1443	82	443	0%	100%
1	016	Short	Empty Steel	Fast	Trough	1750	115	924	0%	99%
2	016	Short	Empty Steel	Fast	Trough	1331	88	495	0%	99%
3	016	Short	Empty Steel	Fast	Trough	1502	77	474	0%	100%
4	016	Short	Empty Steel	Fast	Trough	910	134	1023	0%	3%
1	017	Short	Empty Steel	Slow	Flat	146	11	73	0%	0%
2	017	Short	Empty Steel	Slow	Flat	114	7	40	0%	0%
3	017	Short	Empty Steel	Slow	Flat	121	8	33	0%	0%
4	017	Short	Empty Steel	Slow	Flat	91	11	63	0%	0%
1	018	Short	Empty Steel	Slow	1% Incline	32	6	34	1%	0%
2	018	Short	Empty Steel	Slow	1% Incline	25	6	28	1%	0%
3	018	Short	Empty Steel	Slow	1% Incline	24	5	22	0%	0%
4	018	Short	Empty Steel	Slow	1% Incline	24	5	22	0%	0%
1	019	Short	Empty Steel	Slow	1% Decline	523	22	142	0%	98%
2	019	Short	Empty Steel	Slow	1% Decline	385	19	73	0%	0%
3	019	Short	Empty Steel	Slow	1% Decline	462	27	177	0%	5%
4	019	Short	Empty Steel	Slow	1% Decline	283	40	356	0%	1%
1	020	Short	Empty Steel	Slow	0.5% Decline	273	11	69	0%	0%
2	020	Short	Empty Steel	Slow	0.5% Decline	206	9	38	0%	0%
3	020	Short	Empty Steel	Slow	0.5% Decline	224	11	72	0%	0%
4	020	Short	Empty Steel	Slow	0.5% Decline	158	21	182	0%	0%
1	021	Short	Empty Steel	Slow	Crest	252	14	107	0%	0%
2	021	Short	Empty Steel	Slow	Crest	191	11	65	0%	0%
3	021	Short	Empty Steel	Slow	Crest	193	11	62	0%	0%
4	021	Short	Empty Steel	Slow	Crest	194	12	62	0%	0%
1	022	Short	Empty Steel	Slow	Trough	75	7	52	0%	0%
2	022	Short	Empty Steel	Slow	Trough	61	6	38	0%	0%

Stage	Sim Set ID	Train Length	Train Load	Train Speed	Track Grade	Mean Distance to Target (ft)	Standard Deviation of Distance to Target (ft)	Maximum Deviation from Mean Distance to Target (ft)	Percent Overshoot	Percent Undershoot
3	022	Short	Empty Steel	Slow	Trough	62	5	29	0%	0%
4	022	Short	Empty Steel	Slow	Trough	48	5	44	0%	0%
1	023	Short	Empty Aluminum	Fast	Flat	571	179	1445	1%	1%
2	023	Short	Empty Aluminum	Fast	Flat	571	179	1445	1%	1%
3	023	Short	Empty Aluminum	Fast	Flat	379	110	737	1%	0%
4	023	Short	Empty Aluminum	Fast	Flat	1001	92	701	0%	32%
1	024	Short	Empty Aluminum	Fast	1% Incline	349	94	713	1%	0%
2	024	Short	Empty Aluminum	Fast	1% Incline	140	75	428	1%	0%
3	024	Short	Empty Aluminum	Fast	1% Incline	152	70	383	1%	0%
4	024	Short	Empty Aluminum	Fast	1% Incline	379	172	323	0%	0%
1	025	Short	Empty Aluminum	Fast	1% Decline	624	181	1619	1%	1%
2	025	Short	Empty Aluminum	Fast	1% Decline	260	145	1187	1%	0%
3	025	Short	Empty Aluminum	Fast	1% Decline	640	111	827	1%	2%
4	025	Short	Empty Aluminum	Fast	1% Decline	973	146	1292	0%	22%
1	026	Short	Empty Aluminum	Fast	0.5% Decline	700	234	2019	1%	1%
2	026	Short	Empty Aluminum	Fast	0.5% Decline	220	187	1448	1%	1%
3	026	Short	Empty Aluminum	Fast	0.5% Decline	575	150	1073	1%	2%
4	026	Short	Empty Aluminum	Fast	0.5% Decline	1297	153	1305	0%	99%
1	027	Short	Empty Aluminum	Fast	Crest	498	198	1685	1%	1%
2	027	Short	Empty Aluminum	Fast	Crest	112	161	1190	3%	0%
3	027	Short	Empty Aluminum	Fast	Crest	194	124	832	1%	0%
4	027	Short	Empty Aluminum	Fast	Crest	989	102	807	0%	44%
1	028	Short	Empty Aluminum	Fast	Trough	665	155	1298	1%	99%
2	028	Short	Empty Aluminum	Fast	Trough	306	119	870	1%	2%
3	028	Short	Empty Aluminum	Fast	Trough	543	103	632	1%	87%
4	028	Short	Empty Aluminum	Fast	Trough	1022	94	706	0%	100%
1	029	Short	Empty Aluminum	Slow	Flat	75	12	91	1%	0%
2	029	Short	Empty Aluminum	Slow	Flat	47	10	63	1%	0%
3	029	Short	Empty Aluminum	Slow	Flat	58	8	45	0%	0%
4	029	Short	Empty Aluminum	Slow	Flat	92	7	37	0%	0%

Stage	Sim Set ID	Train Length	Train Load	Train Speed	Track Grade	Mean Distance to Target (ft)	Standard Deviation of Distance to Target (ft)	Maximum Deviation from Mean Distance to Target (ft)	Percent Overshoot	Percent Undershoot
1	030	Short	Empty Aluminum	Slow	1% Incline	7	5	27	2%	0%
2	030	Short	Empty Aluminum	Slow	1% Incline	3	6	27	30%	0%
3	030	Short	Empty Aluminum	Slow	1% Incline	3	5	27	27%	0%
4	030	Short	Empty Aluminum	Slow	1% Incline	9	6	21	8%	0%
1	031	Short	Empty Aluminum	Slow	1% Decline	265	49	462	1%	0%
2	031	Short	Empty Aluminum	Slow	1% Decline	149	35	314	1%	0%
3	031	Short	Empty Aluminum	Slow	1% Decline	244	22	159	0%	0%
4	031	Short	Empty Aluminum	Slow	1% Decline	323	51	471	0%	0%
1	032	Short	Empty Aluminum	Slow	0.5% Decline	156	26	232	1%	0%
2	032	Short	Empty Aluminum	Slow	0.5% Decline	92	18	145	1%	0%
3	032	Short	Empty Aluminum	Slow	0.5% Decline	124	13	81	0%	0%
4	032	Short	Empty Aluminum	Slow	0.5% Decline	190	26	231	0%	0%
1	033	Short	Empty Aluminum	Slow	Crest	133	20	169	1%	0%
2	033	Short	Empty Aluminum	Slow	Crest	80	15	99	1%	0%
3	033	Short	Empty Aluminum	Slow	Crest	87	12	72	0%	0%
4	033	Short	Empty Aluminum	Slow	Crest	164	17	137	0%	0%
1	034	Short	Empty Aluminum	Slow	Trough	32	7	52	1%	0%
2	034	Short	Empty Aluminum	Slow	Trough	19	7	41	1%	0%
3	034	Short	Empty Aluminum	Slow	Trough	30	6	29	0%	0%
4	034	Short	Empty Aluminum	Slow	Trough	43	5	16	0%	0%
1	035	Long	Loaded	Fast	Flat	3064	391	3308	1%	99%
2	035	Long	Loaded	Fast	Flat	2449	510	2432	0%	99%
3	035	Long	Loaded	Fast	Flat	2108	498	2091	0%	99%
4	035	Long	Loaded	Fast	Flat	2384	531	2368	0%	99%
1	036	Long	Loaded	Fast	1% Decline	N/A	N/A	N/A	N/A	N/A
2	036	Long	Loaded	Fast	1% Decline	N/A	N/A	N/A	N/A	N/A
3	036	Long	Loaded	Fast	1% Decline	N/A	N/A	N/A	N/A	N/A
4	036	Long	Loaded	Fast	1% Decline	N/A	N/A	N/A	N/A	N/A
1	037	Long	Loaded	Fast	0.5% Decline	5083	643	5725	1%	99%
2	037	Long	Loaded	Fast	0.5% Decline	4043	744	4232	1%	99%

Stage	Sim Set ID	Train Length	Train Load	Train Speed	Track Grade	Mean Distance to Target (ft)	Standard Deviation of Distance to Target (ft)	Maximum Deviation from Mean Distance to Target (ft)	Percent Overshoot	Percent Undershoot
3	037	Long	Loaded	Fast	0.5% Decline	4014	744	4203	1%	99%
4	037	Long	Loaded	Fast	0.5% Decline	3872	660	2332	0%	100%
1	038	Long	Loaded	Fast	Crest	488	103	842	1%	22%
2	038	Long	Loaded	Fast	Crest	307	148	617	1%	7%
3	038	Long	Loaded	Fast	Crest	256	141	566	2%	6%
4	038	Long	Loaded	Fast	Crest	298	141	608	1%	10%
1	039	Long	Loaded	Fast	Trough	3990	522	4428	1%	99%
2	039	Long	Loaded	Fast	Trough	3083	644	3222	1%	99%
3	039	Long	Loaded	Fast	Trough	3055	647	3194	1%	99%
4	039	Long	Loaded	Fast	Trough	2970	643	2399	0%	100%
1	040	Long	Loaded	Slow	Flat	246	22	164	0%	0%
2	040	Long	Loaded	Slow	Flat	186	39	123	0%	0%
3	040	Long	Loaded	Slow	Flat	171	36	108	0%	0%
4	040	Long	Loaded	Slow	Flat	181	40	113	0%	0%
1	041	Long	Loaded	Slow	1% Incline	57	8	55	0%	0%
2	041	Long	Loaded	Slow	1% Incline	49	7	46	0%	0%
3	041	Long	Loaded	Slow	1% Incline	49	7	46	0%	0%
4	041	Long	Loaded	Slow	1% Incline	49	6	30	0%	0%
1	042	Long	Loaded	Slow	1% Decline	N/A	N/A	N/A	N/A	N/A
2	042	Long	Loaded	Slow	1% Decline	N/A	N/A	N/A	N/A	N/A
3	042	Long	Loaded	Slow	1% Decline	N/A	N/A	N/A	N/A	N/A
4	042	Long	Loaded	Slow	1% Decline	N/A	N/A	N/A	N/A	N/A
1	043	Long	Loaded	Slow	0.5% Decline	504	56	444	0%	91%
2	043	Long	Loaded	Slow	0.5% Decline	357	105	358	0%	8%
3	043	Long	Loaded	Slow	0.5% Decline	356	104	359	0%	6%
4	043	Long	Loaded	Slow	0.5% Decline	368	204	1715	0%	14%
1	044	Long	Loaded	Slow	Crest	303	29	235	0%	0%
2	044	Long	Loaded	Slow	Crest	216	54	158	0%	0%
3	044	Long	Loaded	Slow	Crest	200	52	159	0%	0%
4	044	Long	Loaded	Slow	Crest	214	55	198	0%	0%

Stage	Sim Set ID	Train Length	Train Load	Train Speed	Track Grade	Mean Distance to Target (ft)	Standard Deviation of Distance to Target (ft)	Maximum Deviation from Mean Distance to Target (ft)	Percent Overshoot	Percent Undershoot
1	045	Long	Loaded	Slow	Trough	174	15	121	0%	0%
2	045	Long	Loaded	Slow	Trough	127	26	89	0%	0%
3	045	Long	Loaded	Slow	Trough	127	26	89	0%	0%
4	045	Long	Loaded	Slow	Trough	128	28	155	0%	0%
1	046	Long	Empty Steel	Fast	Flat	1934	164	1367	0%	99%
2	046	Long	Empty Steel	Fast	Flat	1512	368	1032	0%	94%
3	046	Long	Empty Steel	Fast	Flat	1596	359	1035	0%	96%
4	046	Long	Empty Steel	Fast	Flat	1515	442	2157	0%	95%
1	047	Long	Empty Steel	Fast	1% Incline	652	62	431	0%	1%
2	047	Long	Empty Steel	Fast	1% Incline	495	109	357	0%	0%
3	047	Long	Empty Steel	Fast	1% Incline	473	106	318	0%	0%
4	047	Long	Empty Steel	Fast	1% Incline	484	115	307	0%	0%
1	048	Long	Empty Steel	Fast	1% Decline	2085	162	1425	0%	99%
2	048	Long	Empty Steel	Fast	1% Decline	1522	405	1225	0%	88%
3	048	Long	Empty Steel	Fast	1% Decline	1995	432	1209	0%	100%
4	048	Long	Empty Steel	Fast	1% Decline	1495	560	3742	0%	88%
1	049	Long	Empty Steel	Fast	0.5% Decline	2550	214	1839	0%	99%
2	049	Long	Empty Steel	Fast	0.5% Decline	1846	415	1379	0%	98%
3	049	Long	Empty Steel	Fast	0.5% Decline	2273	409	1126	0%	100%
4	049	Long	Empty Steel	Fast	0.5% Decline	1885	629	4366	0%	98%
1	050	Long	Empty Steel	Fast	Crest	1638	143	1158	0%	99%
2	050	Long	Empty Steel	Fast	Crest	1190	271	906	0%	91%
3	050	Long	Empty Steel	Fast	Crest	1168	266	837	0%	86%
4	050	Long	Empty Steel	Fast	Crest	1210	323	1674	0%	87%
1	051	Long	Empty Steel	Fast	Trough	2199	184	1498	0%	99%
2	051	Long	Empty Steel	Fast	Trough	1607	392	1206	0%	96%
3	051	Long	Empty Steel	Fast	Trough	1962	387	1123	0%	100%
4	051	Long	Empty Steel	Fast	Trough	1674	509	2976	0%	96%
1	052	Long	Empty Steel	Slow	Flat	159	13	100	0%	0%
2	052	Long	Empty Steel	Slow	Flat	123	27	70	0%	0%

Stage	Sim Set ID	Train Length	Train Load	Train Speed	Track Grade	Mean Distance to Target (ft)	Standard Deviation of Distance to Target (ft)	Maximum Deviation from Mean Distance to Target (ft)	Percent Overshoot	Percent Undershoot
3	052	Long	Empty Steel	Slow	Flat	127	26	66	0%	0%
4	052	Long	Empty Steel	Slow	Flat	122	29	127	0%	0%
1	053	Long	Empty Steel	Slow	1% Incline	22	5	29	1%	0%
2	053	Long	Empty Steel	Slow	1% Incline	18	6	32	1%	0%
3	053	Long	Empty Steel	Slow	1% Incline	17	6	20	1%	0%
4	053	Long	Empty Steel	Slow	1% Incline	17	6	20	1%	0%
1	054	Long	Empty Steel	Slow	1% Decline	645	32	247	0%	98%
2	054	Long	Empty Steel	Slow	1% Decline	477	103	299	0%	26%
3	054	Long	Empty Steel	Slow	1% Decline	603	120	351	0%	95%
4	054	Long	Empty Steel	Slow	1% Decline	482	176	1401	0%	27%
1	055	Long	Empty Steel	Slow	0.5% Decline	347	17	123	0%	0%
2	055	Long	Empty Steel	Slow	0.5% Decline	259	62	197	0%	0%
3	055	Long	Empty Steel	Slow	0.5% Decline	299	66	209	0%	1%
4	055	Long	Empty Steel	Slow	0.5% Decline	259	93	656	0%	1%
1	056	Long	Empty Steel	Slow	Crest	189	15	119	0%	0%
2	056	Long	Empty Steel	Slow	Crest	141	28	100	0%	0%
3	056	Long	Empty Steel	Slow	Crest	138	26	87	0%	0%
4	056	Long	Empty Steel	Slow	Crest	142	35	193	0%	0%
1	057	Long	Empty Steel	Slow	Trough	114	10	68	0%	0%
2	057	Long	Empty Steel	Slow	Trough	90	16	50	0%	0%
3	057	Long	Empty Steel	Slow	Trough	105	15	47	0%	0%
4	057	Long	Empty Steel	Slow	Trough	93	19	92	0%	0%
1	058	Long	Empty Aluminum	Fast	Flat	657	219	1877	1%	1%
2	058	Long	Empty Aluminum	Fast	Flat	196	359	1244	14%	2%
3	058	Long	Empty Aluminum	Fast	Flat	341	352	877	11%	6%
4	058	Long	Empty Aluminum	Fast	Flat	1420	425	1955	1%	91%
1	059	Long	Empty Aluminum	Fast	1% Incline	310	93	670	1%	0%
2	059	Long	Empty Aluminum	Fast	1% Incline	103	151	466	14%	0%
3	059	Long	Empty Aluminum	Fast	1% Incline	86	151	483	21%	0%
4	059	Long	Empty Aluminum	Fast	1% Incline	561	171	787	1%	1%

Stage	Sim Set ID	Train Length	Train Load	Train Speed	Track Grade	Mean Distance to Target (ft)	Standard Deviation of Distance to Target (ft)	Maximum Deviation from Mean Distance to Target (ft)	Percent Overshoot	Percent Undershoot
1	060	Long	Empty Aluminum	Fast	1% Decline	735	267	2448	1%	1%
2	060	Long	Empty Aluminum	Fast	1% Decline	259	359	1697	13%	3%
3	060	Long	Empty Aluminum	Fast	1% Decline	720	368	1133	3%	25%
4	060	Long	Empty Aluminum	Fast	1% Decline	1586	459	2000	1%	90%
1	061	Long	Empty Aluminum	Fast	0.5% Decline	809	302	2667	1%	1%
2	061	Long	Empty Aluminum	Fast	0.5% Decline	156	420	1747	18%	4%
3	061	Long	Empty Aluminum	Fast	0.5% Decline	488	416	1277	13%	15%
4	061	Long	Empty Aluminum	Fast	0.5% Decline	1869	541	2658	1%	99%
1	062	Long	Empty Aluminum	Fast	Crest	524	225	1965	1%	1%
2	062	Long	Empty Aluminum	Fast	Crest	54	297	1267	47%	1%
3	062	Long	Empty Aluminum	Fast	Crest	141	286	1017	22%	1%
4	062	Long	Empty Aluminum	Fast	Crest	1271	368	2147	1%	91%
1	063	Long	Empty Aluminum	Fast	Trough	786	226	1919	1%	1%
2	063	Long	Empty Aluminum	Fast	Trough	362	356	1297	7%	6%
3	063	Long	Empty Aluminum	Fast	Trough	626	350	956	4%	17%
4	063	Long	Empty Aluminum	Fast	Trough	1696	439	2026	1%	99%
1	064	Long	Empty Aluminum	Slow	Flat	43	9	67	1%	0%
2	064	Long	Empty Aluminum	Slow	Flat	28	12	43	1%	0%
3	064	Long	Empty Aluminum	Slow	Flat	75	15	44	0%	0%
4	064	Long	Empty Aluminum	Slow	Flat	83	15	39	0%	0%
1	065	Long	Empty Aluminum	Slow	1% Incline	4	5	23	16%	0%
2	065	Long	Empty Aluminum	Slow	1% Incline	0	5	23	45%	0%
3	065	Long	Empty Aluminum	Slow	1% Incline	4	5	19	15%	0%
4	065	Long	Empty Aluminum	Slow	1% Incline	7	6	16	11%	0%
1	066	Long	Empty Aluminum	Slow	1% Decline	303	84	805	1%	0%
2	066	Long	Empty Aluminum	Slow	1% Decline	152	110	559	3%	0%
3	066	Long	Empty Aluminum	Slow	1% Decline	287	114	304	0%	2%
4	066	Long	Empty Aluminum	Slow	1% Decline	524	154	514	0%	38%
1	067	Long	Empty Aluminum	Slow	0.5% Decline	164	35	321	1%	0%
2	067	Long	Empty Aluminum	Slow	0.5% Decline	96	53	205	2%	0%

Stage	Sim Set ID	Train Length	Train Load	Train Speed	Track Grade	Mean Distance to Target (ft)	Standard Deviation of Distance to Target (ft)	Maximum Deviation from Mean Distance to Target (ft)	Percent Overshoot	Percent Undershoot
3	067	Long	Empty Aluminum	Slow	0.5% Decline	134	53	121	0%	0%
4	067	Long	Empty Aluminum	Slow	0.5% Decline	295	76	259	0%	0%
1	068	Long	Empty Aluminum	Slow	Crest	71	20	153	1%	0%
2	068	Long	Empty Aluminum	Slow	Crest	31	30	97	13%	0%
3	068	Long	Empty Aluminum	Slow	Crest	38	29	90	10%	0%
4	068	Long	Empty Aluminum	Slow	Crest	139	41	157	1%	0%
1	069	Long	Empty Aluminum	Slow	Trough	57	10	76	1%	0%
2	069	Long	Empty Aluminum	Slow	Trough	36	16	55	1%	0%
3	069	Long	Empty Aluminum	Slow	Trough	49	16	53	0%	0%
4	069	Long	Empty Aluminum	Slow	Trough	96	20	74	0%	0%

Appendix H.
Field Test Pictures

Figure H-1. Field Test Consist

Figure H-2. Field Test Locomotives

Figure H-3. Lead Locomotive Control Stand Setup

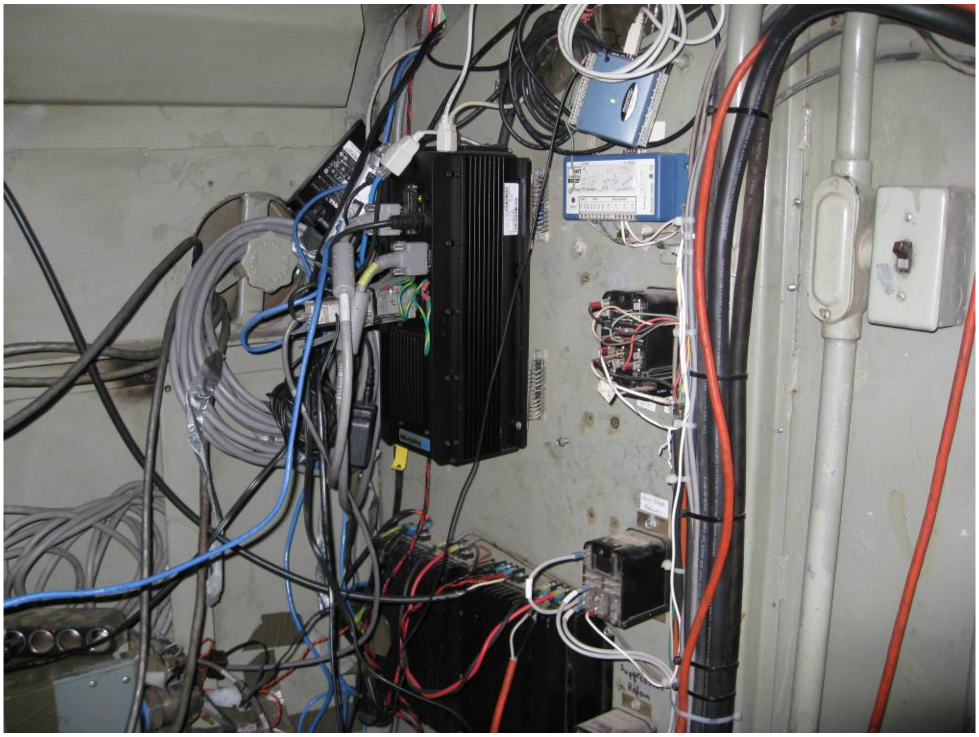

Figure H-4. Train Control Computer and Instrumentation Located in the Nose of the Lead Locomotive Cab

Figure H-5. Instrumented Coupler Installed on Rear Locomotive

Figure H-6. Rear Car Instrumentation including EOT, Data Acquisition Computer, and Antenna

Figure H-7. Rear Car Instrumentation Data Acquisition Computer

Abbreviations and Acronyms

AAR	Association of American Railroads
ALD	Automatic Location Detector
EOT	end-of-train
FAST	Facility for Accelerated Service Testing
FRA	Federal Railroad Administration
GPS	Global Positioning System
GRL	gross rail load
IDOT	Illinois Department of Transportation
NAJPTC	North American Joint Positive Train Control
PC	personal computer
PTC	Positive Train Control
RTT	Railroad Test Track
TCL	Test Controller/Logger
TOES™	Train Operations and Energy Simulator
TTC	Transportation Technology Center (the Site)
TTCI	Transportation Technology Center, Inc. (the Company)
WILD	wheel impact load detector
WRE	Wabtec Railway Electronics