U.S. Department of
Transportation

**Federal Railroad
Administration**

BNSF San Bernardino Case Study:

Positive Train Control Risk Assessment

Office of Research
and Development
Washington, DC 20590

REPORT DOCUMENTATION PAGE

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	September 2014	Final Report

4. TITLE AND SUBTITLE	5. FUNDING NUMBERS
BNSF San Bernardino Case Study: Positive Train Control Risk Assessment	

6. AUTHOR(S)
Daniel Brod, Boaz Leslau

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)	8. PERFORMING ORGANIZATION REPORT NUMBER
Decisiontek, LLC 6337 Executive Boulevard Rockville, MD 20852	

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSORING/MONITORING AGENCY REPORT NUMBER
U.S. Department of Transportation Federal Railroad Administration Office of Railroad Policy and Development Office of Research and Development Washington, DC 20590	DOT/FRA/ORD-14/31

11. SUPPLEMENTARY NOTES
Project Manager: Karen McClure

12a. DISTRIBUTION/AVAILABILITY STATEMENT	12b. DISTRIBUTION CODE
This document is available to the public through the FRA Web site at http://www.fra.dot.gov.	

13. ABSTRACT (Maximum 200 words)

The Federal Railroad Administration funded the BNSF San Bernardino Case Study to verify its Generalized Train Movement Simulator (GTMS) risk assessment capabilities on a planned implementation of the I-ETMS PTC system. The analysis explicitly simulated a 10-year period of railroad operations. During simulation, all initiating errors and failures of PTC-preventable accidents were captured and stored along with the entire system state. Subsequent analysis conducted repeated simulations based on random draws from these stored initiating system states to generate hazards and accidents with equivalent statistical confidence of more than 300 years of conventional Monte Carlo simulation. Subject to model assumptions, Base Case mean time to accident (MTTA) for collisions by type is: head-head 4.5 years, head-tail 11.8 years, and sideswipe 2.56 years. An over-speed derailment accident is predicted with a frequency of once every 8.6 years; risk of work zone accident is negligible. As modeled, I-ETMS mitigates all but negligible risk of PTC-preventable accidents with a high degree of confidence. A sensitivity analysis confirms these results. Changes to operating assumptions that could indicate greater risk in the Base Case actually show small variance in total risk. However, there is greater variance in the mix of accidents by accident type.

14. SUBJECT TERMS	15. NUMBER OF PAGES
Positive Train Control, Generalized Train Movement Simulator, I-ETMS, risk assessment, level splitting, engineering reliability metrics	101
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	

METRIC/ENGLISH CONVERSION FACTORS

ENGLISH TO METRIC

LENGTH (APPROXIMATE)

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

AREA (APPROXIMATE)

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

MASS - WEIGHT (APPROXIMATE)

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

VOLUME (APPROXIMATE)

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

TEMPERATURE (EXACT)

$[(x-32)(5/9)]$ °F = y °C

METRIC TO ENGLISH

LENGTH (APPROXIMATE)

1 millimeter (mm)	=	0.04 inch (in)
1 centimeter (cm)	=	0.4 inch (in)
1 meter (m)	=	3.3 feet (ft)
1 meter (m)	=	1.1 yards (yd)
1 kilometer (km)	=	0.6 mile (mi)

AREA (APPROXIMATE)

1 square centimeter (cm^2)	=	0.16 square inch (sq in, in^2)
1 square meter (m^2)	=	1.2 square yards (sq yd, yd^2)
1 square kilometer (km^2)	=	0.4 square mile (sq mi, mi^2)
10,000 square meters (m^2)	=	1 hectare (ha) = 2.5 acres

MASS - WEIGHT (APPROXIMATE)

1 gram (gm)	=	0.036 ounce (oz)
1 kilogram (kg)	=	2.2 pounds (lb)
1 tonne (t)	=	1,000 kilograms (kg)
	=	1.1 short tons

VOLUME (APPROXIMATE)

1 milliliter (ml)	=	0.03 fluid ounce (fl oz)
1 liter (l)	=	2.1 pints (pt)
1 liter (l)	=	1.06 quarts (qt)
1 liter (l)	=	0.26 gallon (gal)
1 cubic meter (m^3)	=	36 cubic feet (cu ft, ft^3)
1 cubic meter (m^3)	=	1.3 cubic yards (cu yd, yd^3)

TEMPERATURE (EXACT)

$[(9/5) y + 32]$ °C = x °F

QUICK INCH - CENTIMETER LENGTH CONVERSION

Inches	0	1	2	3	4	5

Centimeters	0	1	2	3	4	5	6	7	8	9	10	11	12	13
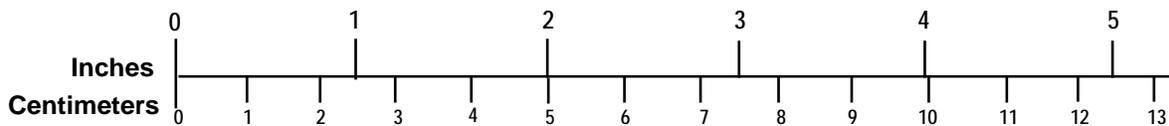
QUICK FAHRENHEIT - CELSIUS TEMPERATURE CONVERSION

°F	-40°	-22°	-4°	14°	32°	50°	68°	86°	104°	122°	140°	158°	176°	194°	212°
°C	-40°	-30°	-20°	-10°	0°	10°	20°	30°	40°	50°	60°	70°	80°	90°	100°
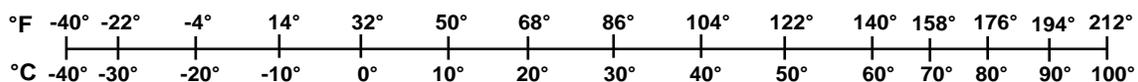
For more exact and or other conversion factors, see NIST Miscellaneous Publication 286, Units of Weights and Measures. Price $2.50 SD Catalog No. C13 10286

Acknowledgements

Contents

Illustrations

Tables

Executive Summary

The BNSF San Bernardino case study demonstrates with a high degree of confidence [1] that, as modeled, a vital I-ETMS Positive Train Control (PTC) system mitigates all but negligible risk of PTC-preventable accidents. Implementing the vital I-ETMS overlay system on the San Bernardino line results in $33.1 million in reduced accident costs over a 25-year period at the 3 percent discount rate and $22.3 million at the 7 percent discount rate.

About this Case Study

This case study evaluates the risk associated with the planned implementation of the I-ETMS [2] PTC system on the BNSF San Bernardino subdivision. The risk assessment meets major requirements of the PTC Rule [3] and is suitable for inclusion in a PTC Safety Plan (PTCSP).

The San Bernardino corridor, 68 miles in length, handles more than 100 freight and passenger trains daily, including trains from BNSF, UP, Amtrak, and Metrolink. The corridor is regarded as one of the most heavily trafficked and operationally complex in the United States.

Analysis Essentials

The case study was conducted using the FRA General Train Movement Simulator (GTMS), a computerized system designed by FRA to estimate the risk associated with implementing PTC systems. Using operating data provided by BNSF Railway, GTMS evaluated scenarios that are both realistic and reflective of highly complex operational scenarios. Certain safety input parameters in the corridor analysis (i.e., those indicating the probability of an accident for certain types of hazards – see Chapter 5) were calibrated to national railroad safety statistics for the period of 2010 to 2012.

The analysis of the corridor explicitly examined simulated operations covering a 10-year period, 428,200 trains, 440,966 train-hours, and 16.24 million train-miles of operations. During this period, the initiating errors and failures of PTC-preventable accidents were captured. The subsequent analysis conducted repeated simulations based on random draws from these initiating events to generate results with equivalent statistical confidence of more than 300 years of conventional Monte Carlo simulation (the methodology of the analysis is explained in Chapter 3).

Table A.1 [4] illustrates the intensity of encountering errors and failures relative to their opportunity and can serve as a basis for comparing simulation results with actual experience.

Figure A.1 shows mean time to hazards for the Base Case (without PTC).

A summary of the simulation results for the MTTA (mean time to accident) metrics in the Base Case shows the following:

- A predicted head-head collision once every 4.5 years
- A predicted head-tail collision once every 11.8 years
- A predicted sideswipe collision once every 2.6 years
- A predicted over-speed derailment once every 8.6 years

The analysis found that a Base Case work zone incursion is likely to occur only once every 5 years, and the analysis assumption is that only 1 in 100 incursions results in an accident. Consequently, a work zone accident is predicted to occur less frequently than once in 300 years. (See Chapter 6 Analysis and Findings for the details.) Also, the combined probability of equipment failure (mis-set or misaligned switch and grade crossing failure) and operator error was found to be so low that the

probability of the combined error was close to zero. The incidence of accident types due to combined operator error and equipment failure was found to be less than once in 300 years.

In the alternate case, the probability of a PTC-preventable accident occurring was found to be less than once in 300 years. The projected effectiveness of PTC is based on the assumptions regarding equipment reliability: the PTC failure rates imply uptime of over 99.9 percent; given this assumption, the probability of a coincidental occurrence of operator error with PTC failure is extremely low.

A sensitivity analysis to key inputs was conducted for the following inputs:

- Traffic volume, human error rates, equipment failure rates, human factors model with sleep deprivation, work zone frequency

The sensitivity analysis found that in the Base Case (without PTC) aggregate accidents (summing for all accident types) showed no marked increase despite increases in risk factors. This can be explained as a combination of: (1) countervailing effects—increased traffic volume creates more exposure opportunities, thereby increasing risk, but simultaneously causes lower average speeds, thus reducing risk and (2) random effects. Additional analysis could determine the magnitude of each of these effects.

The sensitivity analysis did demonstrate significant variation in the mix of accidents. High variance in the mix of accidents seems to be a feature of the territory (i.e., derived from the complexity of the physical plant and traffic). Additional analysis could determine whether this finding is indeed robust.

The sensitivity analysis supports the finding that all but negligible risk of PTC-preventable accidents is mitigated in the Alternate Case with PTC.

Conclusions

GTMS simulation closely replicates operations on the BNSF San Bernardino corridor. Risk in the Base Case includes PTC-preventable train-train collisions. MTTA for collisions by type is: head-head 4.5 years, head-tail 11.8 years, and sideswipe 2.56 years. An over-speed derailment is predicted at a frequency of once every 8.6 years. The risk of a work zone accident is seen to be negligible in the Base Case. As modeled, I-ETMS appears to mitigate all but negligible risk of PTC-preventable accidents with high confidence. The sensitivity analysis shows that the mitigation of all but negligible PTC-preventable accident risk with I-ETMS persists under a range of alternative assumptions. Although accident risk in the Base Case with higher-risk inputs shows small variance in the aggregate, there is large variance in the mix of accidents by accident type.

1. Introduction

1.1 Purpose

The purpose of the case study is to assess PTC-preventable safety risk on the BNSF San Bernardino Corridor before and after implementing the I-ETMS system. The analysis was conducted using GTMS developed by FRA.

1.2 Background and Objectives

Prior to 2008 and with encouragement from FRA, the railroad industry voluntarily began developing microprocessor-based signal and train control systems more commonly known as PTC. After the deadly Metrolink crash in Chatsworth, CA, the U.S. Congress passed the Railroad Safety Improvement Act (RISA) to mandate installation of PTC on a significant portion of the Class I rail network by December 31, 2015. Specifically, RISA requires PTC installation on all lines carrying scheduled passenger traffic, as well as on all Class I railroad main lines (i.e., lines carrying more than 5 million gross tons annually) over which any toxic or poisonous by inhalation hazardous (TIH/PIH) materials are transported. PTC will be installed on an estimated 70,000 miles of track (of this, approximately 63,000 miles are owned by freight railroads). The primary functions of PTC, as specified in the Act, are three-fold:

- Enforce compliance with signal indications and operating authorities;
- Enforce permanent and temporary speed limits; and
- Enforce work zone limits.

In addition, all hand-thrown and powered switches in PTC-equipped territory must be equipped with switch position sensors linked to the train control system so that, if necessary, PTC can prevent train movement over misaligned and incorrectly aligned switches. The goal of the RSIA PTC requirement is to attempt to prevent most train accidents arising from human errors, specifically train-to-train collisions, over-speed derailments, and failures to respond to work zone restrictions. Figure 1.1 illustrates the architecture of a generic PTC system and provides a sense of the complexity of such a system.

In response to RSIA, FRA updated its regulations and procedures for signal and train control systems by adding Subpart I to 49 CFR Part 236 [5]. FRA continued to develop its GTMS computerized system to meet the revised regulatory requirements for more rigorous risk assessment.

Subpart I contains an interoperability requirement so that locomotives and trains can operate over neighboring railroads without having to install multiple PTC systems in the locomotives or in the cabs of multiple-unit trains.

3

Figure 1.1 Generic PTC Architecture
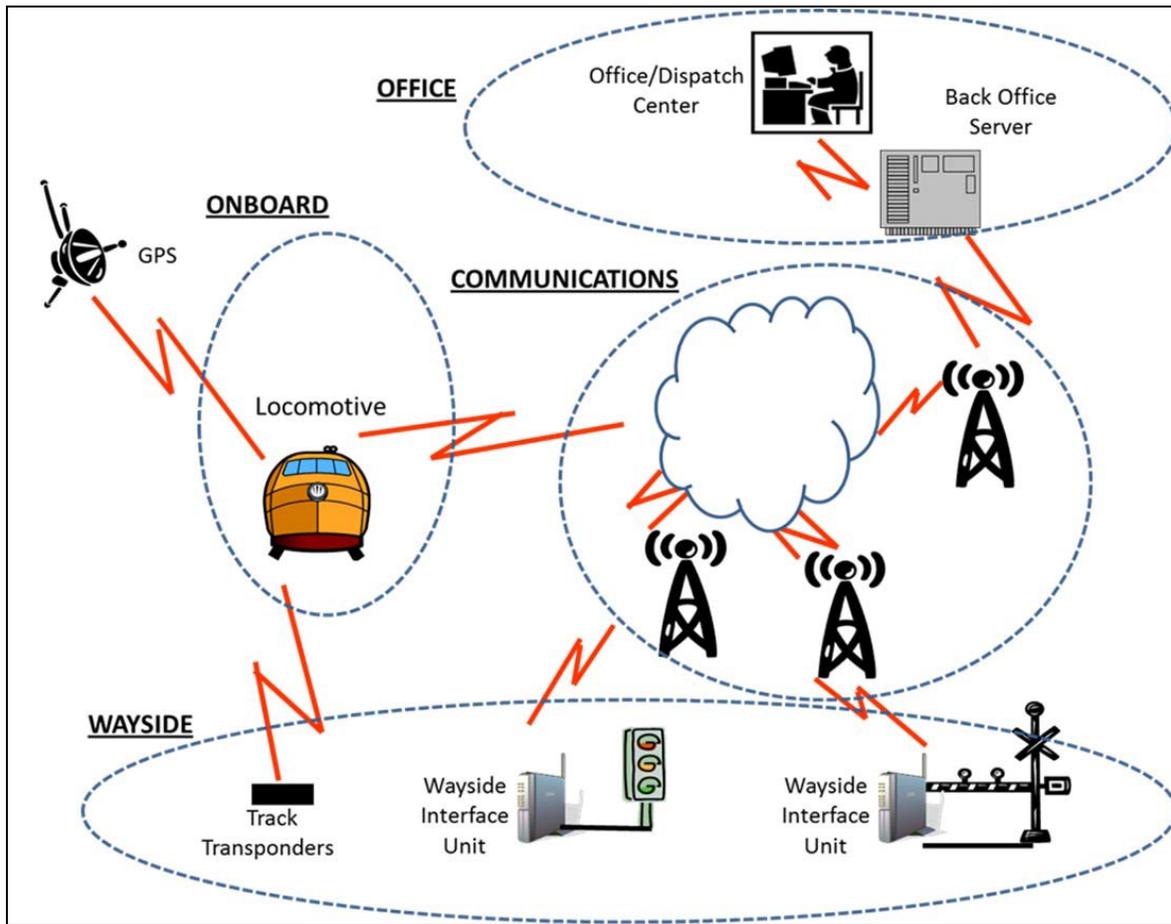
In response to the RISA law, major freight railroads converged on a vital, interoperable version of the Electronic Train Management System (I-ETMS, where I stands for interoperable) installed as an overlay on conventional signaling and train control systems. "Vital" means built in accordance with the safety assurance principles set forth in Appendix C of the Rule (and meets fail-safe standards nearly equivalent to those applied to traditional, non-processor based railroad signal and train control systems). A non-vital variant of ETMS has been installed on selected route segments of BNSF Railway for testing and demonstration, prior to completion of the vital version. I-ETMS – the vital, interoperable version of ETMS – and its implementation on the BNSF San Bernardino Subdivision, is the subject of the analysis in this case study.

A key defining feature of the I-ETMS system is its reliance on GPS for locomotive location and digital radio communications between trains, wayside devices, and the control center.

This case study addresses the risks associated with the operation of the I-ETMS system as an integrated whole and not just as an individual subsystems or components. The case study also provides all engineering reliability metrics including mean time to hazardous event (MTTHE). As modeled, this case study demonstrates with a high degree of confidence that I-ETMS reduces PTC-related accident risk by more than 80 percent, a key regulatory requirement for an overlay PTC system.

Other subpart I requirements focus on the use of software design and hazard mitigation strategies to eliminate all known sources of PTC failures so that only systematic errors remain. Systematic errors are unforeseen by the engineers designing the system and only uncovered during system operations. Component failure rates are provided by the manufacturer of the I-ETMS system. Human error rates are based on FRA and other human factors research and account for time of day and time on shift. Hazard and accident probabilities fully account for train-to-train proximity. (See Chapter 5, including Table 4.1 and Table 4.2.)

1.3   Risk Assessment with Simulation

Simulation of railroad operations is an attractive method of estimating railroad accident risks. Such simulation is able to take into account all relevant details of a specific corridor—infrastructure, trains and consists, the specifics of the signal and train control system in use, and operations details such as schedules, train priorities, and speeds. The simulation replicates the occurrence of potential risk exposure situations, such as signal indications requiring the train to reduce speed and situations that could result in hazards or accidents if human errors, component failures, or a combination of these were to occur. For example, the train encounters a signal aspect that requires the train to reduce speed.

When an exposure to risk occurs, the simulation will trigger the human error or component failure according to best estimates of the probabilities of such occurrences. A sequence of events transpires, and correction or failure to address the original error, along with the proximities of adjacent trains, will result in hazards or accidents with predictability that approximates events in the real world.

For example, a train approaching a location that requires a speed reduction is an exposure (or opportunity for an error), and a failure to comply with the reduced speed because of a human error would further expose the train to a hazardous condition and the possibility of an accident. If the excessive speed is too great, and there is no late brake application, a derailment could result.

Only full simulation of train operations, hazards, errors and failures, and accidents can provide a complete assessment of exposure and its variability within a complex railroad operating environment. Because accidents are rare events, the simulation must run for a very long time, typically tens or even hundreds of years, to generate statistically reliable estimates of accident frequencies; this is impractical. This limitation is addressed by rare-event simulation techniques in GTMS.

GTMS is a computer system that has been under development by FRA since 2005. GTMS integrates a full rail system simulation capability with risk assessment modeling and advanced rare-event simulation techniques.

GTMS addresses the problem of impractically long simulations for risk assessment by using a simulation in stages methodology, which has the advantage of generating statistically reliable estimates while requiring limited computer resources. Chapter 3 describes the analysis methodology.

1.4   Organization of the Report

The analysis in this case study uses GTMS to assess risk before and after the implementation of PTC. The specific rail line corridor under evaluation is the BNSF San Bernardino subdivision, approximately 67.9 miles in length, between West Redondo (near downtown Los Angeles) running east-west to the town of San Bernardino (also referred to as "the corridor" in this case study). The corridor consists mostly of two main track parallel lines, with some sections having three main tracks. The territory is reverse-signaled with CTC and is used for both freight and passenger train

traffic. Used by multiple train operators, it is one of the most complex and busy railroad corridors in the country. The traffic in the corridor passes through heavily populated areas, and there are approximately 130 daily trains operating in the corridor.

The case study chapters are organized as follows:

Chapter 3 provides a detailed review of the math and statistical methodology implemented within the GTMS computerized system to generate the risk assessment results. Readers may skip this chapter and go directly to Chapter 4 and still gain a full understanding of the case study results.

Chapter 4 describes the San Bernardino physical characteristics, infrastructure, traffic, and operations. All aspects of train operations discussed in this section, and their interactions with the I-ETMS system, were explicitly implemented in the GTMS simulations.

Chapter 5 describes the GTMS analysis framework and the models of PTC-preventable accidents that are the focus of the analysis. The framework description is followed by an overview of the risk models and causal chains. The remainder of the section is devoted to a presentation of the risk model parameters and the parameter values used in the analysis.

Chapter 6 presents the findings of the BNSF San Bernardino corridor analysis using GTMS, with the framework, models, and inputs described in the previous chapters. The findings are for both the Base Case, without PTC, and the Alternate Case, with PTC fully operational in the corridor.

Chapter 7 shows a description of the sensitivity analysis and its results. An important test of the robustness of the GTMS results, and one prescribed by the PTC Rule, is an analysis of the sensitivity of the results to changes in key inputs. In particular, the analysis seeks to validate the finding that I-ETMS all but eliminates PTC-preventable accident risk even when key inputs vary significantly.

Chapter 8 summarizes the conclusions drawn from the results discussed in Chapters 6 and 7.

2. Analysis Methodology

2.1 Introduction

This chapter begins with a discussion of the requirement for a risk assessment and the "Safety Case" for the I-ETMS integrated system. This discussion is then followed by a summary of the GTMS risk assessment methodology. Simulations of railroad operations are widely used in planning railroad services and can be adapted for risk assessment by using human factor and equipment failure models and integrating these into operational simulations.

Note: This chapter contains highly technical material. Readers may skip this chapter and refer back to it if seeking more in-depth background of the analysis methodology.

2.1.1 About Simulation

Simulation, generally speaking, is the imitation of real phenomena with a set of mathematical formulas. Essentially, simulation is a program that allows the user to replicate an operation or process without actually performing it. In order for a simulation to be meaningful with respect to its objectives (e.g., measure the effects of modified infrastructure on operational delay; predict accident occurrence) it should:

- Include all of the relevant elements that contribute to the process under examination;
- Validate against actual performance measures; and
- Capture the effects of uncertainty, as reflected by random occurrences and model inputs that are best represented as random variables.

A later section of this chapter describes the GTMS model and its development and how these principles were incorporated in GTMS and the BNSF-SBC analysis.

2.1.2 Modeling the Effects of Uncertainty on Simulation Outcomes

Simulation of real world systems typically involves factors that are uncertain, and these factors are usually modeled as random variables with defined probability distributions. The probability distributions and their underlying parameters are derived from a combination of best practices and available empirical evidence adapted to the specifics of the operations under consideration. The simulation will typically require many values of the uncertain input. Values are drawn from the probability distribution of the random variable representing the uncertain input using a technique called Monte Carlo (MC) sampling [7]. MC sampling is a numerical method of selecting input values for use in the model, so that the values are distributed in accordance with the random variable's probability distribution. With MC sampling, the simulation outcomes are reflective of the effects of uncertainty, as in the real world.

For the simulation of rail operations, train departure delay and certain dispatcher actions are modeled as random variables. For safety risk, human factor and equipment failure models have uncertain inputs that are modeled as random variables, as well. MC sampling is applied to these random variables in operational and risk simulations.

2.1.3 Fixed-Period Simulation and its Limitations

Simulations of rail operations that do not consider safety risk are usually conducted for a fixed period of operations: several hours, days, or one week. When using simulation to inform decisions about commonly occurring events (e.g., operational delay), a fixed-period simulation of limited duration generally produces meaningful results. However, examining rare events like accidents with fixed-period simulation has limited usefulness because a simulation of very long duration is needed:

1. To represent properly the day-to-day variability in operations on a typical U.S. freight railroad with highly variable schedules, and

2. To generate enough rare accident events to yield statistically meaningful outcomes.

The second point above, generating enough accidents, is seen to be so acute as to render impractical fixed-period simulation for risk assessment.

Consider the risk assessment of a rail system using fixed-period simulation (that is, a simulation of rail operations with integrated modeling of errors and failures leading to PTC-preventable hazardous events and accidents). The fixed period of simulation can be viewed as repeated trials of 1-hour duration in which an accident can occur, or not. The count of predicted accidents in the simulation is a binomial random variable [8]. The standard estimator of a rare-event (i.e., accident) probability is the number of simulated rare events (i.e., predicted accidents) divided by the simulation fixed-period of operations. Another measure of risk is the inverse of annual predicted accidents, or the mean time to accident (MTTA).

If the accident probability is, say, 0.2 predicted accidents per year, then the MTTA is 5 years. It is clear that statistically reliable estimates of accident probability and MTTA will require a sufficient number of predicted accidents and a correspondingly long period of simulation, which indicates that fixed-period simulation requires a period of operations at least several times the MTTA.

The research shows that the statistical reliability of the accident probability estimator increases as a square root of the inverse of the number of predicted accidents (or duration of the simulation). [9] This finding indicates that fixed-period simulations may become impractically long: Increased statistical reliability comes at the cost of a much longer period of operations and use of computer resources.

For an illustrative example, Figure 2.1 below shows confidence intervals for probability of accident and the corresponding MTTA as a function of predicted accidents.

Figure 2.1 Confidence Intervals for Accident Probability and MTTA
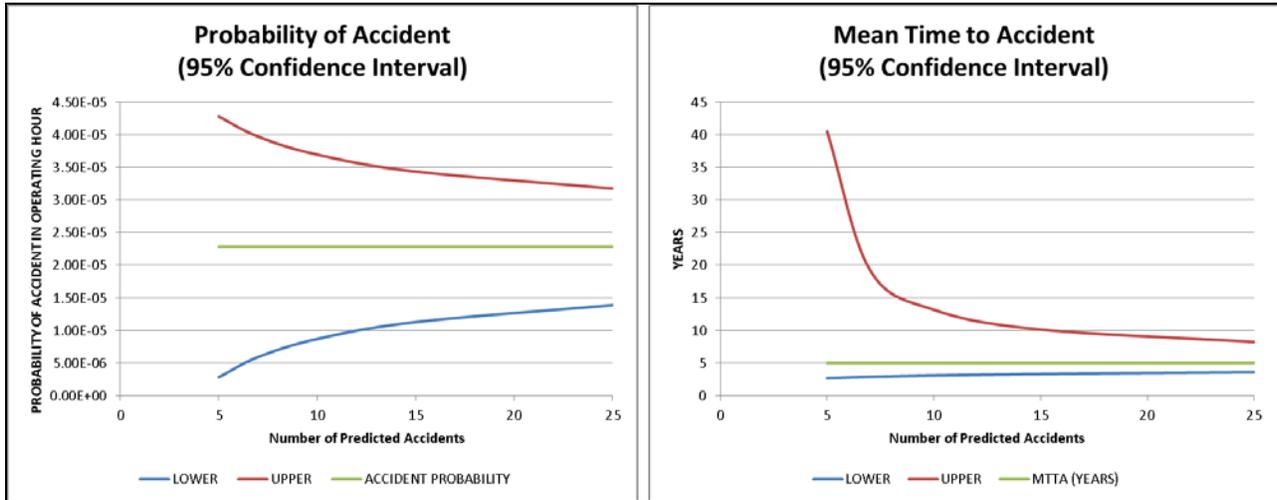
In this example, the MTTA is 5 years. [10] A fixed-period simulation of 25 years yields five predicted accidents, and the upper 95 percent confidence band for the accident probability is 88 percent greater than the mean value. If the fixed-period simulation is increased to 125 years and 25 accident events are generated, the upper 95 percent confidence band of the probability is 39 percent greater than the mean (simulation time grows fivefold, while the confidence half-band decreases from 88 to 39 percent of the mean – 39 is 88 over the square root of five). This illustrates that greater reliability of the accident probability estimator comes at the great cost of computational resources.

In the above example, suppose 25 simulation-generated accidents for the probability estimate with greater reliability were sought, which would require a fixed-period simulation of 125 years. In the BNSF-SBC, there are approximately 1.6 million train-miles of operations per year. Given the complexity of the corridor and with current computer technology, a rate of roughly 20 simulated train-miles per second is possible. At this rate, approximately 90 days of computer resources [11] would be required to generate the simulated accidents. (Ninety days is required for a 95 percent confidence interval of the accident probability estimator that is mean value $\pm$ 39 percent. To achieve a 95 percent confidence interval of mean value $\pm$ 10 percent, 1350 days of computer resources would be required.)

Also note that the length of fixed-period simulations and issues of statistical reliability are further compounded when considering multiple accident types (e.g., collisions and derailments).

2.1.4 Simulation in Stages

GTMS adopts a simulation method more appropriate for rare-event simulation than fixed-period simulation: "multi-level splitting" or "simulation in stages." [12]

This approach "splits" the simulation into stages at events that have an elevated level of risk and are closer to the rare event, or accident. The events of interest at each stage are described in causal chains that lead to accidents.

With simulation in stages, when an event of interest occurs that brings the simulation closer to the sought after rare event, the system state is stored. These stored system states are used as starting points for the subsequent simulation stage. In this way, the problem space is reduced and the analysis focuses on those paths that have some probability of culminating in an event of interest

9

while ignoring those paths that have no such probability. This system yields a comprehensive risk assessment that is conducted within practical constraints, while providing statistically reliable outcomes.

In the example from the previous section, accident probability estimate confidence intervals of mean $\pm$ 88, 39, and 10 percent were achieved with computer run times of 16, 90, and 1,350 days, respectively. Using simulation in stages, the same probability estimate confidence intervals could be achieved in 4, 4.5, and 5 days. [13]

Simulation in stages is well suited for predicting railroad accidents or incidents. Generally, the path to a train accident or incident follows a well-known causal chain, which incrementally elevates the risk of the system until all preconditions for an accident are met. For example, one causal chain for a head-to-head collision accident occurs as follows: from the point at which a train approaches an approach signal at caution, indicating that the next signal will show a stop aspect announcing the end of the train's movement authority. The following three steps describe this causal chain:

1. A train crew fails to initiate timely braking when approaching its end of authority.

2. The train exceeds its authority, entering a block in which it has no movement authority.

3. A second train is granted authority for the block it enters and may collide with the first train depending on their relative positions, speeds, and other factors.

Each event in this example brings the system closer to an accident and is thus defined as the start of a new simulation stage. Alternatively, the train crew may realize their error and initiate emergency braking to restore safe operation, or a PTC system may intervene to initiate penalty braking.

The overall process is illustrated in Figure 2.2 and is described in detail below.

Figure 2.2 Simulation in Stages
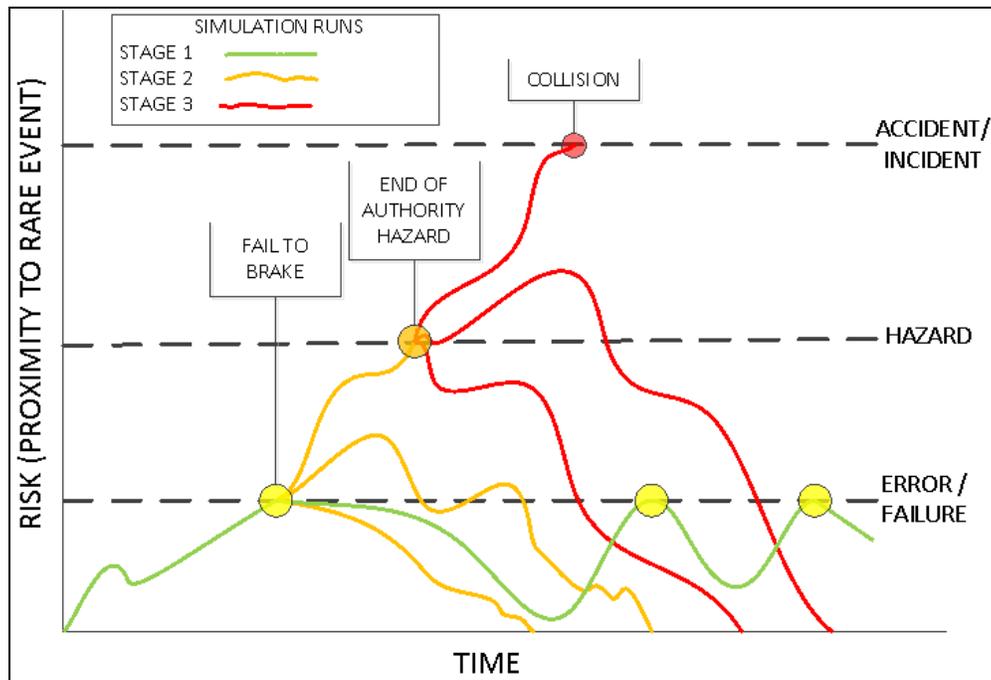
The simulation is conducted in stages. At each stage, available computing resources are used to generate "events of interest," or occurrences, for that stage. In the first stage, the sought-after events are those that initiate the causal chains that lead to accidents. Using our previous example, a Stage 0 event (an error or failure) would be: "Train crew fails to initiate timely braking when approaching its end of authority." During a Stage 1 simulation, trains are permitted to run in the system for a specified time period (say, 5 years). When a Stage 1 event of interest occurs, the simulation does the following:

1) The system state is captured and stored, and then

2) The human error/system failure is corrected for continued safe rail operations.

The "system state" is the entire simulated railroad operating environment at the time of the occurrence and includes the time, position, and speed of each train, the position of each switch, the aspect of each signal, and all movement authorities that have been granted by the central dispatcher and traffic control system. At the end of a Stage 1 simulation run, a pool of system states has been captured at each point where a causal chain originating event has occurred. In Figure 2.2, the Stage 1 event is shown as Error/Failure on the right side of the figure.

Stage 2 simulation runs generate events that extend the causal chains initiated in Stage 1. Revisiting our previous example, a Stage 2 event would be: "The train exceeds its authority, entering a block in which it has no authority to proceed." To generate events, the Stage 2 simulation run randomly samples from the pool of system states captured in Stage 1, and each Stage 2 simulation run resumes at the point at which its system state was stored. By simulating in this manner, each Stage 2 simulation run begins from a Stage 1 event and thereby has a better chance of generating a Stage 2 event rather than just continuing simulated operations along random paths. The method brings the system closer to generating the rare event with much less computational resources. When a Stage 2 event occurs, the simulation does the following:

1) The system state is captured and stored, and then,

2) The simulation run ends, prompting the Stage 2 simulation to sample a new system state from the Stage 1 pool of stored system states.

The simulation run also ends if an intervention (such as late braking by train crew or intervention by a PTC system) prevents a Stage 2 event. In Figure 2.2, the Stage 2 event (initiating event for Stage 3) is shown as Hazard on the right side of the figure.

A simulation in stages can have as many stages as needed to control the unfolding of causal chains (the GTMS Risk Assessment Framework has three stages). All simulation stages after Stage 2 follow the same process, sampling from the previous stage's pool of system states in order to generate a new event of interest in the causal chain. In the final stage, rare events are generated (shown in Figure 2.2 as Accident/Incident on the right side of the figure).

2.1.5 Risk Metrics with Rare-Event Simulation in Stages

The analysis seeks risk metrics expressed as MTTHE, in accordance with the requirements of the PTC Rule. Using the earlier example of head-to-head collisions, the probability of such accidents can be estimated after a sufficient number of these are generated, using a series of outputs produced in each stage of the simulation.

The probability of a head-to-head collision can be stated as the mean time to accident, defined as:

$$(1)\ MTTA_{HHC} = MTTH/p_{HHC|EAH}$$

Where:

- $MTTH$ is the mean time to hazard, or the Stage 2 event of interest from which the accident was generated, and

- $p_{(HHC\ |EAH)}$ is the probability of a head-to-head collision, given that a hazardous condition has occurred. In this case, a train exceeds its authority, possibly encroaching on a block authorized to another train.

At each stage, the probability of the stage event of interest, or p, is equal to the number of occurrences divided by the number of simulation runs required to generate those occurrences. The conditional probability of a rare-event rail accident is $p_1 * p_2 * p_3$, where subscripts 1, 2, and 3 indicate the events of interest at stages 1, 2, and 3, respectively.

The mean time at each event of interest in a stage is the mean time to the previous stage event of interest divided by the current stage probability, except for Stage 1. The mean time to Stage 1 event of interest is equal to the total hours of Stage 1 simulation run, or period of simulated operations, divided by the number of errors or failures generated during that time. The formulae for simulation in stages metrics are as follows:

Stage 1

- Mean time to error or failure is defined as:

$$(2)\ MTTEE = T_E/N_E$$

Where: T_E are the total hours of operations in Stage 1, and N_E is the number of error and failure events generated in Stage 1.

Stage 2

- Probability of a hazardous event, given a human error or equipment failure:

$$(3)\ p_{H|E} = N_H/n_{T2}$$

Where: N_H is the number of hazardous events generated in Stage 2 and n_{T2} is the number of Stage 2 simulation runs.

- Mean time to hazardous event, defined as:

$$(4)\ MTTH = MTTEE/p_{H|E}$$

Stage 3

- Imputed probability of an accident:

$$(5)\ p_{A|H} = N_A/n_{T3}$$

Where: N_A is the number of accidents generated in Stage 3 and n_{T3} is the number of Stage 3 simulation runs.

- Mean time to accident, defined as:

$$(6)\ MTTA = MTTH/p_{A|H}$$

From these formulae can be derived conditions for the sufficiency of the duration of the Stage 1 simulation and the numbers of runs for stages 2 and 3 simulation, as well as an optimal allocation of computer resources across stages. [14] A simple test for the sufficiency of the number of runs at each stage demonstrates that estimated mean conditional probability and its variance are stable and do not change with added runs.

2.1.6 Optimizing the Number of Runs at Each Stage

One of the issues addressed in the paper [15] describing the rare-event simulation method adopted in GTMS is the challenge of optimizing the number of runs at each stage.

- The condition for getting the most "bang for your buck" in terms of computer resources is given in the following equation:

$$(7)\ n_1\sqrt{b_1 p_1} = n_2\sqrt{b_2 p_2} = n_3\sqrt{b_3 p_3}$$

where n, b, and p correspond to the number of runs, the cost per run, and the probability of event of interest at each stage.

2.2 The GTMS Risk Assessment Framework and the BNSF-SBC Analysis

GTMS is a general analysis framework that can be applied to the risk assessment of PTC on any territory in the United States. The analysis of the BNSF-SBC with GTMS is a corridor-specific implementation and validation .

The development of the GTMS analysis of the BNSF-SBC proceeded in two phases, namely:

- Development of the GTMS models and Risk Assessment Framework

- Implementation of the BNSF-SBC in GTMS

The GTMS models and framework have been under development by FRA for the past several years, while the BNSF San Bernardino analysis was recently implemented in GTMS.

The rest of this chapter discusses the steps involved in developing GTMS models and framework, as well as the steps required to implement the BNSF-SBC in GTMS.

2.2.1 GTMS Models and Framework

The GTMS Risk Assessment Framework implements the simulation-in-stages methodology described in the previous sections, and within it a number of models run and interact. The principal models in GTMS are:

- Operational Model

- Risk Model, which includes:
    - Human errors and failures model
    - Hazards and accidents model

The modeling of risk with GTMS is applied only after the affected railroad concurs that the GTMS simulation modeling of its territory accurately captures the operating environment. The GTMS risk model is overlaid on the operational model to capture errors, failures, hazards, and accidents. The GTMS Risk Assessment Framework implements the simulation-in-stages methodology on the integrated operational model with risk.

Table 2.1 summarizes several of the key terms related to the GTMS modeling.

Table 2.1 Summary of GTMS Modeling Terms and Definitions

GTMS Term	Definition
Operational Model	Model of the railroad operational environment including: track infrastructure, grades, curvature, speed zones, traffic by train type and consist, timetables, random departure delay, traffic control and dispatching, train crew directives (e.g., Forms A and B), and work zones
Risk Model	Human factor models of error prediction and engineering models of equipment failure; empirically validated model parameters; and causal chains leading to hazards and incident/accidents – integrated with the operational model

Risk Assessment Framework	Framework for running the risk model and predicting errors/failures, hazards, incidents/accidents, and associated risk metrics (e.g., MTTE, MTTHE, MTTA) using simulation-in-stages

At the core of the GTMS Risk Assessment Framework are two inter-connected simulation models: the operational model and the risk model.

2.2.2 The GTMS Operational Model

The GTMS rail simulation operational model is supported by an extensive set of infrastructure and operational data. The model uses a hybrid of fixed time interval and discrete event simulation: train movements are calculated as discrete events, and these are synchronized to a fixed time interval specified by the user (typically, a value between 30 seconds and 5 minutes). The two principal analytic components of the rail system simulation model are the train movement submodel and the dispatcher submodel. The train movement submodel calculates the forces on the train, including the tractive effort, the braking force, and the resistance forces—grade, curve, and aerodynamics. The train receives its routing information and authority to move from the dispatcher, and it accelerates and decelerates according to its effective speed limit, which is derived from the track speed limit and the authority granted to the train. Trains advance with small incremental changes in speed until the forces on the train are in balance (subject to the speed limit). The resistance forces on the train are recalculated on a car-by-car basis every 500 feet to account for changes in speed, grade, and track curvature.

The dispatcher submodel operates on a node network that is overlaid on the real world network of control blocks. A node represents a minimally sized resource that can only be authorized to a single train at a time. The dispatcher determines the path of trains through the network and grants authorities for movement. Authorities are granted in order to achieve safe separation of trains, facilitate train meets, and overtake lower priority trains. The dispatcher submodel grants an authority to a train only if the movement of the train is free of conflict and will not cause a deadlock. Authorities are revoked only after a train has traversed and exited the authorized block. Through the dispatcher submodel and the configuration of control blocks, alternative train control systems can be simulated. With each iteration of the train movement and dispatcher submodels, the system records data indicating the time, speed, and position of each train and the status of movement authorities granted and revoked.

2.2.3 Human Errors and Equipment Failures Model

Human errors and equipment failures are the initiators of causal chains that potentially evolve to hazardous situations or accidents. In GTMS, as trains traverse the system, there are points where:

- Train operators need to perform an operation in response to a directive (signal, work zone, or speed restriction;
- Trains intersect with infrastructure devices (i.e., switches)

When operator actions are required, the human factors model stochastically determines whether the appropriate action is taken, or the operator commits an error. If an operator commits an error, there may be opportunities for corrective action, determined by a correction function.

Equipment failures of conventional and PTC equipment are allowed to occur in accordance with failure models and empirically based failure rate estimates.

2.2.4 Hazards and Accidents Model

Hazards and accidents in GTMS evolve according to pre-determined causal chains. For example, an end-of-authority hazard can occur if an operator fails to brake when approaching the end of a train's movement authority and encroaches upon an adjacent block in which it has no authority. The hazard may result in a collision if a second train is in the block.

Appendix A contains diagrams of all the causal chains that are implemented in GTMS.

2.2.5 Implementation in GTMS

In GTMS, the rare-event simulation in stages is applied to operations in a railroad territory. The principal actions involved are:

- Preparation of input data for the analysis

- Running each of the simulation stages

- Post-processing simulation and review

Figure 2.3 illustrates the GTMS processes, showing the analysis steps from the top left hand corner to right bottom corner.

The boxes on the left hand side of the diagram detail all the inputs that the analyst specifies, including details of the infrastructure, train schedules, railroad operations, and applicable risk parameters such as human reliability inputs, failure rates, and accident or incident severity.

The second column from the left illustrates the simulation in stages 1, 2, and 3. At each stage, simulation outputs are stored for reporting to the analyst and to provide the inputs for the following analysis stage. As described above, analysis Stage 1 results are derived from a continuous simulation of railroad operations for a long enough period to generate sufficient Stage 1 events (errors and failures) for reliable analysis. Then events generated at Stage 1 are stored and sampled to initiate Stage 2 simulations. Sufficient Stage 2 simulations are performed to generate a statistically reliable sample of Stage 2 events. The results are considered statistically reliable when the ratio between Stage 1 and Stage 2 events is stable and does not change with additional simulations. This process is repeated by sampling Stage 2 results to initiate Stage 3 simulations.

The third column from the left shows the simulation outputs that are stored for later analysis. These logs provide full details of the simulated operations and the errors, hazards, and accidents and incidents that are generated by the stage simulations.

Finally, the stored results are analyzed to provide summary results that describe key features of train operations over the line segment under analysis, as well as the estimated risk of accidents and precursor errors and hazards. The right-hand column shows the specific information provided by this final analysis step.

To assess the risk of a PTC system, a full analysis is conducted for a Base Case without PTC and an Alternate Case with PTC. An average severity (i.e., cost per accident) is assigned to each accident category (e.g., head-head collision, head-tail collision, derailment) to assess the total risk in each of the two cases. Aggregated predicted accidents, monetized by respective costs,

determines whether the alternate case with PTC sufficiently mitigates PTC-preventable risk as prescribed by the PTC Rule.

Figure 2.3 GTMS Process Diagram
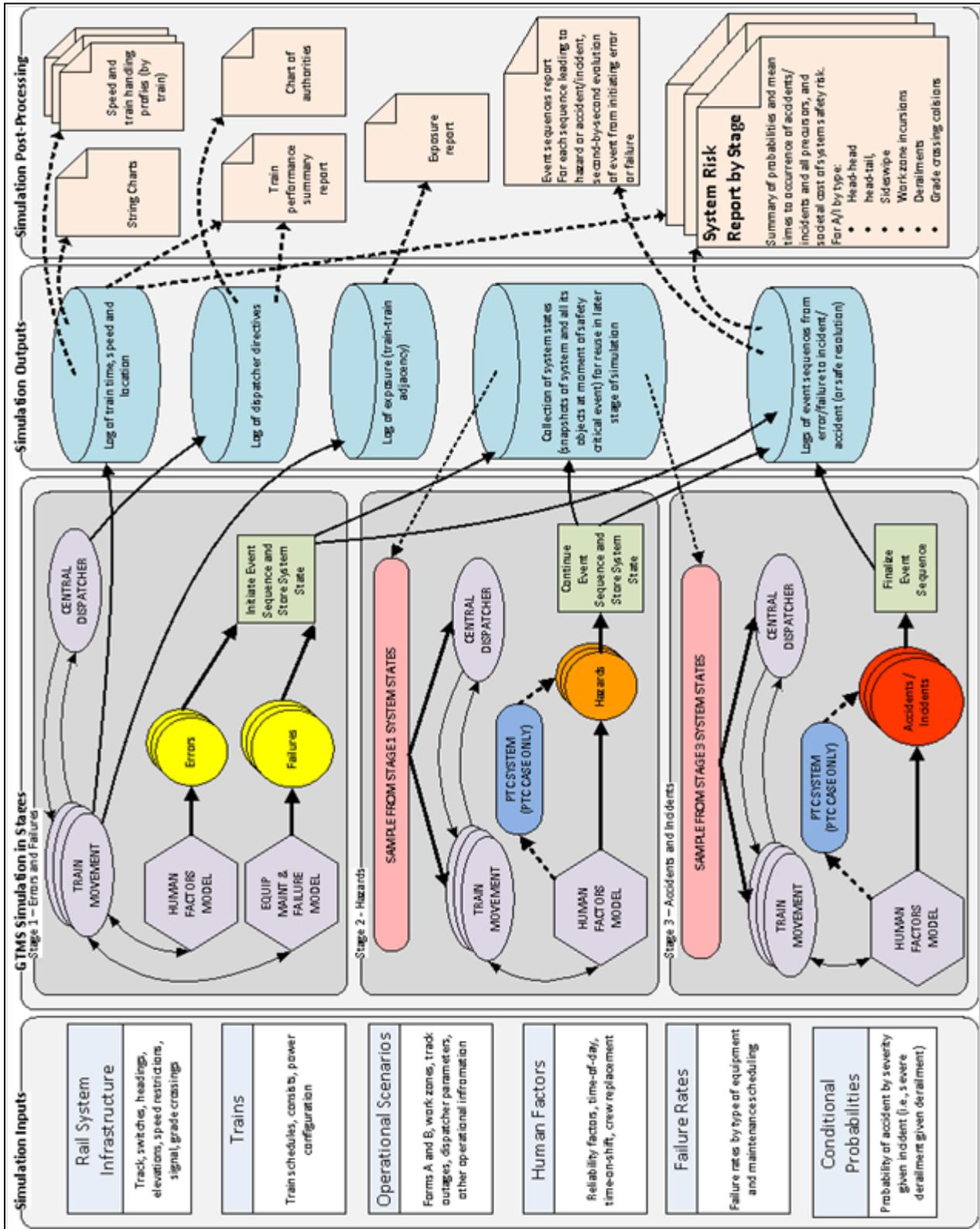
2.2.1 Additional Refinements to GTMS Risk Assessment Framework

Two additional refinements were made to the GTMS Risk Assessment Framework to improve the manageability of GTMS analyses. These refinements are related to the system's ability to:

- Pool runs, and

- Ensure sufficient coverage of hazards of different types that occur with different frequencies.

These refinements do not introduce bias, nor do they impact the statistical reliability of the outcomes.

Pooling of Runs

Stage 1 simulations extend over a defined period of operations, while Stage 2 simulations run for multiple trials. It is advantageous from a manageability standpoint to break simulations into pieces and pool the results for analysis in the subsequent stage. Shorter simulations in Stages 1 and 2 would be less prone to lost effort in the event of a system crash, and multiple runs could be conducted in parallel, thus reducing the overall time to conduct an analysis.

In the Risk Assessment Framework, rather than specifying one predecessor simulation, the user has the option of specifying multiple predecessors. For example, a Stage 2 simulation can specify 20 Stage 1 simulations, each covering a 3-month period instead of a single 5-year simulation. In a Stage 3 simulation, the user can specify 4 Stage 2 simulations of 500 trials each instead of a single simulation with 2,000 trials. The durations of Stage 1 simulations and the number of Stage 2 simulation trials need not be uniform in order to pool them.

GTMS allows the user to ensure that each shorter simulation is sufficiently initialized before capturing errors or failures, not including the period of initialization, so that "clear track" conditions are not given undue weight in the analysis.

The GTMS Risk Assessment Framework ensures that stored states from the previous stage are randomly selected with the correct frequency, and that risk metrics are correctly calculated to account for the effects of pooling.

Stratified Sampling to Cover Hazard Types of Different Frequencies

In a Stage 1 simulation, an "opportunity for an error" (e.g., red signal) may result in an error (e.g., failure to brake), which, in the Stage 2 simulation, may result in a hazard (e.g., train exceeds authority). Another possible sequence is that a civil speed restriction goes unheeded, resulting in an over-speed hazard.

A Stage 1 simulation may yield results that include, say, 100 errors where 90 of them are fail to heed speed restrictions and only 10 fail to brake at end-of-authority. To ensure that in Stage 2 simulations there is sufficient sampling from the lower frequency errors, GTMS allows stratified sampling so that the more rare Stage 1 events are selected with sufficiency in Stage 2 simulations. Lower frequency events are sampled first a number of times, then the rest of the trials are selected from the higher frequency events.

Sampling in this way ensures the rare errors are not overwhelmed by the higher frequency errors. The summary statistics account for the number of samples from the previous stage error so that the result metrics are correct and unbiased.

3. The San Bernardino Corridor

This section of the case study describes the San Bernardino physical characteristics, infrastructure, traffic, and operations. All aspects of train operations discussed in this section, and their interactions with the I-ETMS system, were explicitly implemented in the GTMS simulations.

3.1 About the Corridor

The BNSF San Bernardino Subdivision is a railroad corridor owned and operated by the BNSF Railway Company. One additional freight railroad (UP) and two passenger railroads (Amtrak and Metrolink) also conduct daily operations on the corridor. The corridor extends for 67.9 miles from West Redondo (near downtown Los Angeles) to the town of San Bernardino.

The corridor consists mostly of two main track parallel lines, with some sections having three main tracks. The corridor is reverse signaled (i.e., permitting traffic in either direction on each track) with CTC throughout and is used for both freight and passenger train traffic. It is one of the most complex and busy railroad corridors in the country; tracks are used by multiple train operators, the trains run through heavily populated areas, and close to 100 trains operate daily along parts of the corridor.

Figure 3.1 The BNSF San Bernardino Corridor
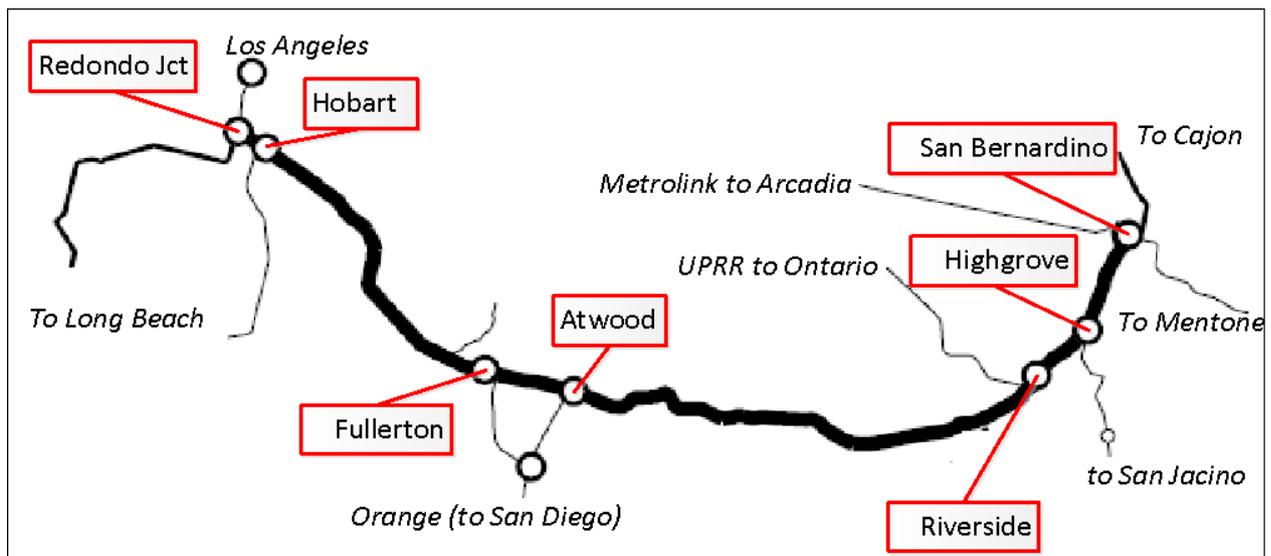
3.2 The Corridor and its Operations

3.2.1 Physical Characteristics

The 67.9 mile long San Bernardino subdivision runs along the Santa Anna River. The grade is generally minimal (under 0.5%) with a few portions having a mild grade (up to 1.08%). The main line has no sharp curves.

3.2.2 Infrastructure

The corridor starts with two main tracks at West Redondo (at milepost 143.19). To the two main tracks a third main track is added at Hobart, milepost 145. At Serapis, milepost 151, the corridor narrows to two main tracks until Valley View, milepost 159, where the corridor widens again to three main tracks. (A third main track is currently under construction between Serapis and Valley View.

[16]) At Fullerton Junction (milepost 165, which changes to milepost 45.7) the corridor narrows to two main tracks, until Esperanza, milepost 32, where three main tracks resume. The corridor narrows to two main tracks, again, at Prado Dam, milepost 26, until West Riverside, milepost 10, where UP's Los Angeles subdivision trains enter the BNSF corridor on track rights, and the corridor widens to three main tracks. The third track runs until Highgrove, milepost 6, where the corridor narrows to two tracks. Further north, UP's Alhambra Subdivision tracks cross the corridor at-grade at Colton Crossing milepost 3.2. Currently, a project is underway to separate the two tracks; project completion is slated for 2014. At milepost 3, the third track resumes, and at Rana, milepost 2.3, a fourth main track is added; this main track takes a shorter route until it meets the other three main tracks at San Bernardino, where the corridor ends.

The corridor contains 280 switches, with power crossovers located every 2–3 miles until Fullerton Junction and every 5–8 miles from Fullerton Junction east. Along the track are three wayside hot box detectors.

The corridor implements CTC, with 372 fixed signals in the corridor.

Speed Limits

The general speed limit for passenger trains is 79 mph from San Bernardino to Fullerton Junction and 60 mph from Fullerton Junction to San Bernardino. General freight train speed limit is 50 mph. There are 1,053 civil speed restrictions in the corridor. Along the corridor, there are a number of yards located at Hobart milepost 145, La Miranda-Bandini milepost 149, Pico Rivera milepost 151, La-Miranda milepost 158, Corona milepost 23, and San Bernardino milepost 1.

Stations

There are a number of passenger stations in the corridor supporting the commuter rail services. The passenger train stations are:

1. Norwalk
2. Buena Park
3. Fullerton Junction
4. West Corona
5. North Main Corona
6. La Sierra
7. Riverside
8. San Bernardino

Grade Crossings

Since the corridor runs through heavily populated areas, there are numerous highway-rail intersections. Many of these are grade separated, but 156 at-grade crossings remain. The active grade crossings in the corridor are protected by flashing lights and gates. Some of the grade crossings have large volume highway traffic. Valley View Drive—designated for grade separation in the near future—has an average annual daily traffic (AADT) of 40,000 vehicles.

A detailed view of the track infrastructure in the corridor can be found in Appendix B: GTMS Track Tool Charts.

3.2.3 Traffic in the Corridor

Train volumes in the San Bernardino corridor are heavy, and in some portions of the corridor there are 100 or more trains per day. Passenger and freight trains operate in the corridor. Passenger trains include long distance Amtrak intercity service, an Amtrak regional service, and three Metrolink commuter services. Freight trains include BNSF trains that operate the length of the corridor and UP trains that move between West Riverside and Colton, with some continuing between Colton and San Bernardino.

Train traffic and train consists for this case study were based on BNSF records of actual train movements over a 35-day period (August 2, 2011, to September 4, 2011). These records were supplemented with the Metrolink and Amtrak timetables. The traffic data used in the analysis closely matches that published in the Southern California Association of Governments (SCAG) Regional Rail Study. [17]

Appendix C: Scheduled Trains in the Corridor contains a detailed list of trains that served as the basis for the operating plan of the GTMS simulations.

Passenger Traffic

Passenger trains follow strict schedules that change infrequently. On most days, few passenger trains incur significant delays, with the exception of the long distance Amtrak train coming from Chicago, which often enters the corridor at San Bernardino with significant delay. Below is a summary of the traffic along the San Bernardino corridor:

1. Amtrak Long Distance Train (Southwest Chief)
    a. Route: San Bernardino – West Redondo and return.
    b. Stations: None.
    c. Frequency: Once a day each direction.
2. Amtrak Regional Trains (Pacific Surfliner)
    a. Route: Fullerton Junction – West Redondo and return.
    b. Stations: Fullerton Junction.
    c. Frequency: 11 trains per day each direction.
3. Metrolink Orange County Line
    a. Route: Fullerton – West Redondo and return.
    b. Stations: Buena Park, Norwalk, Commerce, (not all trains).
    c. Frequency: 10 westbound, 9 eastbound on weekdays, 4 each way on weekends.
4. Metrolink Inland Empire – Orange County Line
    a. Route: San Bernardino/Riverside – Atwood and return.
    b. Stations: San Bernardino (not all trains), Riverside, La Sierra, North Main Corona, West Corona.
    c. Frequency: 8 in each direction on weekdays. Two each direction on weekends.
5. Metrolink Riverside Line
    a. Route: Riverside – West Redondo and return.
    b. Stations: Riverside, La Sierra, North Main Corona, West Corona, Fullerton, Buena Park, Norwalk.

Frequency: 4 trains westbound, 5 eastbound (weekdays only).

Freight Traffic

Freight traffic through the corridor consists of Intermodal, Unit, and General trains. BNSF freight trains operate the length of the corridor from Redondo West to San Bernardino and return. Most of the traffic originates from or is bound to the Ports of Los Angeles and Long Beach. UP has track rights on BNSF San Bernardino Subdivision between Riverside and Colton, which connects UP's Alhambra and Yuma Subdivisions. All UP trains originating in the Los Angeles area use this section. Additionally, several UP trains continue from Colton to San Bernardino and from there connect to UP's Mojave Subdivision. Train operations were based on average train weight and length.

1. Bare Flat Intermodal Trains (B trains)

    a. Daily average of eight bare flat intermodal trains; one from West Redondo to San Bernardino; seven from San Bernardino to West Redondo.

2. Guaranteed Service Intermodal Trains (Q trains)

    a. Daily average of eight guaranteed intermodal trains; five from West Redondo to San Bernardino; three from San Bernardino to West Redondo.

3. Container Stack Intermodal Trains (S trains)

    a. Daily average of 10 container stack intermodal trains; five from West Redondo to San Bernardino; five from San Bernardino to West Redondo.

4. Priority UPS Intermodal trains (Z trains)

    a. Average of five priority UPS intermodal trains; four from West Redondo to San Bernardino; one from San Bernardino to West Redondo.

5. Local Trains (L trains)

    a. Three local trains from San Bernardino to West Redondo.

6. Merchandise Trains (M trains)

    a. Two daily merchandise trains from West Redondo to San Bernardino.

7. Empty Unit Grain Trains (X trains)

    a. One daily empty unit grain train from West Redondo to San Bernardino.

8. Vehicle Unit Trains (Autos and Auto Parts, V Trains)

    a. One daily auto train from Atwood to San Bernardino.

9. Loaded Unit Grain Trains (G trains)

    a. Four times a week from San Bernardino to West Redondo.

10. UP Freight Trains (F Trains)

    a. Daily average of 11.42 UP freight trains between Riverside and Colton.

    b. Daily average of 2.14 UP freight trains between Colton and Riverside.

None of the BNSF trains make regular stops on the corridor. UP trains operate over a short distance in the corridor, interchanging with adjacent UP track, and make no stops on the corridor.

3.2.4 Track Maintenance Work Zones

BNSF issues Form B track bulletins in accordance with General Code of Operating Rules (GCOR). The track bulletins specify the affected track and time period (usually between 8 and 10 hours) for which the Form B is in effect. When a Form B is in effect, all trains must slow to a restricted speed and must receive permission from an employee-in-charge (EIC) before proceeding into the work zone.

BNSF provided Form B data for the period from August to November 2011. The Form B operating constraints were implemented in GTMS, and all trains were required to observe any Form B in effect. GTMS tracks failures to heed Form B and resulting work zone incursions and incidents.

The analysis work zones were representative of the provided data. The specific times and locations of the simulated work zones were as follows:

- Saturday 6 p.m. to 4 p.m. between Fullerton and Atwood
- Tuesday 9 p.m. and 2 a.m. in the Esperanza area
- Thursday 9 p.m. to 2 a.m. between Buena Park and Basta
- Monday 9 p.m. to 2 a.m. between Bandini and Los Nietos

4. Risk Assessment Models and Assumptions

4.1 Introduction

This section describes the GTMS analysis framework and the models of PTC-preventable accidents that are the focus of the analysis. The framework description is followed by an overview of the risk models and causal chains. The remainder of the section is devoted to a presentation of the risk model parameters and the parameter values used in the analysis.

4.2 The GTMS Analysis Framework

The analysis framework seeks to meet, in part, the requirements of a PTC safety plan as mandated by the PTC Rule. Based on data provided by BNSF, the physical plant and operations on the territory were modeled in GTMS. The risk model, accounting for human errors and equipment failures that may evolve to PTC-preventable accidents, was layered on top of the operational model.

Simulation of the San Bernardino corridor is carried out for two risk assessment cases:

- Base Case: San Bernardino Corridor without PTC

- Alternate Case: San Bernardino Corridor with PTC enabled. The I-ETMS PTC system, a vital overlay system, is fully operational in the Alternate Case.

In the Alternate Case, I-ETMS is installed on the San Bernardino Corridor as an overlay to the existing CTC system. This means that the existing safety installations (interlockings, track circuits for signal block occupancy, and wayside block and interlocking signals) are retained. The I-ETMS PTC system adds accurate train location using GPS, a radio communications system linking trains, wayside signals, switches and other devices in the control center, an onboard system that contains a detailed "track map" showing the locations of signals switches, etc., and a system that enforces signal indications, speed limits, and work zone limits. A back office server links these functions and places them under the supervision of the dispatcher.

In more detail, PTC enhances safety by enforcing train movement authorities (with CTC, from signal indications), speed limits, work zone restrictions, and wayside detection alarms (for example, highway-rail grade crossing) as follows:

- Movement Authority Enforcement

   o Predictively enforces end of authority with 75 seconds of a visual alert accompanied at the start by a momentary audible alert prior to enforcement

   o Reactively protects against revoked authorities

   o Includes protection at corridor entrance, transition, and exit (predictive on unambiguous track, reactive on ambiguous track)

- Speed Limit Enforcement

   o Pertains to all permanent and temporary speed limits

   o Predictively enforces impending reduced speed limits with 75 seconds of a visual alert accompanied at the start by a momentary audible alert prior to enforcement

- o Reactively enforces over-speed condition while providing audible and visual alerts (no specific duration) after over-speed occurs until enforcement threshold reached

- Work Zone Enforcement

  - o Predictively enforces entrance into unacknowledged Work Zone with 75 seconds of a visual alert accompanied at the start by a momentary audible alert prior to enforcement

  - o Reactively enforces continued movement after stopping within a Work Zone

- Switch Position Detection

  - o Automatically detects when a switch is out of position, for example due to a defective switch resulting from foreign matter trapped in the mechanism

  - o Automatic detection of a switch that is not aligned for an authorized train movement. Generally used for hand operated switches that are not linked to an interlocking that coordinates switch position with wayside signals.

- Grade Crossing Failure Speed Limit Enforcement

  - o Automatically notifies crew when approaching a failed grade crossing

  - o Predictively enforces impending reduced speed limits with 75 seconds of a visual alert accompanied at the start by a momentary audible alert prior to enforcement

  - o Reactively enforces over-speed condition while providing audible and visual alerts (no specific duration) after over-speed occurs until enforcement threshold reached

  - o Note: This capability is not a standard part of I-ETMS, but may be deployed in limited circumstances. Its evaluation is a GTMS capability

Aggregate risk is determined in the Base and Alternate Cases by assigning an average severity cost to each accident type and comparing the dollar value of accidents/incidents in each case.

4.3 Risk Model and Causal Chains

Beginning with the fully simulated San Bernardino corridor, the GTMS risk model allows human errors and equipment failures to propagate in the system until safe resolution, or until a hazard occurs. Failures occur at random and independently of train movement. Failed equipment remains failed for a period of time equal to the mean time to repair (MTTR), a parameter that is set to 8 hours.

The number of predicted accidents that occur – with and without PTC – determines the efficacy of the proposed PTC system. The case study seeks to quantify the extent to which PTC mitigates Base Case risk and eliminates predicted PTC-preventable accidents.

The GTMS risk model is driven by a number of empirically derived parameters that determine errors and failures; time to correct if an error was committed; and probabilities of certain accidents given hazards.

The risk model parameters are of three basic types:

- Human error parameters – based on error rates by operators

- Correction function parameter – parameter that determines the time interval that transpires until operators recognize and take corrective action after committing an error.

- Equipment failures – train, wayside, or infrastructure devices that fail to operate in the manner in which they were designed to function.

- Probabilities that a hazardous situation will become an incident/accident (For derailments and work zones accidents, train-train collisions resulting from a hazard are determined by simulated train movements.)

PTC minimizes human errors by first warning train crews and, should the crew fail to respond, applying a penalty brake. Similarly, PTC warns and brakes in the event of an unsafe condition due to equipment failure.

Appendix A: Risk Assessment Causal Chains contains the set of sequence diagrams that describes all of the GTMS causal chains.

4.4 GTMS Risk Assessment Framework

The GTMS Risk Assessment Framework uses simulation-in-stages to predict accidents. Each stage concludes when a level of risk is achieved that is closer to an accident.

- Stage 1 – Initiating events of human error or equipment failure

- Stage 2 – Hazardous events where an unsafe condition prevails

- Stage 3 – PTC-preventable accidents or incidents

A Stage 1 simulation runs for a specified period of time. When initiating events occur, the system state is stored and used as starting conditions for a Stage 2 simulation trial. The Stage 1 simulation continues safely after resetting the error. In this manner, multiple errors are captured over the period of simulation.

A Stage 2 simulation runs for a specified number of trials. Each trial selects at random a system state that was stored at Stage 1 and continues from where the error occurred until safe resolution, or until a hazardous condition occurs. If a hazard occurs, the system state is stored and used as starting conditions for a Stage 3 simulation trial.

In Stage 3, a simulation runs for a specified number of trials. Each trial selects at random a system state that was stored at Stage 2 and continues from where the hazard occurred until safe resolution, or until an accident occurs.

4.5 Additional Modeling Issues

4.5.1 Stage 1 – A Shared Baseline

The Stage 1 simulation, which runs for a fixed period of analysis, is not impacted by PTC. In Stage 1, the operations in the corridor are simulated until a human error or equipment failure occurs. When an error or failure occurs in the simulation, the system state is stored (to be selected at random for a trial in a Stage 2 simulation). These Stage 1 results are used in the Stage 2 simulations of both the Base and Alternate Cases.

4.5.2 Pooling of Results

Despite the advantages of simulation in stages, the simulations still consume significant computer resources and a full simulation including all stages and both cases can take several days or more. To

reduce the computation time, several instances of GTMS are run in parallel and the results are pooled in the analysis. The pooling of results is conducted with full regard for the integrity of the analysis and without introducing bias.

4.5.3 Stratified Sampling to Ensure Coverage of Rarer Events

The GTMS risk assessment covers a number of accident types (e.g., train-train collisions, derailments, work zone accidents). The different accident types and their predecessor events occur with frequencies that differ by orders of magnitude. To ensure that the more rare events are sufficiently covered in the analysis, the Stage 2 simulations employ stratified sampling of the rarer Stage 1 events. The result metrics account for the stratified sampling and the summary statistics are reflective of these as well.

4.5.4 Calibration of Parameters to "Per Operation" Basis

The parameters controlling human errors are given on a per operating train-hour basis. In the risk model, when the train crew should perform an operation in accordance with safe operating procedures, the model determines if an error occurs. Since the determination of error is on a per operation basis, the parameters that govern behavior need to be calibrated from a per train-hour to a per operation basis. In San Bernardino, the average number of operator actions per train-hour (found by counts in simulations) is 1.721, and this value is used to convert the per train-hour error rate to per operation rate.

4.5.5 Calibration of Parameters to Reflect National Averages

Actual accident data for the San Bernardino corridor in recent years provides too small a sample upon which to align experience-based risk parameters (e.g., probability of accident given a hazard for accidents that are not directly simulated from the hazard). FRA national averages of PTC-preventable accidents were the basis for these parameters.

4.6 Risk Parameters

This section describes the GTMS risk parameters that determine the frequency of human errors and equipment failures in the Base and Alternate Case simulations. A third set of parameters, also described in this section, determines the probability of accidents given the occurrence of a hazard.

For certain causal chains and accident types, the occurrence of an accident given a hazard is determined dynamically in the simulation based upon the location of trains in the system. All the train-train collisions are determined in this manner. Other accident types, such as work zone accidents or over-speed derailments, are determined by conditional probabilities that an accident will occur given a hazard.

Table 4.1 below provides all of the risk parameter values used in the analysis.

4.6.1 Human Errors

The specific human error parameter definitions used by GTMS to model the San Bernardino corridor are described in this section.

Rate of Train Operator Error

The GTMS Safety Model relies on well-established human factors models and research to simulate human errors.

Currently, GTMS supports two Human Reliability Models:

- Model I assigns a constant rate of human error. [18]

- Model II, based on human factors research conducted by FRA [19], models the human error rate as a function of the train operator effectiveness, where the train operator effectiveness is based on empirical evidence of modeling operator reliability. The model estimates the train crew's time-on-shift and considers the effects of additional factors, such as time of day, to determine the probability of an error occurring.

The baseline analysis uses Model I, and Model II is used as one of the sensitivity analysis scenarios.

In GTMS risk assessment, a train operator commits an error in one of five ways:

- Fail to brake upon approaching end of authority (industry train handling practice, which combines dynamic braking and partial service air braking, is simulated).

- Fail to heed impending speed restriction.

- Fail to heed to an impending work zone.

- Fail to heed to an impeding speed restriction due to grade crossing malfunction (limited deployment in I-ETMS).

Given the rate of error, and the train operator unreliability for a shift t_0 hours long (probability of error when action is required – an exponentially distributed random variable) is given by the formula:

$$(1) \quad F(t) = 1 - e^{-\beta t_0}$$

where β is the rate of operator error and t_0 is the length of operator shift in hours. The analysis assumes an operator shift of 10 hours. Each time a train approaches its end of authority, a speed restriction, a work zone, or a failed grade crossing, a random number is generated on (0,1) (the interval of real numbers between 0 and 1), and if the value is less than that given by the above formula, then the simulation model triggers a human error event.

Given Train Operator Error, Mean Time until Corrective Action Taken

In the event a train operator commits a Fail to Heed End of Authority error, the simulation model predicts the time elapsed (in seconds) until the operator realizes his or her error and initiates corrective action (i.e., applies emergency brakes). The time elapsed is modeled as an exponentially distributed random variable, calculated using the following formula:

$$(2) \quad F(t) = 1 - e^{-\frac{t}{\mu}}$$

where μ is the mean time to corrective action (in seconds) and t is the time elapsed since the occurrence of the human error. The mean time to corrective action μ is set using the 'Given Train Operator Error, Mean Time until Corrective Action Taken' parameter.

4.6.2 Equipment Failures (Non-PTC)

Equipment failures are failures of physical devices to function as designed. Although not targeted by the PTC implementation, they are an important component in the chain of events that leads to accidents. There are two types of equipment failure: basic equipment failures that may be precursors of Stage 1 events and equipment failures that are encountered after a human error occurs. Both types of failures are relevant to the base case and alternate cases, as well as to errors that are part of the I-ETMS operation.

The following are the non-PTC equipment failure parameter descriptions:

Probability of Misaligned Switch given Approaching Train

In the event that a train approaches a switch, the simulation model uses the 'Probability of Misaligned Switch given Approaching Train' parameter to predict whether the approaching switch is in a misaligned state. A misaligned switch is one that is set in neither the normal nor the reverse position. If the switch is misaligned, the signal protecting the switch will be restrictive and the train will not be given authority to proceed (the analysis assumes zero probability of failing to detect a misaligned switch).

Probability that Switch is Aligned against Movement Authority given Approaching Train

When a train approaches a switch, the GTMS uses the 'Probability that Switch is Aligned against Movement Authority given Approaching Train' parameter to predict whether the approaching switch is set in an unauthorized position. If the switch is found to be set in the wrong position, the signal protecting the switch will be restrictive and the train will not be given authority to proceed. (The analysis assumes zero probability of failing to detect a switch aligned against movement authority.)

Probability that the Grade Crossing Device Fails

In the event that the train approaches a grade crossing, the simulation model uses the 'Probability that the Grade Crossing Device Fails' parameter to predict whether the approaching grade crossing safety apparatus is functioning.

If the device is malfunctioning, the train crew is notified and required to slow to a restricted speed so the train will be able to brake within sight distance if necessary.

4.6.3 PTC Equipment (I-ETMS) Failures

The following are the PTC equipment failure parameter descriptions:

Rate of PTC Failure to Warn (failures per hour)

In Alternate Case Risk Assessments (i.e., simulations of PTC-enabled rail systems), a warning is issued to the train crew in the event that:

- Crew fails to brake upon approaching its end of authority,
- Crew fails to heed an impending speed restriction,
- Crew fails to heed an approaching work zone, and
- Crew fails to heed an impending speed restriction at malfunctioning grade crossing.

The parameter 'Rate of PTC Failure to Warn' is an exponentially distributed random variable that determines if the PTC system fails to operate correctly and warn the train crew to take action and

avoid an unsafe condition. If the PTC equipment fails to warn the train crew, or if the train crew fails to take corrective measures, the equipment will attempt to enforce braking.

The parameter assumes all sources of possible failure (i.e., failure due to any PTC subcomponent failure).

Rate of PTC Failure to Enforce Braking (failures per hour)

In Alternate Case Risk Assessments, PTC enforces braking when the train crew fails to take appropriate corrective action in response to PTC's warning of an impending hazard.

GTMS uses the 'Rate of PTC Failure to Enforce Braking' as the parameter of an exponentially distributed random variable to determine whether the PTC equipment will enforce braking and stop the train before a hazard occurs. If the PTC equipment fails to enforce braking the train crew may still correct and attempt to manually stop the train. If the crew fails to brake then a hazard will occur.

4.6.4 *Probability of Accident/Incident given Hazardous Situation Parameters*

Probability of Derailment from Emergency Braking

Given a train operator error, the simulation model calculates the time elapsed until corrective action is initiated (i.e., deployment of emergency brakes). When applying emergency brakes, the simulation model uses the 'Probability of Derailment from Emergency Braking' parameter to determine whether or not the brake application results in a derailment.

Probability of Derailment for Misaligned Switch or Unauthorized Switch Alignment

When a train approaches a switch that is misaligned or aligned against authorized movement, the signaling system detects the equipment failure and displays a restrictive aspect. If the train operator fails to heed the signal, the train can intersect the switch. The simulation model uses the 'Probability of Derailment for Misaligned Switch or Unauthorized Switch Alignment' parameter to predict whether or not the train's intersection with the switch results in a derailment.

Probability of Derailment given Over-Speed Hazard

When a train operator fails to heed an impending speed restriction, he can produce an over-speed hazard. The simulation model uses the 'Probability of Derailment given Over-Speed' parameter to predict if the over-speed results in a derailment.

Probability of Accident/Incident given a Work Zone Incursion

When a train operator fails to pay heed to an approaching work zone, it can result in a work zone incursion hazard. The simulation model uses the 'Probability of Accident/Incident given a Work Zone Incursion' parameter to predict if the incursion results in a work zone accident/incident.

Probability of Derailment from Enforcement Braking

When PTC enforces braking, the simulation model uses the 'Probability of Derailment from Enforcement Braking' to determine if the enforcement braking results in a derailment.

The applicability of the various risk-related parameters for accidents and their value in the analysis of the San Bernardino corridor is shown in Table 4.1. These values were derived, in part, from industry

averages, published studies, and expert opinion, and others were based on empirical or experiential based information. [20]

Table 4.1 Risk Assessment Metrics [21]

Parameters		Head-to-Head, Head-to-Tail, Sideswipe	Misaligned Switch Derailment	Unauthorized Movement thru Switch Accident	Work Zone Accident/ Incident	Over-Speed Derailment	San Bernardino Case Study Values
Human Errors	Rate of Train Operator Error (errors/hour)	✓	✓	✓	✓	✓	4×10^{-4}
	Given train operator error, mean time until corrective action taken (seconds)	✓	✓	✓	✓	✓	20.0
	Average of Operator actions/train-hour	✓	✓	✓	✓	✓	1.721
Equipment Failures	Probability that Switch is set to Neither the Normal nor the Reverse position (misaligned), given approaching train		✓				6.22×10^{-4}
	Probability that Switch is Aligned against Movement Authority, given approaching train			✓			1.24×10^{-6}
	Probability of Derailment with Emergency Braking	✓	✓	✓	✓		0.0001
	Rate of PTC Warning Failure (failures/hour)	✓	✓	✓	✓	✓	1.52×10^{-4}
	Rate of PTC Enforcement Braking Failure (failures/hour)	✓	✓	✓	✓	✓	6.06×10^{-5}

Parameters	Accidents/Incidents	Head-to-Head, Head-to-Tail, Sideswipe	Misaligned Switch Derailment	Unauthorized Movement thru Switch Accident	Work Zone Accident/ Incident	Over-Speed Derailment	San Bernardino Case Study Values
Probability of Accident/Incident Given Hazardous Situations	Rate of Grade Crossing Device Failure (failures/hours)						1.24×10^{-3}
	Mean Time to Repair (hours)		✓	✓			8.0
	Probability of Derailment with Enforcement Braking	✓	✓	✓	✓		1×10^{-6}
	Probability of Derailment for Misaligned or Mis-Set Switch		✓	✓			0.05
	Probability of Derailment Given Over-Speed					✓	0.001
	Probability of Accident/Incident Given a Work Zone Incursion				✓		0.01

4.7 Simulation Control Parameters

Simulation control parameters are described in Table 4.2.

Table 4.2 Simulation Control Parameters

Simulation Stage	Parameter	Description
1	Random Seed	A random seed is a positive integer value used to initialize a pseudorandom number generator. Each random seed yields a unique sequence of pseudorandom numbers that are used in a given simulation. This parameter is the random seed for a Stage 1 simulation.
	Minutes from Start of First Train Until Errors/Failures are Allowable	This parameter is set so that initial condition effects do not distort the statistics of errors and failures. GTMS runs until the effect of starting the simulation with an empty corridor is erased.
2	Random Seed	This parameter is the random seed for a Stage 2 simulation.
	Number of Trials	The number of Stage 2 trials, that is, the number of times in Stage 2 when a stored system state from Stage 1 (unsafe condition due to error or failure) is drawn at random, re-animated, and simulated until either a hazard occurs or the unsafe condition resolves safely.
3	Random Seed	This parameter is the random seed for a Stage 3 simulation.
	Number of Trials	The number of Stage 3 trials, that is, the number of times in Stage 3 when a stored system state from Stage 2 (hazard) is drawn at random, re-animated, and simulated until either an accident/incident occurs or the hazard resolves safely.

5. Analysis and Findings

5.1 Introduction

The chapter presents the findings of the BNSF San Bernardino corridor analysis using GTMS, with the framework, models, and inputs described in the previous chapters. The findings are for both the Base Case, without PTC, and the Alternate Case, with PTC fully operational in the corridor.

5.2 Operational Results and Validation of the Simulation

The shared baseline Stage 1 simulation consisted of 4 simulations of thirty months each that were pooled, totaling 10 years. Simulated operations in the period covered calendar years 2013–2022 and included 428,200 trains, 440,966 train-hours, and 16.24 million train-miles of operations.

An average of 117 trains per day were simulated with daily train-miles averaging 4,407. The minimum average speed for a train was 6.3 mph, and the maximum average speed for a train was 65.6 mph. The average speed for all trains was 36 mph. On average, 1,073 movement authorities were granted per day.

Table 5.1 summarizes the Stage 1 baseline simulation.

Table 5.1 Operational Summary for the Stage 1 Baseline Simulation

Period of Analysis	Number of Trains	Min Average Speed (mph)	Max Average Speed (mph)	Mean Average Speed (mph)	Total Train-Miles
10 years	428,200	6.3	65.6	39.9	16.24 million

Passenger trains operate on a rigid schedule. To maintain ridership, passenger services can tolerate no more than small, infrequent delays. Freight trains are less time sensitive and actual run times may vary significantly from schedule. As San Bernardino is a shared-use corridor, with significant movements of both passenger and freight traffic, one of the challenges in both real-world and simulated dispatching is to prioritize and ensure the on-time arrival of passenger trains while continuing to meet the requirements of freight traffic. An important part of validating the simulation is to demonstrate that passenger trains are not unduly delayed and that the simulation reasonably replicates real world movements of passenger and freight trains in the corridor.

Figure 5.1 shows the delay distribution for the 212,510 passenger trains in the 10-year Stage 1 simulation period. Delay is measured as the difference between (simulated) actual arrival and scheduled arrival time. As shown in Figure 5.1, the majority of trains, 88 percent, arrive with a delay of less than 15 minutes, and only 0.5 percent of trains arrive with a delay of 1 hour or more. Average delay is 5.5 minutes. These values correspond closely to the actual delay data for the corridor and validate that GTMS closely replicates actual operations in the corridor.

Figure 5.1 Passenger Train Delay Distribution
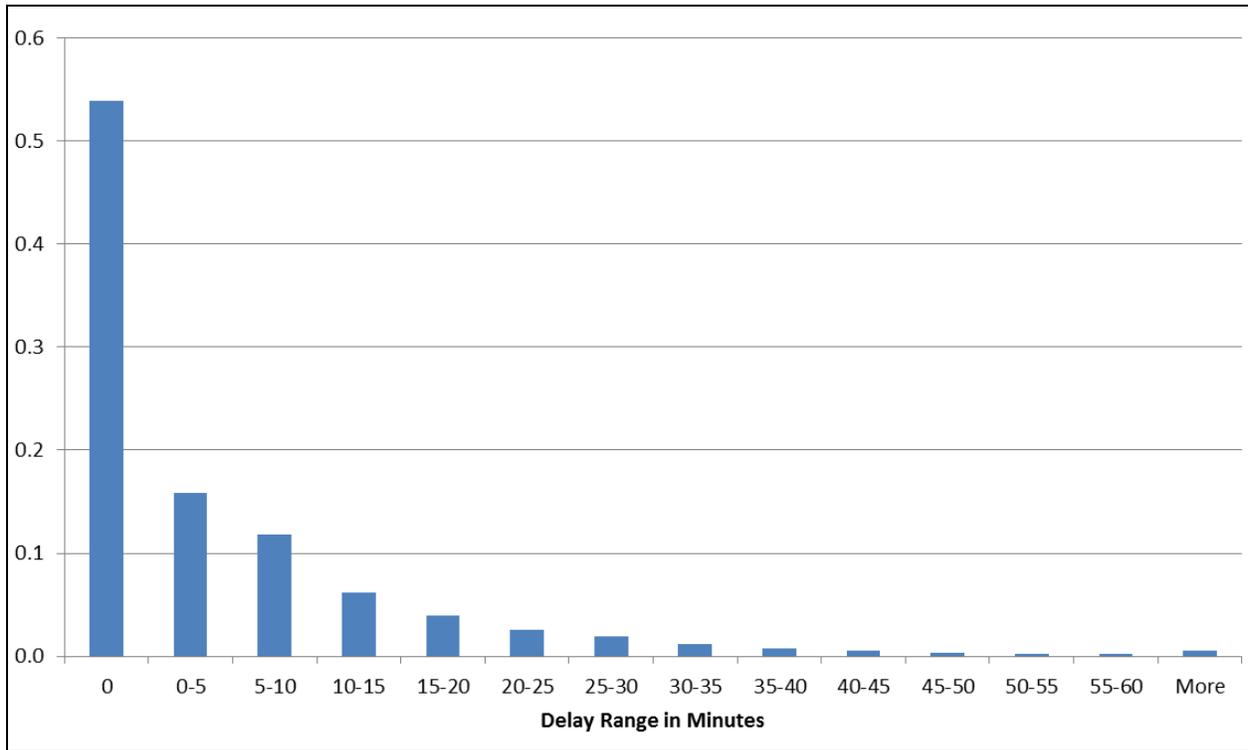
The calculated average speed of simulated freight trains (146,310 trains) operating the full length of the corridor between Redondo West and San Bernardino (67.9 miles) was 37 mph. This closely matches the actual average speeds of freight trains in the corridor, which further validates the operational baseline as a faithful replication of operations in the corridor. [22]

5.3   Risk Assessment Results

5.3.1 Overview of the Analysis Process

The period of analysis of the Stage 1 shared baseline was 3 years. In Stage 1, the events of interest (non-PTC human errors and equipment failures) are not impacted by PTC, so the Base and Alternate Case results are identical.

In Stage 1, regular operations occur until an event of interest is encountered. When this occurs, the system state (a full snapshot of the state of all simulated objects in the corridor) is stored in the GTMS database. The Stage 1 simulation is then restored to a safe operating condition and continues normally until the next event, when the process of storing the system state and restoring to safe operating conditions is repeated.

In the Stage 2 simulation, each trial selects a system state at random from the collection of Stage 1 stored system states, which is used as the initial conditions for the trial.

The categories of Stage 1 events are:

- Fail to Brake
- Fail to Heed Speed restriction

- Fail to Heed Work Zone

- Fail to Heed Grade Crossing Failure Speed Restriction

Stage 2 state selection simulation is executed separately for the Base and Alternate Case. Each Stage 2 simulation continues until either the operation returns to a safe state or a Stage 2 event occurs. Stage 2 simulations are performed until a sufficient number of hazard events are generated, or until the analysis demonstrates that the events are so rare that they fail to be of interest (i.e., MTTA of subsequent accidents from the hazard are less frequent than once in 300 years of operations.).

In the Stage 2 simulation, when a hazardous event occurs the system state is stored for use as the initial conditions for a Stage 3 simulation run. In Stage 3, each trial selects at random from the Stage 2 stored system states.

The duration of the Stage 1 period of analysis, and the number of trials for Stage 2 and Stage 3 simulations, are determined to meet statistical reliability requirements.

5.3.2 Stage 1 Results

Table 5.2 shows the results for the 3-year Stage 1 simulations.

Table 5.2 Stage 1 Results for 3-Year Simulation Period

Stage 1 Events	Number of Stage 1 Events	Mean Time to Stage 1 Event in days (MTTE)	Mean Time to Stage 1 Event in years (MTTE)
Fail to Brake	195	18.73	0.05213
Fail to Heed Speed Restriction	1009	3.62	0.00991
Fail to Heed Work Zone	2	1826.25	5.0

5.3.3 Stage 2 Results

The results for the Stage 2 simulation (hazards) in the base case are shown in Table 5.3; 5,000 total trials were run. Of the 5,000, 1,950 trials were run with fail-to-brake initiating events and 20 trials were run with fail-to-heed work zone initiating events. The remaining 3,030 trials were run with fail-to-heed speed restriction initiating events.

Table 5.3 Stage 2 Results (Hazards) for the Base Case

Stage 2 Events	Stage 1 Event	Number of Stage 1 Event Trials	Number of Stage 2 Events	Probability of Stage 2 Event given a Stage 1 Event	Mean Time to Hazard (MTTH) Years
End of Authority Hazard	Fail to Brake	1,950	1,264	0.64820	0.07911
Over-Speed Hazard	Fail to Heed Speed Restriction	3,030	3,030	1	0.00991
Work Zone Hazard	Fail to Heed Work Zone	20	20	1	5.00

Figure 5.2 MTTH Base Case
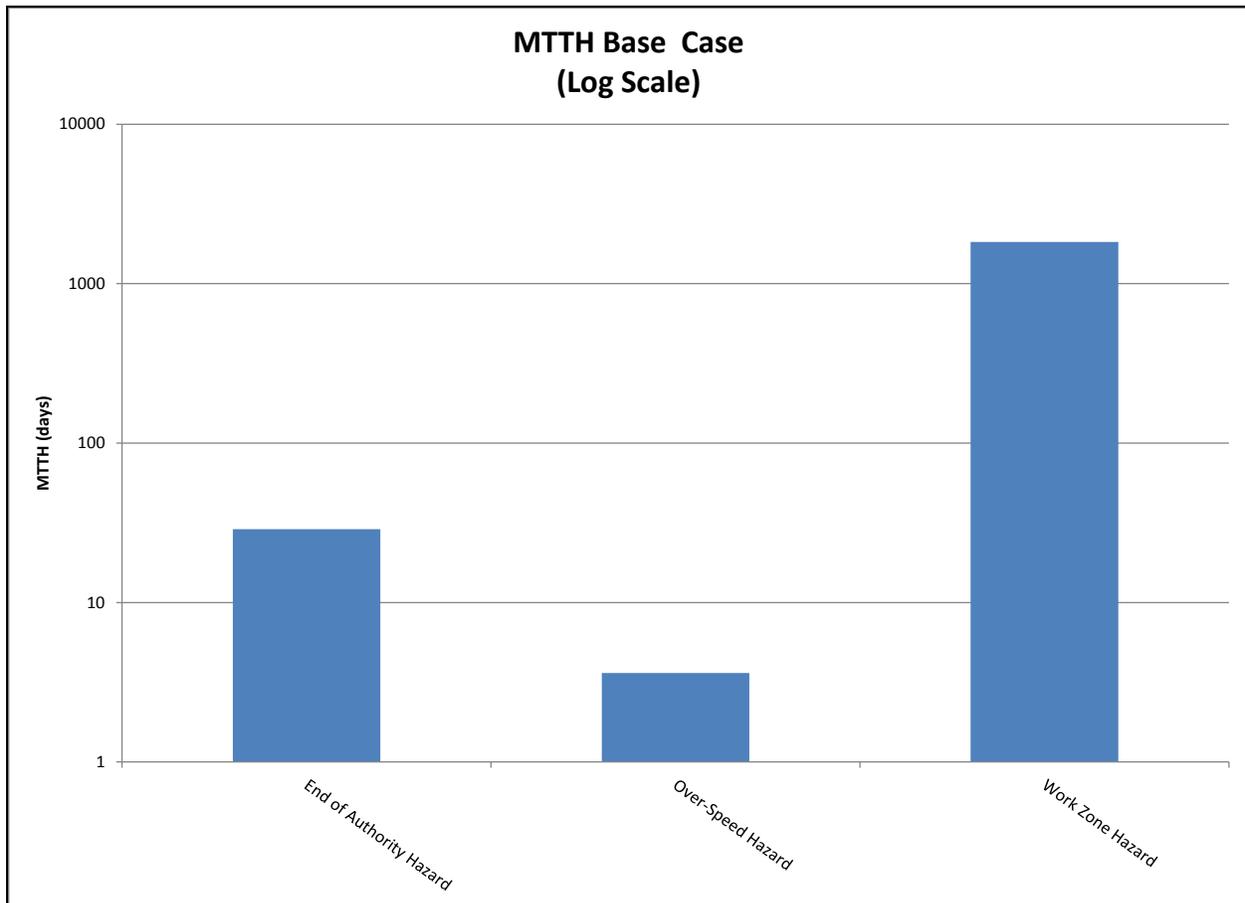
5.3.4 Stage 3 Results

Table 5.4 below shows the Stage 3 results of the risk assessment.

Table 5.4 Stage 3 Results for the Base Case

Stage 3 Events Accident/ Incident	Stage 2 Event	Number of Stage 2 Event Trials	Number of Stage 3 Events	Probability of Stage 3 Event given Stage 2 Event	Mean Time to Stage 3 Event (MTTA) Years
Head-to-Head Collision	End of Authority Hazard	1,489	26	0.017461	4.531
Head-to-Tail Collision		1,489	10	0.006716	11.78
Sideswipe Collision		1,489	46	0.030893	2.56
Emergency Brake Derailments		1,489	0	0.0	>300
Over-Speed Derailments	Over-Speed Hazard	3,488	4	0.00115	8.6422
Work Zone Accident	Work Zone Hazard	28	0	0.00	>300

Figure 5.3 MTTA for Base Case
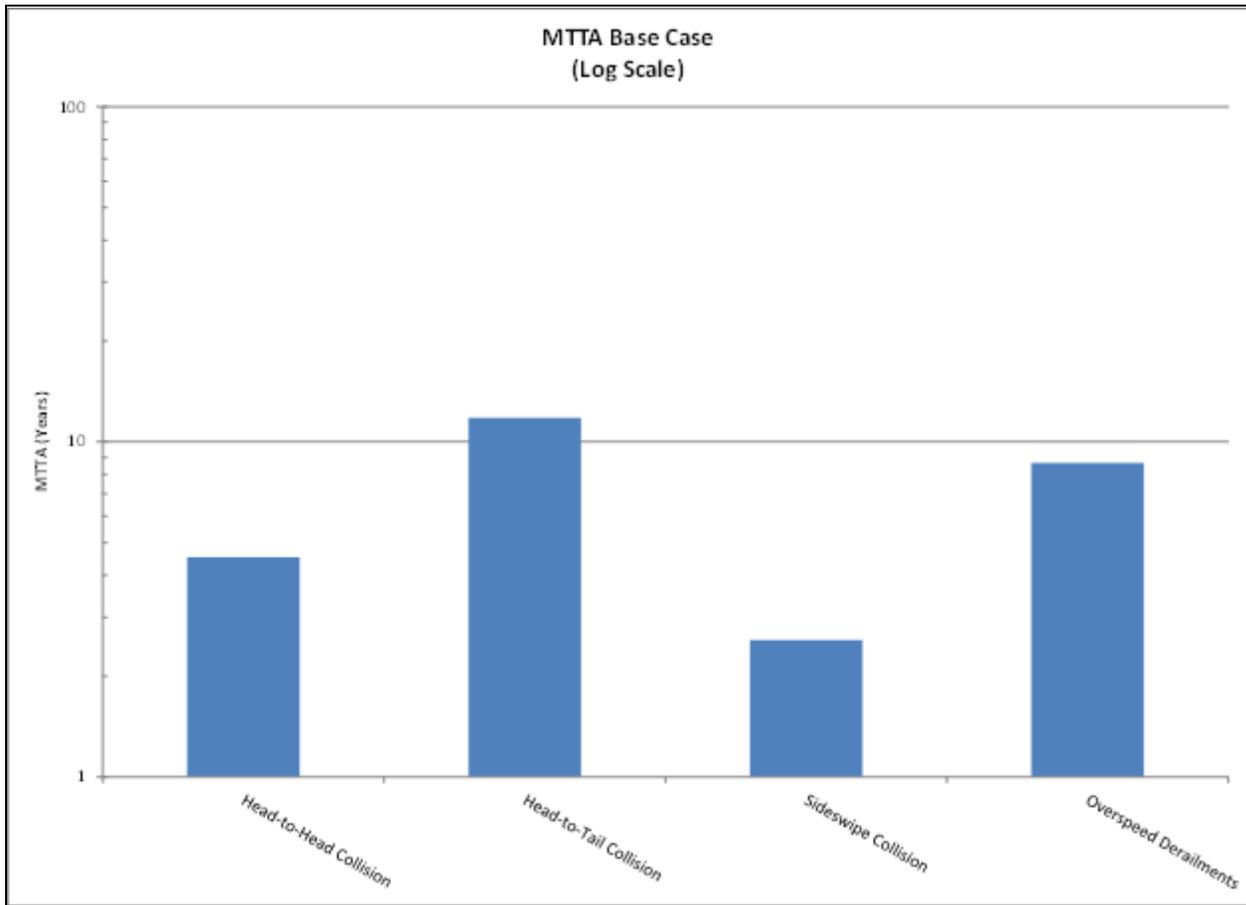
5.4 The Alternate Case (with I-ETMS)

The analysis included simulations of the Alternate Cases, which included the I-ETMS PTC system. However, for a Stage 2 simulation, there was only one end of authority hazard and no other hazards. To arrive at statistically meaningful results, about 150,000 Stage 2 trials would be required followed by a similar number of Stage 3 trials. The following discussion demonstrates that risk in the Base Case is mitigated with I-ETMS to the point that PTC-preventable accidents would occur at a frequency of less than once in 300 years.

Risk of PTC-preventable accidents only exists when the PTC system fails. The failure rate assumption is that PTC fails to warn 1.52×10^{-4} per train-hour. PTC fails to warn and enforce braking with a failure rate of 6.06×10^{-5} per train-hour. Over a 10-year operating period, this translates to 67 warn failures and 27 warn and brake failures. Assuming a mean-time-to-repair of 8 hours, PTC will not enforce braking when errors occur for a total 214 hours of the 10-year period, or, the system non-protecting, downtime is 0.05 percent (and uptime is 99.95 percent). These error rates assume that the failure could be of a general, system-wide nature—or confined to specific train or wayside components. What is important for the analysis is that: (1) the failures are unplanned and without advance notice, and (2) the failures, to create a risk situation, need to coincide with a scenario of operator error.

The analysis has not included planned system downtime, during which Base Case conditions are assumed to prevail. An additional scenario that is not accounted for here is one in which PTC experiences a general or communication failure and, for a small time window, the train crew believes the system is functioning and—based on incorrect, outdated information—performs an unsafe action. The time window from the time of such a failure until the train crew is aware the system has failed is estimated to be under 20 seconds. Unless such failures occur with high frequency, they are not likely to pose a measurable risk—and in this case study the risk is assumed to be negligible.

For the "fail to brake at end of authority" event leading to a hazard and collision, Figure 5.4 illustrates the effects of I-ETMS.

Figure 5.4 Impact of I-ETMS on Base Case Risk – Train Collisions
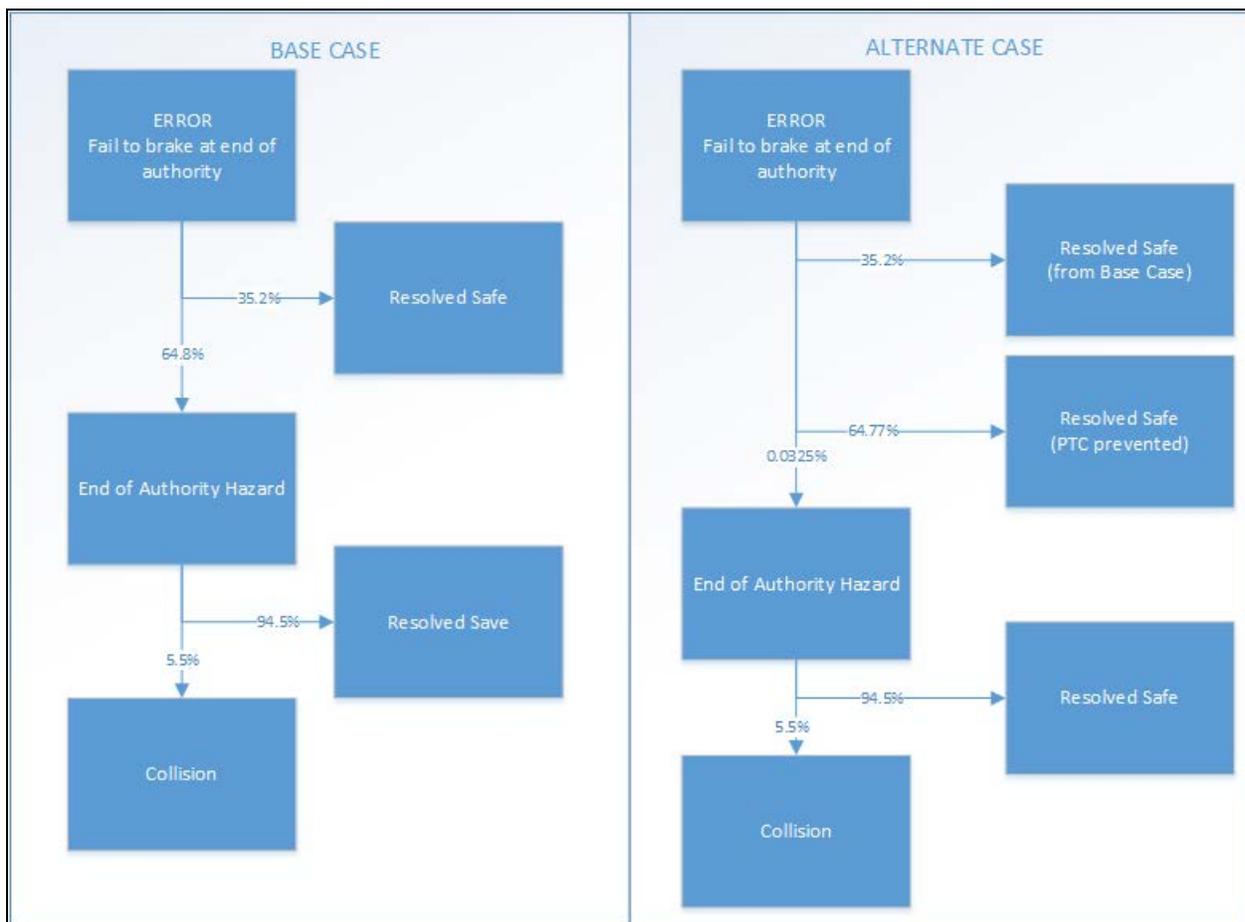
In the Base Case, the simulation analysis shows that, given an error, the probability of a hazard is 64.8 percent. With the I-ETMS system, most of those hazards are mitigated with enforced braking. If the error occurs during a failure of PTC warning and enforced braking capabilities (i.e., 0.05 percent of the time) the error will result in a hazard. For those trains that result in a hazardous situation, 94.5 percent will resolve safely in both the Base and Alternate Cases.

In the Base Case, of those trains that fail to brake for authority, 3.6 percent result in a collision. In the Alternate Case, of those trains that fail to brake for authority, 0.018 percent result in a collision. This represents a mitigation of 99.5 percent of the Base Case risk for train-train collisions. The analysis found that sideswipes were the most common type of train-train collision in the Base Case, with an

MTTA of 2.6 years. The imputed MTTA for sideswipe collisions with PTC is 520 years. The other collision types would occur with even less frequency.

A similar analysis for work zone accidents and over-speed derailments shows that PTC mitigates about 99.5 percent of the risk.

5.5 Severity and Cost

To assess accident severity, GTMS assigns dollar values to each simulated accident type defined in the risk assessment component of the software.

The accidents generated in a GTMS safety analysis are categorized as Collisions or Derailments, with each category representing a different level of severity. Collisions are more severe, on average, than derailments, thus they generate higher accident costs. Also, for each collision accident type, the predicted share of fatal and injury accidents is larger than for derailment accidents; this difference derives from the generally more severe nature of collision accidents.

Table 5.5 presents the Accident Severity Costs used in this risk assessment. The costs are based on an analysis of BNSF system-wide crashes prepared for the ETMS Product Safety Plan [23], with costs updated to reflect 2013 prices.

Table 5.5 Accident Severity Costs

Severity Cost Group	Accident Type	Cost	Share by Accident Type	
More Severe	• Head-to-Head Collision	$2,704,864	Percent Fatal Accident/Incident	0.065
	• Head-to-Tail Collision		Percent Injury Accident/Incident	0.135
	• Sideswipe Collision		Percent Property Damage Only Accident/Incident	0.8
Less Severe	• Emergency Braking Derailment	$203,762	Percent Fatal Accident/Incident	0.0015
	• Misaligned Switch Derailment		Percent Injury Accident/Incident	0.00312
	• Work Zone Accident/Incident		Percent Property Damage Only Accident/Incident	0.9954
	• Over-Speed Derailment			

Severity Cost Group	Accident Type	Cost	Share by Accident Type	
	• Enforcement Braking Derailment		Percent Injury Accident/Incident	0.0208
			Percent Property Damage Only Accident/Incident	0.9777

Table 5.6 shows the average annual accident cost for the Base Case.

Table 5.6 Base Case Accident Costs – Annual Average

Accident Type	Average Annual Predicted Accidents	Annual Average Accident Cost	25 Year PV (3%)	25 Year PV (7%)
Head-to-Head Collision	0.2207	$596,963	$10,395,013	$6,956,764
Head-to-Tail Collision	0.08489	$229,616	$3,998,336	$2,675,848
Sideswipe Collision	0.39049	$1,056,222	$18,392,156	$12,308,775
Over-Speed Derailment	0.1157	$23,575	$410,520	$274,736
Total	0.8118	$1,906,377	$33,196,024	$22,216,123

The analysis indicates that all but negligible PTC-preventable accident risk is mitigated in the Alternate Case with a high level of confidence (i.e., MTTA exceeds 300 years). The predicted average annual accident cost of PTC-preventable accidents is therefore zero in the Alternate Case.

6. Sensitivity Analysis

6.1   Introduction

An important test of the robustness of the GTMS results, and one prescribed by the PTC Rule, is an analysis of the sensitivity of the results to changes in key inputs. In particular, the sensitivity analysis seeks to validate the finding that I-ETMS all but eliminates PTC-preventable accident risk even when key inputs vary significantly.

6.2   Sensitivity Analysis Inputs

Each of the following inputs was modified, and the Base and Alternate Case analyses rerun to test the sensitivity of the results to the inputs:

- Traffic volume – increased by 16 percent, which is an estimate by SCAG [24] of the maximum capacity of the corridor.

- Human error – the rate of operator error was increased from 0.4/1,000 hours of operation to 0.5/1000 hours, and mean time to corrective action was increased from 20 to 30 seconds.

- Equipment failure – All equipment failure rates, which were based on BNSF system-wide rates, were increased by a factor of 10 (e.g., probability of failure was increased from 1.25×10^{-5} to 1.25×10^{-4})

- Human Factors Model II – a human factors model derived from the literature and based on a single parameter was replaced with an empirically based model of railroad-specific research that includes a database of train crew sleep logs mapped to time-of-day. [25]

- Work zone frequency – the number of weekly work zones was increased from 4 to 5, and work zone hours in the corridor were increased on a weekly basis from 25 to 39.

6.3   Sensitivity Analysis Findings

Figure 6.1 shows MTTA for each analysis and the analysis baseline for the Base Case:

Figure 6.1 Summary Chart of Sensitivity Analysis – Base Case
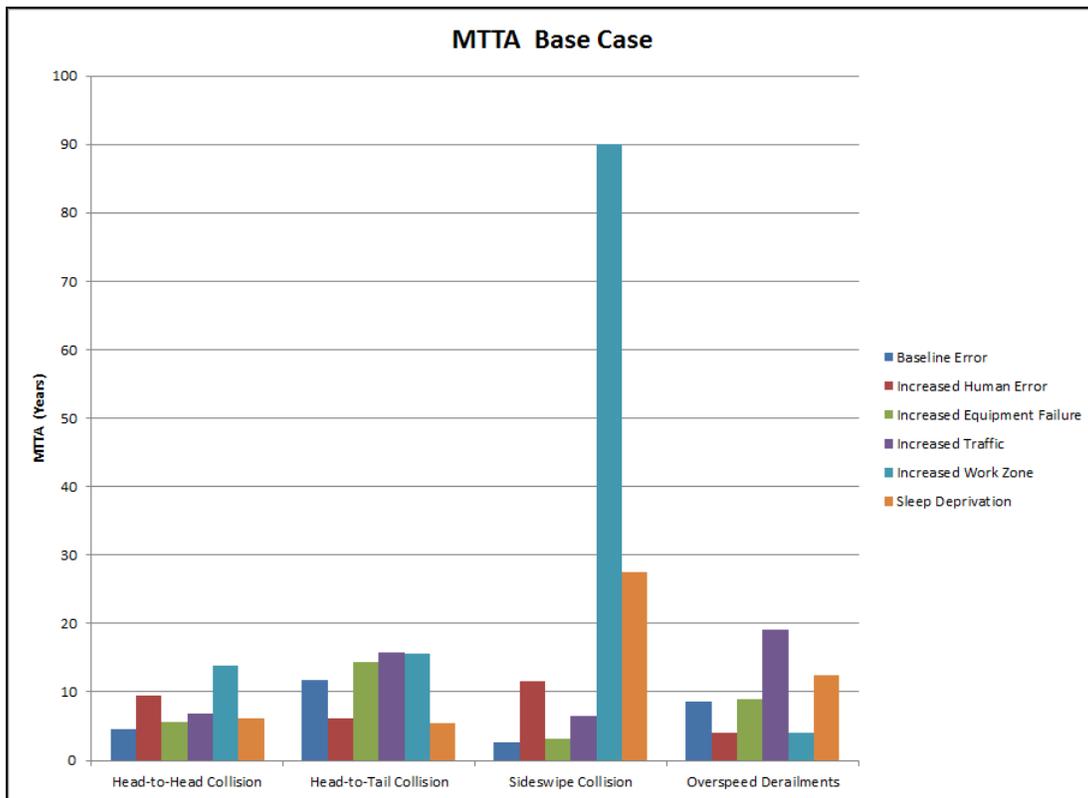
For MTTA, which is the inverse of the predicted annual accidents, taller bars indicate less risk. It appears that for some accident types, risk has declined when the key input has been changed in the direction of greater risk (e.g., sideswipe collisions with increased work zones). There may be a reasonable operational explanation for each phenomenon. For example, in the work zone/sideswipe case, more trains move at restricted speeds, which results in fewer train-to-train collisions (i.e., while there is more exposure to work zone incursion accidents, the countervailing effect of slowing the trains results in fewer end-of-authority hazards with sideswipe collisions).

In other cases, the appearance of reduced accidents is a result of disaggregation such that the accidents by type are not statistically reliable while the aggregate finding is reliable. Numbers of accidents for the individual accident types in the sensitivity scenarios appear to have large variances such that the findings exhibited in the figure are inconclusive. Additional simulation (i.e. more runs) would validate that the numbers of accident for each type would indeed increase with, for example, increases in rates of human error.

Total accident risk varies moderately across all of the cases (see Figure 6.2 below). It is difficult to determine the impact of randomness, so the expected result that accident risk increases compared with the baseline cannot be ruled out with high confidence for all of the sensitivity variables.

The MTTA chart above does indicate that while accidents in the aggregate show moderate variance, the mix of accidents exhibits high variance. This pattern may well be a feature of the complexity of the operations in the territory. Additional inquiry (i.e., more simulation runs) could assist in sorting out the effects of randomness and determining whether the high variance of accident-type mix is a persistent feature.

The following sections show tables of results for the sensitivity analysis to each key input. The chapter concludes with charts comparing the effects of the changes in inputs.

The sensitivity analysis results do support the finding that I-ETMS mitigates all but negligible PTC-preventable accident risk.

Figure 6.2 Total Predicted Accidents – Base Case
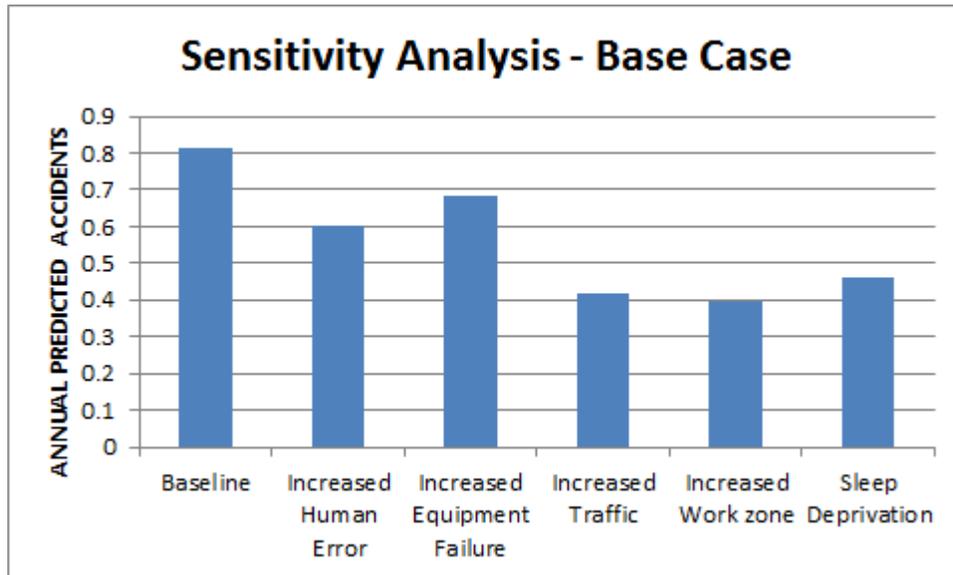
Note: Additional summary charts appear after the tables.

6.4 Traffic Volume

Freight traffic (number of trains) was increased by 16 percent. This is the amount that the recent SCAG study considers the "maximum capacity" of the corridor.

Table 6.1 Stage 1 Results for Increased Traffic Volume

Stage 1 Events	Number of Stage 1 Events	Mean Time to Stage 1 Event in days (MTTE)	Mean Time to Stage 1 Event in Years (MTTE)
Fail to Brake	240	15.219	0.04167
Fail to Heed Speed Restriction	1264	2.890	0.00791
Fail to Heed Work Zone	2	1826.250	5.00000

Table 6.2 Stage 2 Results for Increased Traffic Volume Base Case

Stage 2 Events	Stage 1 Event	Number of Stage 1 Event Runs	Number of Stage 2 Events	Probability of Stage 2 Event given a Stage 1 Event	Mean Time to Hazard (MTTH) Years
End of Authority Hazard	Fail to Brake	11040	6374	0.5774	0.0821
Over-Speed Hazard	Fail to Heed Speed Restriction	3500	3500	1	0.00656
Work Zone Hazard	Fail to Heed Work Zone	4640	4640	1	3.333

Table 6.3 Stage 3 Results for Increased Traffic Volume Base Case

Stage 3 Events Accident/ Incident	Stage 2 Event	Number of Stage 2 Event Runs	Number of Stage 3 Events	Probability of Stage 3 Event given Stage 2 Event	Mean Time to Stage 3 Event (MTTA) Years
Head-to-Head Collision	End of Authority Hazard	3828	46	0.01201	6.830
Head-to-Tail Collision		3828	20	0.005225	15.71
Sideswipe Collision		3828	49	0.01280	6.412
Over-Speed Derailments	Over-Speed Hazard	2916	1	0.0003429	19.129

6.5 Human Error

Rate of train Operator Error (errors per 1,000 hours of train operation changed from 0.4 to 0.5). Given a train crew error, the mean time until corrective action was taken increased from 20 to 30 seconds.

Table 6.4 Stage 1 Results for Increased Human Error

Stage 1 Events	Number of Stage 1 Events	Mean Time to Stage 1 Event in Days (MTTE)	Mean Time to Stage 1 Event in Years (MTTE)
Fail to Brake	240	15.219	0.04167
Fail to Heed Speed Restriction	1264	2.890	0.00791
Fail to Heed Work Zone	2	1826.250	5.00000

Table 6.5 Stage 2 Results for Increased Human Error – Base Case

Stage 2 Events	Stage 1 Event	Number of Stage 1 Event Runs	Number of Stage 2 Events	Probability of Stage 2 Event given a Stage 1 Event	Mean Time to Hazard (MTTH) Years
End of Authority Hazard	Fail to Brake	2440	1986	0.8139	0.05119
Over-Speed Hazard	Fail to Heed Speed Restriction	2480	2480	1	0.007911
Work Zone Hazard	Fail to Heed Work Zone	5060	5060	1	5.000

Table 6.6 Stage 3 Results Increased Human Error – Base Case

Stage 3 Events Accident/ Incident	Stage 2 Event	Number of Stage 2 Event Runs	Number of Stage 3 Events	Probability of Stage 3 Event given Stage 2 Event	Mean Time to Stage 3 Event (MTTA) Years
Head-to-Head Collision		2029	11	0.005421	9.4425
Head-to-Tail Collision	End of Authority Hazard	2029	17	0.008379	6.1099
Sideswipe Collision		2029	9	0.004436	11.5409

Stage 3 Events Accident/ Incident	Stage 2 Event	Number of Stage 2 Event Runs	Number of Stage 3 Events	Probability of Stage 3 Event given Stage 2 Event	Mean Time to Stage 3 Event (MTTA) Years
Over-Speed Derailments	Over-Speed Hazard	3623	7	0.001932	4.0947

6.6 Equipment Failure Rate

Equipment failure parameters were modified as follows:

1. Probability of misaligned switch given approaching train changed from 6.22×10^{-4} to 6.22×10^{-3}.

2. Probability the switch is set against movement authority given approaching train changed from $1.24 \times 10\text{-}6$ to $1.24 \times 10\text{-}^{5}$.

3. Rate of PTC failure to warn (failures per 1,000 hours of train operation) changed from 0.152 to 1.52.

4. Rate of PTC failure to enforce braking (failures per 1,000 hours of train operation) changed from 0.0606 to 0.606.

Table 6.7 Stage 1 Results with Increased Equipment Failure

Stage 1 Events	Number of Stage 1 Events	Mean Time to Stage 1 Event in Days (MTTE)	Mean Time to Stage 1 Event in Years (MTTE)
Fail to Brake	204	17.904	0.04902
Fail to Heed Speed Restriction	1293	2.825	0.007734
Fail to Heed Work Zone	2	1826.25	5.000

Table 6.8 Stage 2 Results with Increased Equipment Failure – Base Case

Stage 2 Events	Stage 1 Event	Number of Stage 1 Event Runs	Number of Stage 2 Events	Probability of Stage 2 Event given a Stage 1 Event	Mean Time to Hazard (MTTH) Years
End of Authority Hazard	Fail to Brake	1245	631	0.5068	0.0967
Over-Speed Hazard	Fail to Heed Speed Restriction	3360	3360	1	0.007734
Work Zone Hazard	Fail to Heed Work Zone	3120	3120	1	5.000

Table 6.9 Stage 3 Results with Increased Equipment Failure – Base Case

Stage 3 Events Accident/Incident	Stage 2 Event	Number of Stage 2 Event Runs	Number of Stage 3 Events	Probability of Stage 3 Event given Stage 2 Event	Mean Time to Accident in Years (MTTA)
Head-to-Head Collision	End of Authority Hazard	1487	26	0.01748	5.5316
Head-to-Tail Collision	End of Authority Hazard	1487	10	0.00672	14.3820
Sideswipe Collision	End of Authority Hazard	1487	46	0.03093	3.1265
Over-Speed Derailments	Over-Speed Hazard	3673	6	0.00087	8.9276

6.7   Human Factors Model II

The empirically based human factors model was used to model human error with the parameters shown in Table 6.10.

Table 6.10 Human Factor Model Parameters

Effectiveness	Error Rate (errors/1000 hours of train operation)
0–50 (Severely Fatigued)	0.619
50–59 (Extremely Fatigued)	0.458
60–69 (Very Fatigued)	0.415
70–79 (Moderately Fatigued)	0.400
80–89 (Mildly Fatigued)	0.400
90–100 (Not Fatigued)	0.315

Table 6.11 Stage 1 Results with Human Factors Model II

Stage 1 Events	Number of Stage 1 Events	Mean Time to Stage 1 Event in Days (MTTE)	Mean Time to Stage 1 Event in Years (MTTE)
Fail to Brake	154	23.718	0.06494
Fail to Heed Speed Restriction	1442	2.533	0.00693
Fail to Heed Work Zone	6	608.750	1.6667

Table 6.12 Stage 2 Results with Human Factors Model II – Base Case

Stage 2 Events	Stage 1 Event	Number of Stage 1 Event Runs	Number of Stage 2 Events	Probability of Stage 2 Event given a Stage 1 Event	Mean Time to Hazard (MTTH) Years
End of Authority Hazard	Fail to Brake	1780	1159	0.6511	0.0997
Over-Speed Hazard	Fail to Heed Speed Restriction	4940	4940	1	0.00693
Work Zone Hazard	Fail to Heed Work Zone	4020	4020	1	1.6667

Table 6.13 Stage 2 Results with Human Factors Model II – Alternate Case

Stage 2 Events	Stage 1 Event	Number of Stage 1 Event Runs	Number of Stage 2 Events	Probability of Stage 2 Event given a Stage 1 Event	Mean Time to Hazard (MTTH) Years
End of Authority Hazard	Fail to Brake	9225	0	0	NA
Misaligned Switch Hazard	Fail to Brake	9225	0	0	NA
Unauthorized Switch Alignment Hazard	Fail to Brake	9225	0	0	NA
Over-Speed Hazard	Fail to Heed Speed Restriction	6175	6	0.0001	2.22
Work Zone Hazard	Fail to Heed Work Zone	5025	10	0.002	7.71
Grade Crossing Over-Speed Hazard	Fail to Heed Grade Crossing Failure	4575	0	0	NA

Table 6.14 Stage 3 Results with Human Factors Model II – Base Case

Stage 3 Events Accident/ Incident	Stage 2 Event	Number of Stage 2 Event Runs	Number of Stage 3 Events	Probability of Stage 3 Event given Stage 2 Event	Mean Time to Stage 3 Event (MTTA) Years
Head-to-Head Collision	End of Authority Hazard	551	8	0.0145	5.728
Head-to-Tail Collision		551	25	0.0453	1.833
Sideswipe Collision		551	2	0.0036	22.91
Emergency Brake Derailments		551	0	0	NA
Over-Speed Derailments	Over-Speed Hazard	3597	4	0.001	1.934
Work Zone Accident	Work Zone Hazard	2851	31	0.011	1.411

Table 6.15 Stage 1 Results with Human Factors Model II – Alternate Case

Stage 3 Events Accident/ Incident	Stage 2 Event	Number of Stage 2 Event Runs	Number of Stage 3 Events	Probability of Stage 3 Event given Stage 2 Event	Mean Time to Stage 3 Event (MTTA) Years
Head-to-Head Collision	End of Authority Hazard	551	9	0.016334	6.106
Head-to-Tail Collision		551	10	0.018149	5.495
Sideswipe Collision		551	2	0.003630	27.475
Over-Speed Derailments	Over-Speed Hazard	3597	2	.000556	12.472

6.8 Work Zone Frequency

An additional work zone was added to the weekly schedule of work zones, increasing the number of weekly work zones from 4 to 5, and work zone hours were increased from 25 to 39.

Table 6.16 Stage 1 Results with Increased Work Zone Frequency

Stage 1 Events	Number of Stage 1 Events	Mean Time to Stage 1 Event in Days (MTTE)	Mean Time to Stage 1 Event in Years (MTTE)
Fail to Brake	71	21.360	0.05848
Fail to Heed Speed Restriction	1451	2.517	0.00689
Fail to Heed Work Zone	6	608.750	1.66667

Table 6.17 Stage 2 Results with Increased Work Zone Frequency – Base Case

Stage 2 Events	Stage 1 Event	Number of Stage 1 Event Runs	Number of Stage 2 Events	Probability of Stage 2 Event given a Stage 1 Event	Mean Time to Hazard (MTTH) Years
End of Authority Hazard	Fail to Brake	7600	4764	0.6268	0.0933
Over-Speed Hazard	Fail to Heed Speed Restriction	1080	1080	1	0.006892
Work Zone Hazard	Fail to Heed Work Zone	7300	7300	1	1.6667

Table 6.18 Stage 2 Results with Increased Work Zone Frequency – Base Case

Stage 3 Events Accident/ Incident	Stage 2 Event	Number of Stage 2 Event Runs	Number of Stage 3 Events	Probability of Stage 3 Event given Stage 2 Event	Mean Time to Stage 3 Event (MTTA) Years
Head-to-Head Collision	End of Authority Hazard	3863	26	0.006731	13.861
Head-to-Tail Collision		3863	23	0.00594	15.669
Sideswipe Collision		3863	4	0.001035	90.097
Over-Speed Derailments	Over-Speed Hazard	1168	2	.001712	4.025

6.9 Sensitivity Analysis – Summary Charts

6.9.1 Errors

Figure 6.3 Ratio of MTTE in Base Case to Baseline Analysis
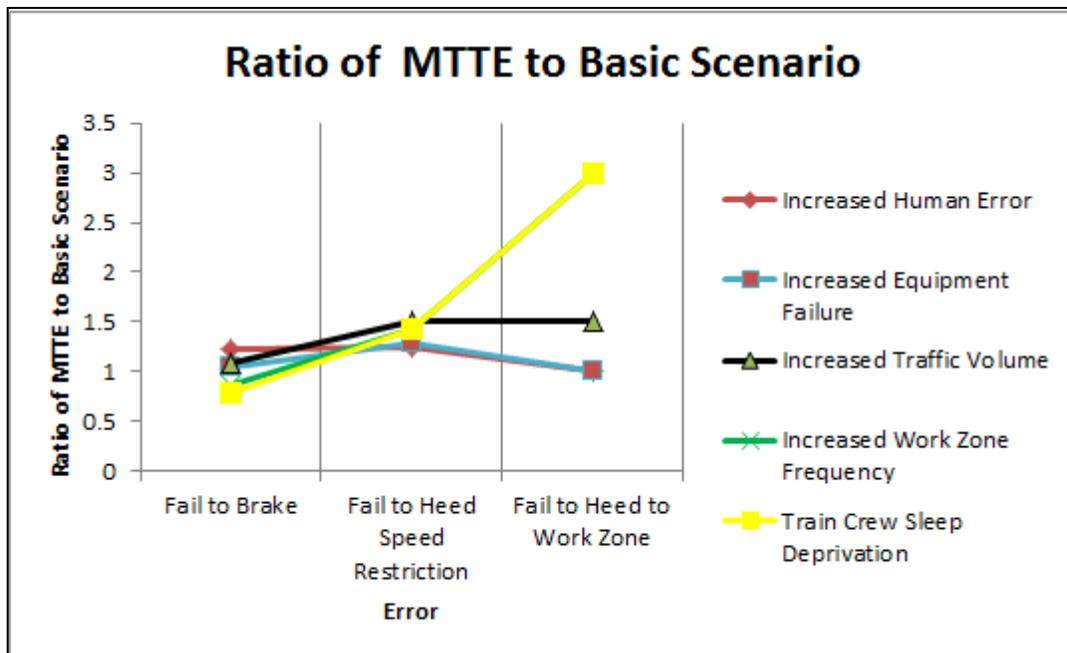
Figure 6.4 Mean Time to Event (Baseline and Sensitivity) Base Case
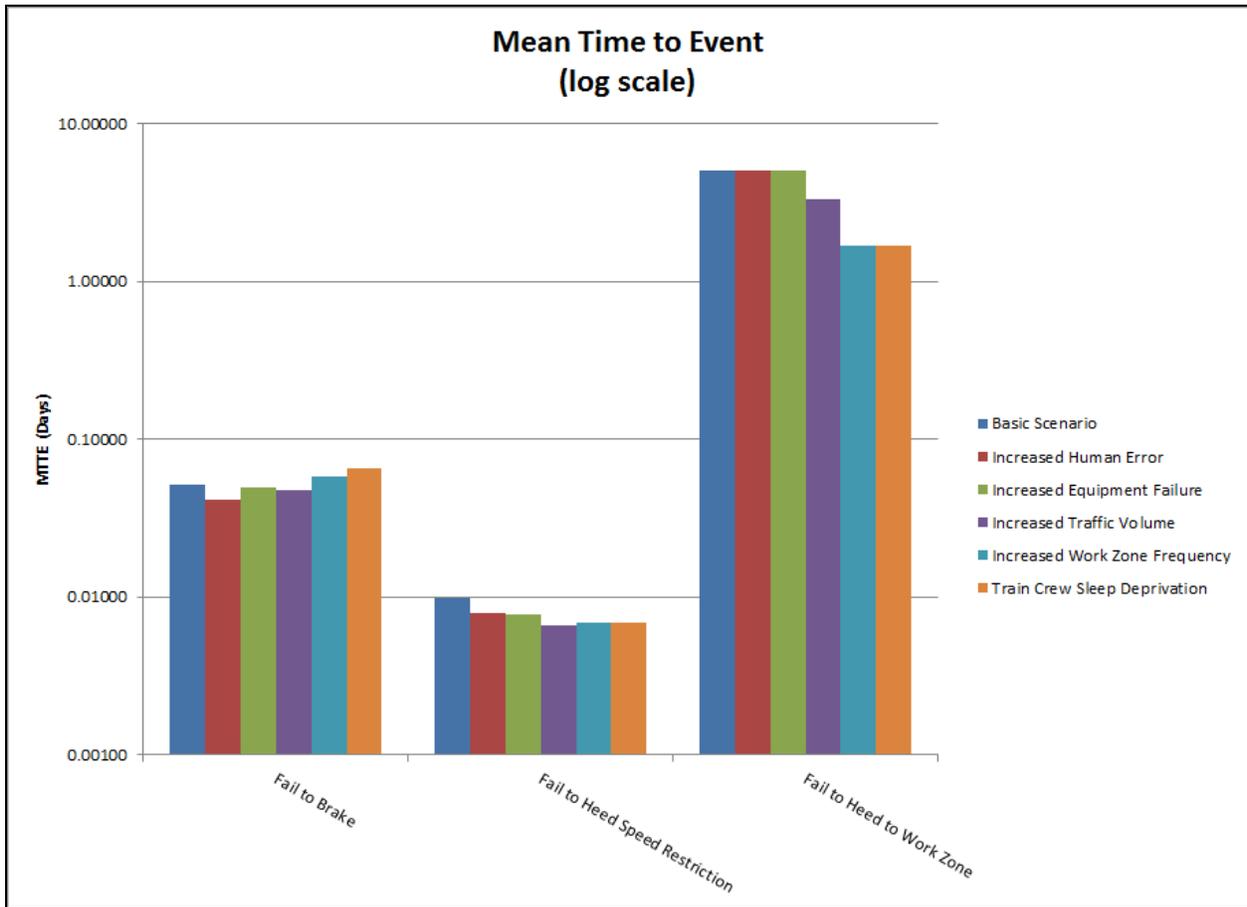
6.9.2 Hazards

Figure 6.5 MTTH in Base Case (Baseline and Sensitivity Analysis)
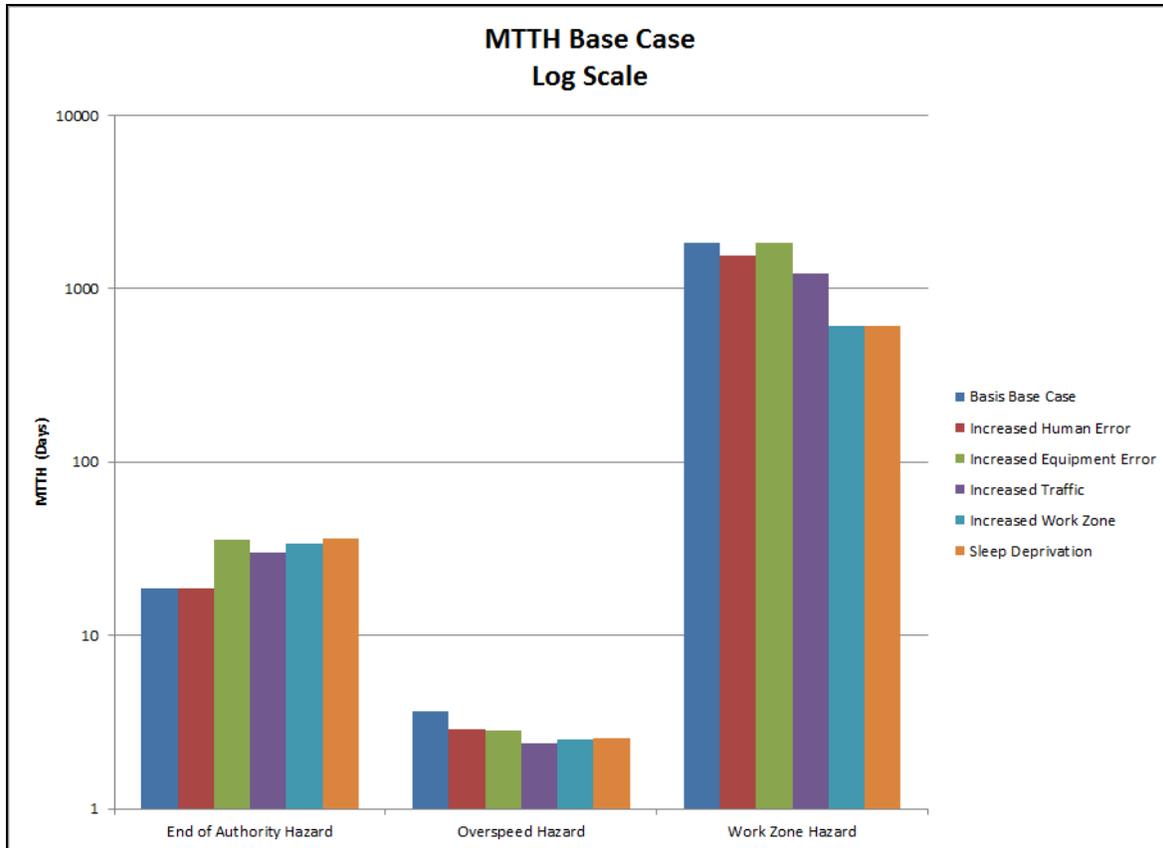
6.9.3 Accidents

Figure 6.6 Comparison of MTTA in Base Case (Baseline and Sensitivity Analysis)
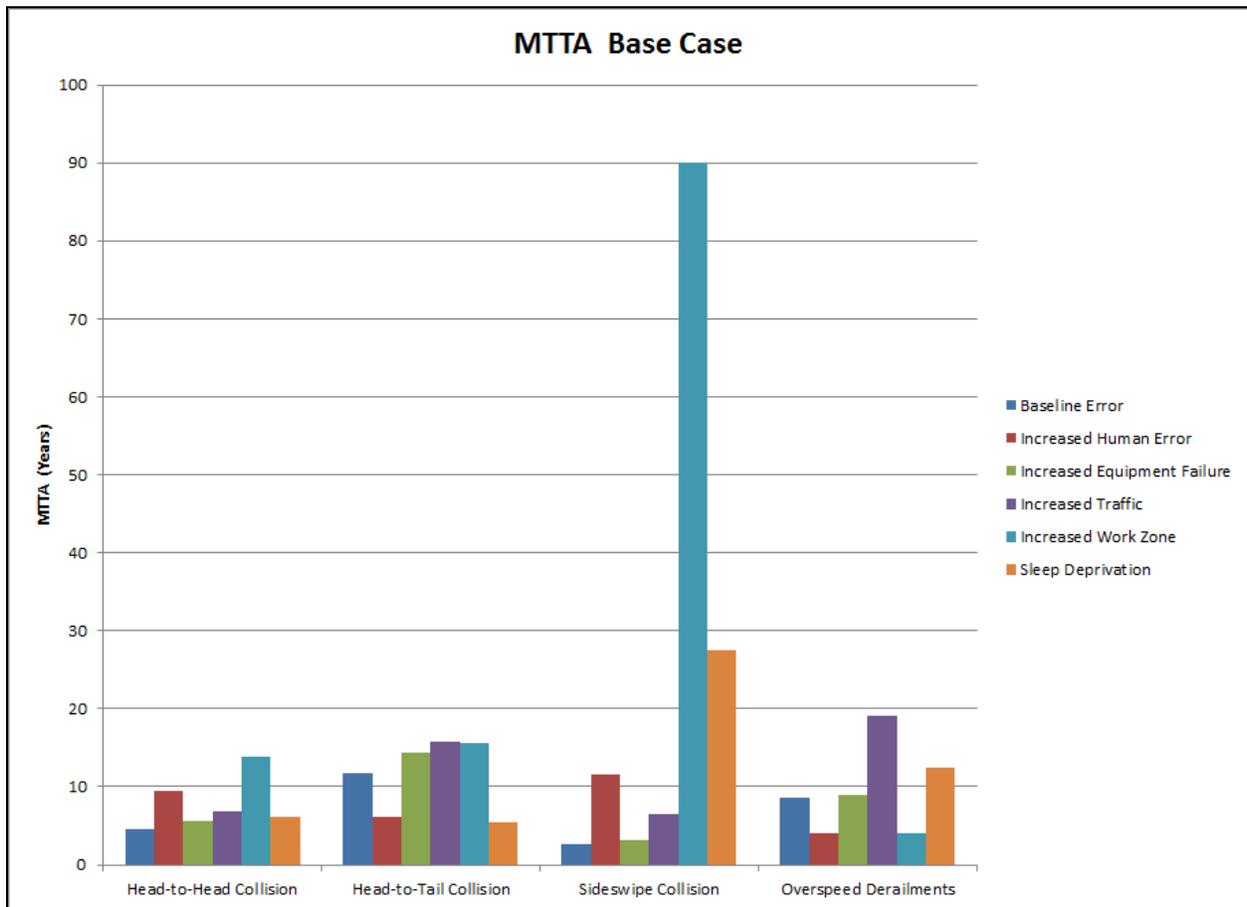
7. Conclusions

7.1 Introduction

The conclusions in the following section derive from the findings in Chapters 6 and 7.

7.2 Conclusions

- GTMS closely replicates operations on the BNSF San Bernardino corridor.

- For the analysis assumptions, risk in the Base Case includes PTC-preventable train-train collisions—one every several years with possible sideswipe collision once every 2 years and an over-speed derailment every 8.6 years. The risk of work zone accidents in the base case was found to be negligible.

- I-ETMS appears to completely mitigate all but negligible risk of PTC-preventable accidents with a high level of confidence.

- In the Base Case, the sensitivity analysis shows that there is moderate variance in the total PTC-preventable accident risk when increasing key inputs in the direction of higher risk.

- In the Base Case, the sensitivity analysis does not show that total accident risk increases as expected when each of the key input variables is changed in the direction of increased risk. However, the expected outcome cannot be ruled out with high confidence because of the unmeasured effects of randomness.

- In the Base Case, the sensitivity analysis shows that there is high variance in the mix of accidents by type.

- For all sensitivity analysis input factors, the findings show that I-ETMS mitigates all but negligible PTC-preventable accident risk with a high level of confidence.

8. Endnotes

1. Confidence is shown by the insensitivity of results to variations in key parameters. See Chapter 7 Sensitivity Analysis.

2. The Interoperable Electronic Train Management System (I-ETMS™) developed by Wabtec Railway Electronics (WRE).

3. 49 CFR Part 229, 234, 235, et al. Positive Train Control Systems; Final Rule, January 15, 2010

4. Tables and charts for the Executive Summary appear in Appendix A.

5. 49 CFR 236 - Rules, Standards, and Instructions Governing the Installation, Inspection, Maintenance, and Repair of Signal and Train Control Systems, Devices, and Appliances. October 1, 2011.

6. FRA, Report to Congress, Positive Train Control Implementation Status, Issues, and Impacts, August 2012. Not all sub-components in the figure are present in all PTC systems.

7. Also called "Monte Carlo method" or "Monte Carlo simulation of the random variable."

8. A type of discrete random variable used to count the number of occurrences of an event in a random sample in a binomial experiment (i.e., an experiment with only two possible outcomes).

9. John F. Shortle, Chun-Hung Chen, Ben Crain, Alexander Brodsky and Daniel Brod (2012): Optimal splitting for rare-event simulation, IIE Transactions, 44:5, 352-367.

10. For a fixed-period simulation of 25 years (or 219,150 hours), one accident occurs, on average, every 5 years. Whether an accident occurs or not in a given hour of operations is a binomial random variable that has mean value 2.28×10^{-5} (i.e., 5 accidents / 219,150 hours). This is the estimated probability of an accident occurring in any given hour (also, the predicted hourly number of accidents). Under Central Limit Theorem assumptions, the 95 percent confidence interval of accident probability is given (close approximation) by: $\mu \pm 1.96\sqrt{\mu/n}$ where μ is the estimated accident probability and n is the number of simulated hours.

11. Parallel processing techniques and use of high-performance computing could reduce the required time and resources, but the principal problem of cost for greater reliability remains using fixed-period simulation.

12. Ibid.

13. The example assumes that 5 years of Stage 1 simulation generates sufficient initiating events and that runs in subsequent stages have small relative cost in terms of computer resources (which has been borne out in practice).

14. Ibid.

15. Ibid.

16. Valley View Grade Separation Project Fact Sheet (http://vvgs.org/wp-content/uploads/2012/08/fact-sheet-20120805-english.pdf)

17. Regional Rail Simulation Findings: Technical Appendix, SCAG, Comprehensive Regional Goods Movement Plan and Comprehensive Strategy (http://www.ieor.berkeley.edu/People/Faculty/leachman-pubs/FinalUpdate_RailTechAppendix_Nov2011.pdf)

18. B.S. Dhillon, "Human Reliability and Error in Transportation Systems," Springer-Verlag London Limited 2007.

19. Thomas Raslear, "Measurement and Estimation of Sleep in Railroad Worker Employees, Research Results," Report Number: DOT/FRA/RR11-02, February 2011, Washington, DC: U.S. Federal Railroad Administration, Department of Transportation.

20. BNSF Railway, Electronic Train Management System Product Safety Plan, Document 2.1, September 20, 2006.

21. These values were derived, in part, from industry averages, published studies, and expert opinion, and others were based on empirical or experiential based information.

22. BNSF data of departures and arrivals confirm this.

23. BNSF Railway, Electronic Train Management System Product Safety Plan, Document 2.1, September 20, 2006.

24. Regional Rail Simulation Findings: Technical Appendix, SCAG, Comprehensive Regional Goods Movement Plan and Comprehensive Strategy (http://www.ieor.berkeley.edu/People/Faculty/leachman-pubs/FinalUpdate_RailTechAppendix_Nov2011.pdf)

25. Thomas Raslear, "Measurement and Estimation of Sleep in Railroad Worker Employees, Research Results," Report Number: DOT/FRA/RR11-02 February 2011 Washington, DC: U.S. Federal Railroad Administration, Department of Transportation.

Appendix A   Executive Summary Tables and Charts

Table A.1 Summary of Error Opportunities in the Analysis

Error Opportunity	Number of Opportunities	Number per Hour of Train Operation	Number of Simulated Errors	Comment
Braking End of Authority	319,391 red signals encountered	0.724	195	Multiple interlockings and traffic control blocks
Speed Zone	2,262,330 civil speed restrictions traversed	5.13	1,009	Usually correspond to grades, curves, or specific features
Work Zone	13,317 trains in work zones	0.0302	2	25 hours of work zones per week
Grade Crossing Failure	1,440 failed grade crossings intersected	0.0033	0	An average train passes approximately 40 grade crossings – approximately one failed crossing per month
Misaligned Switch	0.55 occurrences	Less than 1 per 100 million	0	No simulated errors coincided with a misaligned switch
Mis-Set Switch	274 occurrences	Less than 1 per 100,000	0	No simulated errors coincided with a mis-set switch

Figure A.1 Base Case Mean Time to Hazard
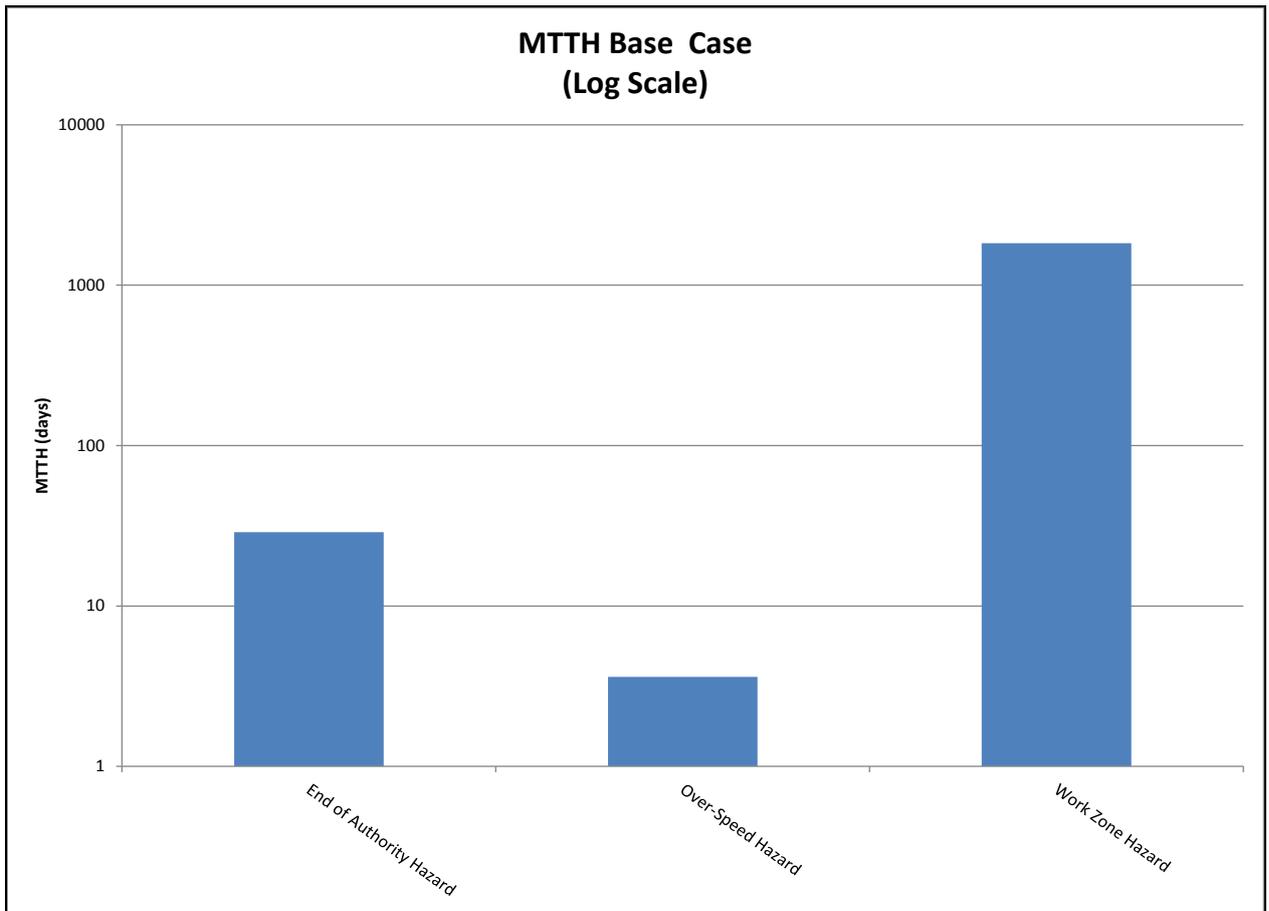
Figure A.2 Mean Time to Accident/Incident – Base Case
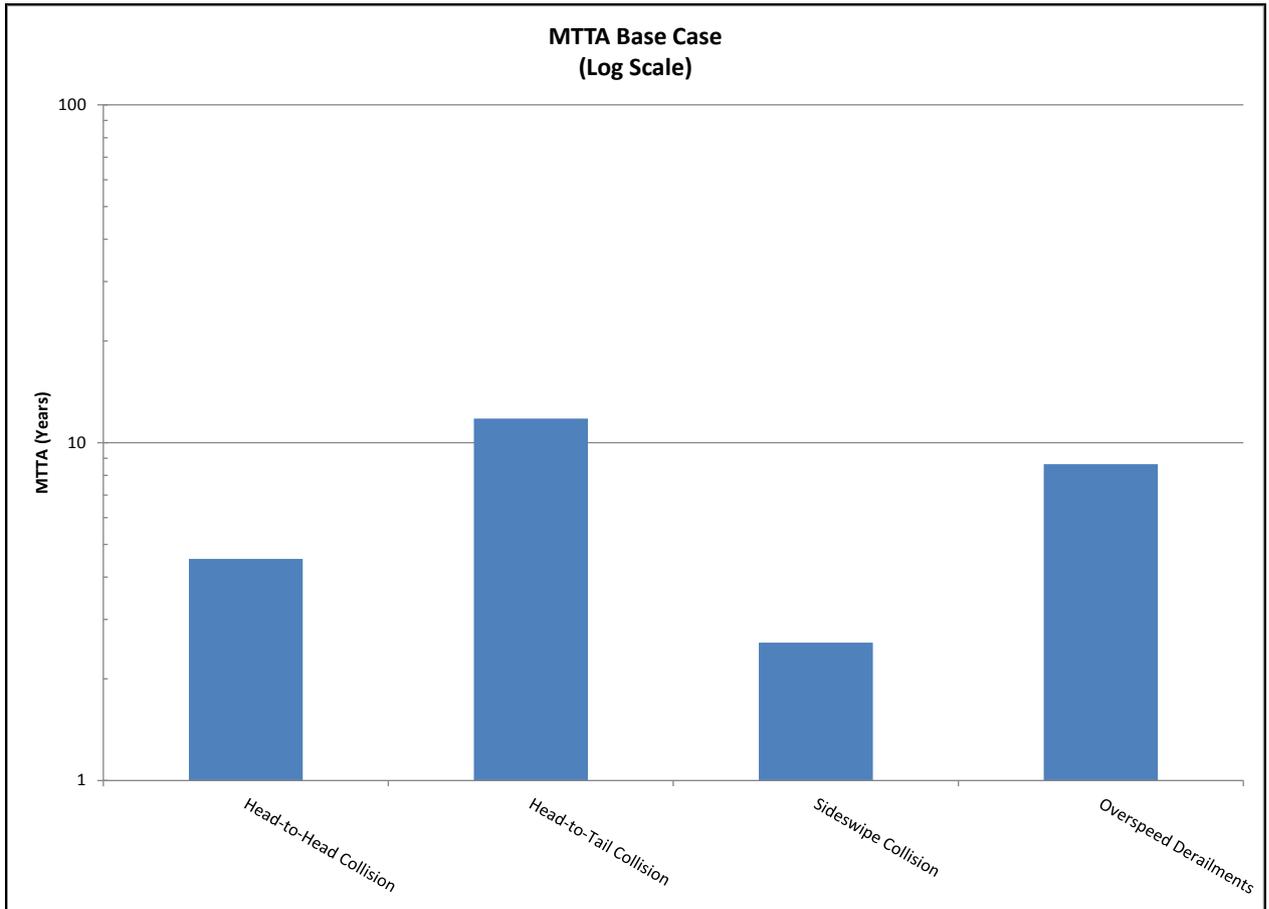
Appendix B   Causal Chains for Risk Assessment

B.1   Introduction

This appendix contains descriptions and sequence diagrams of the risk assessment causal chains associated with each of the models used in the analysis. The analysis compares safety risk before and after implementation of PTC. Consequently, the Base and Alternate Cases each have a unique model and causal chain.

B.2   End of Authority Hazard

An End of Authority (EOA) hazard occurs when a train enters track for which it has no movement authority. When a train operator approaches its end of authority, he or she is expected to apply brakes in order to bring the train to a complete stop. GTMS allows users to specify a train crew's error rate, which determines the probability of a crew failing to initiate braking when approaching its end of authority. Given such an error, GTMS also simulates the time elapsed until the train crew realizes its error and initiates corrective action (applies emergency brakes). The time-speed-position of trains in the system will determine whether the human error evolves into a hazard or an accident. Figure 10.1 and Figure 10.2 depict the evolution of an EOA hazard in the Base and Alternate Cases.

The end of authority hazard is a predecessor event for the following accident types:

- Head-to-Head Collision

- Head-to-Tail Collision

- Sideswipe Collision

- Emergency Braking Derailment

- Enforcement Braking Derailment

Figure B.1 End of Authority Hazard: Base Case
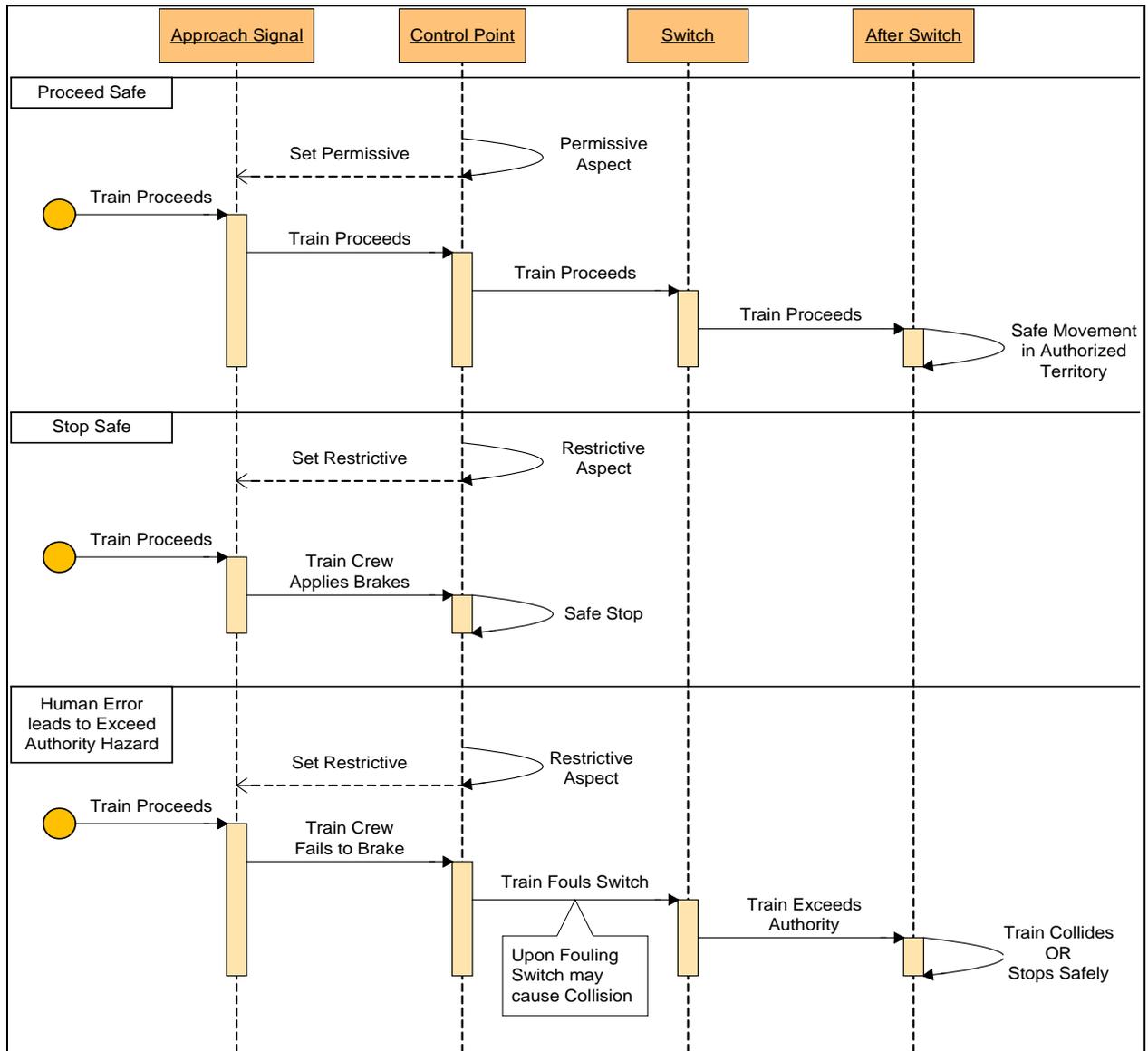
Figure B.2 End of Authority Hazard: Alternate Case
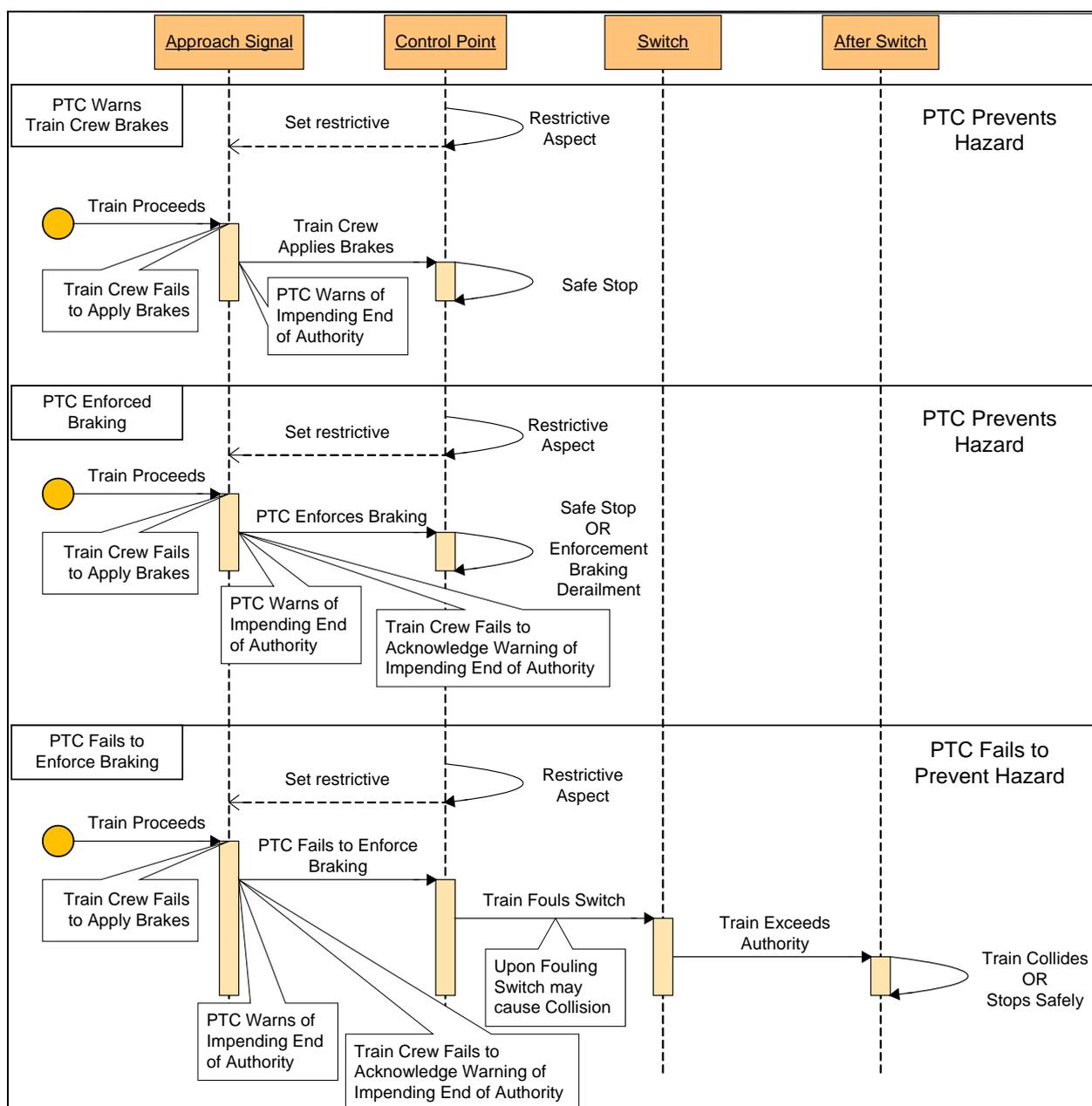
B.3   Misaligned Switch Hazard

A misaligned switch hazard occurs when a train intersects with a switch that is set neither to the normal nor to the reverse position (misaligned). Figure 10.3 and Figure 10.4 depict the evolution of a misaligned switch hazard in the Base and Alternate Cases.

The hazardous event is a predecessor of the following accident types:

- Misaligned Switch Derailment
- Emergency Braking Derailment
- Enforcement Braking Derailment

Figure B.3 Misaligned Switch Hazard: Base Case
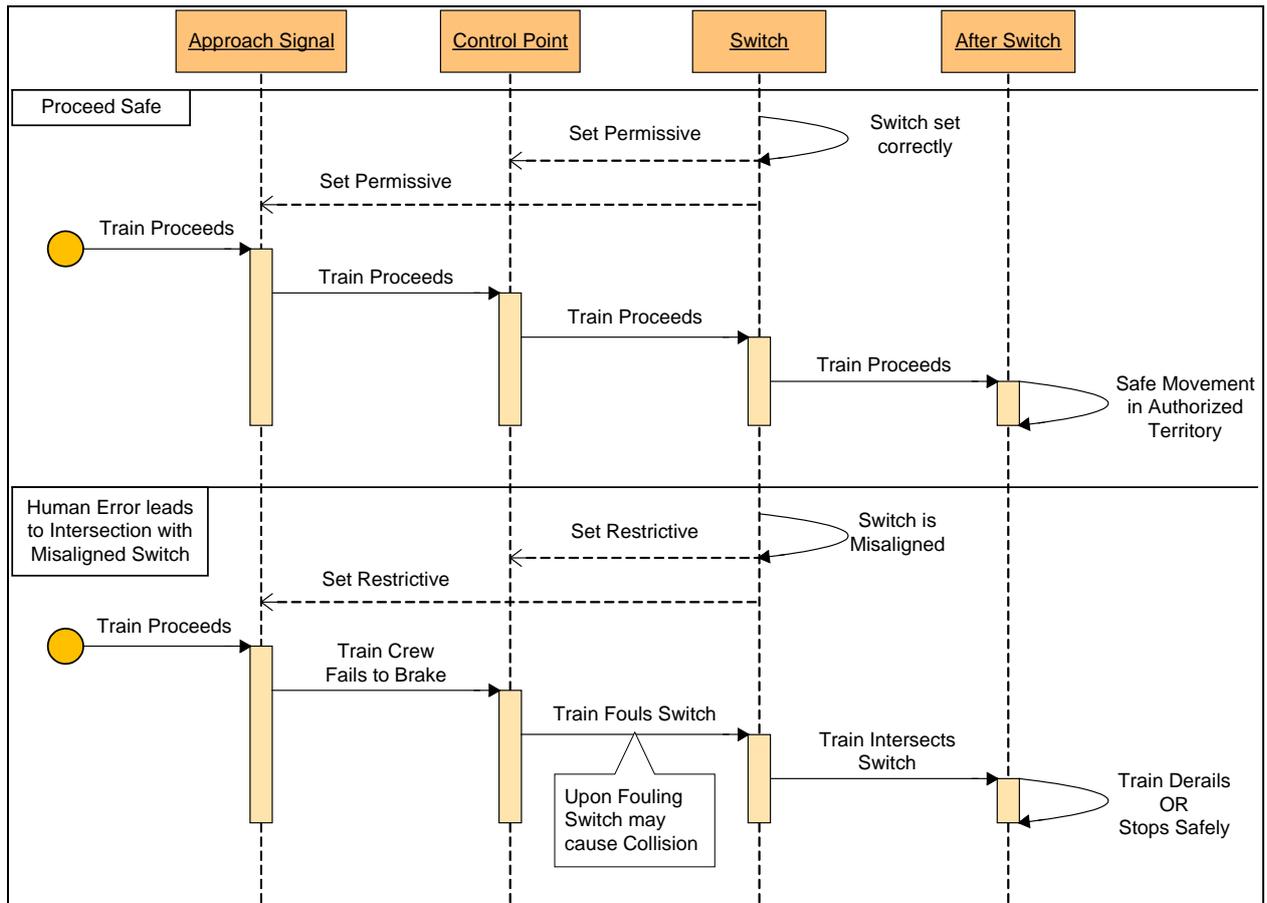
Figure B.4 Misaligned Switch Hazard: Alternate Case
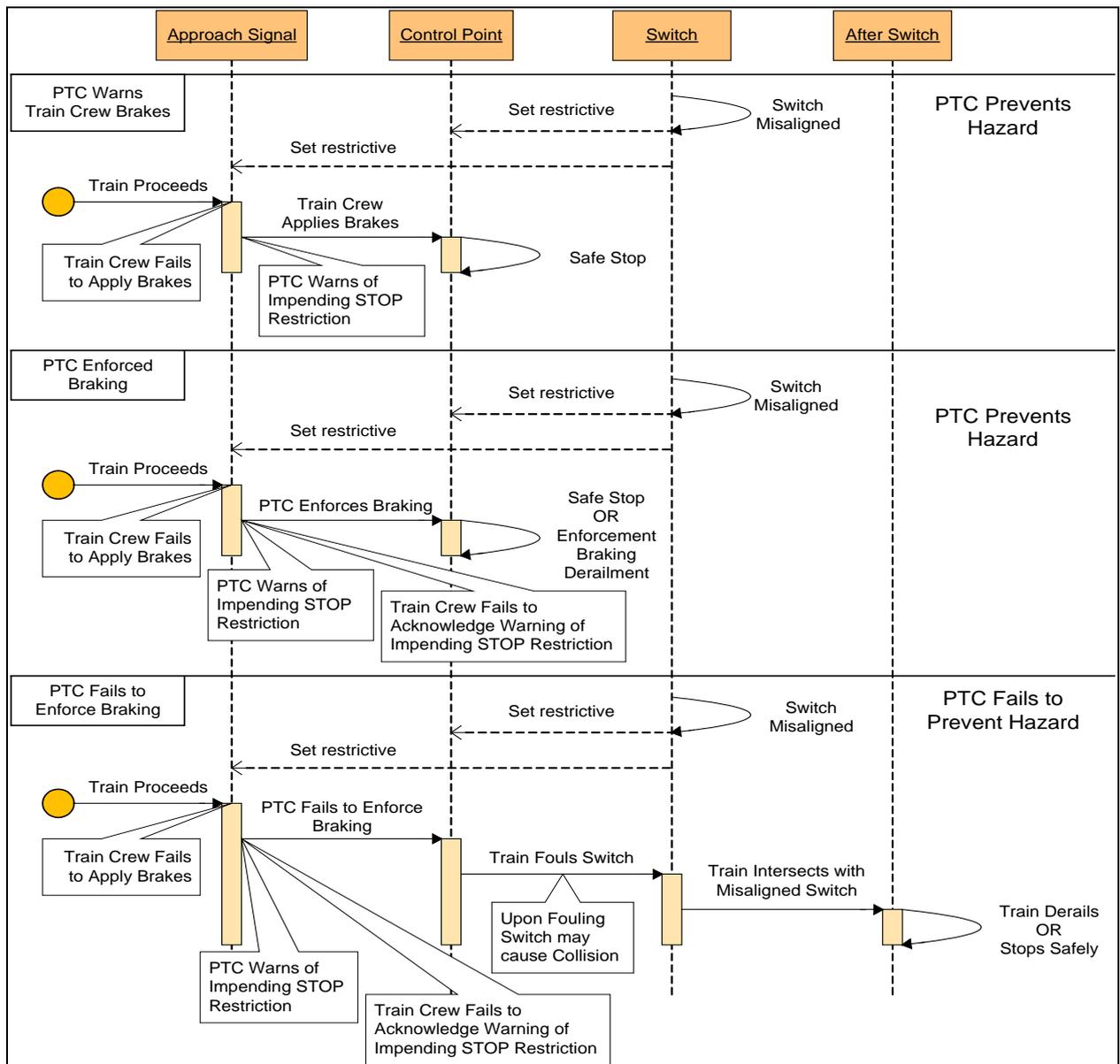
B.4 Switch Set Wrong Hazard

A switch set wrong hazard occurs when a train intersects with a switch that is aligned against the train's movement authority. Figure 10.5 and Figure 10.6 depict the evolution of this hazard in the Base and Alternate Cases.

The hazardous event is a predecessor of the following accident types:

- Unauthorized Alignment Switch Derailment

- Emergency Braking Derailment

- Enforcement Braking Derailment

Figure B.5 Switch Set Wrong Hazard: Base Case
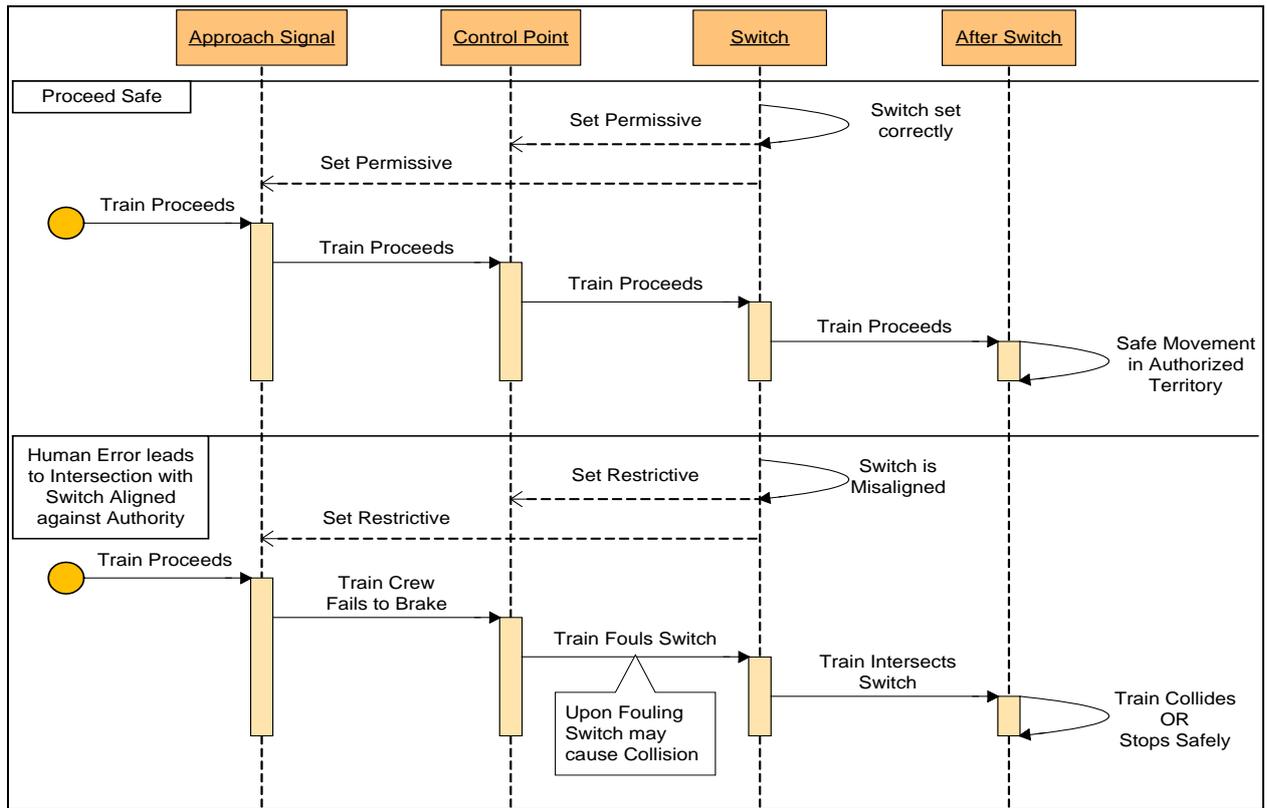
Figure B.6 Switch Set Wrong Hazard: Alternate Case
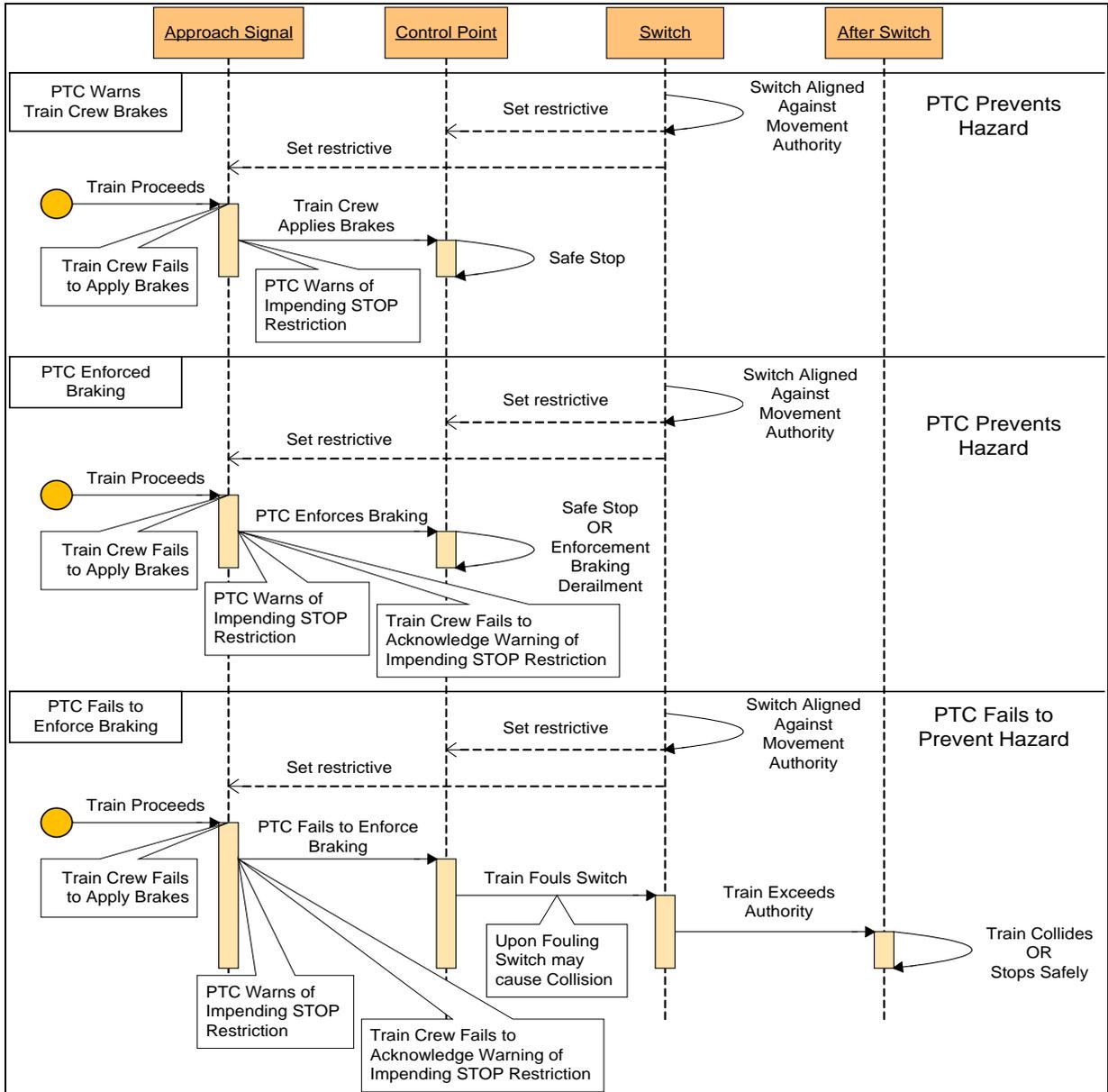
B.5   Work Zone Incursion Hazard

A work zone incursion occurs when a train encroaches on a work zone without observing safe procedures. When a train approaches a work zone (i.e., a Form B track bulletin), the train crew must obtain permission from the EIC in order to proceed. Until the EIC grants entry into the work zone, the train may not enter the work zone, and the train crew must bring the train to a complete stop before reaching the work zone. Once the EIC grants permission for entry, the train may proceed into the work zone at a restricted speed (determined by the Form B).

Figure 10.7 and Figure 10.8 depict the evolution of a work zone incursion in the Base and Alternate Cases.

The hazardous event is a predecessor of the following accident:

- Work Zone Accident/Incident

Figure B.7 Work Zone Incursion Hazard: Base Case
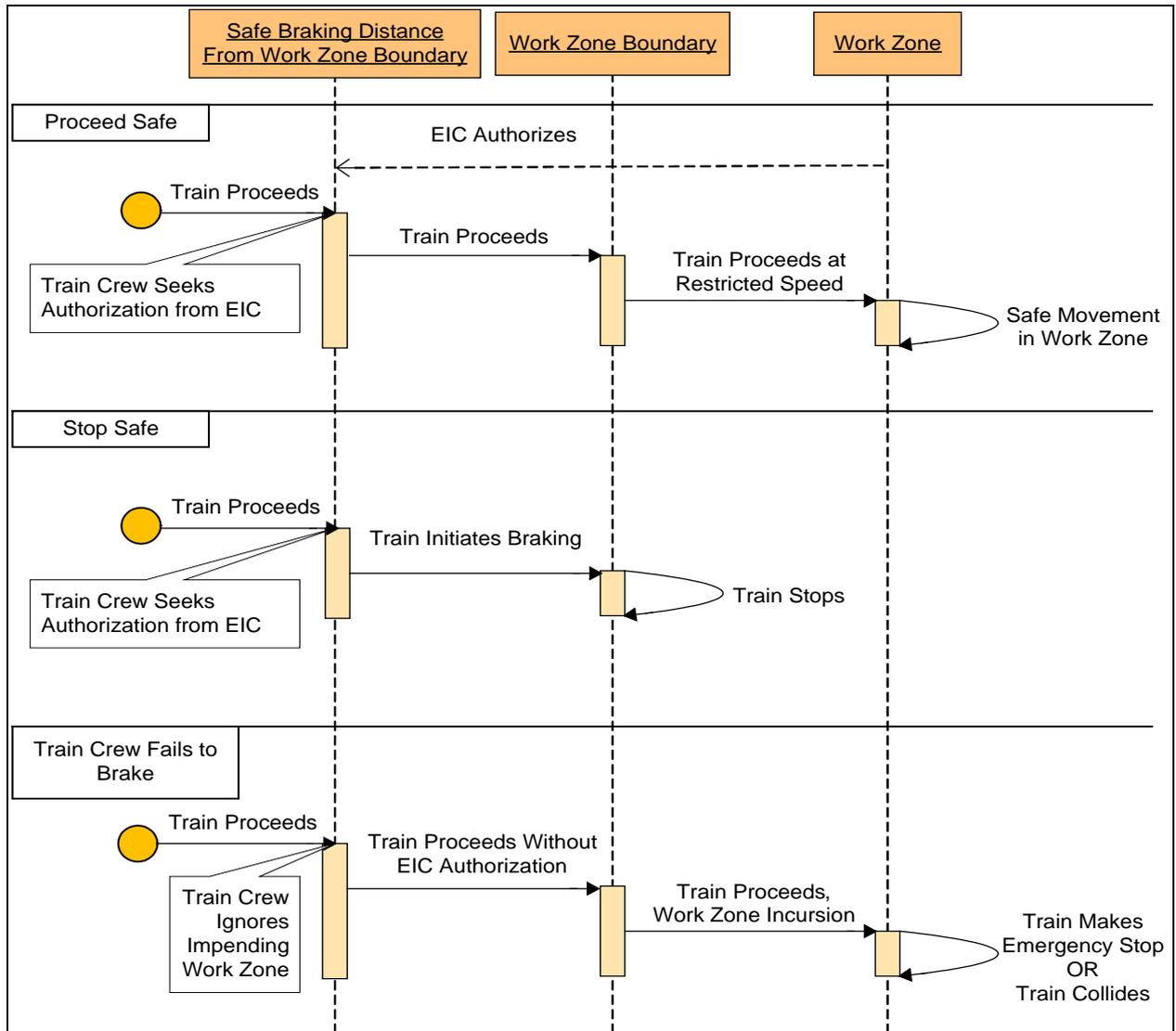
Figure B.8 Work Zone Incursion Hazard: Alternate Case
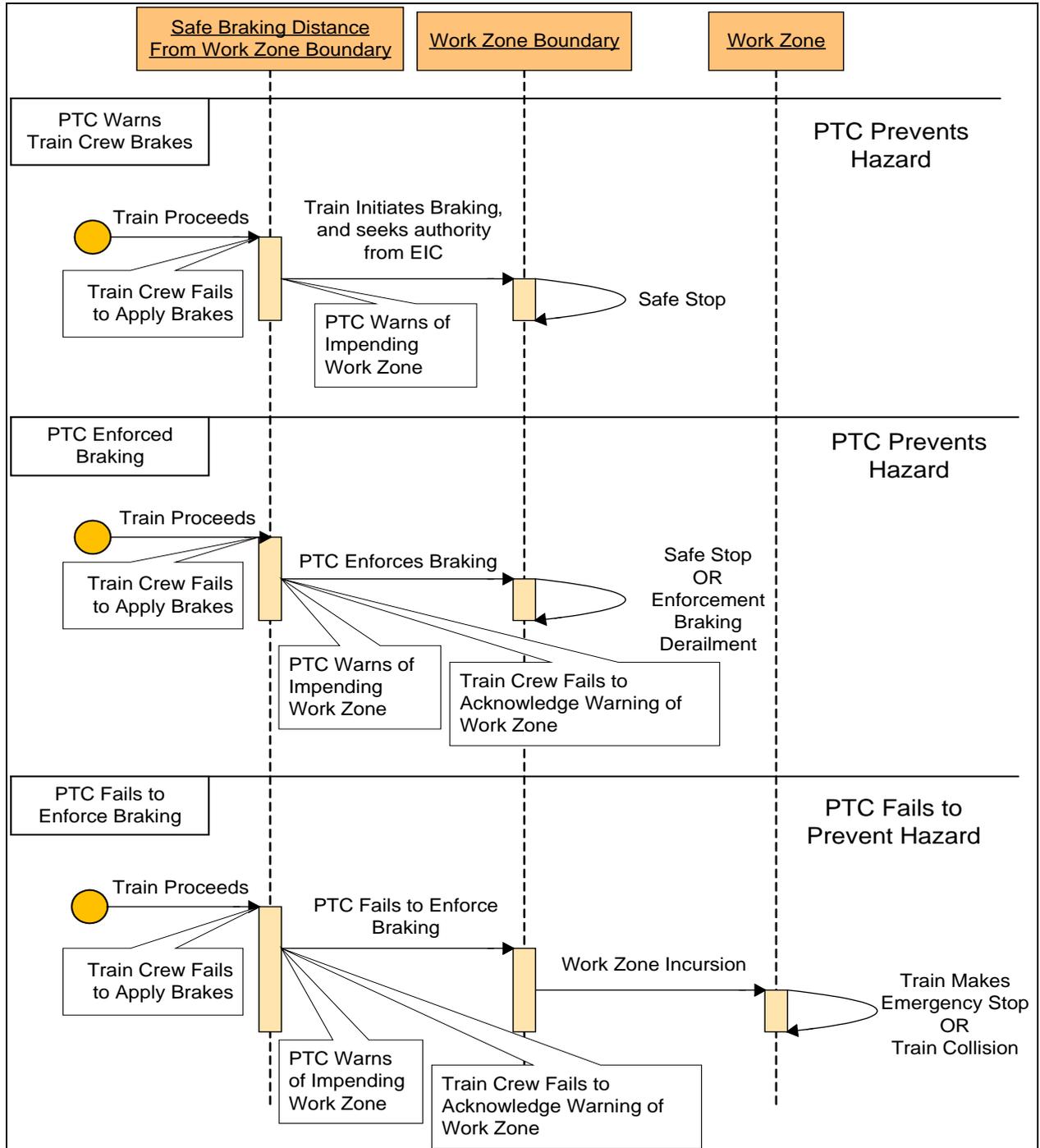
B.6　　　　Over-Speed Hazard

An Over-Speed Hazard occurs when the train crew fails to reduce the train speed when approaching a speed zone with a lower civil speed limit. Figure 10.9 and Figure 10.10 depict the evolution of an Over-Speed Hazard in the Base and Alternate Cases.

This hazard is a predecessor of the following accident type:

- Over-Speed Derailment

Figure B.9 Over-Speed Hazard: Base Case
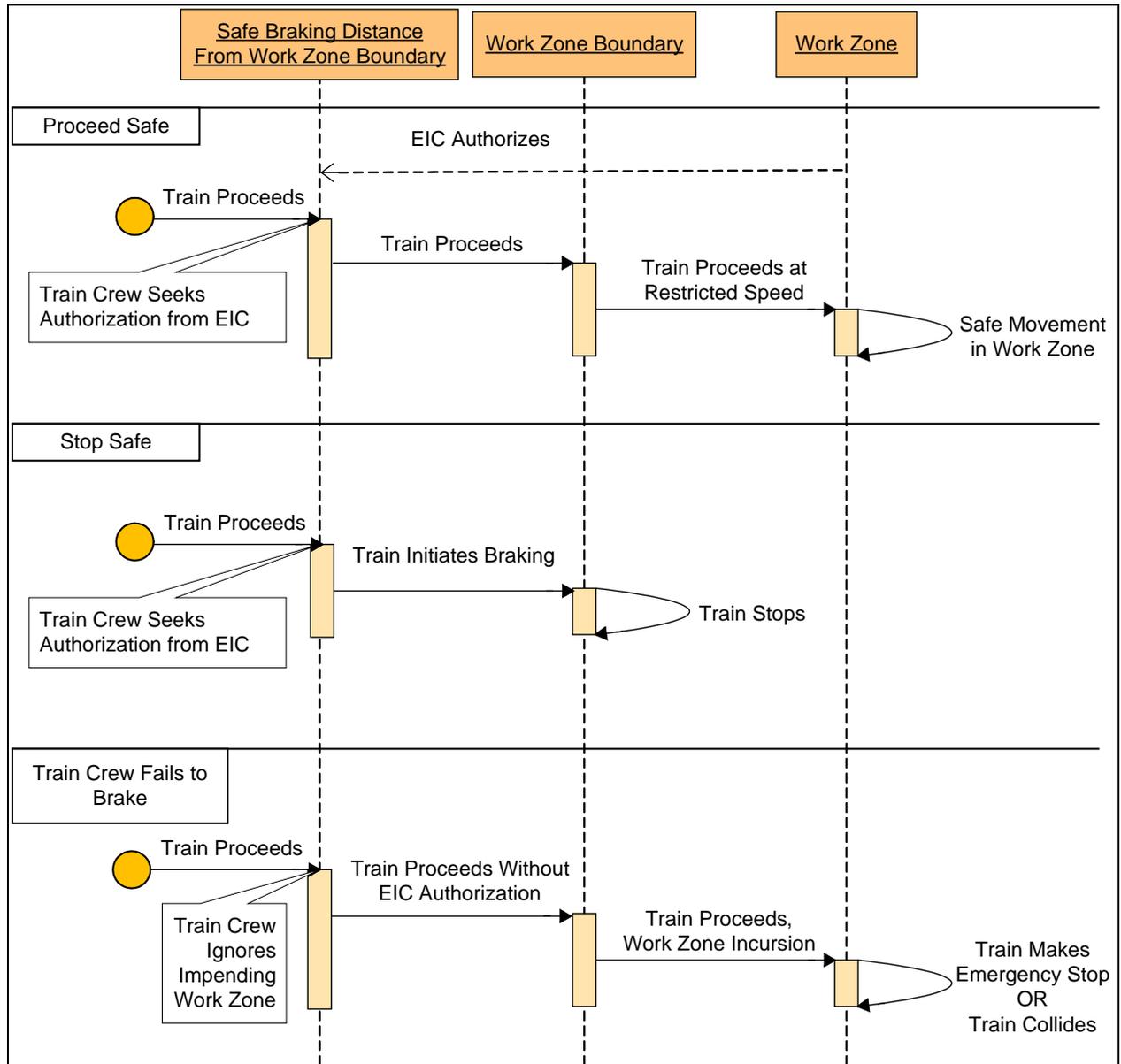
Figure B.10 Over-Speed Hazard: Alternate Case
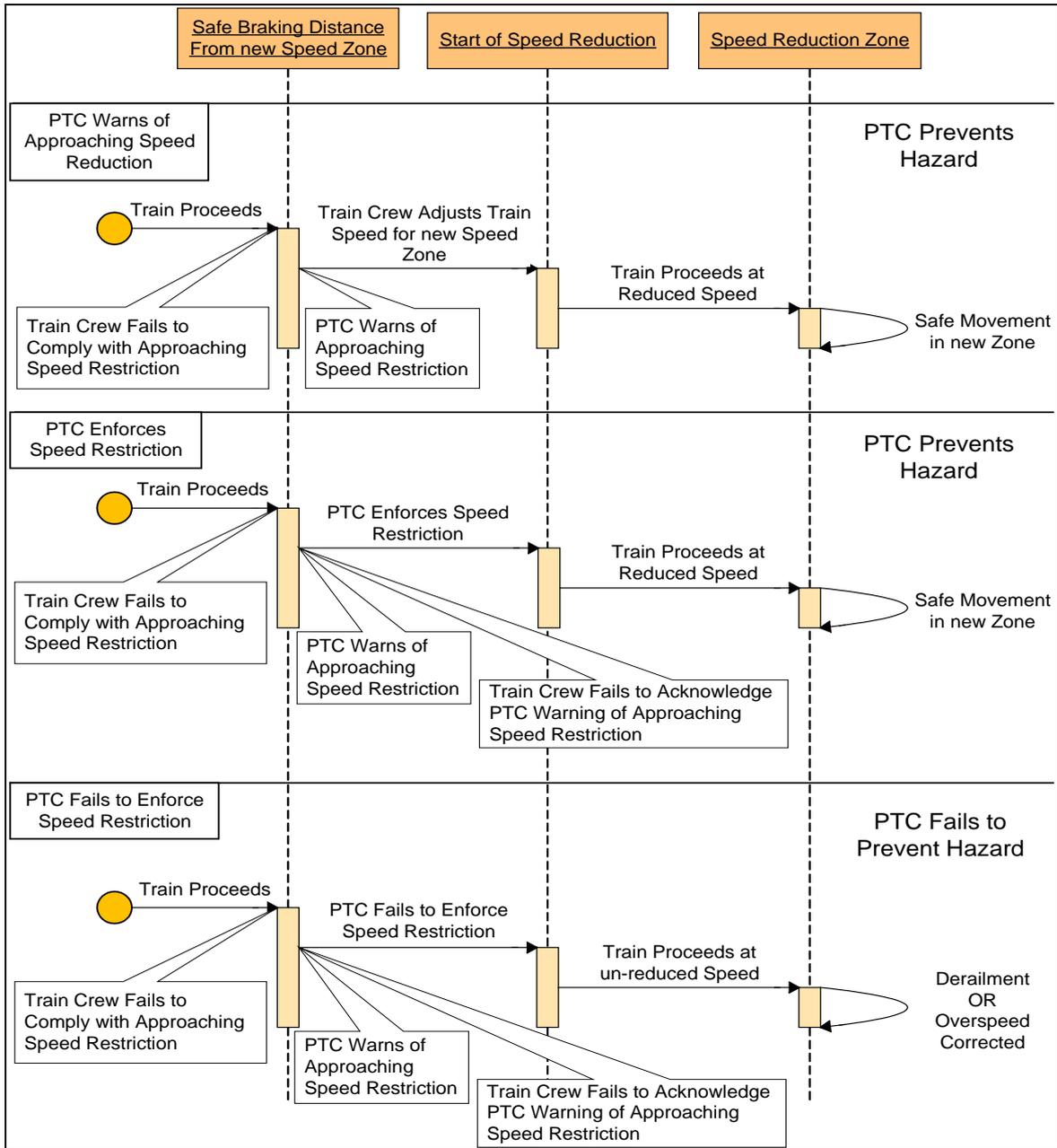
B.7   Grade Crossing Malfunction Over-Speed Hazard

A Grade Crossing Malfunction Over-Speed Hazard occurs when: (a) a grade crossing device malfunctions, and (b) the train crew fails to slow to restricted speed when approaching the crossing. Figure 10.11 depicts the evolution of a grade crossing over-speed hazard in the Base and Alternate Cases.

This hazard is a predecessor of the following accident type:

Over-Speed Derailment

Figure B.11 Grade Crossing Malfunction Over-Speed Hazard: Both Cases

Appendix C   GTMS Track Tool Charts for the San Bernardino Corridor

The following figures display the San Bernardino corridor from west to east as visualized in the GTMS Track Charting tool. The charts display, from top to bottom, speed zones, curves, track, elevations, and distance. Vertical lines represent mileposts.

Figure C.1 MP 143.2 to 149.3

Figure C.2 MP 149.3 to 155.4

Figure C.3 MP 155.2 to 161.2
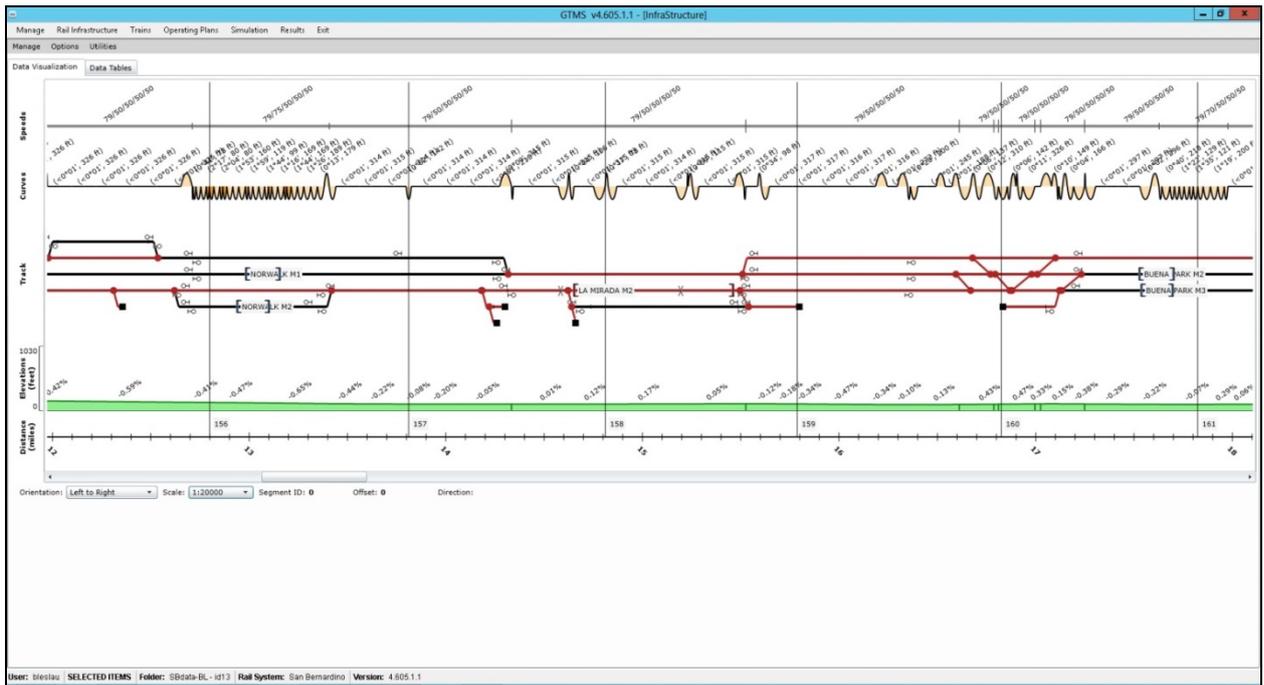
Figure C.4 MP 161.1 to 43.8

Figure C.5 MP 43.9 to 37.8
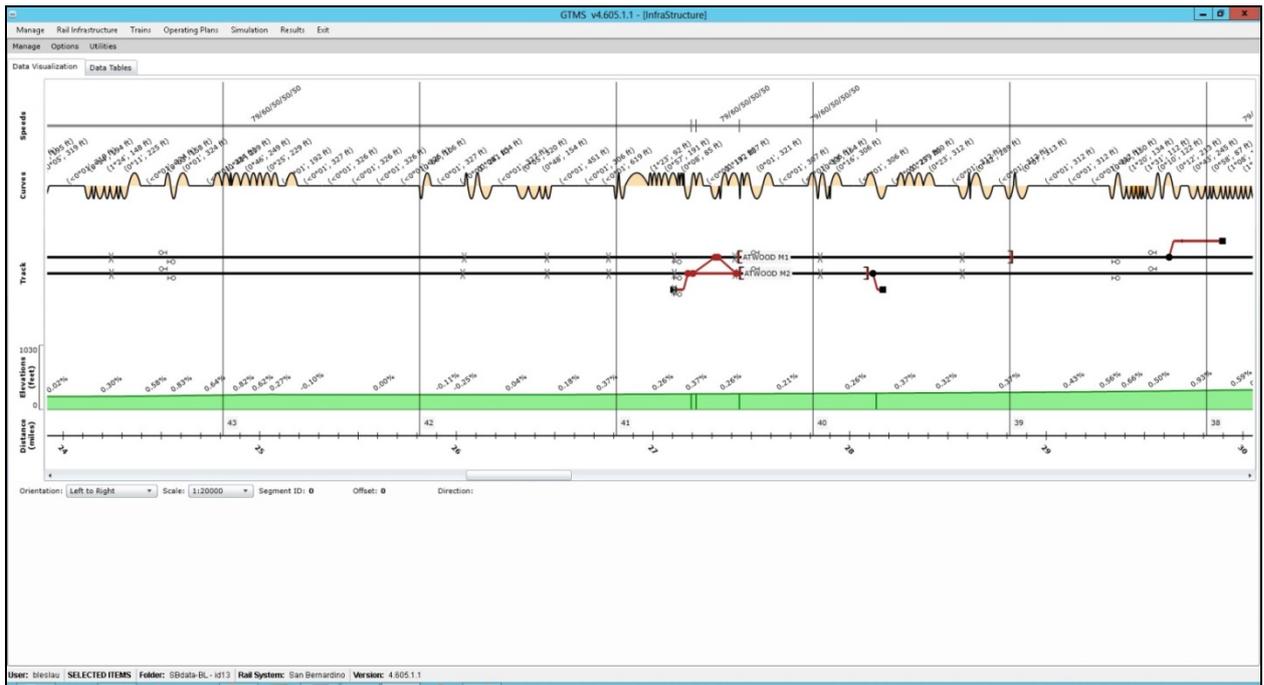
Figure C.6 MP 37.9 to 31.8
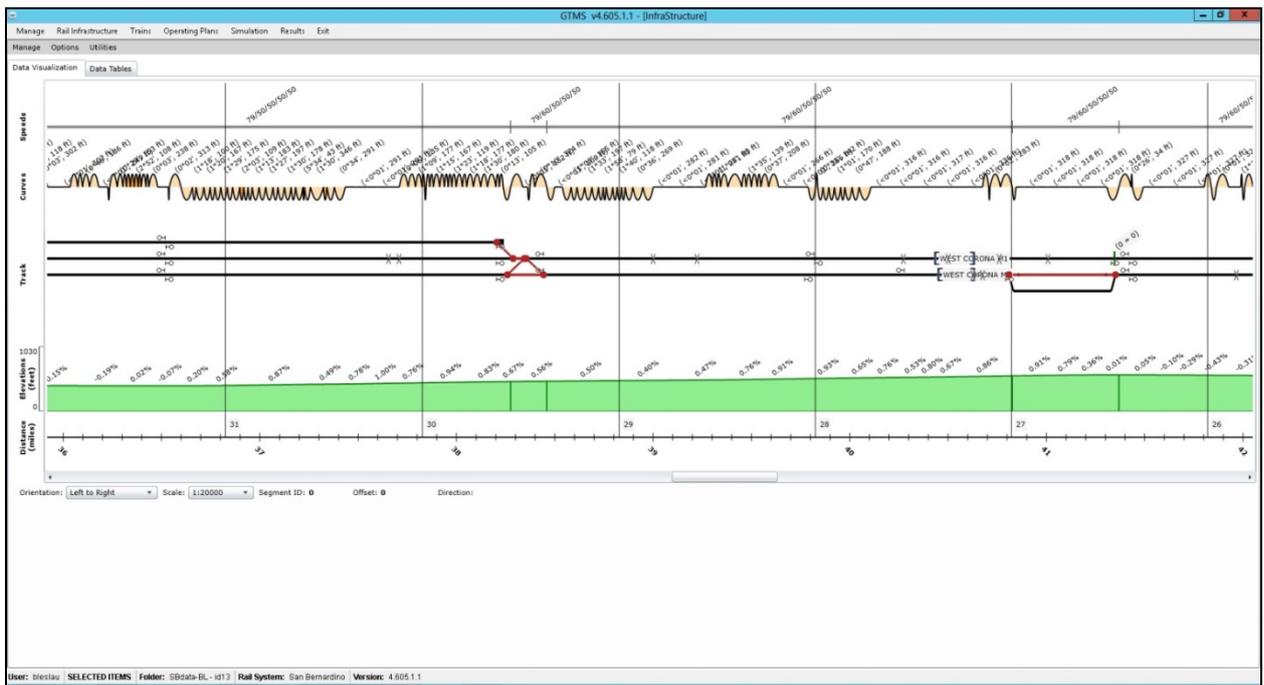
Figure C.7 MP 31.9 to 25.8
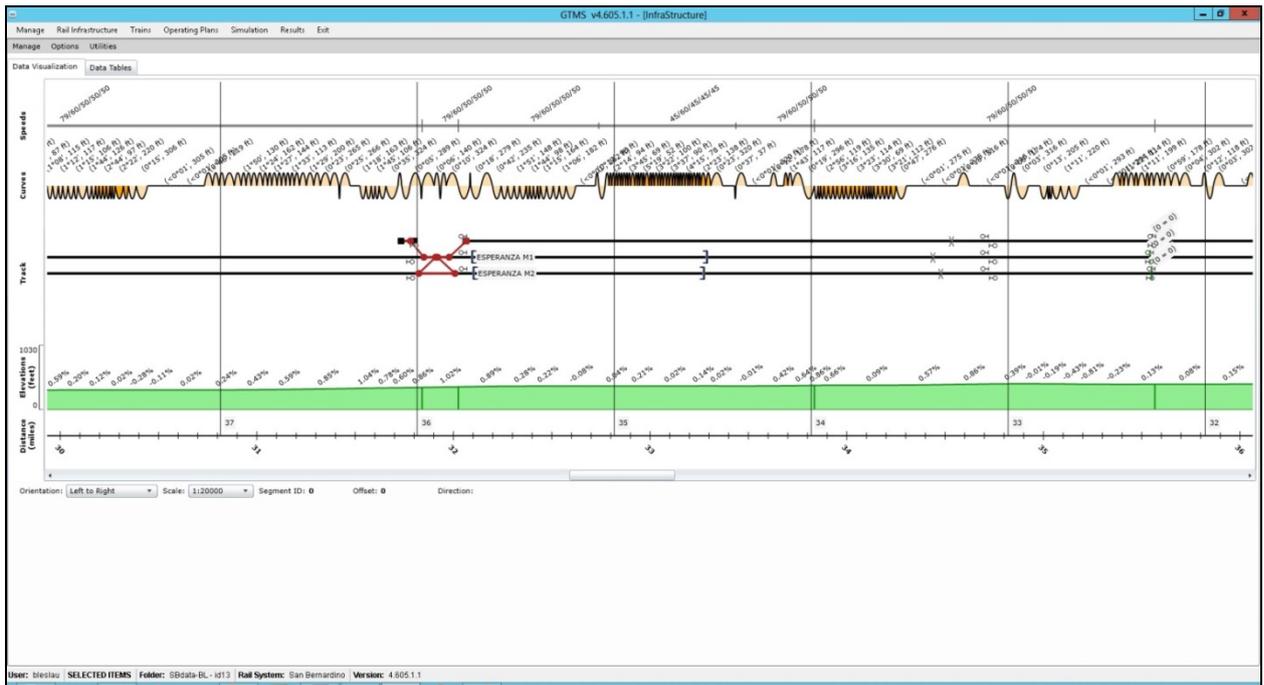
Figure C.8 MP 25.9 to 19.8
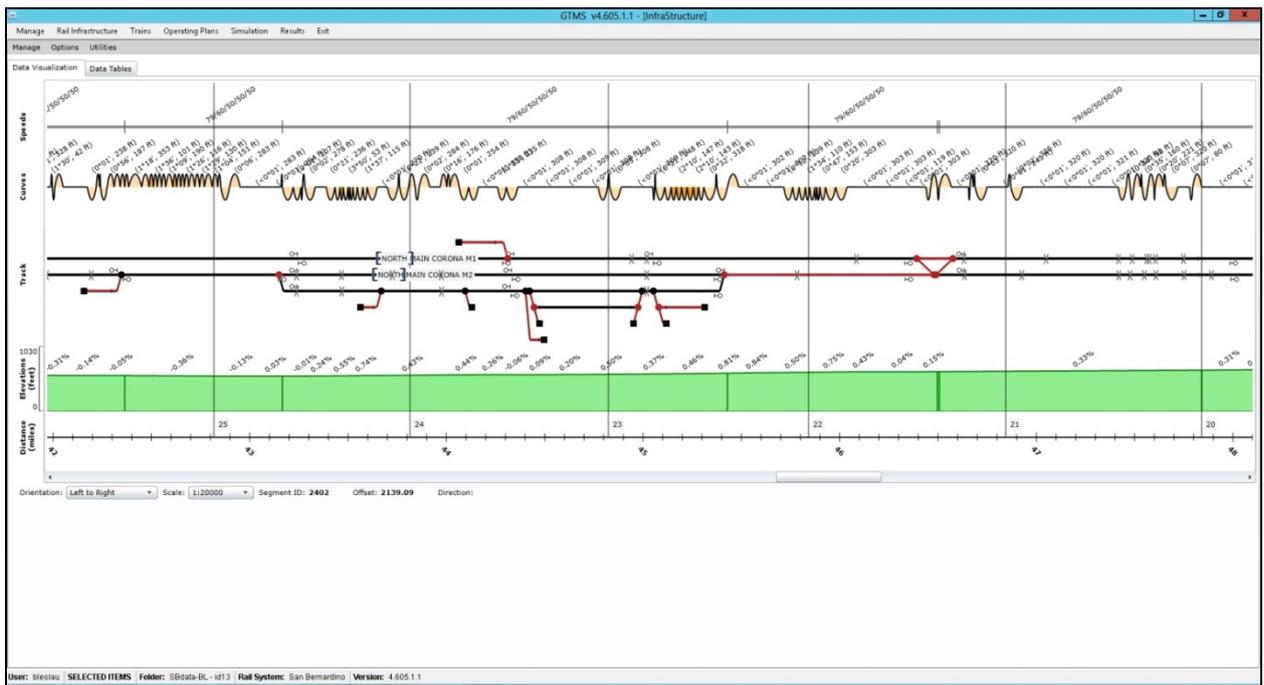
Figure C.9 MP 19.8 to 13.7
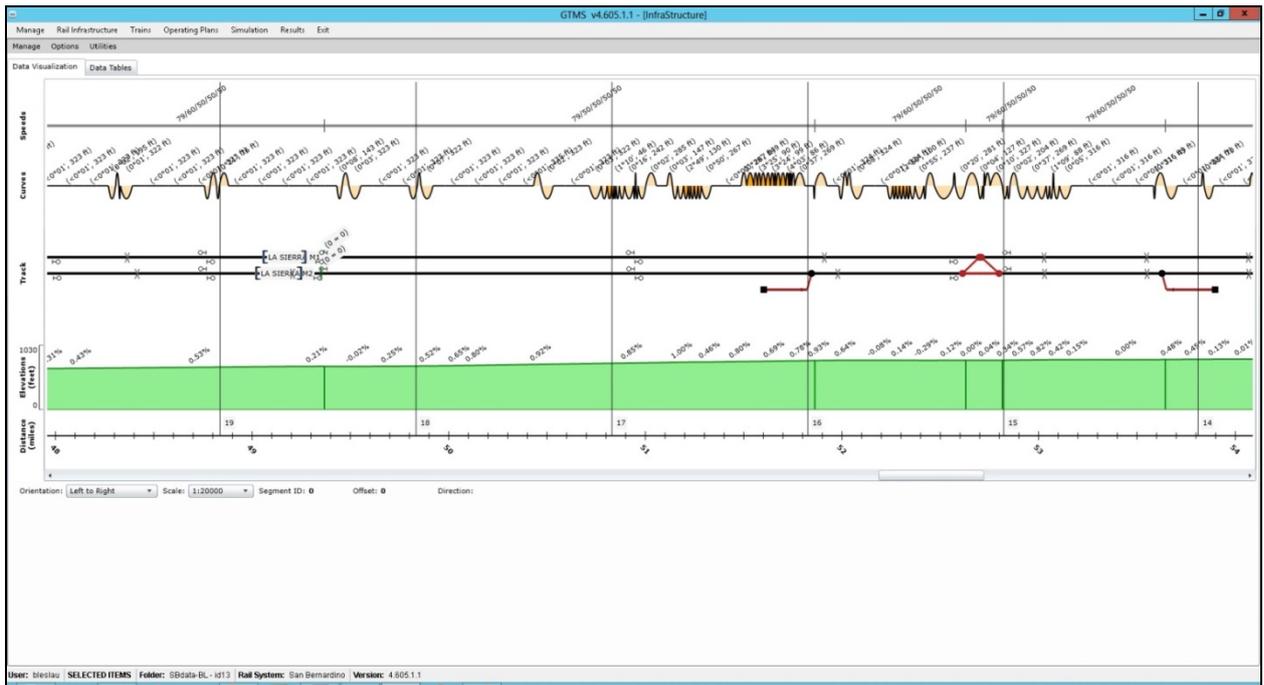
Figure C.10 MP 13.8 to 7.7
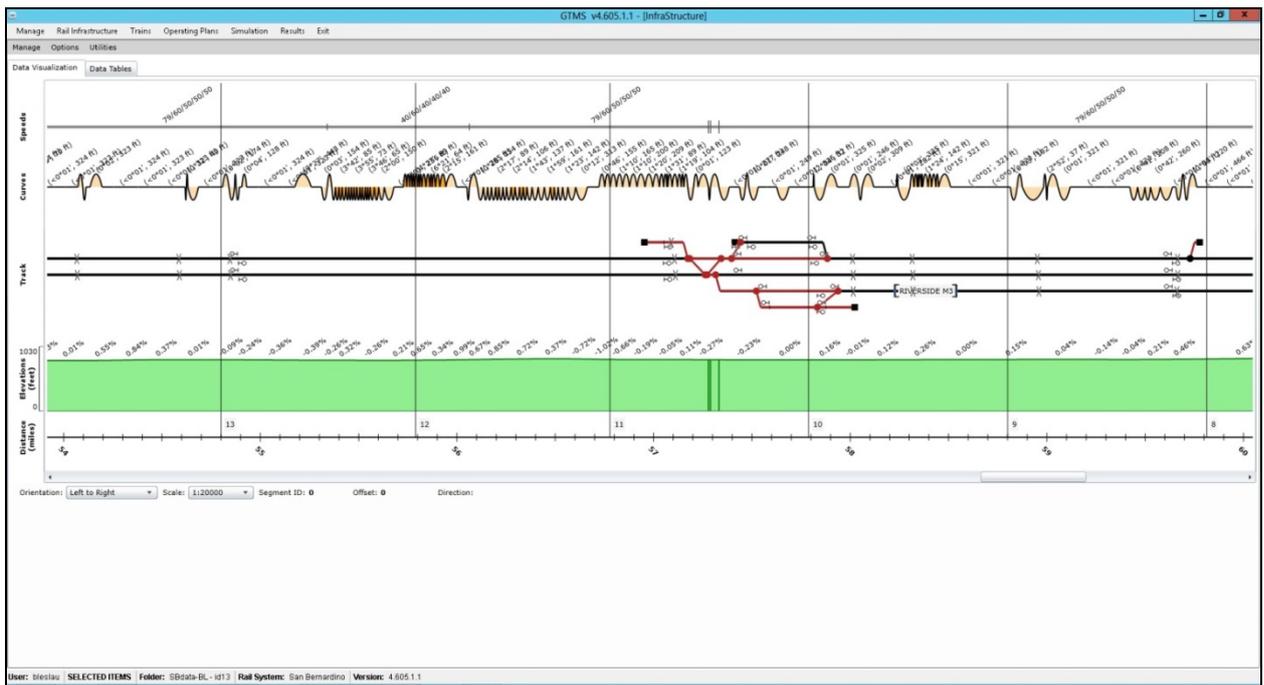
Figure C.11 MP 7.9 to 1.8
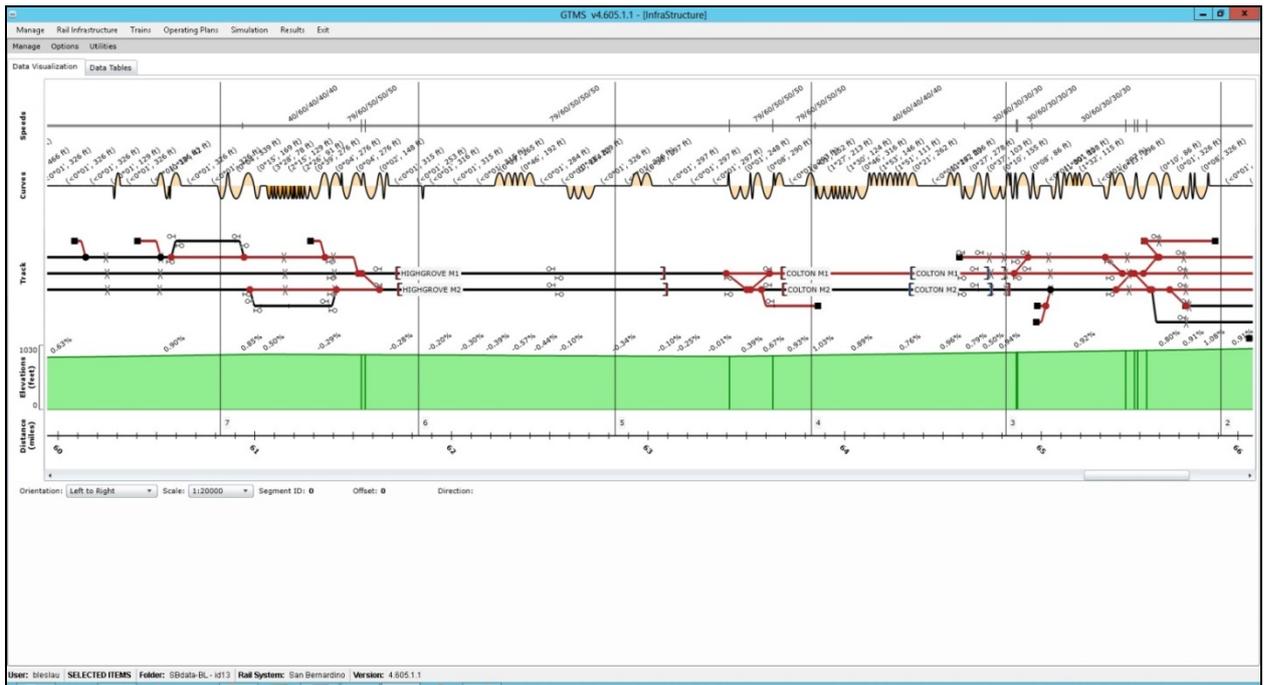
Figure C.12 MP 5 to 0
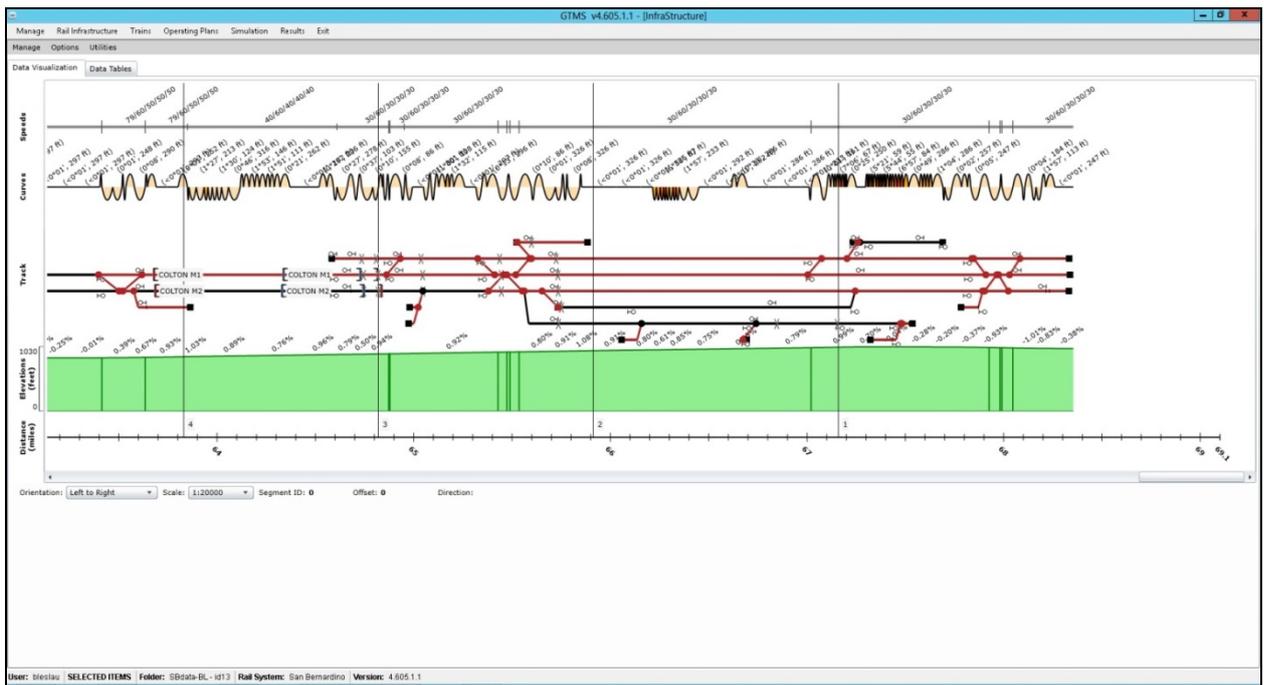
Appendix D GTMS String Chart for a Typical Day

Figure D.1 String Chart for a Typical Day
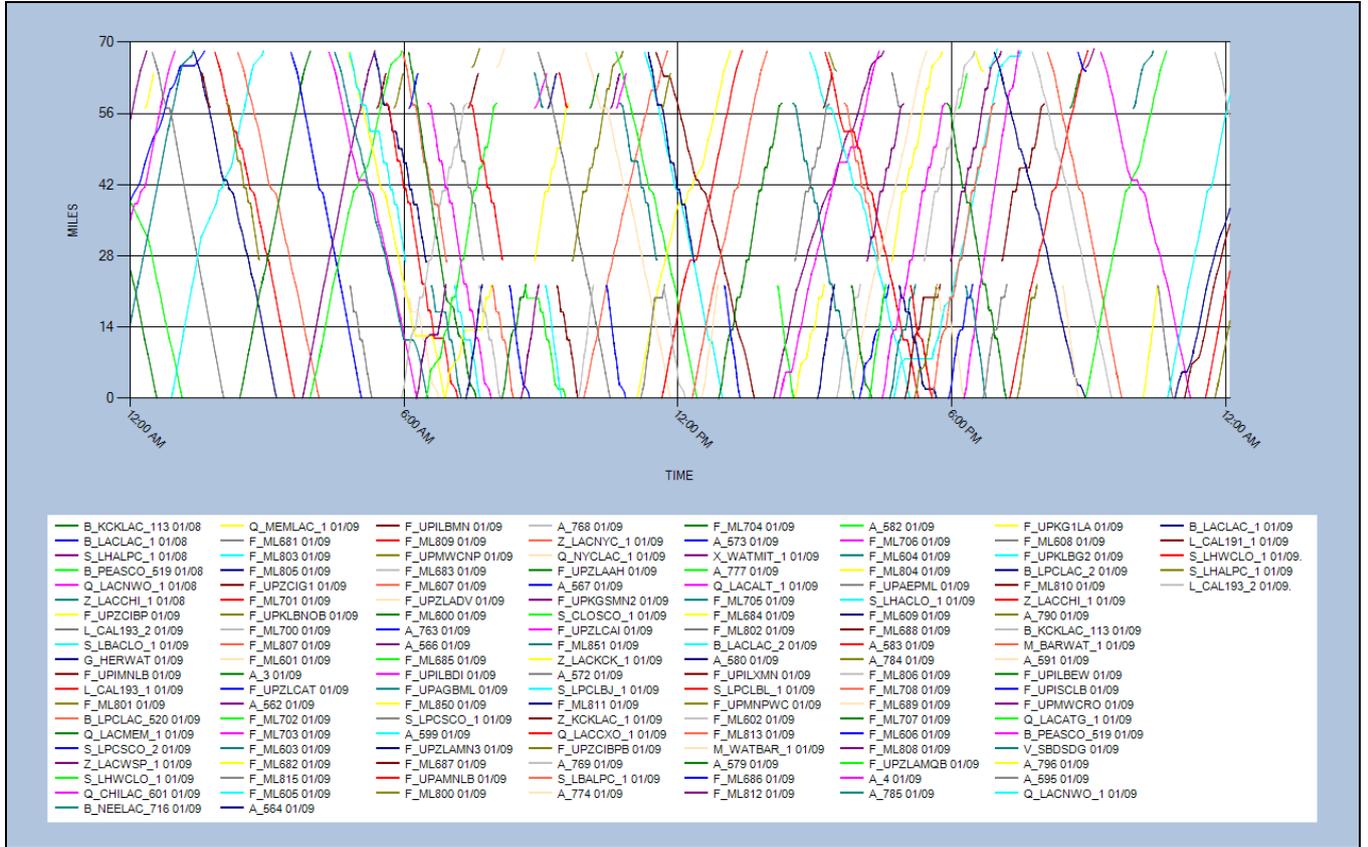
Appendix E   Authorities Charts for a Typical Day

Figure E.1 Authority Chart for a Typical Day
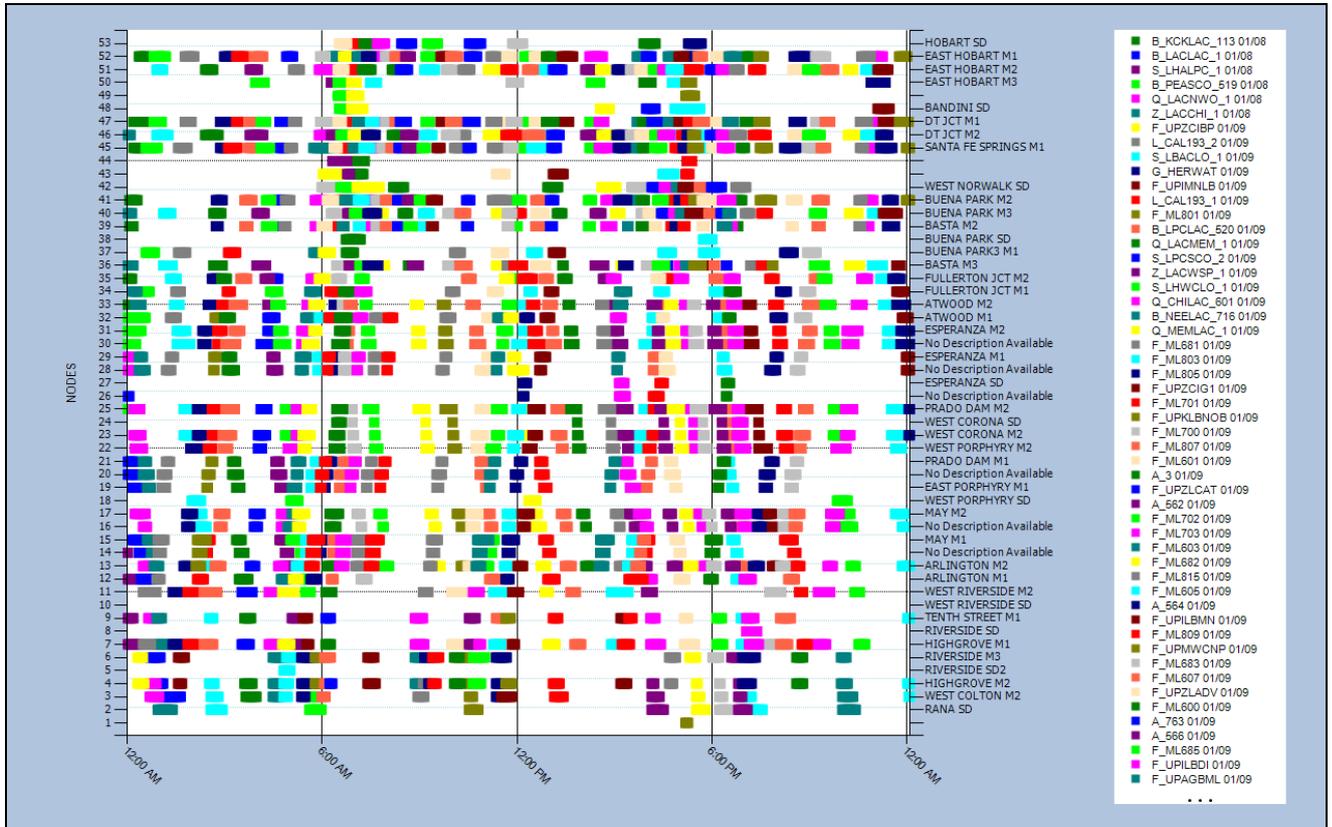
Appendix F   Representative Speed Charts

Figure F.1 Speed Chart for B_LPCLAC_820 1/9/2013
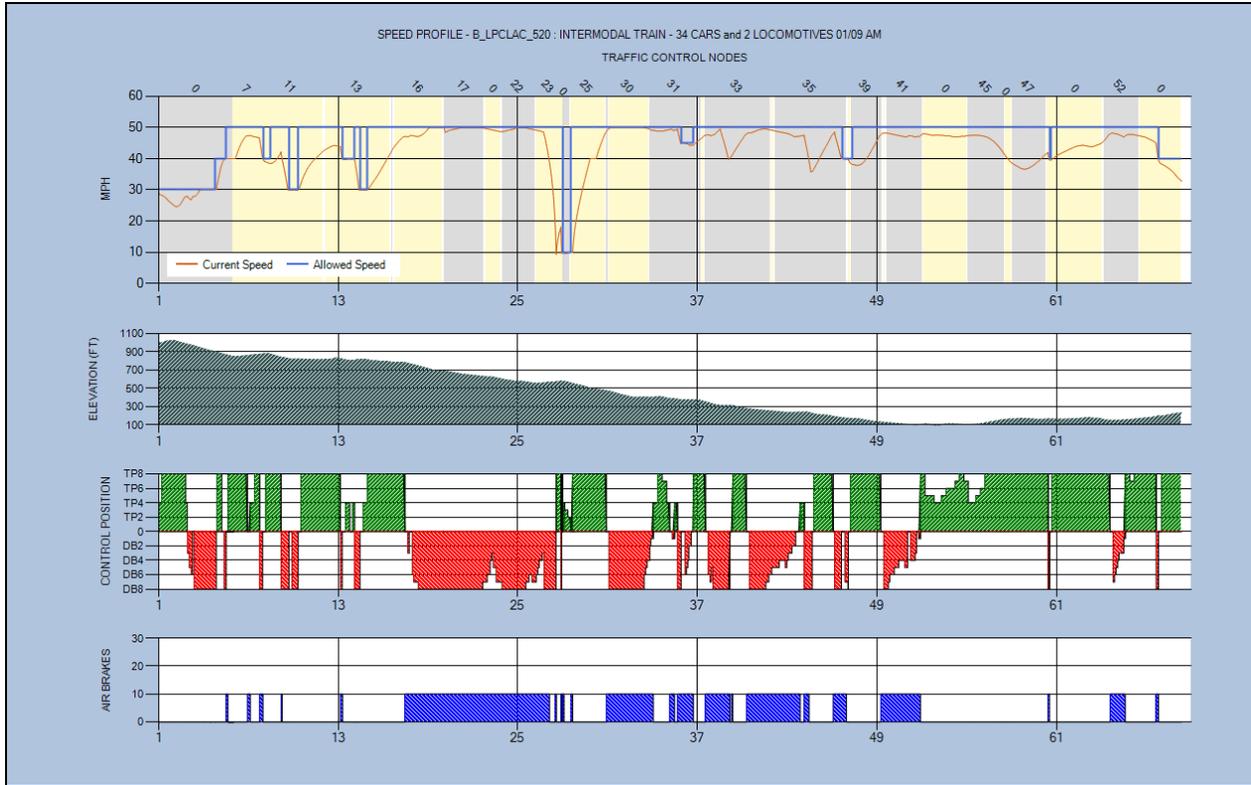
Figure F.2 Speed Chart for B_PEASCO_619 1/9/2013

SPEED PROFILE - B_PEASCO_519 : INTERMODAL TRAIN - 29 CARS and 2 LOCOMOTIVES 01/09 PM
TRAFFIC CONTROL NODES
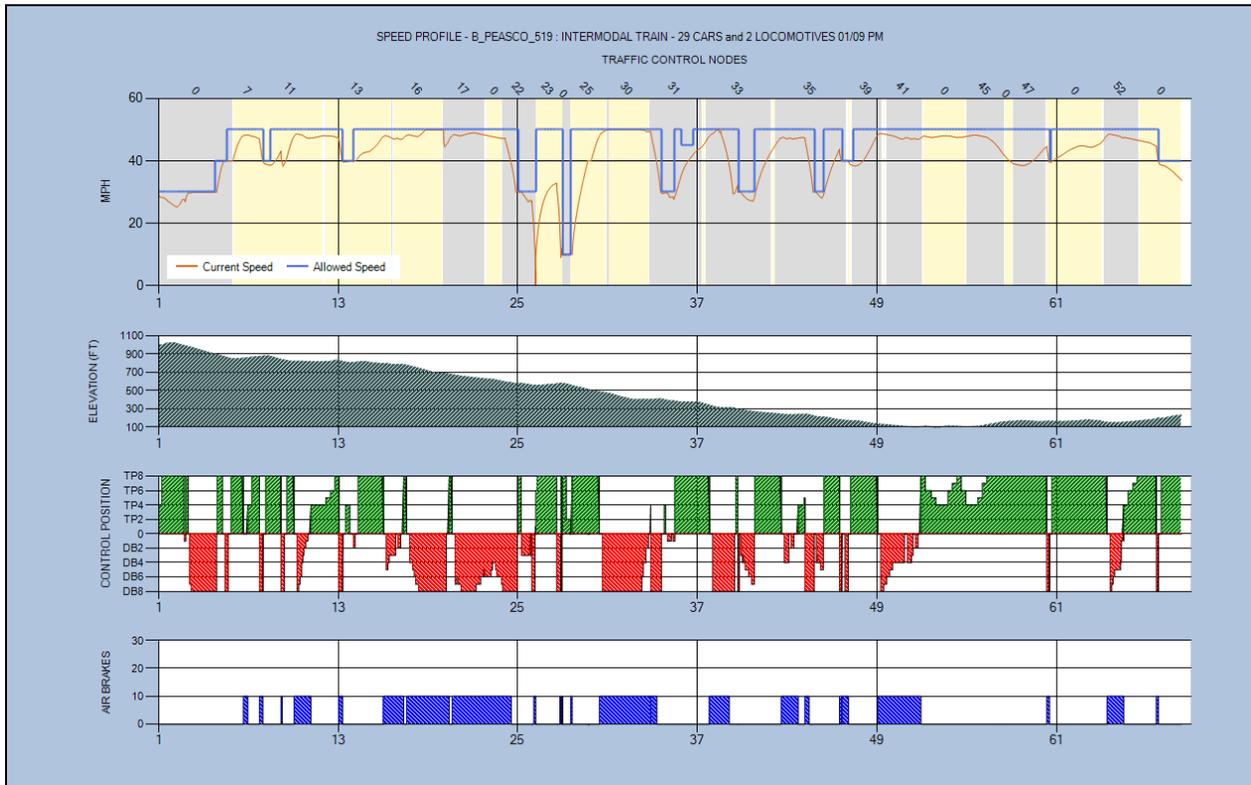
Figure F.3 Speed Chart for F_UPILBMN 1/9/2013

SPEED PROFILE - F_UPILBMN : INTERMODAL TRAIN - 23 CARS and 2 LOCOMOTIVES 01/09 AM
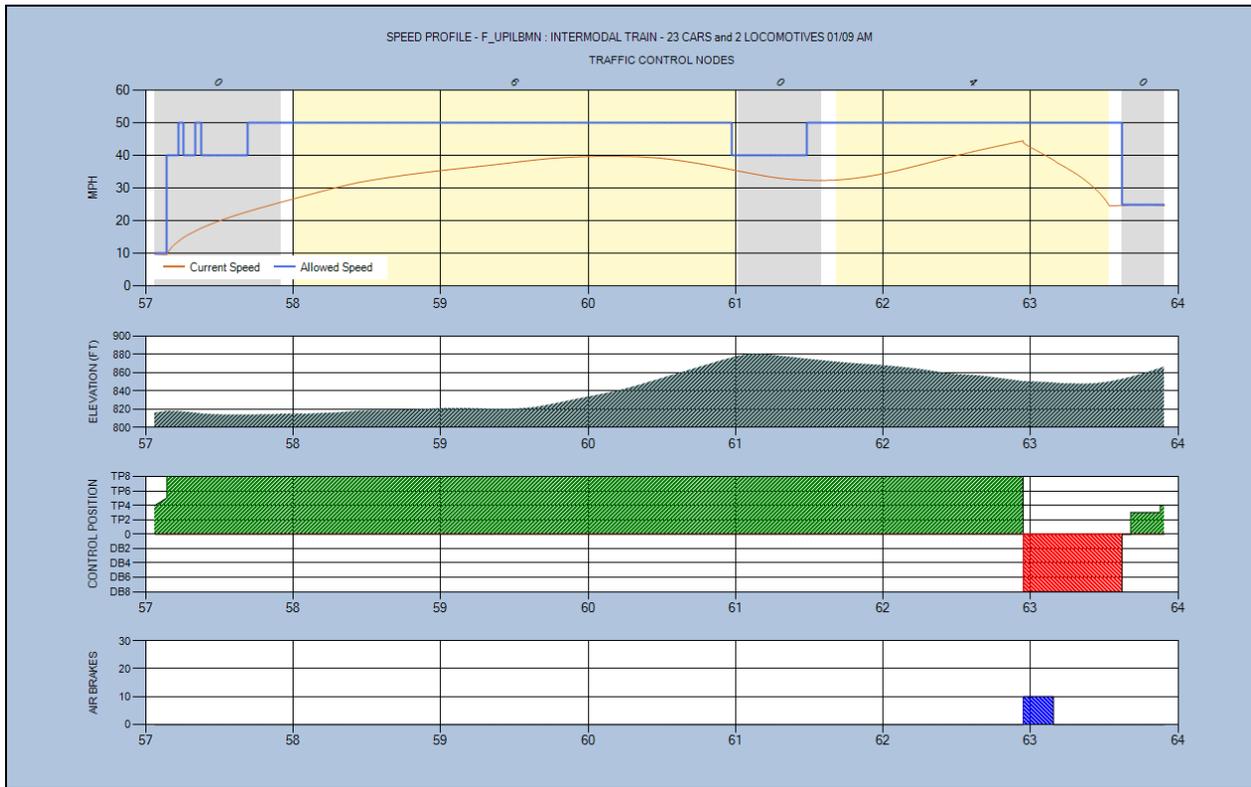
Figure F.4 Speed Chart for F_ML811 1/9/2013

SPEED PROFILE - F_ML811 : PASSENGER TRAIN - 6 CARS and 1 LOCOMOTIVES 01/09 AM
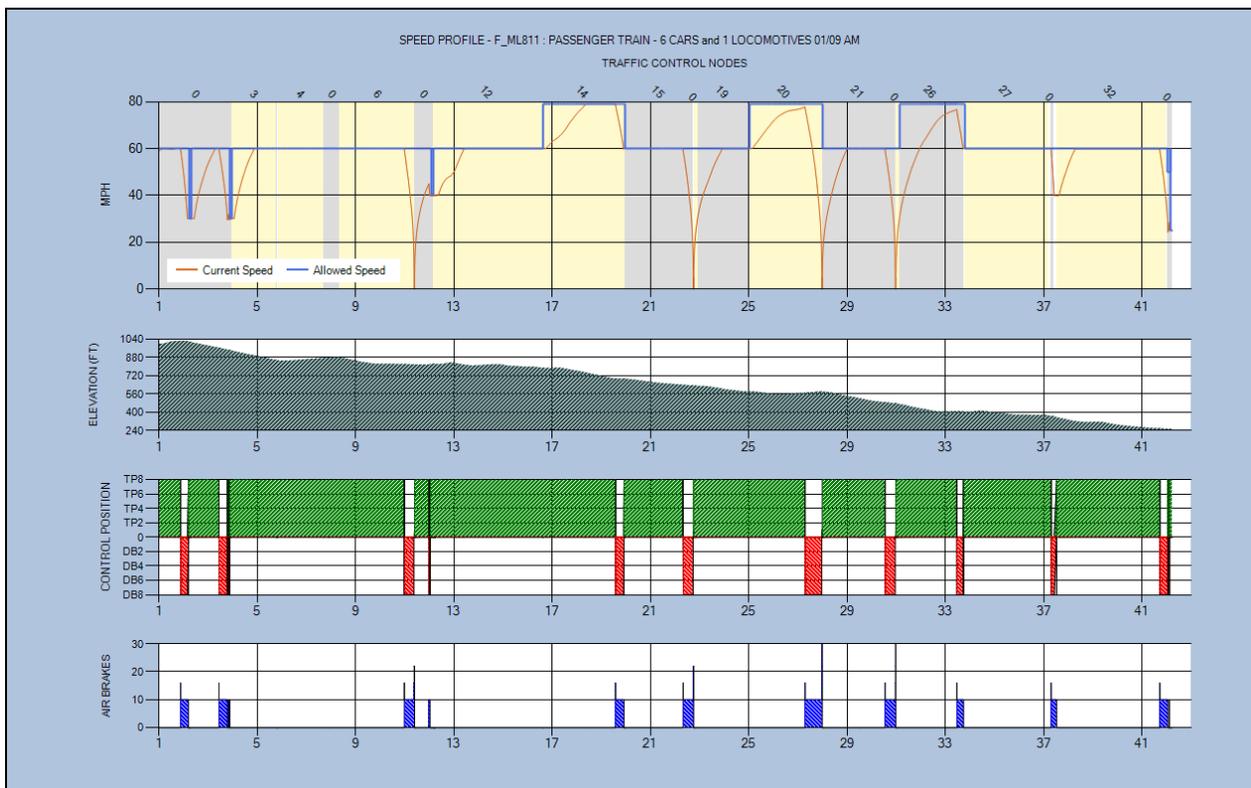
Figure F.5 Speed Chart for A_4 1/9/2013

SPEED PROFILE - A_4 : PASSENGER TRAIN - 10 CARS and 2 LOCOMOTIVES 01/09 PM
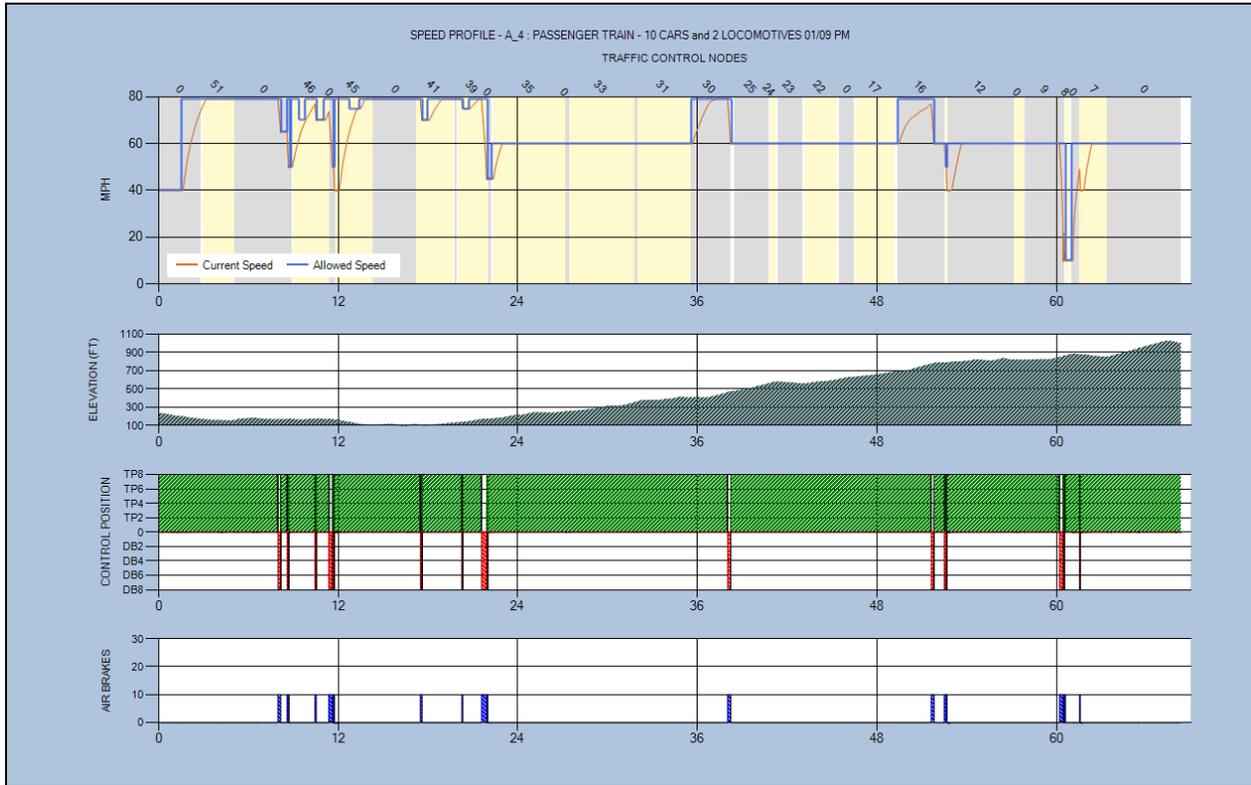
Abbreviations and Acronyms

BNSF	BNSF Railway
CFR	Code of Federal Regulations
EIC	Engineer in Charge
FRA	Federal Railroad Administration
CTC	Centralized Traffic Control
GTMS	General Train Movement Simulator
I-ETMS	Interoperable Electronic Train Management System (trademark of Wabtec Railway Electronics)
PTC	Positive Train Control