

PROBABILISTIC RISK ASSESSMENT OF RAILROAD TRAIN
ADJACENT TRACK ACCIDENTS

BY

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DISSERTATION

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ABSTRACT

Growth in passenger traffic on rail corridors shared with freight trains, and expanded rail transport of hazardous materials have both increased the imperative to understand the factors affecting railway transportation safety and risk. A source of risk that has received relatively little attention are railroad train accidents that may cause collisions with trains operating on adjacent tracks. These adjacent track accidents (ATAs) occur when one train derails in multiple-track territory and its equipment or lading intrudes onto an adjacent track and strikes, or is struck by, another train operating on that track. This dissertation develops data and a formal analytical framework to evaluate the risk of ATAs. Using Probabilistic Risk Assessment methodologies such as Fault Tree Analysis, an ATA is divided into its three principal constituent events: the initial train derailment, the intrusion of derailed rail vehicles onto an adjacent track, and the presence of another train on that track that may collide with the intruding equipment. The probability of each event is assessed, the factors affecting those probabilities are identified, their effects are investigated and discussed, and a formal qualitative and quantitative framework is developed into a comprehensive probability assessment model for ATA occurrences.

Particular attention is given to passenger trains because of their expanded operation on shared-use rail corridors (SRCs) with freight train traffic and consequent exposure to ATA risk. Passenger train accidents are analyzed and the important factors contributing to their frequency and consequences investigated. Derailments and collisions were analyzed to identify and quantify accident causes that have higher frequency and/or severity in terms of casualties to onboard passengers and crew.

Factors affecting train intrusion probability including track center spacing, track alignment, train speed, adjacent structures, elevation differential, and presence of intrusion barriers or containment systems are identified and their effects on intrusion probability investigated. These factors serve as important elements in developing a comprehensive ATA probability assessment model. A semi-quantitative model is developed as a screening-level risk assessment tool for ATAs, accounting for factors affecting the probabilities of the initial train derailment, the intrusion of derailed vehicles onto an adjacent track, and the presence of another train on the adjacent track.

A quantitative model is developed to estimate the probability of train presence on an adjacent track when and where a train intrusion occurs, which is affected by the frequency and operational characteristics of train traffic on both lines. This model also estimates the probability of an adjacent track collision based on traffic control, intrusion prevention or warning systems, point of derailment, train braking capability, and other factors.

The ATA probability assessment framework results in the development of the Adjacent Track Accident Probability Assessment Model (ATAPAM). The ATAPAM provides a step-by-step procedure to assess the probability of ATAs in both quantitative and qualitative forms. The probability of an ATA on a multiple-track segment is evaluated with a qualitative risk indicator showing additional intrusion risk. A case study of the application of ATAPAM on a hypothetical SRC is presented. The ATAPAM can be used as a tool in a decision analysis framework in which risk mitigation strategies for ATAs can be evaluated based on their effectiveness, implementation cost, and constraints such as budget and other resources.

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CHAPTER 1

INTRODUCTION

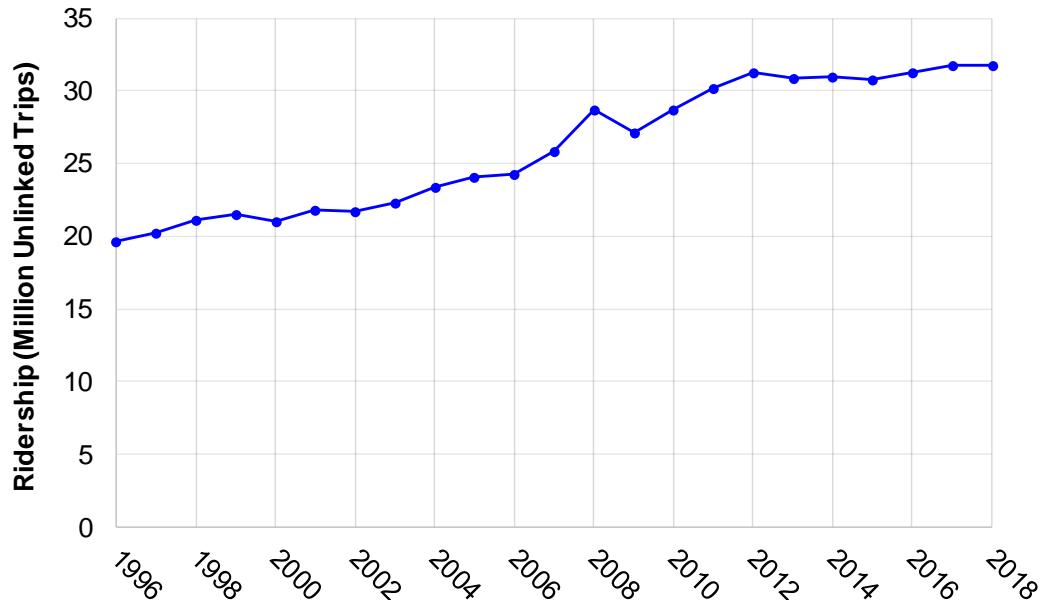
1.1 Shared-Use Rail Corridor Safety

Increasing demand for passenger rail transport in the United States (Figure 1.1) has led to the growth of faster and more frequent passenger rail services. Funding and legislative support for the improvement of existing passenger rail services and new passenger rail corridors has been provided by the federal government (Passenger Rail Investment and Improvement Act, 2008; American Recovery and Reinvestment Act, 2009; Department of Transportation Appropriations Act, 2010; FAST Act, 2015; Passenger Rail Reform and Investment Act, 2015; Peterman, 2018). High-level rail transportation plans to achieve these goals have also been proposed at the state level (WIDOT, 2014; WSDOT, 2014; MnDOT, 2015; Peterman, 2017; CADOT, 2018; IDOT, 2018). The high-speed rail¹ project in California is now under construction (CHSRA, 2018), and the high-speed rail project in Texas is in its planning process (FRA, 2015). Speed, frequency, and service improvement projects are being implemented to achieve higher-speed rail² corridors in the Midwest and on the Northeast Corridor (Peterman, 2016). New intercity passenger rail services have also been constructed or proposed in Florida (OPPAGA, 2018), Massachusetts (MassDOT, 2018a) and other states (Peterman, 2016; National Railroad Passenger Corporation, 2018a). In addition, transit and regional

¹ The International Union of Railways (Union Internationale des Chemins de fer (UIC)) (2018) defines high-speed rail as passenger rail systems whose commercial operating speed is greater than 155 miles per hour (mph) (250 kilometers per hour (km/h)). The United States generally refers to passenger rail systems with maximum operating speed greater than 150 mph (240 km/h) as high-speed rail.

² In the United States, passenger rail systems with maximum operating speed between 90 (mph) and 150 mph (140 (km/h) to 240 km/h) are termed “higher-speed rail” (Peterman et al., 2013).

passenger rail systems are being improved or expanded (Central Puget Sound Regional Transit Authority, 2018; MassDOT, 2018b; WMATA, 2018; Metra, 2019).



**Figure 1.1: Amtrak ridership by million unlinked trips³: 1996 – 2018
(National Railroad Passenger Corporation, 2018b)**

Two approaches are being used to undertake these passenger rail projects and initiatives: incremental upgrade of existing railroad infrastructure and construction of new, dedicated passenger rail lines (Peterman et al., 2013). Both approaches lead to the development of shared-use rail corridors (SRCs) where passenger trains share track, right-of-way (ROW) or railroad corridors with freight trains and other types of passenger trains (Ullman and Bing, 1995; Bing et al., 2010). The United States Department of Transportation (USDOT) Federal Railroad Administration (FRA) defines three types of

³ An unlinked passenger trip is a trip on one train regardless of the type of fare paid or transfer presented. A person riding only one train from origin to destination takes one unlinked passenger trip; a person who transfers to a second train takes two unlinked passenger trips; a person who transfers to a third train takes three unlinked passenger trips (APTA, 2019).

SRCs based on whether or not different types of trains share trackage and the separation distance between adjacent tracks of different railroad systems (Resor, 2003) (Figure 1.2).

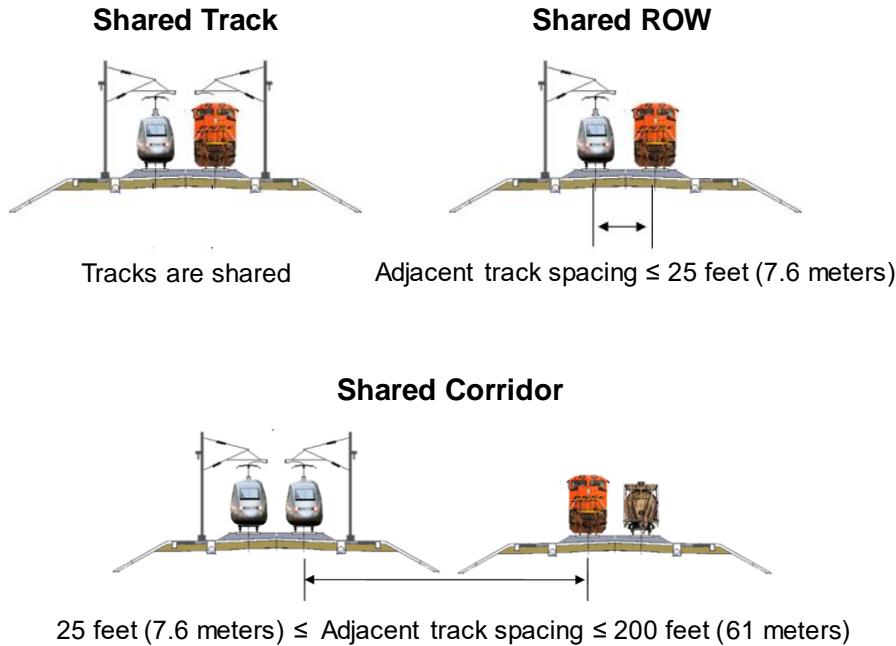


Figure 1.2: Three types of shared-use rail corridors (Resor, 2003)

SRCs offer benefits compared to the construction of new, completely dedicated passenger rail lines. These include: lower capital costs, less economic, environmental and social impact, and easier accessibility to core urban areas (Nash, 2003). However, implementation of SRCs also raises challenges, including safety concerns due to more frequent and higher-speed operations of passenger trains in close proximity to freight trains and maintenance-of-way (MOW) personnel, reduced line capacity due to heterogeneous train traffic, trade-offs in infrastructure and rolling stock designs due to different characteristics of passenger and freight trains, and a number of other factors (Saat and Barkan, 2013) (Table 1.1).

Table 1.1: Shared-use rail corridor challenges (Saat and Barkan, 2013)

Type of Challenges	Specific Issues
Safety	<u>Adjacent Track Accident (ATA)</u> Loss of Shunt Problem Highway-Rail Grade Crossings Pedestrian Risk Risk to Maintenance-of-Way (MOW) and Train Operating Employees
Infrastructure and Rolling Stock	Slab Track/Ballasted Track Design Special Trackwork Curve Superelevation Track Stiffness Transition Zones Track Surfacing Cycles Rail Wear and Defect Rate Electrification Tilting Train Design Level Boarding of Rolling Stock Vehicle-Track Interaction Wheel Load Characteristics
Planning and Operation	Infrastructure Upgrade Prioritization Rail Capacity Planning MOW Scheduling Train Scheduling Patterns <u>Train Scheduling Reliability</u>
Economic	Capacity Cost Allocation New SRC Line Construction Homogenous Freight Operations Impact of Reduced Industry Access Passenger Train Service Sustainability
Institutional	Track Safety Standards Passenger Rail Equipment Safety Standards Liability and Indemnification Grant Agreement Structure

Safety is the most important aspect of any railroad operation and among the important safety issues of SRC implementation is the potential intrusion of derailed rail

equipment onto adjacent railroad tracks. The intruding equipment may strike or be struck by another train running on an adjacent track, resulting in a collision leading to more derailed equipment, infrastructure and rolling stock damage, and potential casualties and releases of hazardous material. This type of collision is referred to as an adjacent track accident (ATA).

Previous FRA-sponsored research identified ATAs as the top-ranked safety concern for SRCs (Saat and Barkan, 2013). Several recent high-profile ATAs further highlighted the need to address ATA risk. In one case, a grain train derailed and equipment intruded onto the adjacent track. An oncoming petroleum crude oil train on that track collided with the intruding rail vehicles, derailing 21 tank cars and causing a number of them to release product and catch on fire (NTSB, 2015a) (Figure 1.3a). In another incident, a passenger train derailed and intruded onto an adjacent track leading to a collision and derailment of another passenger train approaching from the opposite direction on that track and resulting in 65 passenger injuries and severe equipment and track damage (NTSB, 2015b) (Figure 1.3b).



(a) December 30th, 2013, Casselton, ND
(photo credit: Michael Vosburg)

(b) May 17th, 2013, Bridgeport, CT
(photo from the National Transportation Safety Board (NTSB) report)

Figure 1.3: Adjacent track accident scenes for (a) two freight trains and (b) two passenger trains (NTSB, 2015a; b)

1.2 Equipment Loading Gauge and Clearance Envelope

A critical event in ATA occurrence is the intrusion of a train onto an adjacent track. In order to define an intrusion, it is first necessary to understand two related concepts: the equipment loading gauge of a train and the clearance envelope of the track. Railroad equipment loading gauge (also referred to as the “clearance plate” in North American parlance) is a series of standards that define the maximum height and width of locomotives and rolling stock (including lading if it is a freight car) (Figure 1.4a). These are complimented by standards for the infrastructure clearance envelope along a rail line (AREMA, 2016a; b). The clearance envelope, or “clearances”, are the height and width limits of railroad structures to assure safe passage of trains without any possibility of impacting elements of the infrastructure above, below, or beside the track (Figure 1.4b). Clearance specifications must account for dynamic effects of superelevation, track irregularities, and rail vehicle suspension and movement (Hay, 1982). This combination of equipment and infrastructure standards ensures safe passage of trains through tunnels,

bridges, and adjacent railroad structures. With this background knowledge, I define train intrusion and ATAs in the next subsection.

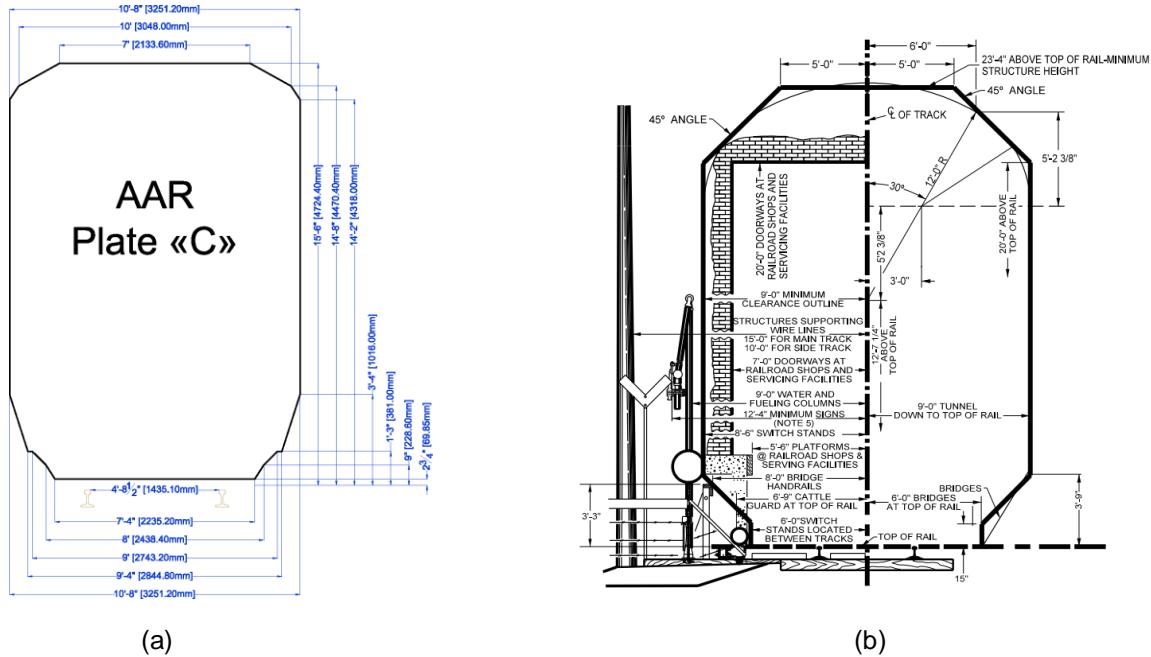


Figure 1.4: Examples of (a) loading gauge (Kratville, 1997) and (b) clearance envelope (Union Pacific Railroad, 2016)

1.3 Adjacent Track Accidents

Railroad equipment and infrastructure is designed so that, in normal operations, the equipment is well clear of equipment operating on an adjacent track (Figure 1.5a). However, if a train derails, the derailed equipment's loading gauge will nearly always exceed its own track's clearance envelope (Figure 1.5b). If the derailed equipment enters an adjacent track's clearance envelope, it is called an intrusion (Figure 1.5c). When an intrusion occurs, there is a possibility that another train is running on the adjacent track, either next to, or approaching, the intrusion location. If so, there is a chance that the train on the adjacent track will collide with the derailed equipment (Figure 1.5d). A collision

resulting from the sequence of events described above is referred to as an adjacent track accident, or ATA.

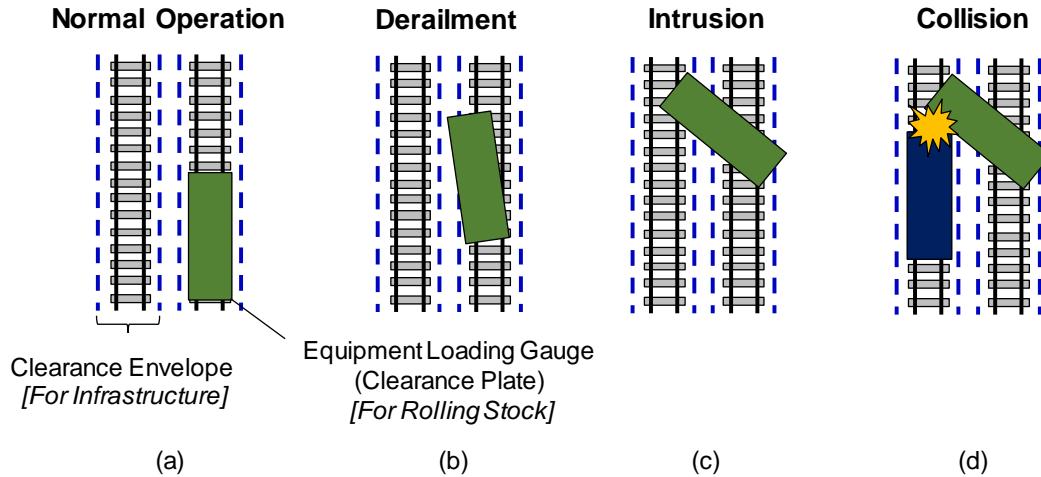


Figure 1.5: A typical ATA event sequence

ATAs can occur in any multiple track territory, but they become more complex and potentially more hazardous on SRCs. As more high-speed and higher-speed passenger train services are introduced, the probability of an ATA increases, because, *ceteris paribus*, at higher speed, it takes more time and distance to stop a train if there is an intrusion ahead. Different speeds, frequencies, and other operational characteristics between passenger and freight trains increase the frequency of train meets and passes, which also increases the probability of trains being close to an intrusion location should one occur. In addition, higher speed also implies greater kinetic energy in collisions, meaning more damage to rail equipment, infrastructure, and potential onboard passenger and crew casualties. Train operation by multiple operators on shared trackage or ROW may also present more opportunities for communication errors, resulting in delayed or failed delivery of a warning to trains on adjacent tracks in a sufficiently timely manner to

avoid a collision if an intrusion occurs. If hazardous materials are transported on an SRC, the potential consequences of an ATA are further increased if these materials released in an accident.

Risk is generally defined as the probability of a particular event multiplied by its consequence (Elvik and Voll, 2014). From this perspective, the risk of ATA consists of its probability and consequence. The probability of an ATA considers the occurrence of an initial train derailment, its intrusion onto another track after it derails, and the collision between the intruding train and another train operating on an adjacent track during or after the intrusion. The potential consequences of an ATA include casualties, releases of hazardous materials, environmental impacts, equipment and infrastructure damage, system disruptions, and unfavorable publicity or perception of rail transportation safety.

In the field of risk management there are four main elements for addressing risk: identification, analysis, evaluation and mitigation (or treatment) (ISO, 2018). Applying these steps to ATA risk assessment involves identifying the specific factors affecting the probability and consequences of ATAs. These are assessed using qualitative, semi-quantitative, and quantitative methods, depending on the available data and scope of analysis. The risk of an ATA is evaluated for different railroad track segments based on their characteristics using models developed in previous investigations of rail transportation safety and risk. Risk mitigation strategies for ATAs are identified and their effects evaluated using the model developed in the risk assessment. These risk mitigation

strategies are then implemented on track segments with high ATA risk based on the results of risk evaluation and the cost effectiveness of different risk reduction strategies.

There are two ways of reducing risk – addressing the probability and addressing the consequence. In general, reducing the probability component of the risk so that the hazardous event does not occur is preferable because the consequences are eliminated. Consequently, many railroad safety studies have focused on assessing the probability of the hazardous event, including freight train derailments and collisions (Dennis, 2002; Anderson and Barkan, 2004; Liu et al., 2011; 2012; Li et al., 2013; Liu, 2015), hazardous material releases (Saccomanno and El-Hage, 1989; Liu et al., 2014; Liu, 2017a), highway-rail grade crossing incidents (Benekohal and Elzohairy, 2001; Mok and Savage, 2005; Raub, 2009; Evans, 2011a), and trespasser incidents (Silla and Luoma, 2011; Havârneanu et al., 2015; Savage, 2016). In the context of ATAs, understanding what can lead to an ATA and how to prevent it can help identify a means of reducing ATA risk.

1.4 Research Objective

The principal objective of my dissertation research is to improve our understanding of how to quantify and reduce the risk of ATAs through development and application of probabilistic risk assessment (PRA) (Modarres et al., 2010) and decision analysis techniques (Clemen and Reilly, 2001) that can be used to evaluate and identify the most effective strategies to improve safety on SRCs. The main contribution of my dissertation research is development of a new, quantitative model to calculate the probability of ATAs by assessing three major probability components in an ATA event

sequence: initial train derailments, intrusion of derailed rail vehicles, and collisions between a train on an adjacent track with derailed equipment. The chapters in my dissertation focus on the development of models to identify and quantify factors that affect one or more of these probability components in ATA probability. The organization and sequence of steps to achieve my research objectives is illustrated graphically in Figure 1.6.

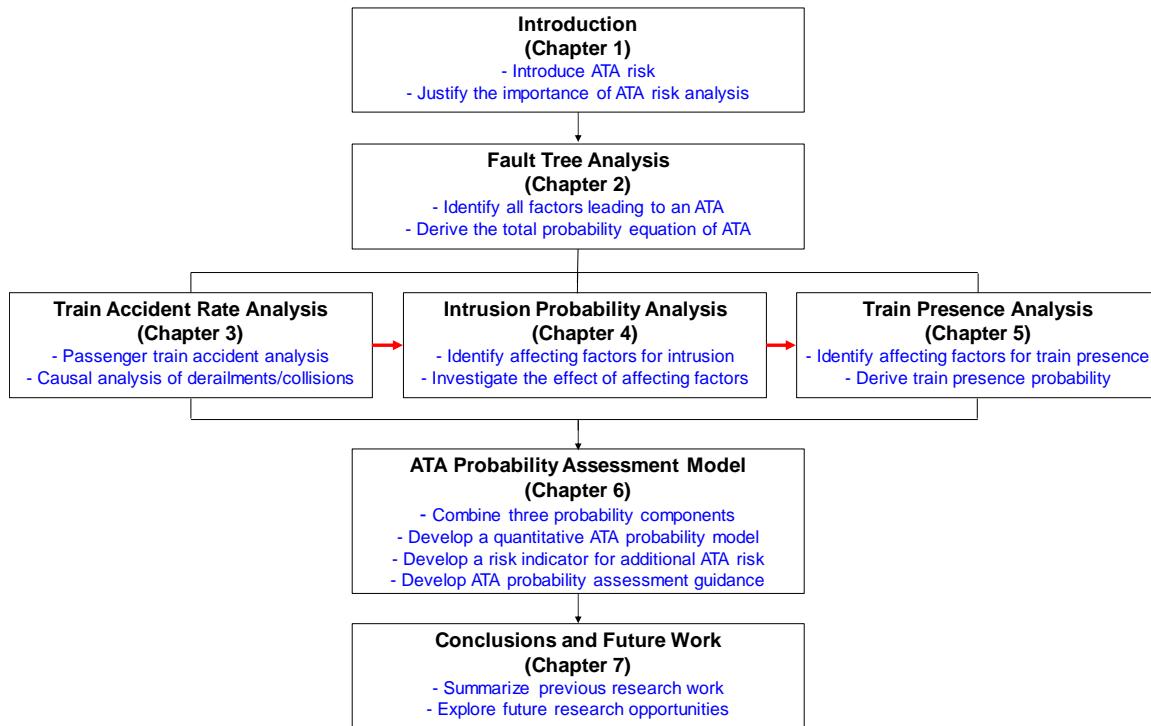


Figure 1.6: ATA research framework

In summary, these steps include:

- 1) Use Event Tree Analysis (ETA) and Fault Tree Analysis (FTA) to identify all scenarios and factors leading to an ATA

- 2) Quantify the probability of initial train derailments on SRCs for different types and combinations of train traffic by conducting statistical and causal train accident analyses
- 3) Identify factors that affect the probability of train intrusions in derailment scenarios and investigate their effects
- 4) Identify and quantify the factors that affect the probability of train presence on adjacent tracks when an intrusion occurs
- 5) Develop an ATA probability assessment model by combining probabilities of initial derailment, train intrusion, and train presence on adjacent tracks.
- 6) Develop a procedure and guidance for ATA probability assessment

Each of these steps represents a chapter in this dissertation except that steps five and six are combined into a single chapter. Taken as a whole, the chapters provide the types of data and models necessary for the development of the complete ATA probability assessment model. I expect my research to contribute to improving the safety of SRC operation by addressing ATA probability. This will allow passenger and freight rail operators to more effectively manage risk while taking advantage of benefits SRCs offer. I envision my research to be implemented by railroad corridor planners and designers to avoid or reduce high-potential-ATA-risk situations when planning and constructing new SRCs, and to more effectively manage ATA risk on existing SRCs. The effectiveness of the proposed risk mitigation strategies can be evaluated using my model and it has the potential to be incorporated with other risk assessment models such as highway-rail grade

crossing risk assessment model (Chadwick, 2017) for more general safety and risk analyses on SRCs.

1.5 Organization of Dissertation

There are 7 chapters in my dissertation (Figure 1.6); summaries of each chapter and explanations of how each chapter contributes to the development of the ATA probability assessment model follow.

Chapter 1: Introduction

This chapter introduces SRC and ATA and presents the motivation and objectives of my dissertation and a description of each chapter.

Chapter 2: Fault Tree Analysis of Adjacent Track Accidents

This chapter presents the event tree and fault tree analyses for ATAs. FTA is a systematic, logical methodology to deduct a hazardous event into a set of basic events such that the probability of the event can be estimated by calculating the probability of each individual basic event. I use FTA to explore all possible basic events leading to the occurrence of ATAs and construct a fault tree to show how each basic event affects the probability of ATAs. Boolean algebra is used to develop the logical relationship among contributing basic events, and the importance and potential application of FTA is discussed. I derive the probability of ATA based on the results of FTA. The FTA developed in this chapter serves as a foundation for further development of quantitative probability assessment and the evaluation of risk mitigation strategies for ATAs.

Chapter 3: Mainline Passenger Train Accident Analysis

This chapter presents the results of a study to identify the most important factors contributing to the risk of passenger train accidents by analyzing the USDOT FRA train accident data. I identify the train accident types posing the greatest risk to onboard passengers and train crews and the primary causes leading to those accidents. The frequency and severity of each type of train accident and their different causes are analyzed. I also consider the effect of train speed on accident causes and Positive-Train-Control-preventable accidents (PPAs) in terms of both frequency and severity. This statistical and causal analysis of passenger train accident is important for rational allocation of resources to most efficiently and effectively reduce passenger train accident occurrences and consequences and provides a foundation for further improvement in passenger train safety. The passenger train accident rates developed in this chapter are used to assess the initial derailment probability in the ATA probability assessment model presented in Chapter 6.

Chapter 4: Intrusion Probability Analysis

When a train derails in multiple track territory, there is a chance that the derailed equipment will intrude onto an adjacent track. The distance between adjacent tracks, track alignment, and other infrastructure and geographic characteristics affect this probability. In this chapter, I explore the factors affecting intrusion probability and discuss their quantitative and qualitative effects. The quantitative intrusion probability identified in this chapter is a key component in the ATA probability assessment model presented in chapter 6. The factors affecting intrusion probability that are not quantified

are incorporated as qualitative risk indicators in that model. In this chapter, I also develop a semi-quantitative risk assessment model to provide a screening-level ATA risk evaluation, considering both the probability and consequence. Factors affecting the probability of initial derailment, intrusion, train presence on adjacent tracks, and consequence are identified, and their effects expressed using a scoring and ranking system to indicate whether these factors increase or reduce ATA risk. I then develop a risk index to allow the evaluation and comparison of relative ATA risk among different railroad track segments.

Chapter 5: Train Presence and Adjacent Track Collision Probability Analysis in Intrusion Scenarios

When an intrusion occurs, the most undesirable consequence is that the derailed equipment intruding onto an adjacent track strikes or is struck by another train operating on that track. There are several factors affecting the probability of such adjacent track collisions: the frequency of train meets and passes on adjacent tracks, the distance between the derailed train on one track and another train on an adjacent track, the position of the first derailed equipment in the intruding train, and braking capability of the train on the adjacent track. When an intrusion occurs, if the train on the adjacent track is more than a certain distance away from the intrusion, there is a chance that the train may be able to stop before colliding with the intruding equipment. Train speed, train type and consist, track grade, and the type of braking system affect the distance required to stop a train. These factors combined with the distance between trains on adjacent tracks and derailed equipment affect the probability of an adjacent track collision. In this

chapter, I develop a generalized model to calculate the probability of collision between intruding derailed equipment and trains on adjacent tracks. This model also serves as a key probability component in the comprehensive ATA risk assessment model presented in chapter 6.

Chapter 6: Adjacent Track Accident Probability Assessment Model

In this chapter, I develop an ATA probability assessment model by combining the three probability models for initial derailment, intrusion, and train presence on adjacent tracks. Track, train, and operational inputs are identified for the model to evaluate the probability. The model presents the ATA probability in two forms: a quantitative probability value and a qualitative risk indicator. I present a case study to demonstrate how the model works using a hypothetical SRC. I also present a standard ATA probability assessment procedure and guidance for the model so users can customize the model to best suit their needs. In addition, I discuss the appropriate circumstances for use of the semi-quantitative ATA risk screening model presented in chapter 4 and the quantitative ATA probability assessment model presented in this chapter.

Chapter 7: Conclusions and Future Work

This chapter summarizes the contribution of my research work and identifies questions needing further investigation and opportunities for research to further refine the ATA probability assessment model based on the findings presented in my dissertation.

CHAPTER 2

FAULT TREE ANALYSIS OF ADJACENT TRACK ACCIDENTS

Adapted from

Lin, C.Y., M.R. Saat, and C.P.L. Barkan. 2016. Fault tree analysis of adjacent track accidents on shared-use rail corridors. *Transportation Research Record: Journal of Transportation Research Record*, 2546: 129 – 136.

2.1 Introduction

Fault Tree Analysis (FTA) is a deductive process used to identify all potential failure paths and factors that lead to an undesirable event (Modarres et al., 2010). A fault tree consists of two elements – events and logic gates. Events are connected by logic gates to show their logical relationships. FTA is an important step in probabilistic risk assessment (PRA) for two main reasons: it embodies all failure modes that contribute to the occurrence of the undesirable event, and it allows the calculation of total probability of the undesirable event. In my research, the “undesirable event” is an adjacent track accident (ATA).

FTA has been extensively applied to railroad safety in a variety of contexts. Li et al. (2013) used FTA to evaluate rear-end train collision accidents and developed models to calculate their probability of occurrence. Wang et al. (2014) used FTA to address the risk of train derailments on urban rail transit systems. Huang et al. (2000) combined FTA and fuzzy theory in general railroad safety analysis. Jafarian and Rezvani (2012) also used the fuzzy fault tree to analyze train derailments and identify the causes that contribute the most to overall derailment probability. European Railway Agency (2015)

applied FTA to various railroad hazards in order to allocate preventive resources most effectively. The Rail Safety and Standards Board (RSSB) (Taig and Hunt, 2012; Fowler et al., 2013; RSSB, 2014) conducted FTA on six major types of train accidents in Europe and used historical train accident data to identify causes with the greatest effect on each type of accident. As part of their work the RSSB developed a fault tree for train-to-train collisions (Figure 2.1). The RSSB used their train database to develop a color-coded relative ranking for each accident cause. Accident causes highlighted in red have the highest risk ranking, meaning that they are most in need of attention. Accident causes highlighted in yellow have medium risk and the ones in green have the lowest risk.

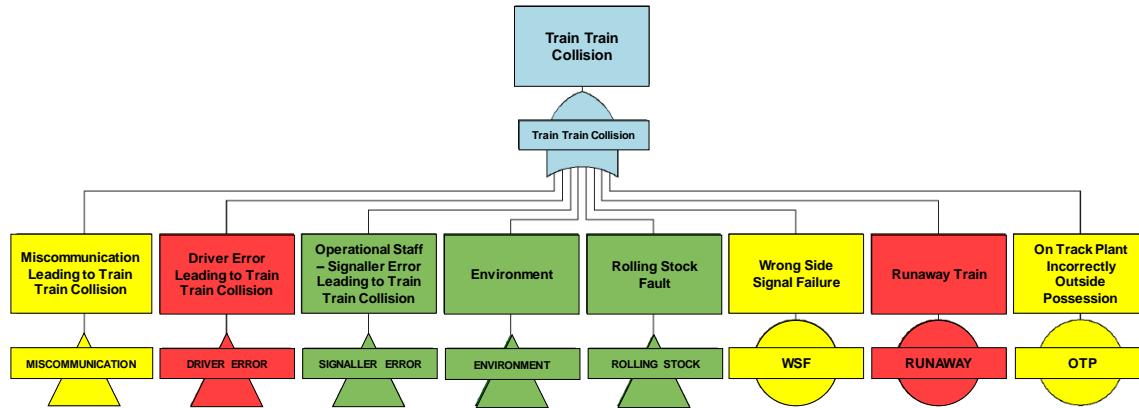


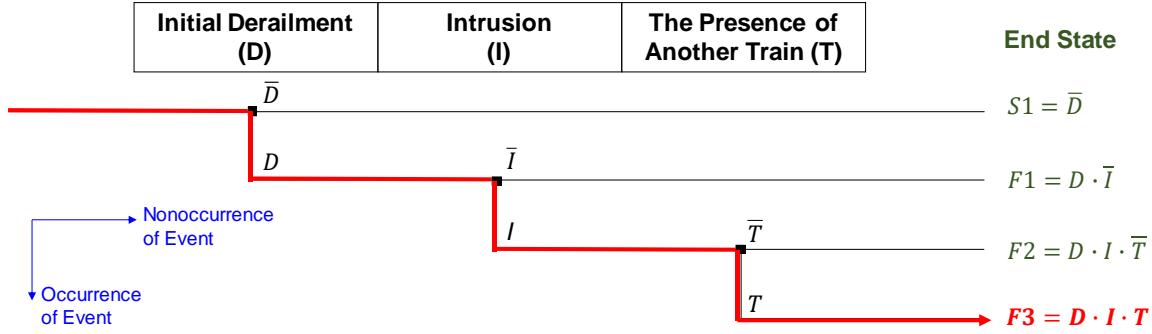
Figure 2.1: RSSB fault tree for train-to-train collision (RSSB, 2014)

In this chapter, I use FTA to assess the probability of ATAs. I first identify scenarios and event sequences leading to ATAs by conducting Event Tree Analysis (ETA), and then I construct a fault tree to identify the elements that contribute to such accidents. The quantitative probability of an ATA is derived using Boolean algebra based on the results of the FTA. The application of FTA to ATAs in planning new SRCs and

improving the safety of existing SRCs is also discussed. This chapter also establishes the PRA framework for the rest of the chapters in my dissertation.

2.2 Event Tree Analysis

An ATA is a sequential event in which an initial derailment occurs on multiple track territory resulting in an intrusion onto an adjacent track, followed by the collision between another train on the adjacent track and the derailed equipment (Figure 1.5). The probability of this sequential event can be formally described using ETA (Figure 2.2). ETA is a logical methodology to explore all possible outcomes of a system due to the occurrence of an initiating event and calculate the probabilities of each outcome (Modarres et al., 2010). ETA is a powerful tool to identify and assess the probability of system failures when the system is complex, or the system failure consists of multiple events. It is widely used in risk analyses of complex systems such as nuclear plants (Kaplan, 1982), tunnel boring machines (Hong et al., 2009), and oil or gas drilling systems (Ramzali et al., 2015).



Define success (S) to be the non-occurrence of an accident (safe operation), and failure (F) to be the occurrence of an accident or a hazardous situation (system failure).

The descriptions for each end state are as follows:

S1: Train does not derail. Railroad system operates normally.

F1: Train derails but does not intrude onto adjacent track. Although the railroad system is interrupted, this does not result in an ATA.

F2: Train derails and intrudes onto adjacent track but no other trains are at, or approaching, the intrusion location on the adjacent track at the time. Although service on multiple tracks is affected, there is no collision between trains on adjacent tracks.

F3: Train derails and intrudes onto the adjacent track and collides with another train operating on that track.

Figure 2.2: Event tree analysis for ATA

An event tree is the product of the ETA that contains an initiating event, intermediate events, and end states. In the context of ATAs, the initiating event is the derailment of a train in multiple-track territory, denoted as D. It can be caused by a derailment, or by a collision of two trains on the same track. Thus, D is the rate of derailments, head-on collisions, or rear-end collisions in multiple-track territory. These are generally measured in terms of number of accidents per unit of traffic exposure such as train-miles or ton-miles. The first intermediate event, an intrusion, occurs when the adjacent track is “fouled” by equipment derailed in the initial derailment and is denoted as I. The second intermediate event where another train on an adjacent track is either next to, or approaching, the intrusion location, is denoted as T. The black square nodes in the event tree represent divergence points indicating whether an event occurs or not. Each such divergence on the event tree implies a probability element.

A “success” in the event tree is defined as an event where hazardous situations do not occur, i.e. the safe alternative. A “failure” means that the hazardous event(s) do occur and represents the unsafe alternative. For instance, the first black node on the left of the event tree indicates whether an initial derailment occurs (Figure 2.2). If it does, it is considered a “failure” because the occurrence may lead to an intrusion, which is the next stage of an ATA. Therefore, the path for the probability of the occurrence of the initial derailment event, D , goes downward (the direction of occurrence), while the path for its complement probability, \bar{D} , goes to the right (the direction of non-occurrence and results in a success scenario (no accident). I define the “success” of the system as the non-occurrence of an accident (end state $S1$ in Figure 2.2), and the “failure” of the system as the occurrence of an accident (end states $F1$, $F2$ and $F3$ in Figure 2.2). The event tree is divided into four end states and each of them is introduced as follows.

End State S1

When an initial derailment does not occur, the train runs normally, and the system is safe. The probability of $S1$ is simply the non-occurrence of the initial derailment (denoted as \bar{D}). The subsequent probability components are not examined in this case because the initiating event does not occur.

End State F1

If the initial derailment occurs but does not result in an intrusion, the derailed train will not collide with trains on adjacent tracks. Although this scenario may still cause infrastructure or rolling stock damage and system disturbance, it will not result in an

ATA. The probability associated with this end state is the probability of the occurrence of an initial derailment multiplied by the probability of the non-occurrence of an intrusion (denoted as $D \cdot \bar{I}$).

End State F2

When both the initial derailment and an intrusion occur, the derailed train is exposed to a hazardous situation in which another train on the adjacent track may not be able to stop before colliding with derailed equipment. This may be because the engineer (train driver) of the train on the adjacent track is unaware of the intrusion, or because of insufficient braking distance. The probability that there is no train on, or approaching on, the adjacent track when the intrusion occurs is denoted as $D \cdot I \cdot \bar{T}$.

End State F3

The probability that there is a train at, or approaching, the location where and when the intrusion occurs that results in a collision between the intruding rail equipment and the train on the adjacent track, is denoted as $D \cdot I \cdot T$ and is labeled as end state F3. End state F3 representing the event sequence for ATAs and is the focus of my dissertation research. In the next subsection, I use FTA to further analyze the factors contributing to this end state.

2.3 Event Tree Analysis and Fault Tree Analysis

The ETA identifies the event path toward occurrence of an ATA and the three probability components, and derives the equation for the total probability of ATAs. To

assess the individual probability components in more detail, FTA is used. FTA provides a logical and graphical presentation of various combinations of the basic events that can lead to the top event (Ericson, 2005). Each of the three probability components can be considered as a top event and broken down into basic events, allowing easier data collection and probability calculation. The combination of ETA and FTA provides a comprehensive PRA method and structure to address the probability of ATA (Figure 2.3).

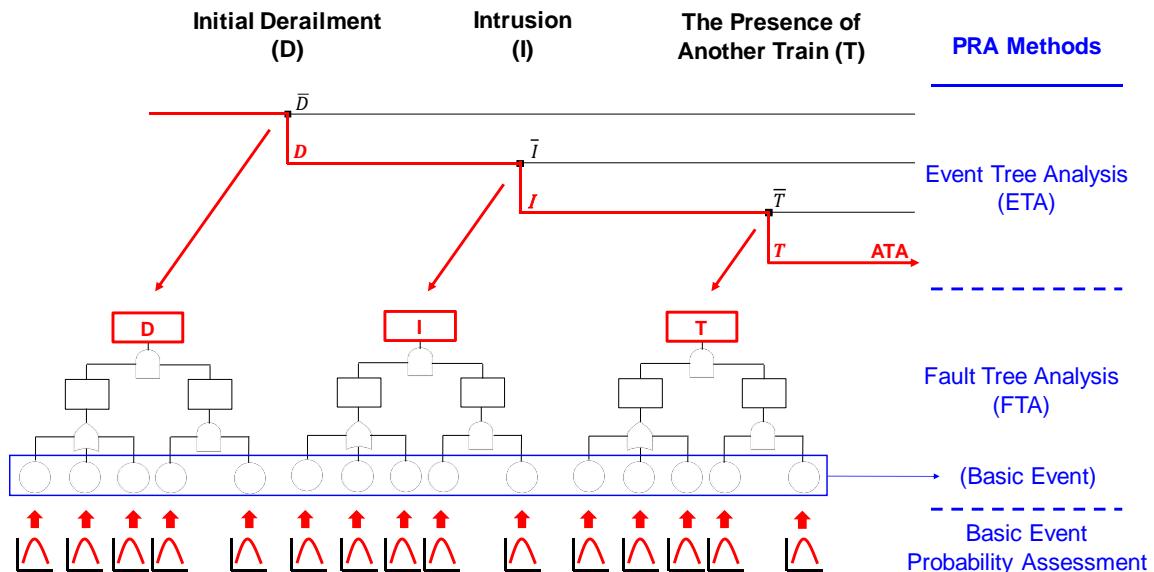


Figure 2.3 PRA structure for ATAs

2.4 Fault Tree Construction

A fault tree consists of events and logic gates (Figure 2.4). Different logic gates represent different probability calculation processes (Table 2.1). For example, an AND gate connecting event F and event G with event B means that both event F and event G have to occur to trigger the occurrence of event B. An OR gate connecting events C, D and E with event A means that event A will be triggered when at least one of the event C,

D or E occurs. Events C, D, E, F and G, are basic events and are the lowest level of event that contribute to the occurrence of the top event whose probability can be evaluated.

Events A and B are intermediate events between the top event and basic events. The top event is the hazard of interest whose probability is to be assessed. In my research, the top event is an ATA. Conditioning events specify the order for a sequence of events to occur. External events are those that contribute to the occurrence of the top event from outside the defined system.

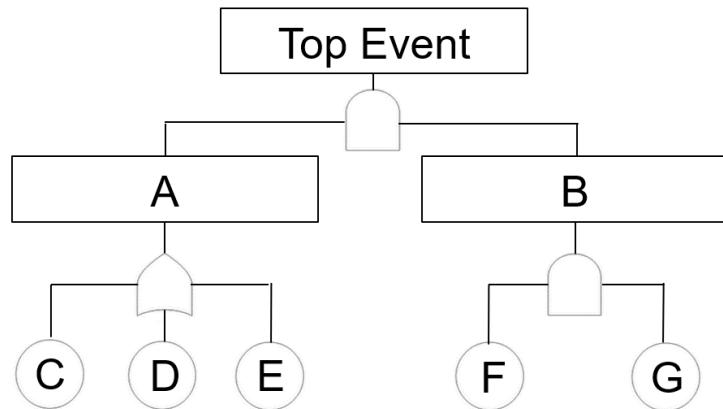


Figure 2.4: Fault tree example

Table 2.1: Common legend used for a fault tree

Name	Symbol	Description
Events		
Basic Event		An event requiring no further deduction
Intermediate Event		An event that occurs because the lower-level events connected with it occur through certain logic gates
External Event		An event which is normally expected to occur
Conditioning Event		An event with specific conditions or restrictions applying to any logic gates connected with it
Logic Gates		
AND		The higher-level event occurs only when all lower-level events connected through logic gate occur
OR		The higher-level event occurs if at least one of the lower-level events connected through logic gate occur
PRIORITY AND		The higher-level event occurs only when all lower-level events connected through logic gate occur in a specified sequence
TRANSFER		The connection to other fault trees

The development of the ATA fault tree is based on: a) existing fault trees developed for train accidents on typical railroad systems, b) analysis of previous ATA reports, and c) expert judgment. Fault trees have previously been developed for various types of train accidents as discussed in the literature review. These were used as a reference for developing an ATA-specific fault tree. For example, train accidents in Europe have been broken down into causes (aka, “deducted”) by the RSSB (2014). I used a similar approach based on the United States Department of Transportation (USDOT) Federal Railroad Administration (FRA) Rail Equipment Accident database to deduct the initial derailment data into accident causes. I treated these accident causes and other factors that lead to an ATA as basic events and connected them with logic gates. A fault

tree is developed for an ATA (Figure 2.5). The initial derailment, the intrusion and the train presence on an adjacent track are connected by the AND gate to the top event (an ATA), meaning that all three intermediate events have to occur so that an ATA will occur as illustrated by the event tree (Figure 2.2). Although each of the three probability components can be considered as a top event, they are treated as intermediate events in the ATA fault tree so that the probabilistic relationship between them and the top event ATA can be established. I introduce the branches for the three intermediate events in the fault tree in the following paragraphs.

2.4.1 Initial Derailment (D)

The initial derailment results from various train derailment causes. Thus, this intermediate event is deducted into five types of accident causes: infrastructure (DT), equipment (DE), signal and communication (DS), human factor (DH), and miscellaneous (DM) as defined by the FRA (2011). Each type of accident cause is further deducted into accident-cause subgroups. For instance, infrastructure caused derailment events (DT) are deducted into seven accident-cause subgroups: track geometry (T1), broken rail or welds (T2), rail defects (T3), turnout defects (T4), buckled track (T5), roadbed defects (T6), and other track and structure defects (T7). These accident-cause subgroups are treated here as basic events due to the resolution of the data currently available; however, any accident-cause subgroup can be further deducted if more in-depth analyses are required or more detailed data become available. Statistical and causal analysis of train accidents are presented in chapter 3, and how the result of the analysis is used in the comprehensive ATA probability assessment model is discussed in chapter 6.

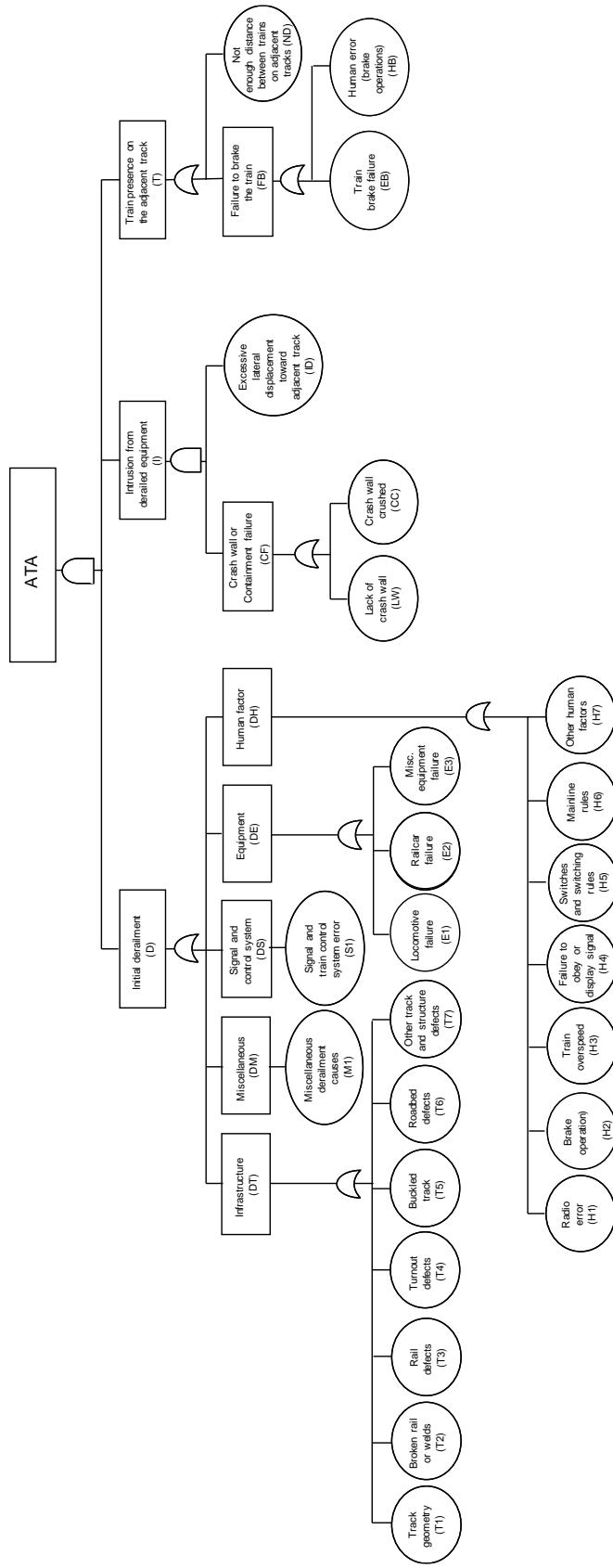


Figure 2.5: ATA fault tree

2.4.2 Intrusion from Derailed Rail Equipment (I)

The major impact of an intrusion event is the excessive lateral displacement of derailed equipment (ID). Some studies have analyzed the probability distribution of lateral displacement of rail equipment in derailments (Barkan, 1990; English et al., 2007; Clark et al., 2013). When lateral displacement of derailed equipment exceeds the track center spacing of two adjacent tracks, the derailed equipment will intrude onto the adjacent track. Installation of crash walls or containment may prevent the intrusion by keeping the derailed equipment off adjacent tracks. Crash walls are earth berms, concrete walls or other types of barrier constructed between tracks that can prevent such intrusions (Hadden et al., 1992; Moyer et al., 1994; Ullman and Bing, 1995). Containment is some structure located directly on the infrastructure to prevent the train from rolling over and intruding onto adjacent tracks, such as a parapet or guard rail (Abtahi, 2013; Bae et al., 2018a) (Figure 2.6). Crash walls and containment act in similar ways to reduce the occurrence of intrusion. There are two circumstances where they cannot protect the adjacent track from an intrusion: if they are not present on the track segment where the intrusion occurs (LW), or they are installed but are overcome by the impact force of the derailed equipment during the intrusion (CC). The probability of intrusion given an initial train derailment and the factors affecting this probability are discussed in chapter 4; integration of the intrusion probability into the comprehensive ATA probability assessment model is presented in chapter 6.

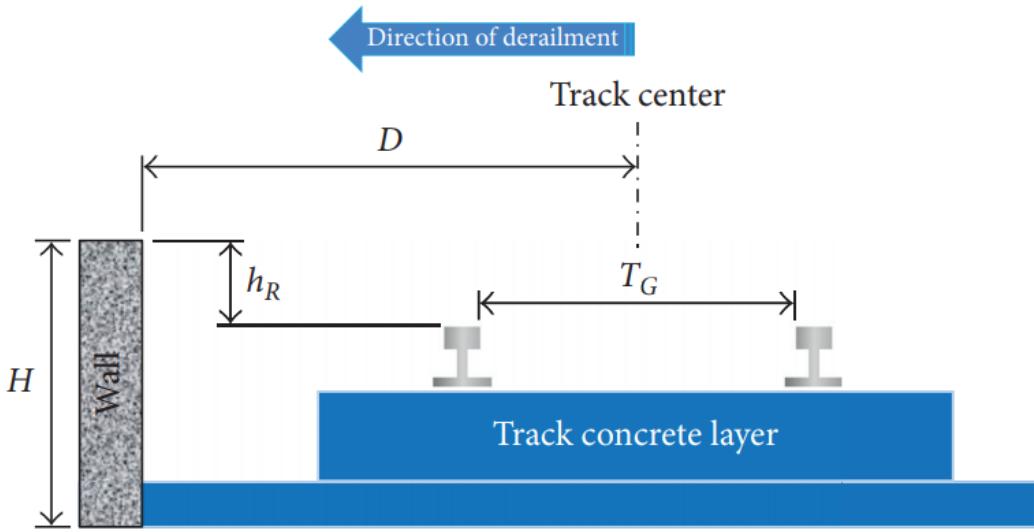


Figure 2.6: Geometric conditions of the containment wall (Bae et al., 2018a)

2.4.3 Train Presence on Adjacent Tracks (T)

When an intrusion occurs, there may be another train on an adjacent track, resulting in a collision between the derailing train and the train on the adjacent track. If the train on the adjacent track is right next to the train derailing and intruding its equipment onto the adjacent track, a collision is almost inevitable. If the train on the adjacent track is at a certain distance away from the intrusion location, there is a possibility that the train on the adjacent track can stop before striking the intruding equipment. Two factors contribute to the probability of stopping the train on the adjacent track before it strikes the intruding equipment: installation of an intrusion detection warning (IDW) system and braking capability of the train on the adjacent track. IDW systems are special fences or chains that are equipped with sensors located between adjacent tracks to detect train intrusions (Figure 2.7). When an intrusion is detected, a

warning signal is sent to the train engineer so that they can stop the train, or an automatic train protection will apply the train's brake.



Figure 2.7: Washington Metropolitan Area Transit Authority (WMATA) trackage (center) and CSX trackage (outer) with intrusion detection fence between them
(Photo credit: Matt Johnson)

The failure or absence of the IDW system increases the probability that the train on the adjacent track will be unable to stop soon enough before striking the intruding equipment; however, since the failure or absence of the IDW system does not guarantee the occurrence of an ATA, they are not included in the fault tree. That said, the IDW system is included in the comprehensive ATA probability assessment that I introduce in chapter 6.

Braking capability of the train on the adjacent track is another factor affecting the train presence probability. Train speed, train type and consist, track grade, and the type of

braking system affect the distance required to stop a train. These factors combined with the distance between trains on adjacent tracks and derailed equipment when an intrusion occurs affect the probability of an adjacent track collision (ND). Another brake-related factor is the reliability and failure rate of the train braking systems (FB). If the train braking system malfunctions (EB) or the train engineer fails to properly apply the train's brakes (HB), the train on the adjacent track will not be able to avoid the collision even if the initial distance between the train and the intruding equipment is long enough for it to have stopped. The probability of a train collision occurring, given the distance between two trains operating on adjacent tracks when an intrusion occurs, and the braking capability of trains is discussed in chapter 5. The reliability of the train braking system, and how it affects the probability of train presence and the overall probability of ATA, is discussed in chapter 6.

2.5 Boolean Algebra

Once the fault tree is constructed, the probability of top event occurrence can be calculated using Boolean algebra. Each intermediate and basic event is denoted by two-letter abbreviations, except initial derailment (D), intrusion (I), and train presence on the adjacent track (T). In the fault tree, the OR gate represents the union of input events, and the Boolean expression for the OR gate is $Q = A \cup B$, or $A+B$. The AND gate represents the intersect of input events, and the Boolean expression for the AND gate is $Q = A \cap B$, or $A \cdot B$. By definition, the occurrence of an ATA is the intersect of the occurrences of initial derailment, the intrusion, and the presence of trains on the adjacent track:

$$P_{ATA} = D \cdot I \cdot T \quad (2.1)$$

The rate of the initial derailment is the sum of the rates of the infrastructure (DT), equipment (DE), signal and communication (DS), human factor (DH), and miscellaneous (DM) caused derailment, head-on collision, and rear-end collision events. Each corresponds to the rates of the union of lower level events shown in the fault tree (Figure 2.5), assuming all basic events are mutually independent:

$$\begin{aligned} D &= DT + DM + DS + DE + DH \\ &= (T1 + T2 + T3 + T4 + T5 + T6 + T7) + M1 + S1 + (E1 + E2 + E3) \\ &\quad + (H1 + H2 + H3 + H4 + H5 + H6 + H7) \end{aligned} \quad (2.2)$$

The probability of an intrusion given an initial derailment is the probability of the union of the crash wall and containment failure (CF) intersecting with the excessive lateral displacement toward the adjacent track (ID). Assuming all basic events are mutually independent, the probability of intrusion can be expressed as:

$$I = CF \cdot ID = (LW + CC) \cdot ID = LW \cdot ID + CC \cdot ID \quad (2.3)$$

Finally, the probability of train presence on adjacent tracks given an intrusion is the probability of the union of failing to brake the train (FB) and not enough distance between trains on adjacent tracks (ND). Each corresponds to the probability of the union

of lower level events shown in the fault tree (Figure 2.5), also assuming that all basic events are mutually independent:

$$T = FB + ND = (EB + HB) + ND \quad (2.4)$$

The probability of an ATA can therefore be expressed in Boolean algebra as:

$$\begin{aligned} ATA &= D \cdot I \cdot T \\ &= ((T1 + T2 + T3 + T4 + T5 + T6 + T7) + M1 + S1 + (E1 + E2 + E3) \\ &\quad + (H1 + H2 + H3 + H4 + H5 + H6 + H7)) \\ &\quad \cdot (LW \cdot ID + CC \cdot ID) \cdot ((EB + HB) + ND) \end{aligned} \quad (2.5)$$

The result can be used to identify the minimal cut set of basic events such that they guarantee the occurrence of the top event. A cut set is a set of basic events whose occurrence ensures that the top event occurs, and the minimal cut set is the cut set that cannot be reduced without losing its status as a cut set (Modarres et al., 2010). For example, the cut set “T2·LW·ID·ND” represents an ATA scenario where a broken rail derailment occurs (T2) resulting in an intrusion due to excessive lateral displacement of derailed equipment (ID) and the lack of crash wall protection (LW), followed by a collision between the derailed equipment and another train on an adjacent track because there is not enough distance for the train on the adjacent to brake and stop (ND). If any of the four events does not occur, the ATA will not occur. Thus, cut set “T2·LW·ID·ND” is

a minimal cut set. Assuming that all the basic events are independent of each other, the probability of an ATA caused by this minimal cut set is:

$$P_{ATA,T2\cdot LW\cdot ID\cdot ND} = P(T2) \times P(LW) \times P(ID) \times P(ND) \quad (2.6)$$

The probability of the union of all minimal cut sets equals the probability of an ATA. Once the data for each basic event of the fault tree are acquired, the probability of an ATA can be calculated. The mutual independence assumption among each basic event needs further testing and verification in order to increase the accuracy of PRA.

2.6 Discussion

2.6.1 Data Sources and Analysis Requirements

In order to implement the FTA and its corresponding probabilistic model, existing accident databases such as the FRA's Rail Equipment Accident database (FRA, 2011) or the RSSB's Safety Management Information System (SMIS) database (RSSB, 2018) can be combined with the respective country or region's rail traffic data to estimate the derailment rate for a specific rail line or network. Additional sources needed to estimate the probabilities of intrusion and adjacent train presence may include the data collection for lateral displacement of derailed equipment, IDW systems, crash walls and containment, braking capability of trains and reliability of train braking systems, and records of close calls (or near misses) where a collision might have occurred but did not. Additional analyses needed include quantitative assessment of the factors affecting intrusion probability, the effectiveness and reliability of crash walls and containment in

preventing intrusion, effectiveness and reliability of IDW systems, and stochastic modeling of train presence at a specific location.

2.6.2 FTA and New Rail System Planning

When planning a new rail system, safety is a critically important consideration, specifically, minimization of potential hazards and mitigation of consequences if they do occur. Before these hazards can be addressed, potential causes must be systematically identified. When all factors and possible ways for them to result in the hazards are explored, the risk of those hazards can be comprehensively addressed, and risk mitigation or prevention measures can be deployed effectively and efficiently. The FTA described here provides a foundation for the evaluation of ATA on a new rail system.

For a new rail system with multiple track sections or potential SRCs, the FTA and corresponding probabilistic model can be implemented to evaluate the ATA probability. Factors affecting ATA probability can be evaluated and the relationships among them compared to determine the effect of possible design alternatives on ATA probability for the new system. ATA risk mitigation strategies can also be evaluated using the FTA. For example, the spacing between two tracks affects intrusion probability. Wider track spacing reduces the risk of an ATA due to the reduced intrusion probability; however, at many locations, the space for railroad right-of-way and construction is constrained, or land acquisition is difficult or impractical. In order to mitigate ATA probability at such locations, installation of crash walls, barriers or containment systems, or IDW system may be considered. The model can be used to evaluate the ATA probability for different

track segments of the new rail system and the results used to optimize the design for safe and efficient train operations.

2.6.3 FTA and Existing Railroad Network Safety Improvement

The FTA presented here can also be used to improve existing or expanded multiple track sections in a railroad corridor. These can be divided into segments based on route characteristics, traffic composition, presence of crash walls and other relevant factors, and the FTA can be used to evaluate segment-specific ATA risk. Segments where ATA risk is high can be identified and prioritized for risk mitigation. Similar to the design of a new rail system, the FTA can also evaluate the effectiveness of risk mitigation strategies on existing corridors.

2.7 Conclusions

In this chapter, I explored and identified the basic events that contribute to the occurrence of ATA and developed a methodological structure to evaluate its probability using ETA and FTA. I used Boolean algebra to develop the logical relationships among basic events in the ATA fault tree. I also discussed the importance and potential application of FTA in the context of ATA probability assessment. The developed ATA fault tree serves as a foundation for further development of PRA and the evaluation of risk mitigation strategies for ATA.

CHAPTER 3

MAINLINE PASSENGER TRAIN ACCIDENT ANALYSIS

Adapted from

Lin, C.Y., M.R. Saat, and C.P.L. Barkan. 2018. Analysis of mainline passenger train accidents in the United States and safety implications on shared-use rail corridors. *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit* (under review).

3.1 Introduction

Research on train-accident analyses in the United States has focused primarily on freight train derailments (Birk et al., 1990; Dennis, 2002; Barkan et al., 2003; Anderson and Barkan, 2004, 2005; Liu et al., 2011; 2012; 2013a; Liu, 2015; Liu et al., 2017; Li et al., 2018), hazardous material releases (Nayak et al., 1983; Saccomanno and El-Hage, 1989; 1991; Kawprasert and Barkan, 2008; Bagheri et al., 2011; Liu et al., 2013b; 2014; Liu and Hong, 2015; Liu, 2017a; b) and grade crossing incidents (Benekohal and Elzohairy, 2001; Austin and Carson, 2002; Saccomanno et al., 2004; Mok and Savage, 2005; Saccomanno et al., 2007; Chadwick et al., 2014; Williams et al., 2015a; b).

Relatively few studies have focused on quantitative analysis of U.S. passenger train safety. Much of the research that has been done was investigating passenger rail equipment damage resistance and crash energy management systems. These systems are intended to reduce casualties in a train collision or derailment (Simons and Kirkpatrick, 1999; Kirkpatrick et al., 2001; Tyrell 2002a; b; Tyrell and Perlman, 2003). Lin et al. (2016) conducted a fault tree analysis to identify major factors that could lead to an adjacent track accident on shared passenger and freight rail corridors. Lin and Saat (2014)

developed a semi-quantitative risk assessment model to evaluate adjacent track accident risk and identified factors that affect train intrusion probability.

Internationally, there have been more quantitative studies of passenger train accidents. Niwa (2009) analyzed significant Japanese railway accidents by five major aspects, namely liveware-person concerned, liveware-other personnel, hardware, software, and work place, and conducted case studies of several severe accidents. Ouyang et al. (2010) used System Theoretic Accident Models and Process (STAMP) to analyze a severe railway accident on the Jiaozji Railway in China. Chen et al. (2017) used Associated Rule and other data mining techniques to analyze Chinese passenger train accidents. Britton et al. (2017) conducted causal analysis of train derailments in Australia.

Studies of passenger rail safety are especially rich in Europe. Evans (2000) conducted a statistical analysis of fatal train accident trends on British railways. The author proposed an exponential function to predict the declining trend of train accident rates and applied it to other mainline railway systems in Japan, Britain, and Europe (Evans, 2007; 2010; 2011b). Silla and Kallberg (2012) studied the development of railway safety in Finland and Santos-Reyes and Beard (2006; 2009) used the Systemic Safety Management System model to analyze two major passenger train accidents in the United Kingdom.

These studies provide insights into accident analysis methodologies and results for reference and comparison; however, there are a number of differences in operating practices, rolling stock, and organizational structure that affect passenger train safety in the U.S. environment. This is especially so in the context of North American shared-use corridors (SRCs) where heavy-axle-load freight trains are the norm, but are rare on most other nations' rail systems. On many European and Asian rail networks, passenger trains generally outnumber freight trains and trains usually run on fixed schedules, whereas in North America, freight trains are the dominant type, and most of them operate on a flexible schedule (Furtado, 2013). Another difference is the design of passenger rolling stock. In Europe and Asia passenger cars are lighter weight and run at higher speeds with more rapid acceleration and deceleration rates. In North America, passenger rail equipment is heavier because it must meet robust crash-worthiness standards because of possible collisions with heavy locomotives and freight cars in accidents. Consequently, results from previous research on passenger train accidents in other parts of the world are not directly transferrable to the U.S. rail environment. Further study of passenger train accidents is necessary to understand how to most effectively manage and reduce the risk associated with U.S. passenger train operation.

In this chapter, I present an analysis of mainline passenger train accidents in the United States from 1996 to 2017. The objective is to understand the general trend of mainline passenger train accident rates, quantify the frequency and severity of different accident types, and identify the major factors that cause them. In addition, I explore the

potential effect of positive train control (PTC) and train speed on passenger train accident risk, and the implications of passenger train accident analysis to SRC risk management.

3.2 Passenger Train Accident Analysis 1996 – 2017

Train accident data from the United States Department of Transportation (USDOT) Federal Railroad Administration (FRA) were used for the analysis (FRA, 2017a). Railroad accidents/incidents that result in monetary loss exceeding a specified threshold must be reported to the Rail Equipment Accident (REA) database maintained by FRA (2019). This threshold is periodically adjusted for inflation and is low enough so that only relatively minor incidents are not included. The FRA categorizes train accidents into thirteen types (Table 3.1). For the purpose of the analysis described in this chapter, these thirteen types were consolidated into five broad accident categories. Incidents caused by defective pantograph or overhead catenary system occur relatively infrequently, and although such incidents can cause large monetary damage to railroad infrastructure and equipment and thus must be reported, they pose little, if any, hazard to on board passengers and crew, which is the principal interest of my research. Therefore, these incidents were not included.

Table 3.1: FRA train accident type and categorization

Accident/Incident Type	Type Code	Category in This Chapter
Derailment	1	Derailment
Head-on collision	2	Collision
Rear collision	3	Collision
Side collision	4	Collision
Raking collision	5	Collision
Broken-train collision	6	Collision
Grade crossing incident	7	Grade Crossing
Railroad crossing collision	8	Collision
Obstruction	9	Obstruction
Explosive-detonation	10	Miscellaneous
Fire/violent rupture	11	Miscellaneous
Other impact	12	Miscellaneous
Others (with description)	13	Miscellaneous
Pantograph/OCS	N/A	Excluded

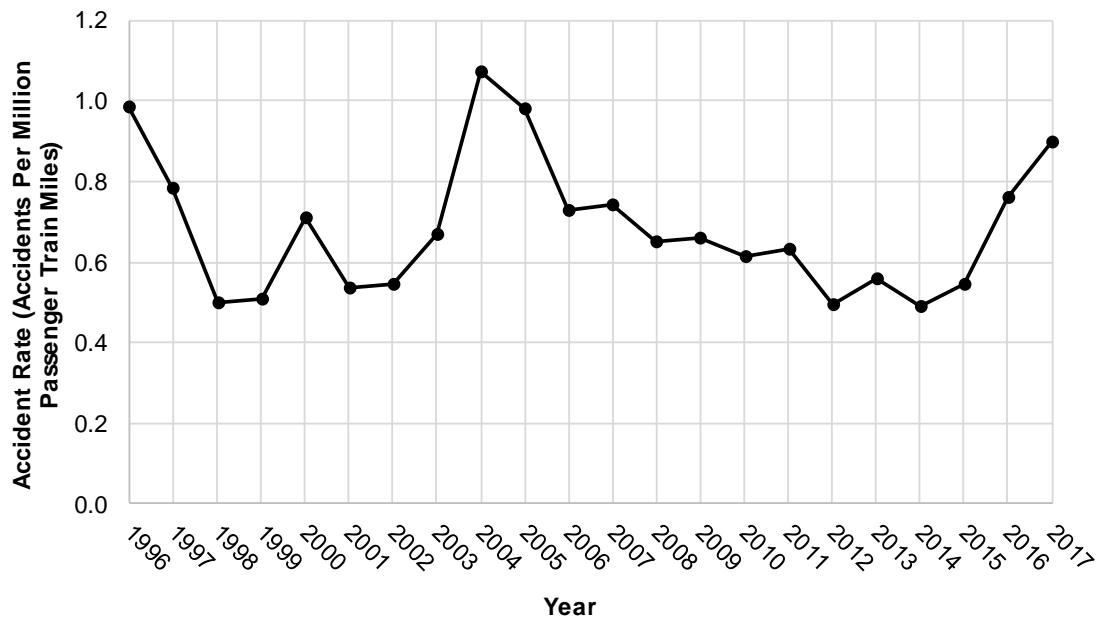
Passenger train accident rate is calculated as the number of accidents per million passenger train miles. In 1996, the first year of my study period, there were 0.99 accidents per million passenger train miles. In 2017, the most recent year for which data were available, this figure had dropped to 0.90 accidents per million passenger train miles (Table 3.2). During the intervening years this rate fluctuated widely, peaking at 1.075 in 2004 (Figure 3.1a).

To understand what was affecting the rate, the data were broken down by the five accident categories defined above: derailment, collision, grade crossing, obstruction, and miscellaneous (Figure 3.1b). The fluctuations appear to be driven primarily by grade crossing and obstruction accidents, both of which are largely outside of railroads' control. Derailments and collisions showed a weak but generally downward trend. This is consistent with the downward trend of mainline freight train derailment and collision rates, although the freight railroad trend is more obvious (and in fact, statistically significant) (Liu, 2015; 2016).

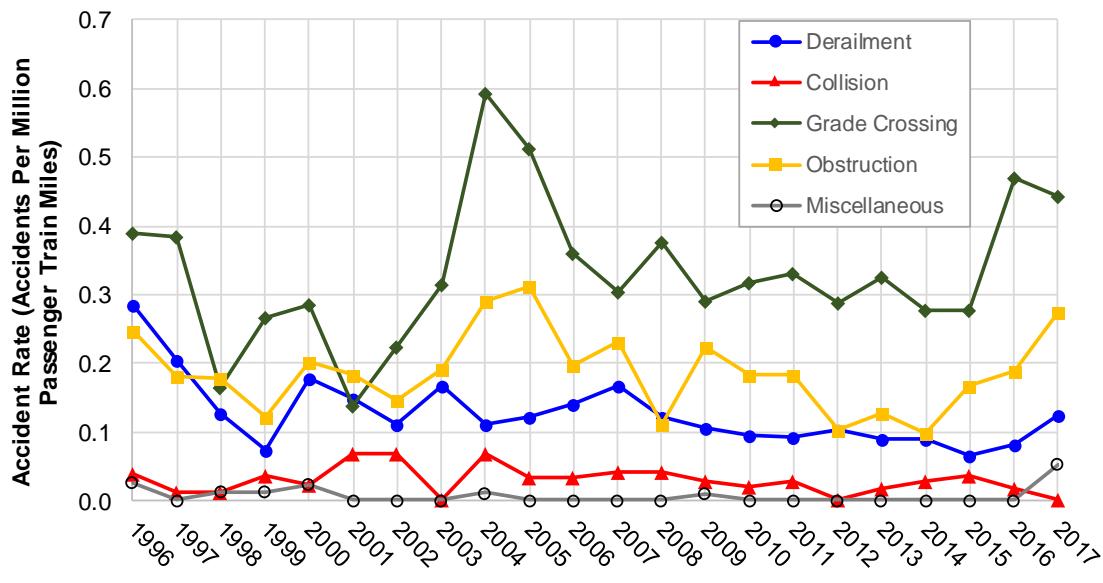
Year	Traffic*	Derailment		Collision		Grade Crossing		Obstruction		Miscellaneous		Total
		Accident	Rate	Accident	Rate	Accident	Rate	Accident	Rate	Accident	Rate	
1996	77.0	22	0.286	3	0.039	30	0.390	19	0.247	2	0.026	76
1997	78.0	16	0.205	1	0.013	30	0.384	14	0.179	0	0.000	61
1998	78.4	10	0.128	1	0.013	13	0.166	14	0.179	1	0.013	39
1999	82.4	6	0.073	3	0.036	22	0.267	10	0.121	1	0.012	42
2000	84.3	15	0.178	2	0.024	24	0.285	17	0.202	2	0.024	60
2001	87.8	13	0.148	6	0.068	12	0.137	16	0.182	0	0.000	47
2002	89.6	10	0.112	6	0.067	20	0.223	13	0.145	0	0.000	49
2003	89.4	15	0.168	0	0.000	28	0.313	17	0.190	0	0.000	60
2004	89.3	10	0.112	6	0.067	53	0.593	26	0.291	1	0.011	96
2005	89.9	11	0.122	3	0.033	46	0.512	28	0.311	0	0.000	88
2006	92.0	13	0.141	3	0.033	33	0.359	18	0.196	0	0.000	67
2007	95.3	16	0.168	4	0.042	29	0.304	22	0.231	0	0.000	71
2008	98.1	12	0.122	4	0.041	37	0.377	11	0.112	0	0.000	64
2009	102.9	11	0.107	3	0.029	30	0.291	23	0.223	1	0.010	68
2010	104.1	10	0.096	2	0.019	33	0.317	19	0.182	0	0.000	64
2011	109.1	10	0.092	3	0.028	36	0.330	20	0.183	0	0.000	69
2012	107.5	11	0.102	0	0.000	31	0.288	11	0.102	0	0.000	53
2013	110.7	10	0.090	2	0.018	36	0.325	14	0.126	0	0.000	62
2014	112.3	10	0.089	3	0.027	31	0.276	11	0.098	0	0.000	55
2015	108.1	7	0.065	4	0.037	30	0.278	18	0.167	0	0.000	59
2016	110.5	9	0.081	2	0.018	52	0.470	21	0.190	0	0.000	84
2017	112.6	14	0.124	0	0.000	50	0.444	31	0.275	6	0.053	101
Total	261	0.138	61	0.032	706	0.374	393	0.208	14	0.007	1,435	0.761

* Million passenger train miles

Table 3.2: Annual number of FRA-reportable mainline passenger train accident by accident category, 1996 – 2017



(a)



(b)

Figure 3.1: FRA-reportable mainline passenger train accident rates, 1996 – 2017
(a) overall rates (b) rates by accident category

Miscellaneous accidents were uncommon and showed no evident trend. Perhaps the most interesting pattern observed is the contrast between passenger train grade crossing accident rate and freight train grade crossing accident rate, which has steadily declined over the same time period (Mok and Savage, 2005; FRA, 2017b). In the past two years the passenger train accident rate has increased evidently due primarily to an increase in grade crossing and obstruction accidents. Whether this is simply due to random fluctuation associated with the relatively small number of accidents, or indicative of an actual increasing trend is not known.

A time series analysis was conducted for the different types of passenger train accident data (Table 3.3). Negative binomial and Poisson regressions were used to fit the data and passenger train traffic and time trending factors were selected as parameters to be estimated. I used the Akaike Information Criterion method (AIC) and Bayesian Information Criterion method (BIC) to determine which regression model provided a better fit to the data. The results show that no particular temporal trend was evident for the different types or for the overall total. Passenger train traffic has increased over the analysis period as suggested above (Table 3.2); however, the effect of passenger train traffic is not statistically significant in most of the categories with the exception of obstruction incidents. This suggests that the increase in passenger train traffic over time does not appear to be related to the increase or decrease of passenger train accident rates.

Table 3.3: Time series analysis of FRA-reportable mainline passenger train accident by accident category, 1996 – 2017

Type of Accident	Derailment	Collision	Grade Crossing
Fitted Model	Poisson	Poisson	Negative Binomial
Intercept	2.85	-0.33	21.40
Traffic (t-statistic)	-2.14E-09 -7.78E-02	2.07E-08 3.66E-01	1.31E-10 1.32E-04
Time Trending Variable (t-statistic)	-1.53E-02 2.94E-01	-5.55E-02 5.16E-01	9.56E-01 5.09E-01
Log-likelihood	-55.5	-43.0	-79.9
AIC	117.0	91.9	167.7
BIC	120.3	95.2	172.1

Type of Accident	Obstruction	Miscellaneous	Total
Fitted Model	Poisson	Negative Binomial	Negative Binomial
Intercept	6.69	0.55	55.10
Traffic (t-statistic)	-5.30E-08 2.43E+00	3.23E-12 2.54E-11	1.00E-08 6.58E-09
Time Trending Variable (t-statistic)	1.10E-01 2.70E+00	7.62E-03 3.16E-02	8.87E-01 3.08E-01
Log-likelihood	-65.8	-23.3	-89.9
AIC	137.6	54.6	187.8
BIC	140.9	59.0	192.1

Number of sample (years) (n)	22
Number of coefficient (k)	4
Degree of freedom (n-k-1)	18
5% critical value for the t-statistic	2.552
1% critical value for the t-statistic	1.734

Risk is generally defined as the probability of a particular event multiplied by its consequence (Elvik and Voll, 2014). In order to identify the types of accidents that pose greater threat (i.e. higher probability, consequence, or both), accident rate and severity for each category of mainline passenger train accident were plotted in a frequency-severity graph (Figure 3.2). Frequency-severity graphs are a helpful risk visualization tool for train accidents because they enable comparison of the relative frequency and severity of different accident types. They have been used in a number of other railroad accident

analyses (Barkan et al., 2003; Dick et al., 2003; Liu et al., 2012; Wang et al., 2019). The graph is divided into four quadrants on the basis of average frequency (AF) and average severity (AS) along each axis.

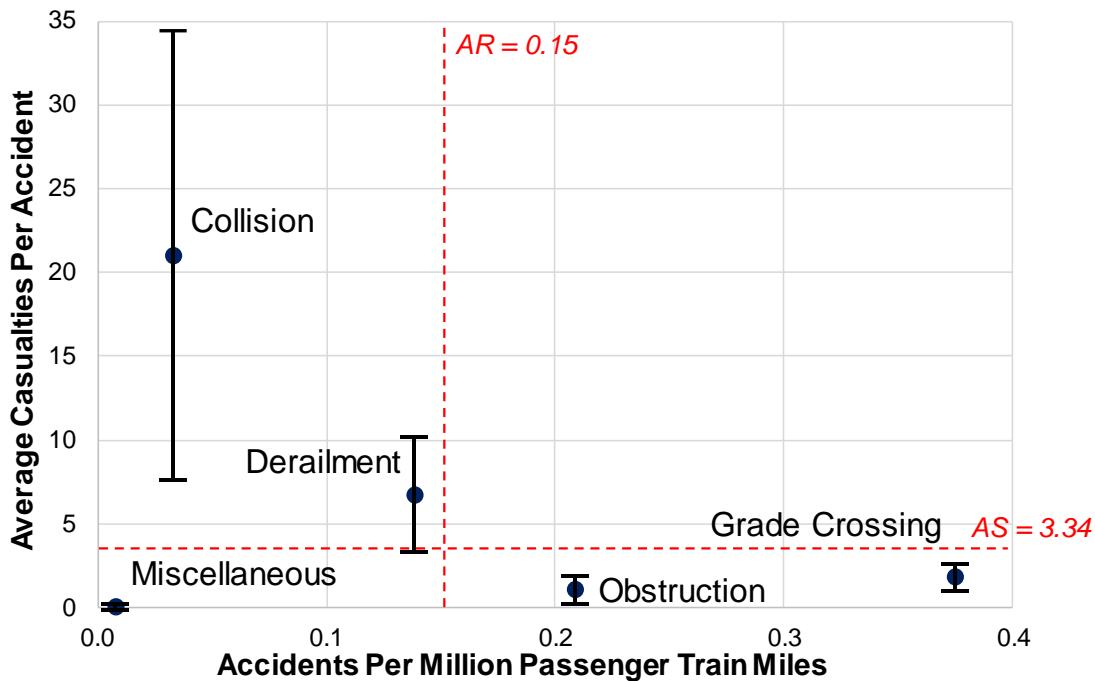


Figure 3.2: Frequency-severity graph for FRA-reportable mainline passenger train accidents, 1996 – 2017

Frequency in this graph is defined as train accident rate. Several different variables were considered to measure passenger train accident severity. The number of railcars derailed has often been used as a proxy variable to measure freight train accident severity (Saccomanno and El-Hage, 1989; 1991; Barkan et al., 2003; Kawprasert and Barkan, 2008; Liu et al., 2012; 2013a; b; 2014; Wang et al., 2019). For passenger trains, casualties are another important metric of accident severity (Evans, 2000; 2007; 2010; 2011; Lin et al., 2016; Chen et al., 2017). In this research, casualties are defined as the

total number of onboard passenger and crew injuries and fatalities, and were used as the primary severity indicator.

To distinguish the difference in severity implied by injuries and fatalities, I used the Fatality Weighted Index (FWI). The FWI assigns different weights to a fatality, a major injury, and different levels of minor injuries (Bearfield et al., 2013). Weights for each category differ by approximately an order of magnitude: one fatality is equivalent to ten major injuries, 200 reportable minor injuries, and 1,000 non-reportable minor injuries. FWI is used in train accident analyses involving human injuries and fatalities (Aas et al., 2008; Sadler et al., 2016). There are only two levels of severity for onboard passengers and crew recorded in the FRA REA database: a person is either injured or fatally injured. Therefore, a ten to one ratio was assigned to a fatality, meaning that one fatality was equivalent to ten injuries.

Accident categories in the upper-right quadrant of the frequency-severity graph are the most likely to pose the greatest risk because they are both more frequent, and more severe, than average. None of the five accident categories fell in this quadrant, but derailments and collisions were most likely to result in high-casualty incidents. Together, they accounted for about 22% of passenger train accidents, but caused about 63% of total casualties (Table 3.4). Derailments and collisions also caused more damage to rail equipment and infrastructure and were more likely to result in onboard passenger and crew casualties. Although grade crossing incidents had the highest frequency, they were among the least severe in terms of consequences to onboard passengers and crew.

Obstruction incidents also had above-average frequency and low severity. These are incidents in which trains collide with foreign objects such as trees, boulder or vehicles that are not at grade crossings (Table 3.5). With few exceptions, obstruction incidents were less likely to cause severe onboard passenger and crew casualties. Therefore, in this chapter I examine mainline passenger derailments and collisions in more detail.

Table 3.4: Summary of frequency, accident rate, casualties and average casualties for different types of passenger train accidents, 1996 – 2017

Type	Frequency	Percentage	Average Accident Rate	Total Casualties	Percentage	Average Casualties
Grade Crossing	706	49.2%	0.3743	1,311	27.3%	1.86
Obstruction	393	27.4%	0.2084	436	9.1%	1.11
Derailment	261	18.2%	0.1384	1,765	36.7%	6.76
Collision	61	4.3%	0.0323	1,284	26.7%	21.05
Miscellaneous	14	1.0%	0.0074	10	0.2%	0.71
Total	1,435	100.0%	0.1522	4,806	100.0%	3.35

Table 3.5 List of foreign objects in obstruction incidents and frequency, 1996 – 2017

Object	Frequency
Vehicle (not at grade crossings)	138
Tree	100
Unknown Debris	44
Boulder/Rock	33
Metal	16
Bumper	11
No Description	7
Uncategorized Debris	7
Crossing Gate	6
Animal	5
Bridge Plate	4
Concrete Block	4
Fence	4
Ice/Snow	3
Asphalt	2
Shopping Cart	2
Utility Pole	2
Bar Stool	1
Cable Spool	1
Gallon Drum	1
Pleasure Boat	1
Signal Equipment	1
Total	393

3.3 Causal Analysis for Passenger Train Derailment and Collision Accidents

To further understand which factors contributed the most to passenger train derailments and collisions, I conducted a causal analysis (Barkan et al., 2003; Liu et al., 2011; 2012). When a railroad reports a train accident, they identify the cause using the predefined FRA (2011) cause codes. There are two types of accident causes in the FRA accident reporting system: primary cause and contributing cause. A primary cause is the most direct cause leading to the occurrence of the accident, and a contributing cause is a factor that may have directly or indirectly led to the accident, but was not as important as the primary cause. The FRA's accident reporting system allows one primary cause code entry and one contributing cause code entry. In some cases, two cause codes may be equally important. In these cases, the determination of which one is considered as the primary cause is left to the accident reporting personnel's best judgment. In some cases, when the primary cause code for an accident is clear, but multiple contributing causes were identified, the most relevant or appropriate one is entered based on the accident reporting personnel's best judgment.

Railroad accidents usually result from two types of causes: direct causes and underlying causes. Examples of the former include failure to obey signals, broken rail, broken wheel, and signal equipment failure. Underlying causes do not directly lead to the occurrence of an accident but may foster a negative environment that makes an operation more prone to train accidents. Some examples of underlying causes are: engineer (train driver) fatigue (Sussman and Coplen, 2000; Dorrian et al., 2011; Zeinab et al., 2016), improper maintenance of infrastructure or rolling stock (Singh and Kumar, 2015), and

poor safety culture in the organization (Farrington-Darby et al., 2005; Baysari et al., 2008). The FRA accident-cause codes capture most of the direct causes but are not as effective in identifying underlying causes. Some causes can be both a direct cause and an underlying cause of an accident, but in the FRA's reporting system, those causes are primarily used as the former (for example, engineer fatigue). In this analysis, the primary accident-cause codes of passenger train derailments and collisions were used to plot the frequency-severity graph.

FRA train-accident-cause codes are hierarchically organized and categorized into major cause groups – track (infrastructure), equipment (rolling stock), human factor, signal, and miscellaneous (FRA, 2011). Each of these major cause groups has subgroups that include individual codes for related causes. In this chapter, I use the adjusted FRA subgroups developed by Arthur D. Little (ADL) and the Association of American Railroads (AAR) in which similar cause codes were grouped based on expert opinion (ADL, 1996). The ADL groupings enable greater resolution for certain train accident causes. For example, FRA combines broken rails, joint bars and rails anchors in the same subgroup, whereas the ADL grouping distinguishes between broken rail and joint bar defects (Liu et al., 2012). (A complete list of FRA accident cause codes and ADL cause groupings is presented in the Appendix)

The frequency and severity graph of mainline passenger derailments and collisions by major accident-cause groups was plotted (Figure 3.3). As in Figure 3.2, the graph is divided into four quadrants to enable comparison of the frequency and severity

of the different cause groups. The Train Operation Human Factor cause group had above-average frequency and was the most severe in terms of average casualties, accounting for 30% of the total derailments and collisions, but 69.6% of the total casualties (Table 3.6). Track, Roadbed, and Structures accidents were more frequent than Train Operation Human Factor, but less severe (40.1% of the total derailments and collisions and 25.8% of the total casualties). Both Train Operation Human Factor and Track, Roadbed, and Structure related accident causes consistently represented the most frequent and severe accident-cause groups, together accounting for a total of 70.2% of derailments and collisions, and 95.3% of casualties; therefore, they were analyzed in more detail.

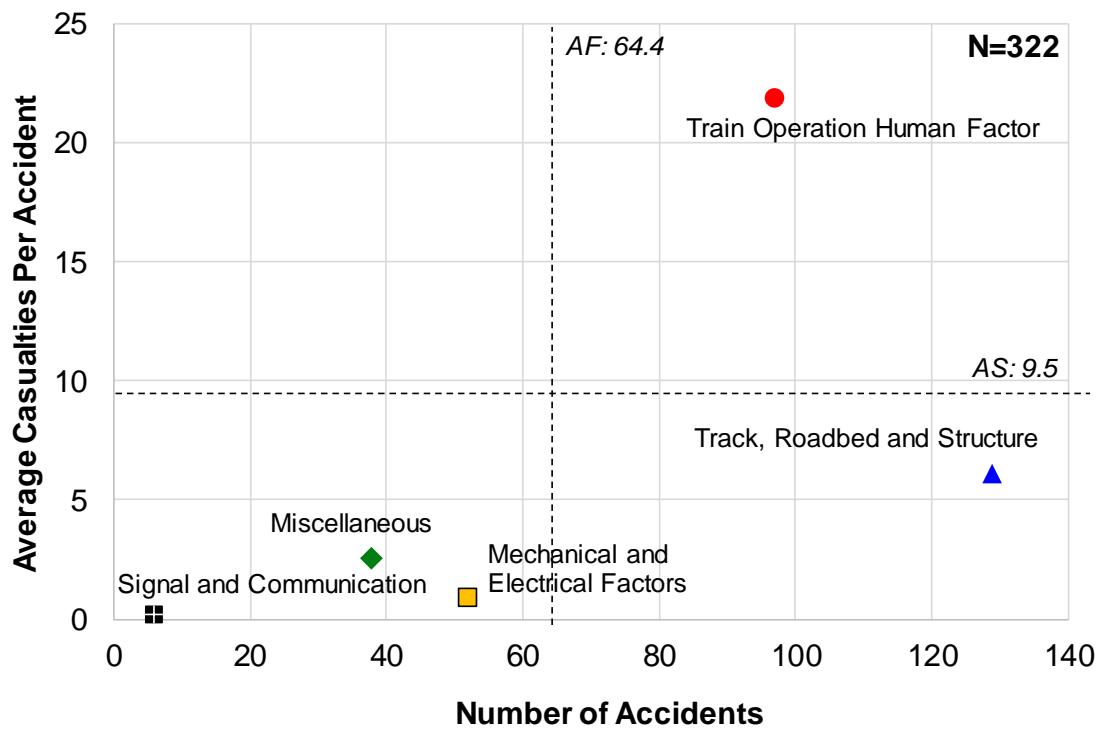


Figure 3.3: Frequency and severity graph of mainline passenger derailments and collisions, 1996-2017, by accident-cause group with average casualties

Table 3.6: Summary of frequency, accident rate, casualties and average casualties of mainline passenger derailments and collisions, 1996 – 2017, by accident-cause group

	Frequency	Percentage	Average Rate	Total Casualties	Percentage	Average Casualties
Train Operation Human Factor	97	30.1%	0.0514	2,121	69.6%	21.87
Track, Roadbed, and Structure	129	40.1%	0.0684	786	25.8%	6.09
Miscellaneous	38	11.8%	0.0201	97	3.2%	2.55
Mechanical and Electrical Factors	52	16.1%	0.0276	44	1.4%	0.85
Signal and Communication	6	1.9%	0.0032	1	0.0%	0.17
Total	322	100.0%	0.1707	3,049	100.0%	9.47

In order to identify trends in specific accident causes, the five-year moving average of combined derailment and collision rate was broken down by accident-cause group (Figure 3.4). Track, Roadbed and Structure and Train Operation Human Factor were consistently the most frequent accident-cause groups over the 22-year study period, with Track, Roadbed and Structure being the highest for every five-year interval except 1998 – 2002, 2008 – 2012, and 2012 – 2016. The trend implies that there is a change in the distribution of accident causes for passenger train derailments and collisions over time and may reflect the railroad industry’s emphasis on preventing certain types of accident causes. For example, prior to 2010, infrastructure-related accidents comprised a large fraction of passenger train derailments, but these have been substantially reduced since then due to investment in infrastructure and defect detection technologies. The decreasing trend of infrastructure-related accidents has led to a shift in focus toward reduction of human-factor-caused accidents.

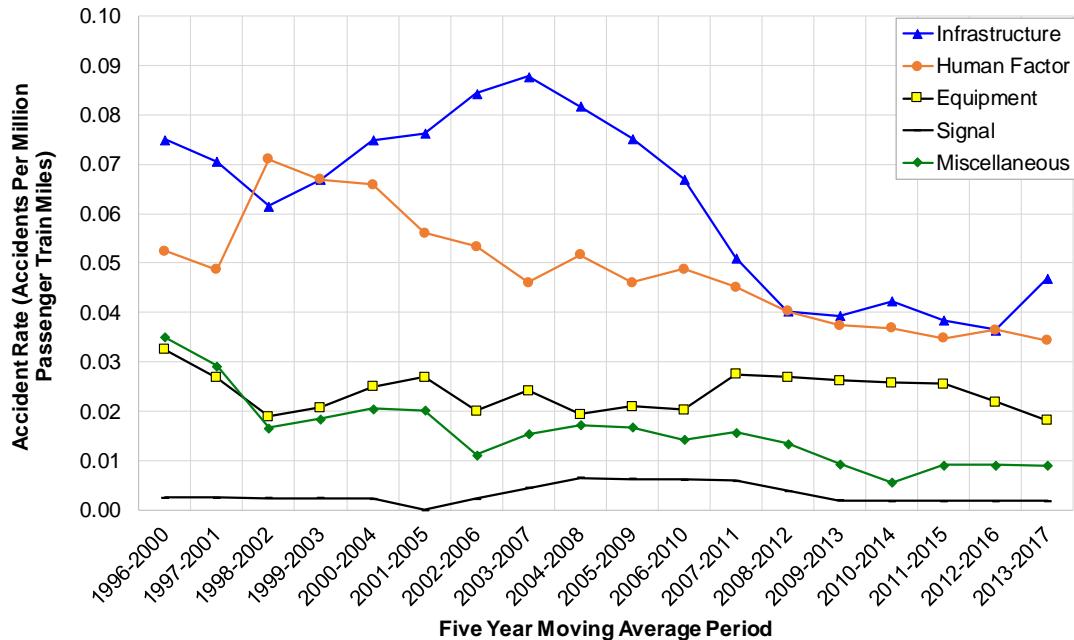


Figure 3.4: Five-year moving average of combined mainline passenger train derailment and collision rate, 1996 – 2017, by accident-cause group

The accident-cause groups were further analyzed by preparing a frequency and severity graph for the more detailed accident-cause subgroups (Figure 3.5). Each data point represents one accident-cause subgroup. Data points with the same color and shape indicate that these subgroups are in the same accident-cause group. In terms of average casualties, four accident-cause subgroups were in the upper-right quadrant, and thus most likely to pose the greatest risk due to their high frequency and severity. All of them are from the Train Operation Human Factor group:

- Failure to Display/Obey Signals (05H)
- Train Speed (10H)
- Miscellaneous Human Factors (12H)
- Mainline Rules (08H)

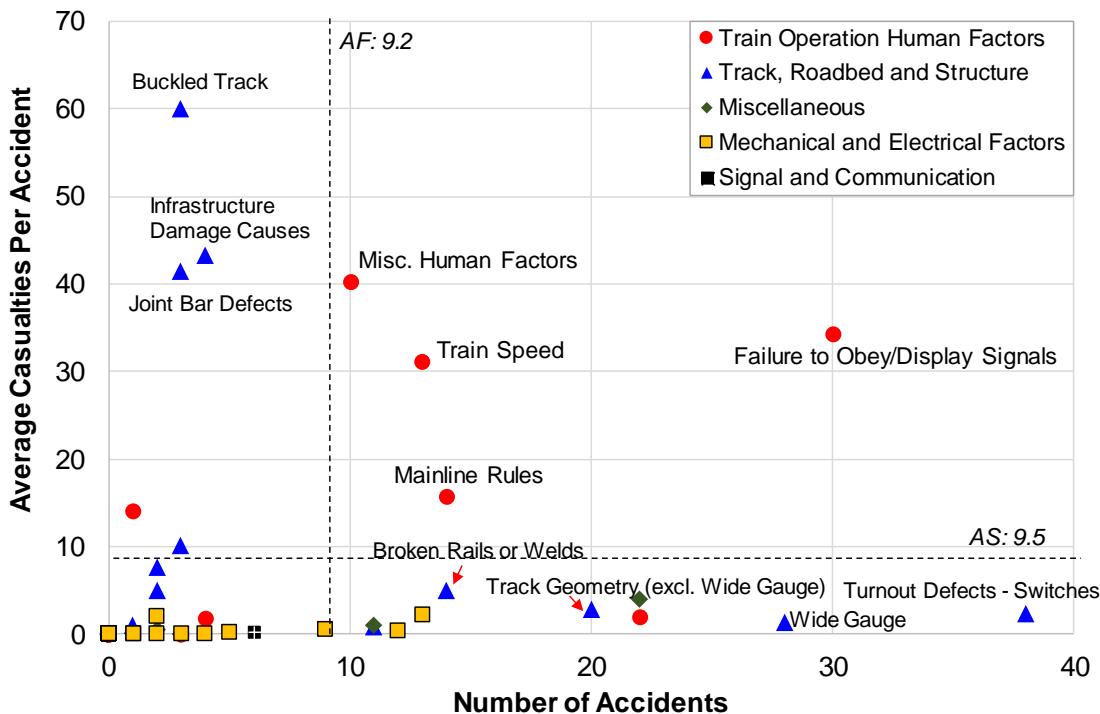


Figure 3.5: Frequency and severity graph of mainline passenger derailments and collisions, 1996-2017, by accident-cause subgroups with average casualties

These four subgroups accounted for 20.8% of the total mainline passenger derailments and collisions but 67.5% of total casualties (Table 3.7). Among all the subgroups identified in the upper-right quadrant, Misc. Human Factors, had the highest average casualties per accident, followed by Failure to Display/Obey Signals, Train Speed, and Mainline Rules. Overall, the five most frequent accident-cause subgroups were: Turnout Defect – Switches, Failure to Obey/Display Signals, Wide Gauge, Other Miscellaneous, and Use of Switches. Combined they accounted for 43.5% of total derailments and collisions and 41.9% of total casualties. Two of the top five most frequent accident-cause subgroups were infrastructure related, two of them were human factor and one of them was miscellaneous.

Table 3.7: Summary of frequency, accident rate, severity and average severity of mainline passenger train derailments and collisions, 1996 – 2017, by accident-cause subgroups with at least one occurrence

ADL Cause Subgroup Code	ADL Cause Subgroup Description	Frequency		Accidents Per Million Train Miles	Casualties			Cars Derailed		
		Number	Percentage		Number	Percentage	Average	Number	Percentage	Average
05T	Buckled Track	3	0.9%	0.0016	180	5.9%	60.0	25	2.9%	8.3
02T	Infrastructure Damage Causes	4	1.2%	0.0021	173	5.7%	43.3	21	2.4%	5.3
07T	Joint Bar Defects	3	0.9%	0.0016	124	4.1%	41.3	22	2.5%	7.3
12H	Misc. Human Factors	10	3.1%	0.0053	403	13.2%	40.3	35	4.0%	3.5
05H	Failure to Obey/Display Signals	30	9.3%	0.0159	1030	33.8%	34.3	101	11.6%	3.4
10H	Train Speed	13	4.0%	0.0069	405	13.3%	31.2	46	5.3%	3.5
08H	Mainline Rules	14	4.3%	0.0074	219	7.2%	15.6	21	2.4%	1.5
04H	Employee Physical Condition	1	0.3%	0.0005	14	0.5%	14.0	18	2.1%	18.0
06T	Rail Defects at Bolted Joint	3	0.9%	0.0016	30	1.0%	10.0	20	2.3%	6.7
01T	Roadbed Defects	2	0.6%	0.0011	15	0.5%	7.5	8	0.9%	4.0
09T	Other Rail and Joint Defects	2	0.6%	0.0011	10	0.3%	5.0	4	0.5%	2.0
08T	Broken Rails or Welds	14	4.3%	0.0074	69	2.3%	4.9	59	6.8%	4.2
05M	Other Miscellaneous	22	6.8%	0.0117	86	2.8%	3.9	75	8.6%	3.4
04T	Track Geometry (excl. Wide Gauge)	20	6.2%	0.0106	57	1.9%	2.9	47	5.4%	2.4
15E	Loco Trucks/Bearings/Wheels	13	4.0%	0.0069	29	1.0%	2.2	18	2.1%	1.4
10T	Turnout Defects - Switches	38	11.8%	0.0201	84	2.8%	2.2	75	8.6%	2.0
09E	Sidebearing, Suspension Defects (Car)	2	0.6%	0.0011	4	0.1%	2.0	5	0.6%	2.5
11H	Use of Switches	22	6.8%	0.0117	43	1.4%	2.0	36	4.1%	1.6
02H	Handbrake Operations	4	1.2%	0.0021	7	0.2%	1.8	14	1.6%	3.5
03T	Wide Gauge	28	8.7%	0.0148	35	1.1%	1.3	86	9.8%	3.1
11T	Turnout Defects - Frogs	1	0.3%	0.0005	1	0.0%	1.0	5	0.6%	5.0
01M	Obstructions	11	3.4%	0.0058	10	0.3%	0.9	41	4.7%	3.7
12T	Misc. Track and Structure Defects	11	3.4%	0.0058	8	0.3%	0.7	23	2.6%	2.1
18E	All Other Car Defects	9	2.8%	0.0048	5	0.2%	0.6	10	1.1%	1.1
04M	Track-Train Interaction	2	0.6%	0.0011	1	0.0%	0.5	5	0.6%	2.5
13E	Other Wheel Defects (Car)	12	3.7%	0.0064	5	0.2%	0.4	17	1.9%	1.4
06E	Centerplate/Carbody Defects (Car)	5	1.6%	0.0027	1	0.0%	0.2	2	0.2%	0.4
01S	Signal Failures	6	1.9%	0.0032	1	0.0%	0.2	9	1.0%	1.5
11E	Other Axle/Journal Defects (Car)	4	1.2%	0.0021	0	0.0%	0.0	10	1.1%	2.5
17E	All Other Locomotive Defects	3	0.9%	0.0016	0	0.0%	0.0	5	0.6%	1.7
07H	Switching Rules	3	0.9%	0.0016	0	0.0%	0.0	3	0.3%	1.0
03M	Lading Problems	3	0.9%	0.0016	0	0.0%	0.0	0	0.0%	0.0
14E	TOFC/COFC Defects	2	0.6%	0.0011	0	0.0%	0.0	6	0.7%	3.0
07E	Coupler Defects (Car)	1	0.3%	0.0005	0	0.0%	0.0	1	0.1%	1.0
19E	Stiff Truck (Car)	1	0.3%	0.0005	0	0.0%	0.0	1	0.1%	1.0
Total		322	100.0%	0.029	3,049	100.0%	9.5	874	100.0%	2.7

The frequency and severity for each accident-cause subgroup for mainline passenger train derailments and collisions were ranked by average casualties (Table 3.7). Buckled Track, Infrastructure Damage Causes, and Joint Bar Defects were the top three accident-cause subgroups indicating that although they occurred infrequently, on average they had high severity when they did occur. This characteristic is also illustrated by their placement in the upper left quadrant of Figure 3.5, indicating that derailments and collisions resulting from these accident causes, although infrequent, can lead to severe passenger casualties. Misc. Human Factors, Failure to Obey/Display Signals, Train Speed, and Mainline Rules were the fourth to seventh ranked accident-cause subgroups. They also had high average severity, but they were more frequent than the previous three accident-cause subgroups. This is also consistent with the result shown by the frequency-severity graph (Figure 3.5).

3.3.1 Positive Train Control (PTC) Preventable Accident Causes

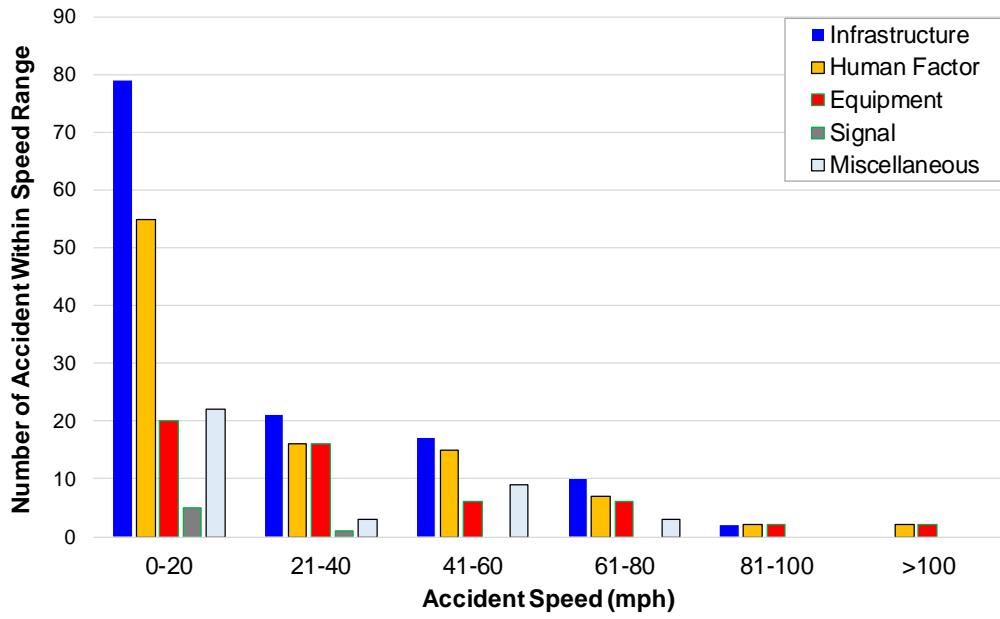
Positive Train Control, or PTC, refers to an advanced train control system that is being implemented to prevent train-to-train collisions, overspeed derailments, incursion into established work zones, and derailments due to misaligned switches (FRA, 2018). Among the most frequent passenger-train accident-cause subgroups are PTC-preventable accidents (PPA). For example, accidents due to Failure to Obey/Display Signals (05H), Use of Switches (11H), Mainline Rules (08H), Train Speed (10H) will often be PPAs. All four accident-cause subgroups identified in the upper-right quadrant in the frequency-severity graph are also generally PPAs. The average casualties for these PPA cause

subgroups are greater than the average severities for all accident-cause subgroups combined (Table 3.7).

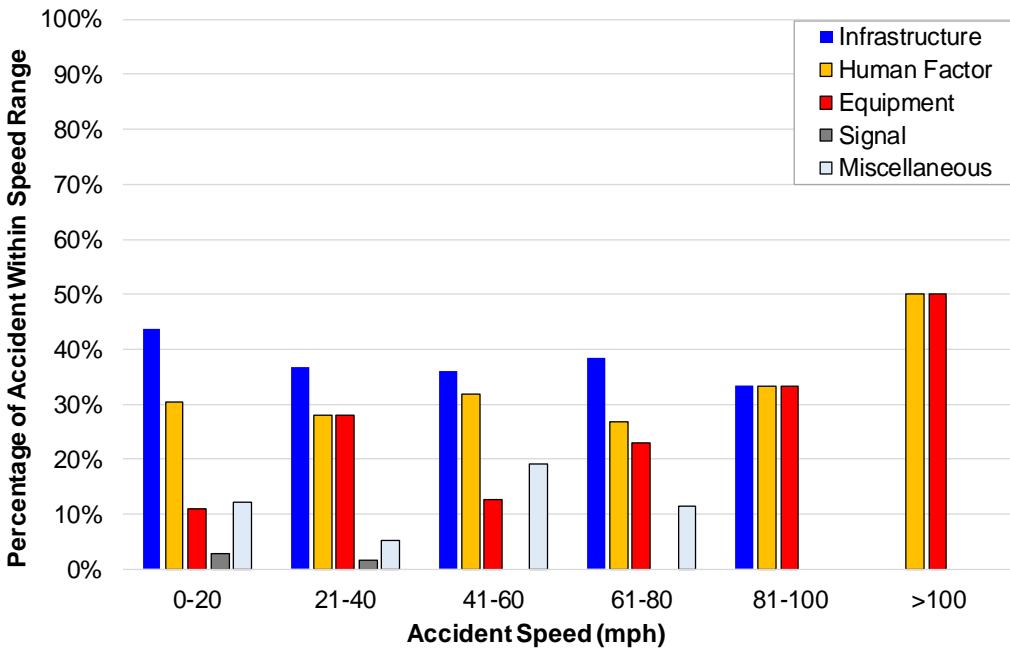
3.4 Effect of Speed on Passenger Train Derailment and Collision Cause

Previous research has shown that on average the speed of a train at the time of derailment was positively correlated with derailment severity (Nayak et al., 1983; Saccomanno and El-Hage, 1989; 1991; Barkan et al., 2003; Liu et al., 2011; 2012; 2013a). Previous research has also found an inverse relationship between FRA track class and freight train derailment rate (Nayak et al., 1983; Anderson and Barkan, 2004; Liu et al., 2013a; 2017).

The number and percentage of mainline passenger train derailments and collisions by speed range and accident-cause category were plotted (Figure 3.6). The majority of train accidents – about 57% – occurred at speeds below 20 mph. This may be related to the relatively high frequency of defective-turnout-caused derailments. Turnouts are found at stations, terminals, and the ends of sidings where trains are likely to slow down due to speed restrictions, scheduled stops, or meet/pass activities. Infrastructure related accidents occurred in almost all speed ranges and had the highest percentage except the >100 mph category. No specific trends were found for human-factor-caused and equipment-caused accidents. The three accidents that occurred above 100 mph were caused by human factors and equipment.



(a)



(b)

Figure 3.6: Number (a) and percentage (b) of mainline passenger train derailments and collisions by speed range and accident-cause category, 1996 – 2017

To further understand what caused derailments or collisions at different speeds, the number of mainline passenger train derailments and collisions by accident-cause subgroup in different speed ranges was analyzed (Table 3.8). In the 0-20 mph range, Turnout Defects – Switches was the top accident-cause subgroup, consistent with the previous suggestion regarding low-speed accident causes. In the 21-40 mph and 41-60 mph ranges, Failure to Obey/Display Signals was the most frequent subgroup. In the 61-80 mph and 81-100 mph ranges, some equipment-related accident-cause subgroups, namely All Other Car Defects and Other Wheel Defects (Car) were the top causes. The three accidents in which speed was above 100 mph were in the following three subgroups: All Other Locomotive Defects, Centerplate/Carbody Defect (Car) and Misc. Human Factors. Summaries of these three accidents are as follows (in order of accident date):

1. April 12th, 2001. Amtrak train was side-swiped by an improperly secured locomotive door from a freight train on the adjacent track (accident type: raking collision; Amtrak train speed: 110 mph, no cars derailed; no casualties; accident-cause subgroup: All Other Locomotive Defects)

2. January 24th, 2004. Amtrak train was side-swiped by an improperly secured freight car door from a freight train on the adjacent track (accident type: raking collision; Amtrak train speed: 110 mph, no cars derailed, no casualties, accident-cause subgroup: Centerplate/Carbody Defect (Car))

3. May 12th, 2015. Amtrak train derailed while traveling at 102 mph in a curve with a 50 mph civil speed restriction, resulting in 1 locomotive and 7 passenger cars derailed; 229 casualties; accident-cause subgroup: Misc. Human Factors (NTSB, 2015c).

Table 3.8: Most frequent accident-cause subgroups of mainline passenger train derailments and collisions, 1996 – 2017, by accident speed ranges

	Ranking by Frequency	Accident Speed Range (mph)				
		0-20	21-40	41-60	61-80	>100
Top Accident Cause Subgroups	1	Turnout Defects - Switches	Failure to Obey/Display Signals	Failure to Obey/Display Signals	All Other Car Defects	Other Wheel Defects (Car) Misc. Human Factors
	2	Failure to Obey/Display Signals	Loco Trucks/Bearings/Wheels	Broken Rails or Welds	Joint Bar Defects	Track Geometry (excl. Wide Gauge) All Other Locomotive Defects
	3	Use of Switches	Wide Gauge	Wide Gauge	Broken Rails or Welds	Train Speed Centerplate/Carbody Defects (Car)
	4	Wide Gauge	Turnout Defects - Switches	Other Miscellaneous	Misc. Human Factors	Handbrake Operations
	5	Other Miscellaneous	Mainline Rules	Obstructions	Track Geometry (excl. Wide Gauge)	Infrastructure Damage Causes
Number of Accidents		182	57	47	26	7 3

3.5 Discussion

In this chapter, I analyzed passenger train accidents in the 22-year period from 1996 to 2017 and identified major accident types and causes. I also investigated the relationship between train speed and accident frequency, severity and accident causes. These findings provide understanding of factors affecting passenger train accident risk and a basis for further improvement in passenger train safety. Based on these results, several directions for future research are discussed.

3.5.1 Adjacent Track Accidents on Shared-Use Rail Corridors

With the development of high-speed rail, as well as continued improvement in the conventional passenger rail system in the United States, there will be more SRCs and

consequently more mixed passenger and freight train operations (Shih et al., 2015). In such an environment, the consequences of train derailments and collisions have important implications for passenger safety. Of particular interest are adjacent track accidents (Saat and Barkan, 2013). Adjacent track accidents, or ATAs, occur when a train derails and intrudes onto adjacent tracks, and then strikes or is struck by, trains on those tracks. With more trains operating on a corridor, the probability of train interactions also increases, meaning that if a train derails and intrudes onto an adjacent track, there is a greater chance that another train will be present or approaching on the adjacent track. Furthermore, higher passenger train speed on these SRCs means the potential consequences of an accident are also greater. Focusing on the risk of adjacent track accidents will help improve our understanding of this risk and lead to more effective risk reduction strategies.

ATAs are likely to increase in relative frequency in the coming decade due to the expected decline in frequency of PPAs as PTC is fully implemented. Most of the accident-cause groups occupying the upper-right quadrant in Figure 3.5 are PPAs whereas ATAs will not be substantially affected by PTC, leaving them as a relatively more important source of risk on SRCs, especially in multiple track territories.

3.5.2 Comparison of Passenger Train Derailment/Collision and Freight Train Derailments/Collisions

Another important aspect of SRC safety is more accurate estimation of train accident rate. Due to different train characteristics, infrastructure, rolling stock designs,

and operating practices, the train accident rates and predominant accident causes likely differ between passenger and freight rail systems. From the analysis presented in this paper some differences in general trends in accident rates were observed. Further study of the differences in passenger and freight train derailment and collision rates, as well as the distribution of accident causes will inform more effective risk management and mitigation strategies. This is particularly important for quantifying and managing the risk on SRCs. This can be achieved by combining the statistical findings from this study with previously developed freight train derailment and collision statistics.

3.5.3 Accident Precursors

As safety continues to improve in the railroad system, statistical analyses to reliably estimate risk will become more challenging due to the smaller empirical basis for analysis (Elvik and Roll, 2014). To address this, accident precursors must be considered. An “Accident Precursor” is defined by the National Aeronautics and Space Administration (NASA) as:

“an anomaly that signals the potential for more severe consequences that may occur in the future, due to causes that are discernible from its occurrence today (NASA, 2011).”

An example of an accident precursor in a railroad system is a locomotive engineer over-running a stop signal, but without any further consequence such as a collision or derailment. Train accidents are a subset of accident precursors, meaning that under

certain conditions, accident precursors will result in train accidents, but most will not. Analyzing accident precursors provides more data and consequently more robust predictive risk estimates. Studying accident precursors also allows researchers to identify preventive measures that can reduce risk at the precursor event level, and potentially further reduce the occurrence of train accidents. For example, if a preventive measure can effectively reduce the probability of an engineer passing a stop signal, it can also reduce the probability of a train accident caused by Failure to Obey/Display Signal. Positive Train Control is an example of a preventive measure that will prevent this type of precursor event, as well as accidents associated with this cause, and certain others as well. Accident precursor analysis has been implemented in the United Kingdom (Fowler et al., 2013) and in the United States. The Confidential Close Call Reporting System has been implemented by the FRA to collect close call (or “near miss”) data (FRA, 2017c). Analyses of data from such reporting systems are likely to reveal promising candidates for safety improvement.

3.5.4 Positive Train Control

My analysis indicates that PPA causes account for a large proportion of passenger train derailment and collision risk, in terms of both frequency and severity. These results suggest that reducing the number of accidents due to PPA cause subgroups will reduce the overall risk of passenger train derailments and collisions. Current railroad industry implementation of PTC is expected to substantially reduce the occurrence of many of these accidents (Zhang et al., 2018). PTC is a crucial element in SRC implementation because of its potential to reduce the risk of train accidents involving hazardous materials

or passengers. Consequently, further research on the specific types and circumstances of accidents that PTC is intended to prevent may enable further refinement of its capabilities and those circumstances where other approaches to improving train safety will be more effective.

3.5.5 Human Factor Analysis

Train Operation Human Factor was identified as the most frequent and severe passenger train accident-cause category. Consequently, addressing these causes will be critical to the success of further passenger train risk reduction efforts. In the previous subsection, several human-factor causes can be reduced or prevented by implementing PTC, including Failure to Obey/Display Signal and Train Speed Violation.

Certain human factor causes, while not the major source of risk that PTC is intended to prevent, are also important for railroad operational safety and thus require risk assessment. As discussed in the introduction to the FRA accident data reporting system, causal analyses presented in this analysis accounted for the direct accident causes for passenger train accidents. There are some underlying causes that indirectly contribute to the occurrence of these accidents. Examples include, but are not limited to, employee fatigue, maintenance error, excessive workload, and organizational safety management and safety culture. Although these factors do not directly lead to train accidents, they affect a wide range of railroad operations and therefore incur greater overall risk. These factors also are the root causes, or common causes, for those direct accident causes. Railroad human factor research encompasses a wide spectrum of topics including human

fatigue in train operation, ergonomics, and human performance in the train control system. Overall, there are important opportunities to reduce passenger train derailments and collision risk by addressing human factors.

3.5.6 Data Mining Applications in Railroad Safety Improvement

Expanded automated data collection systems, combined with rapid advances in data mining technology, mean that new methodologies are available for rail safety analyses. These include associated rules (Chen et al., 2017), STAMP (Ouyang et al. 2010), and Maximal Information Coefficient (Shao and Li, 2017). Data mining techniques can be implemented to increase risk model accuracy and to handle complex effects from multiple (and perhaps correlated) influencing factors.

3.6 Conclusions

In this chapter I presented the results of a study to identify the most important factors contributing to the risk of passenger train accidents. Derailments and collisions were identified as the most potentially significant train accident types, while human factor accidents and track failures were the primary causes of those accidents. Accident causes related to human factors and train operations such as train speed violations and failure to obey signals are often high-consequence accidents and therefore pose the greatest risk. Higher risk infrastructure-related factors include track geometry defects and broken rails or welds. PPAs also account for a large portion in terms of both frequency and severity. This analysis of train accident causes is important for rational allocation of resources to reduce accident occurrence and consequences and provides a foundation for

further improvement in passenger train safety. Passenger train accident rate developed in this chapter is used in assessing initial derailment probability in the comprehensive ATA risk model.

CHAPTER 4

INTRUSION PROBABILITY ANALYSIS

4.1 Introduction

When a train derails in multiple-track territory, there is a possibility that derailed equipment will intrude onto adjacent tracks. As depicted in the adjacent track accident (ATA) event tree (Figure 2.2), intrusion is one of the key events that may lead to subsequent collisions with other trains on adjacent tracks; therefore, it is important to address its probability while assessing ATA risk.

Intrusion risk was first formally identified in a study conducted by Booz Allen & Hamilton (1989) for the Washington Metropolitan Area Transit Authority. Since then Hadden et al. (1992) conducted a qualitative risk assessment of shared-use rail corridors (SRCs), including intrusion risk and evaluated the effectiveness of risk mitigation measures. Barkan (1990) used data from the National Transportation Safety Board (NTSB) to quantify the distribution of lateral distance traveled by derailed equipment in train accidents. English et al. (2007) extended this work by incorporating data from the FRA and the Canadian Transportation Safety Board, in addition to the NTSB data, to develop a more sophisticated understanding of the lateral and longitudinal displacements of derailed equipment under various conditions. Clark et al. (2013) further developed an analytical tool based on English et al.’s work to evaluate lateral distance traveled by derailed rail equipment and the effectiveness of prevention measures.

Cockle (2014) conducted a semi-quantitative risk analysis to address the risk of intrusions of conventional trains onto high-speed rail trackage. The assessment considered accident rates on conventional railroad tracks and various factors affecting the likelihood of intrusion. Cockle's model calculated the ratio of the derailment rate of a conventional track section adjacent to HSR track and the national average derailment rate, and multiplied that by estimated traffic volume. This provided a base value for Site-Specific Derailment Frequency (SSDF). A rating system was developed to evaluate the intrusion risk and effects of influencing factors. Factors that affect the probability of intrusion were identified and each factor was assigned a rating based on its effect on intrusion probability. These factors were assigned to one of three categories: causation factors, effect factors, and nullifying factors that conditionally negate the entire SSDF (Table 4.1). Finally, a risk index system, the Relative Hazard Frequency Assessment, was developed by multiplying SSDF and all ratings assigned from intrusion factors to evaluate and compare site-specific intrusion risk.

Table 4.1: Factors affecting SSDF (Cockle, 2014)

Category	Condition	Value
Causation Factors:		
Horizontal Alignment	Tangent	0
	Horizontal Curve	0.1
Vertical Alignment	Grade < 1%	0
	Vertical Curve or Grade ≥ 1%	0.1
Type of Movement	Through Movement, No Stops	0
	Speed Change or Routine Stopping Point	0.1
	Yard or Industrial Switching	0.3
Special Track Work	None	0
	Single	0.1
	Multiple	0.2
Movement Authorization	Timetable or Special Instruction Only	0
	Block Signal System	-0.1
	Positive Train Control	-0.5
Access to Right-of-Way (ROW)	Open, No Controls	0
	Access-Control Barrier	-0.1
Highway-Rail Grade Crossing	None	0
	Private	-0.1
	Public	-0.3
Train Defect Detectors	None	0
	Standard Train Defect Detector within Five Miles	-0.1
	Wheel Impact Load Detector within 50 Miles	-0.2
Effect Factors:		
Horizontal Alignment	Tangent	0
	High-Speed Rail Track on Inside of Curve	-0.2
	High-Speed Rail Track on Outside of Curve	0.2
Speed	Less Than 20 mph	0
	Between 21 and 40 mph	0.1
	Greater Than 40 mph	0.2
Horizontal Distance	Greater Than 102 Feet	0
	102 Feet to 86 Feet	0.1
	85 Feet to 59 Feet	0.3
	Less Than 59 Feet	0.6
Elevation	At-Grade	0
	Elevated Greater Than Ten Feet	0.4
	Below-Grade Greater Than Ten Feet	-0.4
Adjacent Structure	None	0
	Deflects Derailment Toward High-Speed Rail Track	0.1
	Mitigates Derailment Per TM 2.1.7 Criteria	-0.7
Overhead Structure	None, or Protected	0
	Unprotected Overhead Structure	0.2
Nullifying Factors:		
Horizontal Distance	125 Feet or Greater	0
	Less Than 125 Feet	1
Horizontal and Vertical Separation	Horizontal Separation > 25 Feet and Vertical Separation > 10 Feet	0
	Other Than Above	1

The aforementioned studies established a foundation for addressing intrusion risk by qualitatively identifying the risk and potential mitigation measures and conducting preliminary quantitative intrusion probability analysis; however, there is still a gap between current research in intrusion risk and a comprehensive risk assessment model for ATAs. Specifically, development of a general intrusion probability model that can be used for all types of railroad systems and incorporating the intrusion probability model into a comprehensive ATA risk assessment model has not been addressed. Cockle's model is a useful attempt to develop an ATA risk assessment model that takes into account both the initial derailment rate and intrusion probability, but it does not account for the probability of train presence on adjacent tracks. His model focuses on interactions between trains operating on conventional rail lines and high-speed trains on adjacent trackage and assumes that once an intrusion occurs, a collision between a conventional train and a high-speed train on adjacent tracks is inevitable and will result in unacceptable consequences. Cockle's model focuses on identifying factors affecting intrusion probability but does not delve into factors affecting the initial derailment rate.

In this chapter, I identify the critical factors that affect intrusion probabilities and how can they be incorporated in the comprehensive ATA risk assessment mode. I also identify factors that affect initial derailment rates, probabilities of train presence, and consequences of ATAs. These factors are different from the basic events identified in the fault tree analysis in chapter 2, because those are the elements contributing to the occurrence of an ATA, while the affecting factors identified in this chapter do not lead directly to an ATA, but instead affect its likelihood. The affecting factors identified in

this chapter are used to develop the comprehensive ATA probability assessment presented in chapter 6. In addition, I present a semi-quantitative ATA risk assessment model that considers key factors affecting the probability and consequence of an ATA. I develop a risk index system similar to Cockle's model but consider several additional factors that affect all three probability components in an ATA enabling comparison of ATA risk among different track segments in any type of railroad system. I also discuss the data needed to conduct a fully quantitative risk analysis. This semi-quantitative risk model serves two purposes: 1) it is an interim step towards a comprehensive ATA risk assessment model, as the intrusion probability derived in this chapter is a key probability component in that model and 2) it can also serve as a standalone screening-level ATA risk assessment tool to provide high-level risk evaluation to identify locations, track segments, or portions of railroad corridors that require more detailed, quantitative risk analysis. The factors affecting intrusion probability that are not quantified here will be incorporated in qualitative form in chapter 6.

4.2 Semi-Quantitative Risk Analysis

4.2.1 Introduction

Semi-quantitative risk assessment is a technique that uses numerical values to describe and evaluate relative risk (Gadd et al., 2003). These numerical values may be order-of-magnitude risk estimates, some ordinal risk metric, or risk indices. Although these values do not reflect the actual probability and/or consequences of hazards, they can provide information regarding the relative scale of risk. Semi-quantitative risk analysis is useful in relative risk comparison, especially when a full quantitative risk analysis is

infeasible due to insufficient data to support a fully quantitative risk calculation. It is also used to identify factors contributing most to risk in a system, the portion of a system with the highest hazards, and can help managers determine whether quantitative risk assessment is needed and in what elements of the system.

Semi-quantitative risk assessment has been implemented in various fields of scientific study including veterinary (Delahay et al., 2007), food hygiene (Ross and Sumner, 2002; Sumner and Ross, 2002), occupational safety (Jacinto and Silva, 2010), supply chain network (Moonis et al., 2010) and transportation safety (Reniers et al. 2010). In railroad applications, besides Cockle's model, semi-quantitative risk assessment has been used to address railroad human factors on European railroads (Bepperling, 2008). I am unaware of any previous research focused on semi-quantitative risk assessment of ATAs.

4.2.2 Risk Model

A common definition of risk is the product of the probability of an event and the consequence of that event. It is commonly expressed as follows:

$$R = P \times C \quad (4.1)$$

where:

R: Risk

P: Probability

C: Consequence

The probability, P, is divided into three components corresponding to the three major events described in the ATA event tree. The semi-quantitative ATA risk model is thus defined using a risk index system as follows:

$$R = P(D) \times P(I|D) \times P(T|I|D) \times C \quad (4.2)$$

where:

R: The risk index for an ATA

P(D): The probability of an initial derailment on a multiple track section

P(I|D): The conditional probability of intrusion (CPI) given an initial derailment

P(T|I|D): The conditional probability of the presence of a train on an adjacent track given an intrusion

C: The consequence of an ATA

The risk index system consists of probability and consequence components. Each model component has five levels with corresponding values from one (lowest) to five (highest). To obtain the level for each component, various infrastructure, rolling stock, train operating characteristics, and any other relevant factors are considered. Selection of these characteristics and factors is based on previous studies and expert judgment. Each relevant characteristic or factor contributes “scores” to the level of specific model component(s), and based on the total score, levels of model component are determined. Using these levels, an ATA risk index is assigned (Figure 4.1). A railroad corridor being analyzed is divided into multiple segments and risk indices for each segment are calculated using equation 4.2. In the following subsections, I introduce and discuss each factor affecting the model’s components.

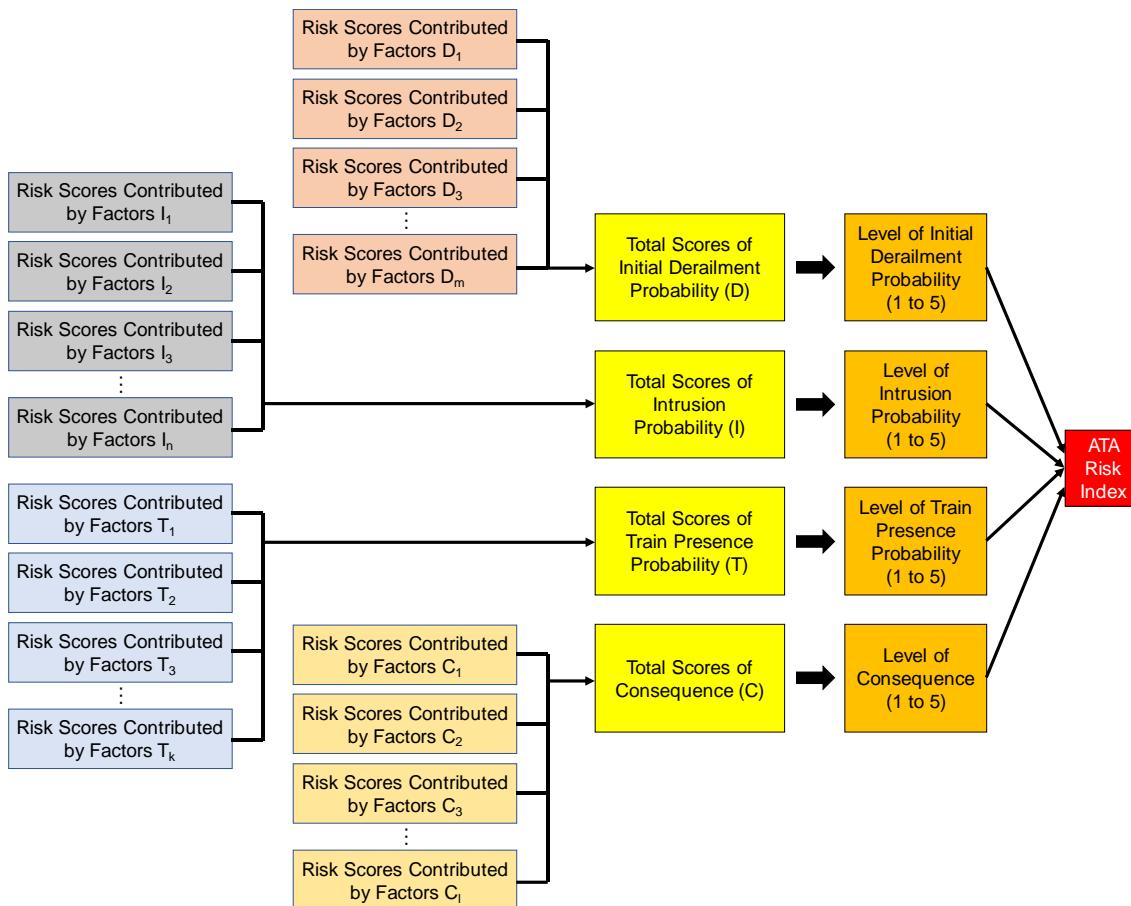


Figure 4.1: Risk score, risk level, and ATA risk index

4.2.3 Probability of Initial Derailment, $P(D)$, and Accident Factors

The probability of an initial derailment can be estimated by analyzing historical train accident data. The United States Department of Transportation (USDOT) Federal Railroad Administration (FRA) Rail Equipment Accident/Incident (REA) database contains train accident data as well as annual railroad traffic volume data in the US (FRA, 2011). Five factors affecting the probability of initial derailment are identified and discussed below: method of operation, track quality, traffic density, type of equipment, and rolling stock defect detection technology.

4.2.3.1 Method of Operation

In the context of this research, method of operation indicates the presence or absence of a wayside signal or automatic train control system. Previous research found that accident rate on signaled track segments is lower than non-signaled track segments (Liu et al., 2017; Wang et al., 2019). In this study, track segments are classified as either signaled or non-signaled based on the results from these studies.

4.2.3.2 Track Quality

The FRA classifies railroad track into nine classes based on maximum authorized speed and maintenance standards. Previous research has found an inverse relationship between FRA track class and train derailment rate (Nayak et al., 1983; Anderson and Barkan 2004; Liu et al., 2017). In this research, track classes are categorized into five groups based on their differences in train derailment rate (Liu et al., 2017; Wang et al., 2019). Track classes 6 and higher are grouped together because they are primarily used for passenger train operation. I am unaware of any quantitative analyses of derailment rates for FRA track classes higher than 5 but based on the research cited above, we presume that they are at least as low, and probably lower, than class 5.

4.2.3.3 Traffic Density

Traffic density is measured in annual millions of gross tons (MGTs). It includes the total weight of all locomotives, rolling stock, and lading operating on a particular segment of track. Higher traffic densities are correlated with lower derailment rates (Liu et al., 2017; Wang et al., 2019). The exact mechanism for this is not known but it may

result from more frequent inspection, maintenance, and frequency of wayside defect detection systems on high density rail lines. Dedicated passenger lines also have lower derailment rates due to higher track maintenance standards and inspection frequency. In addition, lighter axle loads of passenger equipment inflicts relatively less damage to the track structure, reducing the potential for accidents due to track defects. Thus, it is assumed that, *ceteris paribus*, dedicated passenger lines have lower derailment rates than freight only or mixed freight and passenger traffic lines.

4.2.3.4 Type of Equipment

Failures of wheels, axles, and other rolling stock components can cause derailments. Different component designs may have different failure rates; however, there is little quantitative data on how these may affect derailment rates. In this study, I assume that passenger railroad equipment has higher reliability than freight rail equipment due to the more frequent and detailed equipment inspection and maintenance. Future research is needed to better understand the effect of type of equipment on train derailment rate.

4.2.3.5 Defect Detectors and Track Inspections

Wayside defect detection technology is used to identify incipient flaws in various rolling stock components before they fail, thereby reducing the likelihood of a derailment. For example, Wheel Impact Load Detectors are used to identify wheel defects that can lead to a mechanical failure (Johansson and Nielsen, 2003; Stratman et al., 2007; Hajibabai et al., 2012; Van Dyk et al., 2013). Similarly, various types of track inspections

and technologies are used to identify defects before they result in a failure such as a broken rail, thereby reducing the likelihood of infrastructure-related derailments (Dick et al., 2003; Barkan et al., 2003; Liu et al. 2012; 2013a; b; c; 2014). Although it is well accepted that these technologies and practices are effective at reducing derailment likelihood, the quantitative relationship between the use of a particular technology and its preventive effect has not been measured. Thus, future research is needed to better understand and quantify the effect of wayside defect detectors and track inspections on derailment rate reduction. In this study, I assume that track segments with defect detectors have lower derailment rates than track segments without defect detectors.

I assign an Accident Factor Score (AFS) to each factor affecting derailment probability (Table 4.2). The AFS ranges from 1 to 2 for each factor where the base value is 1. The higher the AFS, the greater the increase in initial derailment probability. For a given track segment, the AFS values are summed, and based on the total AFS, a level of initial derailment probability is assigned (Table 4.3). The effects of different factors on the initial derailment probability may vary. For instance, the effect of FRA track class may be different from the effect of traffic density.

Table 4.2: Summary of factors affecting the initial derailment probability and AFS

Accident Factor	Criteria Level	AFS
	6 or above	1.00
FRA	5	1.25
Track	4	1.50
Class	2, 3	1.75
	X, 1	2.00
<i>Freight-Train only or Freight and Passenger Shared Lines:</i>		
Traffic Density	More than 60 MGT 40 - 60 MGT 20 - 40 MGT Less than 20 MGT	1.00 1.33 1.67 2.00
<i>Passenger-Train only Lines:</i>		
Method of Operation	Dedicated Passenger Line Signaled Non-Signaled	1.00 1.00 2.00
Type of Equipment	80% or More Passenger Train Traffic Mixed Traffic	1.00 1.50
	80% or More Freight Train Traffic	2.00
Defect Detectors	Present Absent	1.00 2.00
The highest AFS possible		10.00
The lowest AFS possible		5.00

Table 4.3: Total AFS and level of initial derailment probability

Total AFS	Level of P(D)
AFS \leq 6	1
6 < AFS \leq 7	2
7 < AFS \leq 8	3
8 < AFS \leq 9	4
AFS > 9	5

The effects on probability from different levels of the same factor may also vary.

Taking FRA track class as an example, the change in effect on train derailment

probability between class 4 track and class 5 track is likely to differ from the change of

effect on train derailment probability between class 5 track and class 6 track. Some of these relationships are addressed by quantitative analyses, while others are not fully understood. In this research, I used a linear approach for affecting factors in which each has an equal effect on the initial derailment probability, and each level within a factor also has an equal impact on initial derailment probability. For the purpose of consistency and simplicity, there are some underlying assumptions for the AFS: the effect of each factor is weighted equally, the AFS for each factor is equally divided by the number of categories for the factor, and the total AFS is equally divided into 5 levels.

4.2.4 Conditional Probability of Intrusion, $P(I|D)$, and Intrusion Factors

Several factors affect intrusion probability including distance between track centers, track alignment and geometry, elevation differential, adjacent structures, containment, train speed, and point of derailment. In order to account for these factors in the model, an Intrusion Factor Score (IFS) is assigned to each factor for a track segment similar to AFS. The effects of each factor are discussed in the following sections.

4.2.4.1 Distance between Track Centers

Research by English et al. (2007) found an inverse relationship between the distance between track centers and probability of intrusion. The authors developed the distribution of maximum lateral distance traveled by derailed rolling stock (Figure 4.2) and found a gamma distribution was the best fit for the data. The parameters for the fitted gamma distribution were later updated by Clark et al. (2013) and these are used in the comprehensive ATA probability assessment model presented in chapter 6. In the model

described in this chapter, IFS for distance between track centers is assigned based on the 25th, 50th, 60th and 80th percentile from the probability distribution of lateral displacement from English et al.'s research.

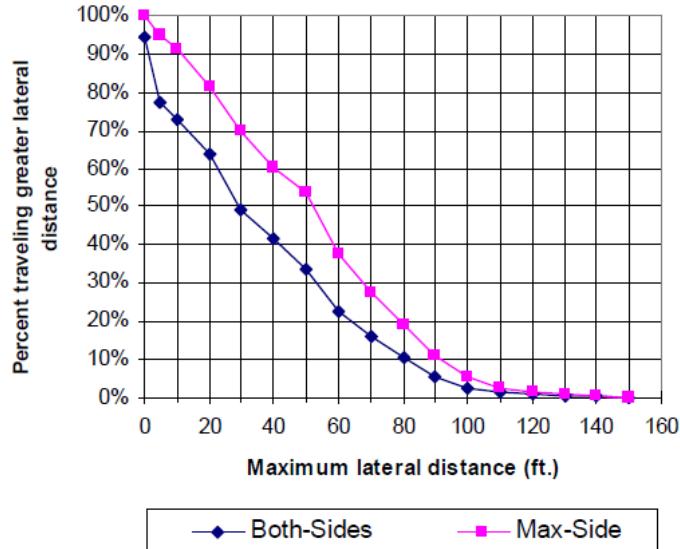


Figure 4.2: Maximum lateral travel distribution (English et al., 2007)

4.2.4.2 Track Alignment and Geometry

Track alignment and geometry indicates whether a track segment is tangent, curved, level, or on a grade. A level, tangent track segment is considered the base case scenario. If a derailment occurs on a curved track segment, additional lateral forces may increase the intrusion probability. A derailment on a grade affects longitudinal forces that indirectly affect intrusion probability. These longitudinal, in-train forces do not directly cause lateral movement of equipment; however, they may affect the extent that derailed rolling stock collides with other equipment in the train. These impacts may cause equipment to be moved laterally or rotate causing an intrusion on an adjacent track.

When these two factors occur together I assumed that, *ceteris paribus*, these track sections will have higher intrusion probability than curved-only or gradient-only sections.

4.2.4.3 Elevation Differential between Adjacent Tracks

If there is an elevation difference between two adjacent tracks, derailments occurring on either track may have different intrusion rates. Specifically, derailments on the high track are more likely to intrude onto the lower track due to derailed equipment falling down the embankment (Figure 4.3a). Conversely, derailed equipment on the lower track is less likely to intrude onto the higher adjacent track because of the constraining effects of gravity and the embankment (Figure 4.3b).

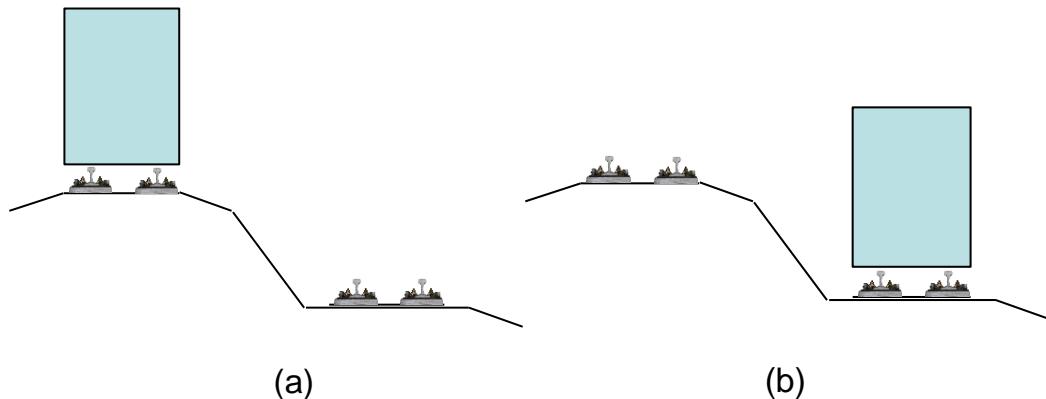


Figure 4.3: Effect of elevation differential on intrusion probability

4.2.4.4 Adjacent Structures

Adjacent structures along a railroad line may have a "rebound" effect (Figure 4.4) that alters the direction of travel of derailed equipment. If a structure is close enough to the railroad tracks and strong enough to redirect the movement of derailed equipment

from “away from adjacent tracks” to “toward adjacent tracks”, then its presence could affect intrusion probability. Adjacent structures, depending on their shape and density, are classified into three types: single, discrete, and continuous structures. A single structure is an independent, self-supported structure such as a bridge abutment or a pier. Discontinuous structures could be multiple buildings located close to each other along a track segment, such as a group of grain elevators or silos. Examples of a continuous structure are noise barriers located alongside the track or residential buildings along the track in an urban area.

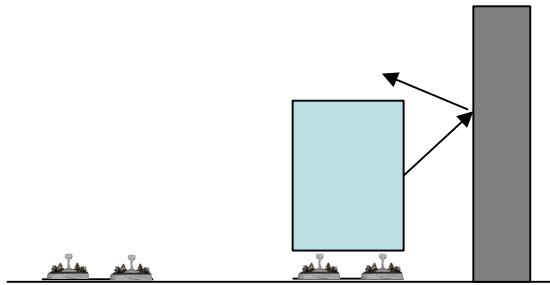


Figure 4.4: Effect of adjacent structure on intrusion probability

4.2.4.5 Containment

Containment refers to structures that prevent derailed equipment from intruding onto adjacent tracks. Containment may also reduce the consequences by absorbing energy from derailed equipment (further discussed in the Consequence section of this chapter). Two types of containment are currently used in HSR systems in Europe and Asia: parapets and physical barriers (Hadden et al., 1992; Moyer et al., 1994; Ullman and Bing, 1995; Rulens, 2008). Parapets are reinforced railings or structures mounted adjacent to the track to keep the derailed trucks (bogies) of equipment in line and prevent

it from intruding onto adjacent tracks (Figure 4.5). Physical barriers can be earth berms or concrete walls (Figure 4.6) installed between adjacent tracks to absorb the impact forces of derailed equipment and prevent it from intruding onto adjacent tracks.

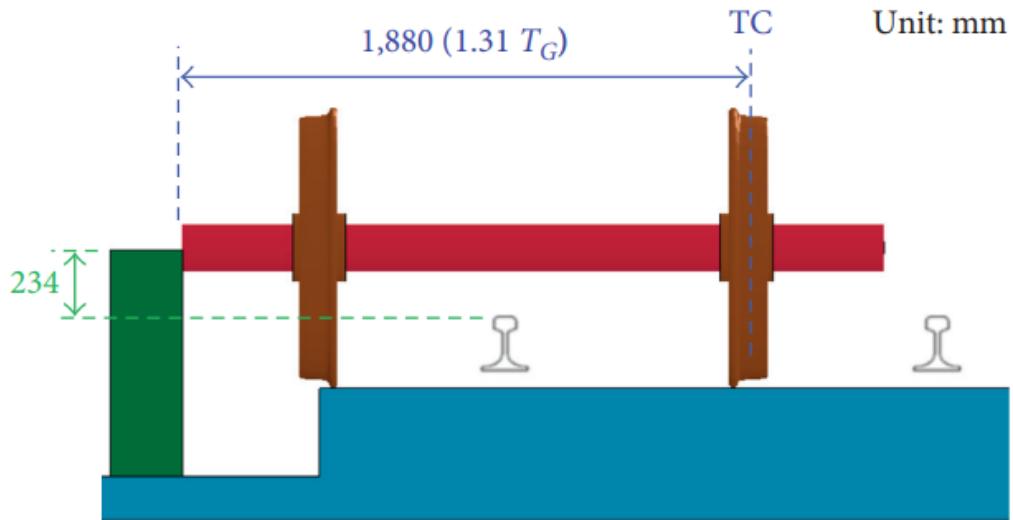


Figure 4.5: Parapet contains the wheel set of derailed equipment and prevents the equipment from intruding onto an adjacent track (Bae et al., 2018a)

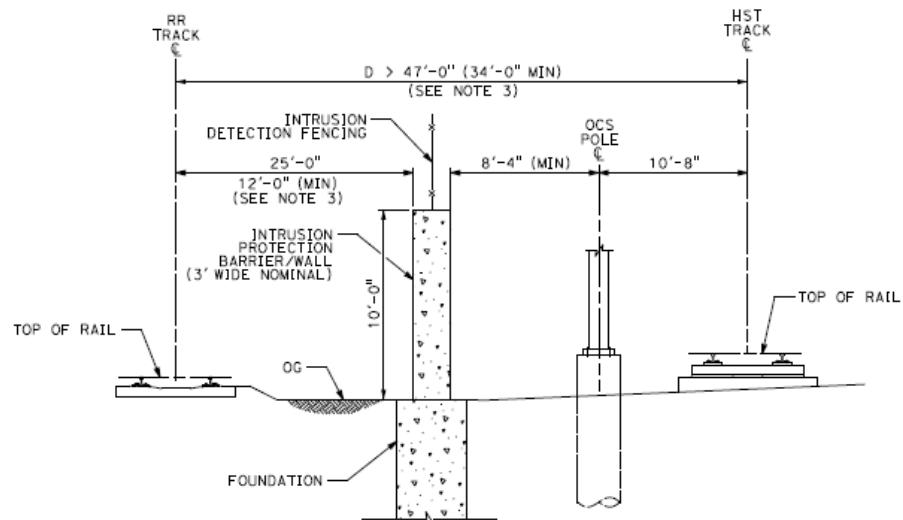


Figure 4.6: Drawing of a physical barrier between a high-speed rail train and a freight train (Rulens, 2008)

4.2.4.6 Train Speed

Train speed may affect intrusion probability because the higher the speed, the more energy involved when a train derails, resulting in more opportunity for the derailed equipment to move farther and foul adjacent tracks. Train speed on a track segment is assigned high, medium, or low, based on the average speed for the segment. The average train speed is affected by various factors such as type of traffic (bulk freight, inter-modal, passenger, etc.), traffic heterogeneity, track alignment, track class, and method of operation. Two speeds were selected for categorization: 23 mph for the average speed of freight trains on major railroads in the US, and 79 mph which is the maximum authorized speed of passenger trains on most US passenger and freight shared rail corridors. These speeds were selected to represent typical North American railroad operating conditions.

4.2.4.7 Point of Derailment

Point of derailment (POD) has been used to refer to the position of the first vehicle derailed in a train (Anderson, 2005; Liu et al., 2013a). This position may affect intrusion probability due to reaction forces at the coupler. Also, because the first and last vehicle are only coupled at one end, they are less restrained with regard to lateral movement and might have more chance to rotate and foul adjacent tracks in a derailment. Vehicles elsewhere in the train consist are coupled at both ends, providing greater restraining force. The most common situation is when a single vehicle in a train derails and causes other vehicles to derail, resulting in a larger derailment and intrusion. Due to this level of uncertainty, the effect of POD is not known and will require further research to better understand the effect of this mechanism. Compared with other intrusion factors,

POD is a post-accident factor rather than a pre-accident factor. That is, we would not know which car in the train consist will derail before the derailment occurs. As such, it is difficult to pre-assign scores to this factor in the model.

Similar to AFS, IFS is assigned for each intrusion factor. The higher the IFS, the greater the increase in intrusion probability. Each factor has an IFS ranging from 1 to 2 where the base value is 1. For a track segment, the IFS values from all intrusion factors are summed. Based on the total IFS, a level of intrusion probability (from 1 to 5) is assigned. The intrusion probability has the same assumption as the probability of initial derailment. Table 4.4 summarizes intrusion factors except POD and associated IFS and the relationship between total IFS and corresponding levels of $P(I|D)$ (Table 4.5).

Table 4.4: Summary of intrusion factors and IFS

Intrusion Factor	Criteria (Level)	IFS
Distance Between Track Centers, X, in feet (meters)	X > 80 (24.4)	1.00
	55 (16.7) < X ≤ 80 (24.4)	1.25
	30 (9.1) < X ≤ 55 (16.7)	1.50
	15 (4.5) < X ≤ 30 (9.1)	1.75
	X ≤ 15 (4.5)	2.00
Track Alignment	Tangent and level	1.00
	Tangent and on gradient when traveling upward	1.13
	Tangent and on gradient when traveling downward	1.25
	Curved on outside track and level	1.38
	Curved on inside track and level	1.50
Elevation Differential	Curved on inside track and on gradient when traveling upward	1.63
	Curved on outside track and on gradient when traveling upward	1.75
	Curved on outside track and on gradient when traveling downward	1.88
	Curved on inside track and on gradient when traveling downward	2.00
	The track where a train derail is 10 ft. lower than adjacent track	1.00
Adjacent Structure	The track where a train derail is level with adjacent track	1.50
	The track where a train derail is 10 ft. higher than adjacent track	2.00
	No adjacent structure	1.00
	Single structure	1.33
Containment	Discrete structure	1.67
	Continuous structure	2.00
	Both containments installed	1.00
	Physical barrier installed only	1.33
Train Speed	Parapet installed only	1.67
	No containment installed	2.00
	Low (less than 23 mph)	1.00
	Medium (24 mph to 79 mph)	1.50
	High (more than 79 mph)	2.00
	The highest IFS possible	12.00
	The lowest IFS possible	6.00

Table 4.5: Total IFS and level of intrusion probability

Total IFS	Level of $P(I D)$
$IFS \leq 7.2$	1
$7.2 < IFS \leq 8.4$	2
$8.4 < IFS \leq 9.6$	3
$9.6 < IFS \leq 10.8$	4
$IFS > 10.8$	5

4.2.5 Conditional Probability of Presence of Trains on Adjacent Tracks, $P(T|I|D)$, and Train Presence Factors

The third probability component of the ATA risk model is the presence of trains on adjacent tracks given an intrusion. There are two variants for the presence of a train. One is that when an intrusion occurs, there is a train adjacent to the derailing equipment, and the other is that the train on the adjacent track is approaching the intrusion location. Factors affecting this probability include intrusion detection systems, traffic density, method of operation, and train speed.

4.2.5.1 Intrusion Detection and Warning System

An intrusion detection and warning (IDW) system detects intruding rail equipment when it derails and breaks the fences installed with detectors between tracks (Hadden et al., 1992; Ullman and Bing, 1995; Saat and Barkan, 2013). If trains on adjacent tracks are a sufficient distance away from the intrusion location, the IDW system will allow them to stop before reaching it. If not, they may be able to slow down if not completely stop thereby reducing the consequence of a collision if it occurs.

4.2.5.2 Traffic Density

The higher the traffic density, the more likely it is that there will be a train at or near an intrusion location. The traffic density for dedicated passenger lines is assigned the highest level, while on a mixed-traffic corridor, the traffic density of a track segment is measured using freight gross tonnage. This is because on a railroad corridor with only passenger trains, these trains are likely to have similar operating patterns such as station stops and speed profiles; therefore, the capacity of the corridor increases, and more trains can be accommodated. On the other hand, a railroad with mixed traffic encounters differing schedules and patterns between passenger and freight trains, meaning that the traffic heterogeneity is high, resulting in more train conflicts and consequent delay and reduction in traffic density (Dingler et al., 2009; Shih et al., 2015; Sogin et al., 2016).

4.2.5.3 Method of Operation

Train control systems have differing levels of precision in determining train location. They also vary in their ability to communicate the information between engineers (train drivers) and dispatchers. For example, a conventional track circuit system identifies a train's location by "signal block" but does not provide the exact position of the train, whereas more advanced train control systems are capable of identifying the trains' location more precisely. Such systems include the European Rail Traffic Management System in European countries and Advanced Train Administration & Communications System in Japan. These advanced train control systems communicate information between dispatchers and engineers more efficiently than traditional communication methods. IDW can also be integrated with advanced train control systems

so that the intrusion warnings can be more efficiently delivered to other trains in their proximity (Hadden et al., 1992; Ullman and Bing, 1995).

In the model described in this chapter, train control systems are divided into three categories: advanced train control systems, conventional train control systems that detect train presence using track circuits, and non-signaled (dark) territory in which there is no automatic means of detecting train presence.

4.2.5.4 Train Speed

If train speed is high enough, a train approaching an intrusion location may not be able to stop before striking the derailed equipment fouling the track. Train speed for a track segment is assigned high, medium, or low based on the average train speed of the adjacent track.

Based on engineering judgment, a Train Presence Score (TPS) is developed for each factor (Table 4.6). Similar to the initial derailment probability and intrusion probability, each train presence factor has a TPS ranging from 1 to 2 where the base value is 1. The total TPS for a specific track segment is calculated by summing the TPS from all train presence factors. Total TPS is then converted to levels of train presence (Table 4.7). The higher the level, the more likely the probability. Although not all the combinations are considered, the selected factors are assumed to be representative of most circumstances. TPS probability holds the same assumption as AFS and IFS.

Table 4.6: Train presence factors and TPS

Train Presence Factors	Criteria (Level)	TPS
IDW	Presence	1.00
	Absence	2.00
<i>Freight or Freight and Passenger Shared Lines:</i>		
	Less than 20 MGT	1.00
	20 - 40 MGT	1.33
Traffic Density	40 - 60 MGT	1.67
	More than 60 MGT	2.00
<i>Passenger Lines:</i>		
	Dedicated Passenger Line	2.00
Method of Operation	Advanced train control	1.00
	Typical train control system	1.50
	Dark territory	2.00
Average Train Speed	Low (less than 50 mph)	1.00
	Medium (50 mph to 79 mph)	1.50
	High (more than 79 mph)	2.00
The highest TPS possible		8.00
The lowest TPS possible		4.00

Table 4.7: Total TPS and level of train presence probability

Total TPS	Level of P(T I D)
$TPS \leq 4.8$	1
$4.8 < TPS \leq 5.6$	2
$5.6 < TPS \leq 6.4$	3
$6.4 < TPS \leq 7.2$	4
$TPS > 7.2$	5

4.2.6 Consequence and Consequence Factors

Consequence is the impact from an ATA. The major concern is the consequence resulting from a collision between derailed equipment and trains on adjacent tracks. Previous research showed that the average casualties for passenger train collisions is greater than passenger train derailments (Lin et al., 2013). The consequences of ATAs include multiple types of impacts as follows:

- Casualties (injuries and fatalities)
- Equipment damage
- Infrastructure damage
- Non-railroad property damage
- System disturbance and delay
- Environmental impact
- Economic loss

I discuss the factors affecting the severity of ATA accidents - speed of train, equipment damage resistance, containment, and product being transported - in the following subsections.

4.2.6.1 Equipment Damage Resistance

Equipment damage resistance is a key factor for reducing on-board casualties from the derailment and/or collision impact. Carolan et al. (2011) conducted crashworthiness analyses for higher-speed passenger trains to understand how equipment with crash energy management (CEM) design can withstand greater collision impact force and result in less structural damage and fewer passenger casualties. Rolling stock is classified into two categories: CEM-designed equipment and conventional equipment. CEM-designed equipment refers to passenger cars that meet the FRA Tier I or higher crashworthiness regulations. Conventional equipment refers to cars that do not meet the CEM-designed standards.

4.2.6.2 Train Speed

With higher train speed, there will be more energy when a derailment or collision occurs. Research has shown that higher derailment speed is correlated with a greater number of cars derailing (Barkan et al., 2003; Liu et al. 2011); therefore, more severe consequences are expected if the train speed is higher.

4.2.6.3 Containment

The presence of containment reduces the probability of intrusion and also the consequences by absorbing the impact forces from derailed equipment (Hadden et al., 1992; Moyer et al., 1994; Ullman and Bing, 1995).

4.2.6.4 Product Being Transported (Freight Train Only)

If a collision involves freight trains carrying hazardous materials, it may cause a release resulting in more severe consequences.

A Consequence Factor Score (CFS) is assigned to each consequence factor (Table 4.8). The total CFS is calculated by summing the CFS from individual consequence factors together. The total CFS is then related to the level of consequences (Table 4.9).

Table 4.8: Consequence factors and CFS

Consequence Factor	Criteria (Level)	CFS
Equipment Strength	CEM-designed equipment	1.00
	Traditional equipment	2.00
Speed	Low (less than 40 mph)	1.00
	Medium (40 mph to 70 mph)	1.50
	High (more than 70 mph)	2.00
Containment	Containment Present	1.00
	No Containment	2.00
Product being transported	No Hazardous material	1.00
	Hazardous material	2.00
The highest CFS possible		8.00
The lowest CFS possible		4.00

Table 4.9: Total CFS and level of consequence

Total CFS	Level of Consequence
$CFS \leq 4$	1
$4 < CFS \leq 5$	2
$5 < CFS \leq 6$	3
$6 < CFS \leq 7$	4
$CFS > 7$	5

4.2.7 Overall Probability

Levels of probability for initial derailment, intrusion, and train presence can be multiplied together to obtain the overall probability P using equation 4.2. Based on the values of P, a level of overall probability is assigned (Table 4.10).

Table 4.10: Overall probability level definitions

Multiplication of $P(D)$, $P(I D)$, and $P(T I)$	Overall Probability Level, P
$1 < P \leq 10$	1
$10 < P \leq 20$	2
$20 < P \leq 30$	3
$30 < P \leq 50$	4
$P > 50$	5

After obtaining the overall probability level, using equation 4.1, an ATA risk index, R , is obtained by multiplying the overall probability level, P , and the consequence level, C . Note that the risk index is not a quantitative measure of ATA risk. Instead, it indicates the relative risk of a track segment compared to other track segments.

4.2.8 Model Application

The proposed semi-quantitative model enables evaluation and comparison of ATA risk on different track segments. A track segment is defined as a portion of a railroad corridor including tracks, infrastructure, structures, and signals. A railroad corridor is divided into multiple track segments. Segment length varies depending on site characteristics and the desired resolution of the analysis. Using the semi-quantitative risk model, the ATA risk index is calculated for each track segment based on its infrastructure, rolling stock, and operational characteristics.

Evaluation of ATA risk index is based on the number of track pairs. For example, if there are two tracks, A and B, adjacent to each other on a segment (Figure 4.7a), the ATA risk index for the segment is:

$$R_{AB} + R_{BA} \quad (4.3)$$

where:

R_{AB} : the risk of having an ATA where a train on track A derails and intrudes onto track B and strike or is struck by another train on track B

R_{BA} : the risk of having an ATA where a train on track B derails and intrudes onto track A and strike or is struck by another train on track A

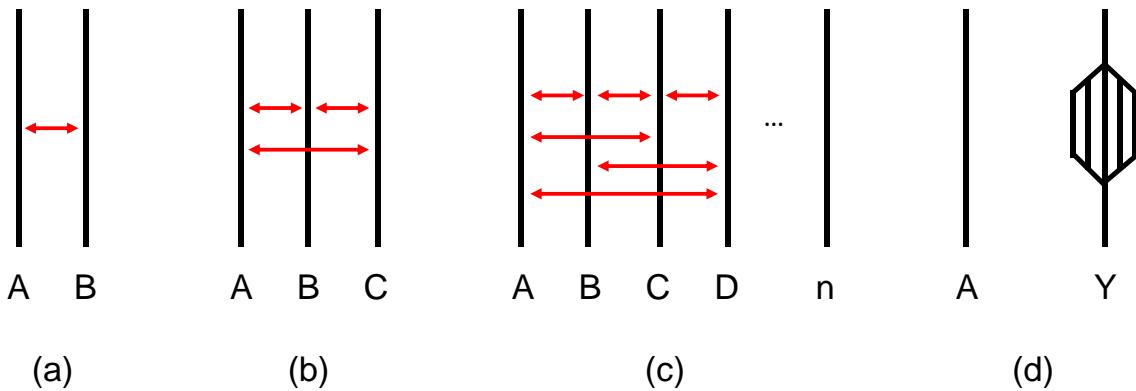


Figure 4.7: ATA risk relevance among different adjacent tracks

One of the complexities of evaluating ATA risk index is multiple risks being calculated on one track segment. If three tracks are adjacent to each other in a segment (Figure 4.7b), the ATA risk is calculated for each pair of tracks, and the risk index for this track segment is the sum of the risk indices from each pair of tracks:

$$R_{AB} + R_{BA} + R_{AC} + R_{CA} + R_{BC} + R_{CB} \quad (4.4)$$

If there are n tracks adjacent to each other in a segment (Figure 4.7c), the ATA risk index for this segment is evaluated as follows:

$$\sum_i^n \sum_j^n (R_{ij} + R_{ji}) \quad (4.5)$$

where:

$$i < j \quad \forall i, j$$

The aforementioned calculations consider train interactions on adjacent main tracks. If there is a railroad yard or terminal in the track segment (Figure 4.7d), the ATA

risk between mainline tracks and tracks in a railroad yard or terminal is evaluated separately. Since there are usually multiple tracks in a yard, numerous calculations need to be done when a train passes by. Accident rates on yard and terminal tracks are higher than on mainline tracks (Anderson and Barkan, 2004). In a busy yard or terminal there are many switching operations and thus trains going back and forth in the yard, which increases the train presence rate. Most of the train operations in yards and terminals are at low speed, which results in lower intrusion rate and consequence. For simplicity, the yard or terminal track that is the closest to the mainline represents the whole yard or terminal and the ATA risk index between a mainline and a yard or terminal is:

$$R_{AY} + R_{YA} \quad (4.6)$$

where:

R_{AY} : the risk of having an ATA where a train on track A derails and intrudes onto the closest yard track and strike or is struck by another train on the yard track

R_{YA} : the risk of having an ATA where a train on the yard track closest to track A derails and intrudes onto track A and strike or is struck by another train on track A

The total ATA risk index on the railroad corridor is the summation of risk indices on all segments, which can be written as:

$$\sum_{m=1}^p (\sum_{mi}^n \sum_{mj}^n R_{ij} + R_{ji}) \quad (4.7)$$

where:

n: total number of tracks in a segment

i, j: tracks in the segment m

$i < j$ $\forall i, j$

m: track segment

p: total number of track segments in the railroad corridor

4.3 Model Limitations and Future Opportunities

There are some limitations in the proposed semi-quantitative risk assessment model. First, the effects of each factor on the probability or the consequence of an ATA are weighted equally, but this assumption will generally not be the case. For example, distance between track centers may have more effect on the intrusion probability than other intrusion factors such as elevation differential and adjacent structure. Second, I assume a linear relationship between the change of a factor and its corresponding effect on the probability or the consequence of an ATA. This assumption will also not actually be the case. For instance, changes in the distance between track centers and the corresponding changes in intrusion probability may not result in a linear relationship. Addressing the differences in the influence of each factor on P(D), P(I|D), P(T|I|D), and C requires quantitative data analyses, but at present, insufficient data are available to quantify these relationships; hence the use of a semi-quantitative approach. Development of quantitative answers to these questions should be the subject of future research.

Another limitation of the model is that identification of factors and categorization of levels of probability and consequence rely on engineering judgment. This is because there has not been a general model to encompass all risk components (P(D), P(I|D), P(T|I|D), and C) and factors affecting these risk components. A contribution of this

research developing a semi-quantitative risk assessment model is identification of factors affecting all ATA risk components.

Despite the aforementioned model limitations, the proposed semi-quantitative risk assessment model provides a foundation for addressing ATA risk. Once quantitative data for each factor are collected, further quantitative analyses can be performed based on the proposed, semi-quantitative risk assessment. This model is also dynamic because additional factors can be incorporated once they are identified and the model can be modified accordingly.

4.4 Conclusions

The research described in this chapter presents the first comprehensive assessment of the factors affecting ATA risk, and the likelihood and consequence of ATAs. A semi-quantitative risk analysis was developed to fulfill this objective. I also defined levels of probability and consequence, and various factors affecting the initial derailment, the intrusion, the presence of trains on adjacent tracks, and the consequences. The model enables comparisons of the relative ATA risks among different track segments. It can also be used to locate high-risk locations (risk hotspots) on a railroad corridor where the ATA risk is high, and therefore more in-depth analyses and risk mitigation measures may be appropriate.

The semi-quantitative model derived in this chapter serves as a key interim step towards the development of a comprehensive ATA risk model. Factors affecting intrusion

probability that are not quantified will be incorporated in semi-quantitative form in the final model. The model structure, combined with engineering judgement, provides a useful tool to conduct sensitivity analyses that can be used to refine the understanding of which factors are the most important to further investigate. In this way it can provide guidance to railroads, the FRA, and others interested in reducing ATA risk on SRCs.

CHAPTER 5

TRAIN PRESENCE AND ADJACENT TRACK COLLISION PROBABILITY ANALYSIS IN INTRUSION SCENARIOS

5.1 Introduction

When an intrusion occurs, the most undesired consequence is that the derailed equipment intruding onto an adjacent track strikes or is struck by another train traveling on that track. There are several factors affecting the probability of such a collision, referred to as an adjacent track collision. The first is the frequency of train meets and passes on adjacent tracks. The more train meets and passes, the more likely it is that when an intrusion occurs, another train will be next to, or approaching, the intrusion location on the adjacent track. The second factor is the distance between the intruding rail vehicle and the train on the adjacent track. When an intrusion occurs, trains on the adjacent track may be far enough away from the intrusion location that there is little chance of an adjacent track collision. Alternatively, they may be close enough to the intrusion location that there is a very high likelihood of collision, and in the most extreme situation, a train derails and intrudes onto a track while another train is adjacent to it, resulting in an immediate collision. Between these two extremes the probability of adjacent track collision is affected by two other factors: point of derailment of the intruding equipment and the braking capability of trains on the adjacent track.

In railroad train accident investigations, the point of derailment (POD) generally refers to the location on the tracks where the first derailed locomotive or railcar leaves the

rails. In statistical and risk analysis research on train safety the term POD has also been used to refer to the first car or locomotive to derail in a train (Anderson and Barkan, 2005; Liu et al., 2014) and this is the definition I use in my research. This distribution of POD has been shown to vary depending on the cause of the derailment (Liu et al., 2014). Train speed, resistance, type and consist, track grade, curvature, friction, and the type of braking system all can affect the stopping capability of trains.

In this chapter, I develop probability distributions for adjacent track collisions in train meet and train pass scenarios. I also derive a generalized model to quantitatively evaluate the probability of train presence on an adjacent track when an intrusion occurs. The probability models developed in this chapter are key elements of the comprehensive adjacent track accident (ATA) probability assessment model presented in chapter 6. For clarity, the probability of an adjacent track collision referred to in this chapter is the conditional probability of train collision given an intrusion occurs, and the probability of an ATA refers to the probability of the whole event sequence introduced in the ATA event tree (Figure 2.2). Therefore, an adjacent track collision can be considered as the end state of an ATA.

5.2 Methodology

I divide train presence and adjacent track collision probability model development into the following steps:

- 1) Calculate the frequency of train meet and pass events

- 2) Calculate the critical distance where two trains on adjacent tracks pose collision risk to one another
- 3) For each train meet or pass event, develop probability distributions for collisions between derailed rail vehicles and another train on an adjacent track
- 4) Derive train presence probability for a track segment in an intrusion scenario considering multiple train meets and passes

I describe the methodology and techniques used to carry out each step of the model development in the following subsections. The focus of this chapter is to develop a collision probability model for train meet and pass activities and identify the factors that affect this probability. Another important output is the segment-level train presence probability, which serves as part of the ATA probability assessment model.

5.2.1 Frequency of Trains Passing and Meeting Each Other

To evaluate collision probability between trains on adjacent tracks, we need to define the terms train “meet” and “pass”. A train meet (TM) occurs when two trains traveling on adjacent tracks in opposite directions go past one another (Figure 5.1a), and a train pass (TP) occurs when one train overtakes another train on an adjacent track (Figure 5.1b) (Lamorgese and Mannino, 2015).

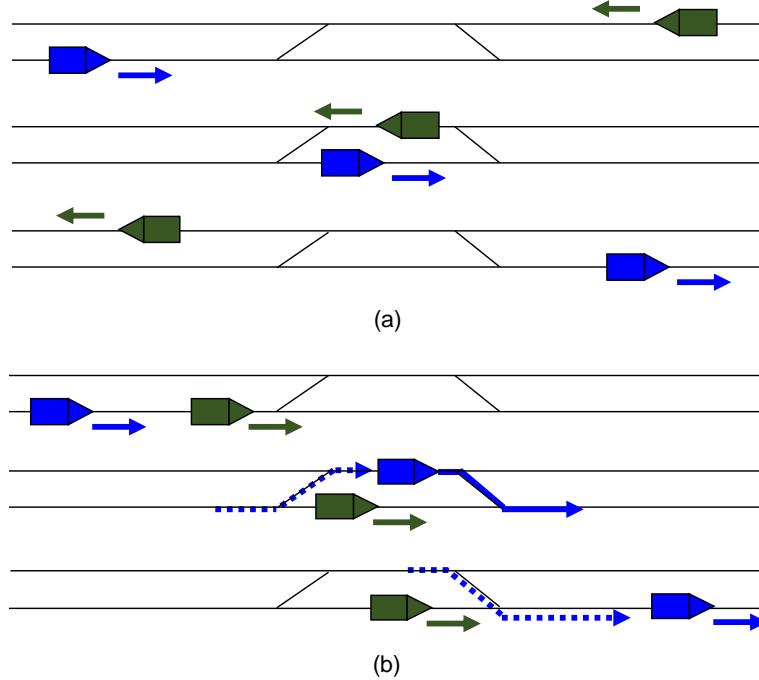


Figure 5.1: Typical (a) train meet (TM) and (b) train pass (TP) scenarios

The more TM and TP activities occurring on a track segment, the higher the probability of having an adjacent track collision. For instance, when there is only one train running on one track on a multiple track railroad corridor (Figure 5.2a), there is no chance of having an adjacent track collision because there are no TM or TP opportunities. When there is another train on an adjacent track that will meet the first train (Figure 5.2b), that event represents the only opportunity for an adjacent track collision if either train derails and intrudes onto the adjacent track. If there are two trains (B_1 and B_2) running on the adjacent track (Figure 5.2c), all else being equal, the frequency of TMs on the corridor doubles and so does the probability of adjacent track collisions. There is also a possible TP opportunity between trains B_1 and B_2 if train B_2 is running at higher speed than B_1 or if the train dispatcher decides to let train B_2 pass B_1 at some point on this track segment. In this case, the probability of adjacent track collision triples. If there are

multiple trains on both tracks (Figure 5.2d), the probability of an adjacent track collision increases accordingly based on the total number of TM and TP events.

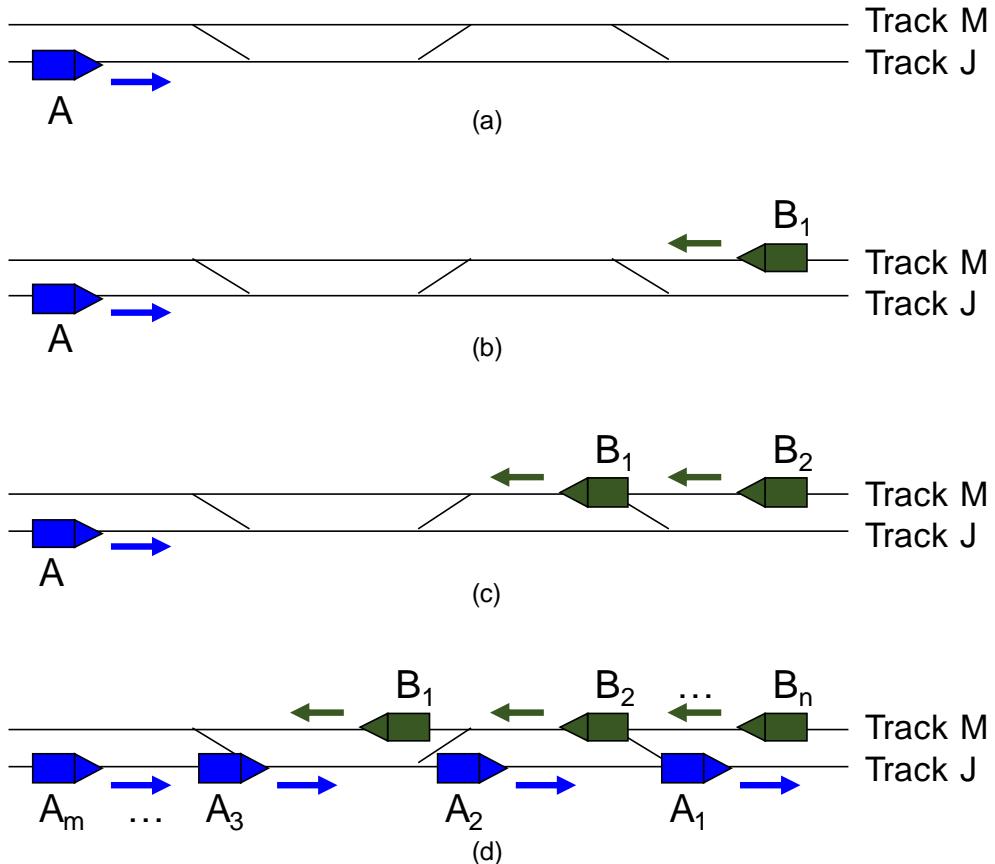


Figure 5.2: Train meets on adjacent tracks

If all trains have a fixed schedule and there is no delay on a railroad corridor, the number of TM and TP events can be calculated directly by identifying all those events on the operating schedule; however, in North America, most freight trains run on flexible schedules (Dick et al., 2018), meaning that they do not have a precise departure or arrival time on a given day, nor do they have exact locations to perform TMs and TPs during their trip (Martland, 2008). Although most passenger trains and certain types of freight

trains (e.g. some intermodal trains) run on a more structured schedule (Furtado, 2013; Pouryousef et al., 2013) where trains have pre-determined departure time, arrival time, and TM and TP locations (Martland, 2008), their operations are not planned in detail nor are their schedules as strict as many European or Asian railroad operations (Furtado, 2013). Therefore, TM and TP locations may still change in these semi-structured operations. Train delay may also change the number and location of TM and TP events. If a train is delayed, it may not be able to meet or pass other trains where and when it is scheduled to.

TM and TP event identification has been analyzed using econometrics (Oh et al., 2004; Gorman, 2009; Şahin, 2017; Sørensen et al., 2017) and simulation methods (White, 2005; D'Ariano et al., 2007; Shih et al., 2017). In my research, I use the train conflict screening tool developed by Shih et al. (2017) to identify the number of TM and TP events. This model calculates TM and TP events using a Monte Carlo process to address the uncertainty caused by flexible train scheduling and potential train delays (Figure 5.3). The output of this model is the average number of TM and TP events on different track segments along a railroad corridor, given track, train and operational characteristics. Other methods of identifying TM and TP events may be used if they are more suitable for the particular rail corridor being analyzed.

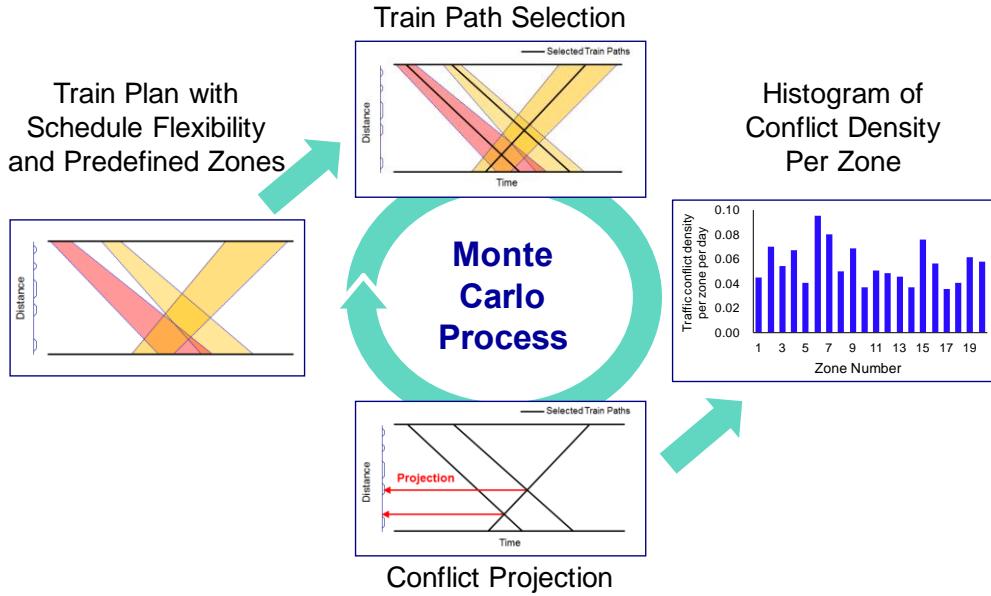


Figure 5.3: Monte-Carlo-process-based train conflict identification model (Shih et al., 2017)

In the following subsections, I present the collision probability assessment for TM and TP events in two steps. First I calculate the maximum distance between two trains on adjacent tracks that may result in a collision at the time an intrusion occurs (Subsection 5.2.2), while accounting for the point of derailment of intruding rail equipment (Subsection 5.2.3). Then, I develop a generalized model to evaluate the probability of train collision between two trains within the calculated distance for TM and TP scenarios, as well as segment-level train presence probability (Subsection 5.2.4).

5.2.2 Critical Distance (CD)

When two trains on adjacent tracks meet or pass and are within a certain distance of each other when an intrusion occurs, a collision may result. I define the maximum distance between two trains on adjacent tracks posing potential collision risk to each other as “Critical Distance (CD)”. In other words, any distance greater than CD will not

result in an adjacent track collision even if the front of the intruding train derails and fouls the adjacent track, given everything else functioning normally. CD is crucial in train presence probability calculation because it bounds the collision probability distribution.

CD is calculated using minimum train braking distance. Two main factors affect braking distance: initial train speed and train deceleration rate (IEEE, 2009). Previous research developed methodologies to calculate train braking distances based on train and track characteristics (Hay, 1982; IEEE, 2009; Thurston, 2011; ERA, 2014). The minimum braking distance is calculated as:

$$D_{brake} = 0.7333 \times \frac{V^2}{b + 0.008 \times R + 0.2 \times G} \quad (5.1)$$

where:

D_{brake} = train braking distance (feet)

V = initial speed of the train (miles per hour)

b = train deceleration rate (miles per hour per second)

R = curvature (degree)

G = grade (percent; positive value indicates ascending grades and negative value indicates descending grades)

The initial speed refers to the train speed when the train engineer applies brakes. The grade and curvature are obtained directly from the infrastructure characteristics of the track segment of interest. The train deceleration rate is affected by the total weight of the train and train resistance, which is further affected by train speed, air drag factor, flange friction, and journal resistance.

Two types of deceleration rate are considered in the model: full-service brake deceleration rate and emergency brake deceleration rate. The former is the rate used when a normal, maximum full service brake application is made. The latter is the deceleration rate used when an emergency brake application is made. In this case, all of the possible braking power is applied to stop the train. In an air brake system, this means using all of the air pressure stored in both the auxiliary and emergency reservoirs on each car in a train to achieve the maximum possible braking force and deceleration rate.

The selection of deceleration rate depends on different TM and TP scenarios. Train engineers avoid use of emergency brakes unless it is truly an emergency because it may cause discomfort or injuries to passengers, is potentially harmful to rolling stock and infrastructure, causes excessive delay while recharging the air brake system, and has the potential to cause a derailment. If an intrusion is identified by the engineer of the train on the adjacent track when the train is far enough away from the intrusion location, a full-service brake application will be sufficient to stop the train; therefore, under these circumstances I assume the deceleration rate for a full-service brake. Alternatively, if the intrusion occurs while the oncoming train is in the adjacent signal block, then I assume an emergency brake application will be made because the engineer on that train will observe a signal displaying a stop indication without having prior warning. If the train is already in the signal block then only direct communication or visual detection will inform the engineer, and again an emergency brake application is assumed.

For TM scenarios, CD will be the sum of D_{brake} for the train intruding onto an adjacent track and the train on that track. Even when a train derails, the train may continue moving forward until it comes to a complete stop. Although the deceleration rate in derailments is most likely greater than the deceleration rates in regular full-service brake and emergency brake application, the resulting deceleration distance still contributes to the overall CD.

For a TP scenario, I only consider D_{brake} for the train running on the adjacent track trying to stop and avoid the collision, but I do not consider D_{brake} for the train that derails and intrudes onto the adjacent track. The reason is that, in the TP scenario, the intruding train and the train on the adjacent track are running in the same direction. Therefore, when the intruding train derails and continues moving forward before it stops, this movement increases the distance available for the train on the adjacent track to brake and stop. Although as mentioned above, trains do continue to move forward after they derail, the distance can vary considerably. For example, if a derailment results in a pile-up of equipment, or if derailed equipment collides with other objects while intruding onto an adjacent track, it will not travel as far from the initial derailment location. To avoid underestimating the risk of adjacent track collision, D_{brake} for the intruding train is not included in the CD calculation in TP scenarios.

5.2.3 Point of Derailment

CD defines the maximum distance where two trains pose adjacent track collision risk to one another. If we assume that the front of the intruding train derails and intrudes

onto the adjacent track, and the two trains on adjacent tracks are within their CD when the intrusion occurs, a collision is inevitable. However, the first rail vehicle derailed may not be the first piece of equipment in the train consist. If the first derailed equipment is further back in the train, there will be additional distance for the adjacent train to apply brakes and avoid a collision within the CD. The POD thus plays a key role in train presence probability assessment and understanding the probability distribution of POD enables more accurate estimation of the probability of an adjacent track collision.

Trains vary in the number of pieces of equipment in the consist and consequent train length. The normalized point of derailment (NPOD) was developed to account for this variation (Saccomanno and El-Hage, 1989; 1991). Previous research found that NPOD is affected by accident causes (Liu et al., 2014). Different derailment causes result in different probability distributions for NPOD. Liu et al. (2014) found that a beta distribution provided the best fit for the POD and NPOD probability distributions for most derailment causes (Figure 5.4). In my research, I adopt a beta distribution ($\alpha = 0.6793$, $\beta = 0.8999$) for the probability distribution of NPOD based on Liu et al.'s (2014) work. Given train length L, the probability that the POD is at the nth position in a train, $P(n)$, can be estimated using the following equation:

$$P(n) = F\left(\frac{n}{L}\right) - F\left(\frac{n-1}{L}\right) \quad (5.2)$$

where:

$P(n)$: probability of POD being at the nth car of a train

F: the cumulative density distribution of the fitted beta distribution

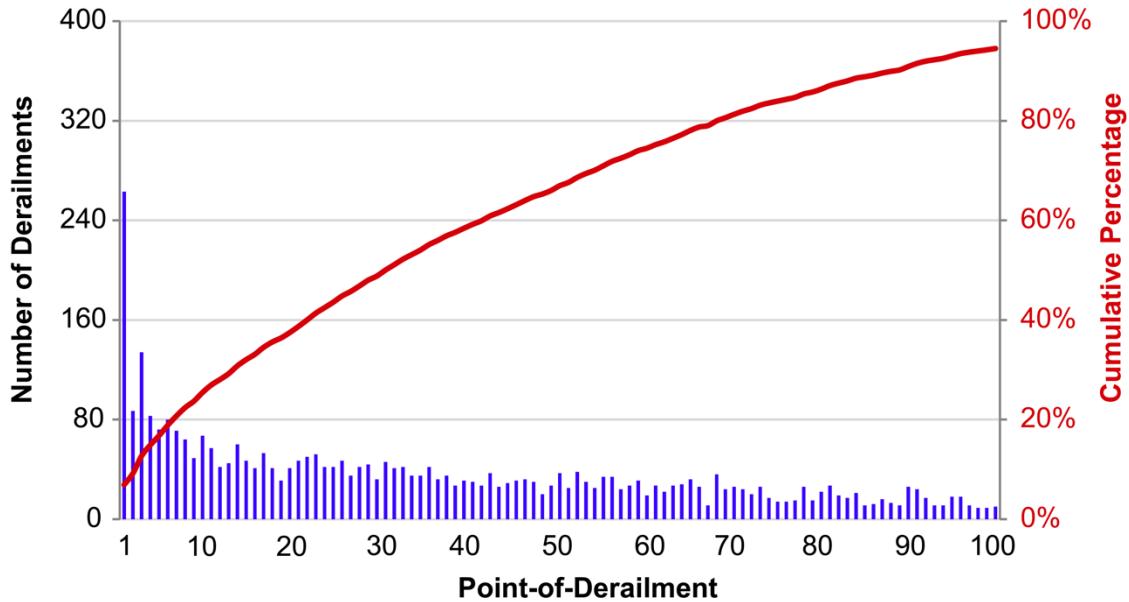


Figure 5.4: Distribution of the point-of-derailment for Class I railroad, mainline, freight-train derailments due to all causes, 2002–2011 (Liu et al., 2014)

5.2.4 Adjacent Track Collision and Train Presence Model

5.2.4.1 Adjacent Track Collision Probability in TM Scenario

Consider two trains B and A running at speed V_B and V_A in opposite directions towards each other on Main Track (track **M**) and Adjacent Track (track **J**), respectively (Figure 5.5a). When the distance between the front of the two trains, the Available Distance, or D_{avail} , is greater than their CD, there is no risk of an adjacent track collision. When $D_{\text{avail}} = \text{CD}$ (Figure 5.5b), they will just make contact if train B derails and intrudes its front end onto track J, and the engineer of train A makes an immediate brake. The collision probability where D_{avail} being CD is set to zero. When D_{avail} is less than CD (Figure 5.5c), the probability of collision can be expressed as:

$$P_{\text{collision,TM}} = \sum_{n=1}^K P(n) \quad (5.3)$$

where:

$P(n)$: probability of POD being at the n th car of train B's consist
 K : the K th car in train B's consist so that:

$$\sum_{k=1}^K l_k > (D_{brake} - D_{avail}) \quad (5.4)$$

where l_k is the length of the k th rail equipment in train B's consist.

As two trains approach each other, the distance between them diminishes, resulting in increasing collision probability (Figure 5.5d). After the rear end of train A passes the front end of train B (Figure 5.5e), I assume that the portion of train B passed by train A will not pose any threat to train A if it derails. For example, if the end of train A has passed the 14th car of train B (counting from the front) while the POD of train B is at the 8th car, this situation will not lead to an adjacent track collision. Therefore, the collision probability can be modified as:

$$P_{collision,TM} = \sum_{n=1}^K P(n) - \sum_{n=1}^S P(n) \quad (5.5)$$

where S is the S th car in train B's consist that is passed by the end of train A

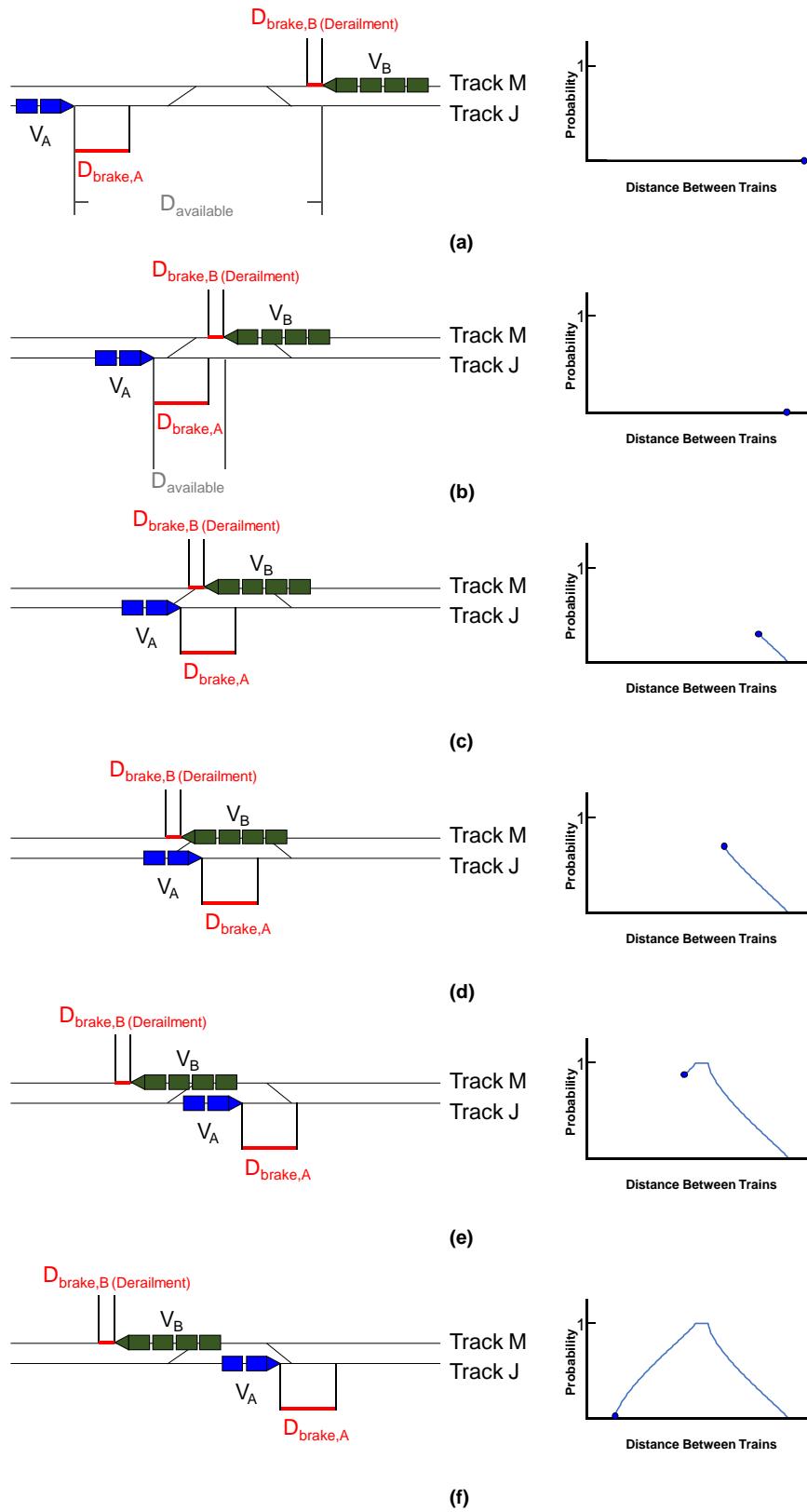


Figure 5.5: Adjacent track collision probability for a TM scenario

The collision probability exists until the two trains completely pass each other (Figure 5.5f). At this point, the probability of collision returns to zero. I call the sum of CD and the total length of two trains the “Collision Zone (CZ)”, because the risk of an adjacent track collision is greater than zero when the two trains on adjacent tracks are within this distance.

5.2.4.2 Adjacent Track Collision Probability in TP Scenario

Train collision probability calculation for the TP scenario is similar to the calculation in the TM scenario, except that now the two trains are running in the same direction. Consider trains B and A running at speed V_B and V_A in the same direction on Main Track (track **M**) and Adjacent Track (track **J**), respectively (Figure 5.6a). When the distance between the front end of train A and the rear end of train B, the Available Distance, or D_{avail} , is greater than their CD, there is no risk of adjacent track collision. When D_{avail} is their CD (Figure 5.6b), they will just make contact if train B derails and intrudes its rear end onto track J, and the engineer of train A applies the brake immediately.

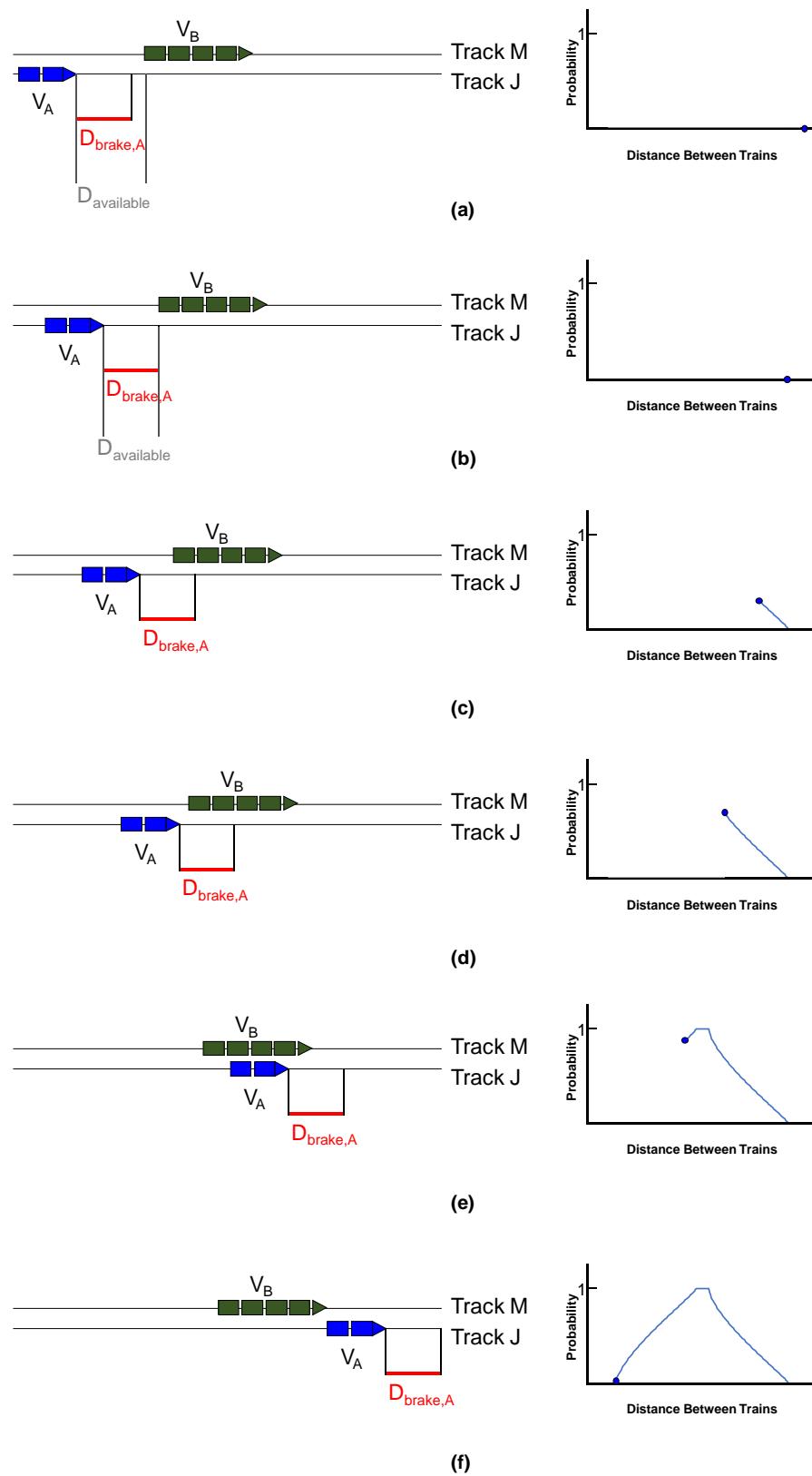


Figure 5.6: Adjacent track collision probability for a TP scenario

The collision probability where $D_{avail} = CD$ is set to zero. When D_{avail} is less than CD (Figure 5.6c), the probability of collision can be expressed as:

$$P_{collision,TP} = \sum_{n=1}^K P(E - n) - \sum_{n=1}^S P(E - n) \quad (5.6)$$

where:

$P(n)$: probability of POD being at the nth car of train consist
 K : the Kth car in train B's consist so that:

$$\sum_{k=1}^K l_{(E-k)} > (D_{brake} - D_{avail}) \quad (5.7)$$

where l_k is the length of the kth rail equipment in the train consist.

E: the last car in train B's consist

S: the Sth car in train B's consist (counting from the rear) that is passed by the end of train A

As train A approaches train B, the distance between them diminishes, resulting in increasing collision probability (Figure 5.6d). After the rear end of train A passes the rear end of train B (Figure 5.6e), if train A has completely passed the POD of train B when it derails, I assume that this will not result in an adjacent track collision. The collision probability exists until the rear end of train A passes the front end of train B (Figure 5.6f). In this case, the probability of collision becomes zero again. The definition of CZ is the same as in a TM scenario: the sum of CD and the total length of the two trains.

The major difference in probability calculation for the TP scenario compared to the TM scenario is that the NPOD reference for the derailing train is reversed because the train is running in the same direction as the train on the adjacent track, so the adjacent train is approaching the rear of the potential derailing and intruding train instead of its front.

5.2.4.3 Segment-level Adjacent Track Collision Probability

To obtain the adjacent track collision probability given an intrusion in a track segment, I investigated how frequently TM and TP events will occur on a track segment. If there are relatively few such events on this segment, then the probability of an intrusion occurring in proximity to another train is low. On the other hand, if TMs and TPs are sufficiently frequent, then it is likely that if an intrusion takes place, another train will be at, or approaching, the intrusion location, and thus the collision risk is high. I use the concept of average spacing to obtain adjacent track collision probability on a track segment. Average spacing means the average distance between trains. I develop two types of average spacing: average spacing for TM events and average spacing for TP events. Average spacing for TM events, denoted as S_M , is the average distance between trains that will meet each other in the track section, and average spacing for TP events, denoted as S_P , is the average distance between trains that will pass one another on the track segment.

There is also a minimum spacing between trains traveling at normal speed on the same track in the same direction. This spacing should consider the longest safe braking

distance among the trains on the track segment and the length of signal blocks, depending on the train control systems used, so that trains are safely separated. The average spacing of trains on the same track on the track segment should be equal or greater than the minimum train spacing of the track segment.

When an intrusion occurs, two trains on adjacent tracks can be any distance away within average spacing. If this distance is also within CZ, then the risk of adjacent track collisions exists. Therefore, I consider CZ as a proportion of the average train spacing to calculate the probability that the distance between two trains on adjacent tracks is within CZ (Figure 5.7a). When the distance between two trains on adjacent tracks is within CZ, the average collision probability from the derived distribution is used to calculate the adjacent track collision probability for the track segment, assuming the probability of the distance between two trains on adjacent tracks is uniformly distributed within the average spacing (Figure 5.7b).

For each TM and TP event, the probability of an adjacent track collision given an intrusion is calculated as:

$$P_T = \frac{CZ}{S} \times E(P_{collision}) \quad (5.8)$$

where:

P_T: the probability of train presence given an intrusion on a track segment
 CZ: collision zone in feet

S: average spacing (S_M or S_P) based on TM or TP scenarios in feet
 E(P_{collision}): the mean of the probability of adjacent track collisions

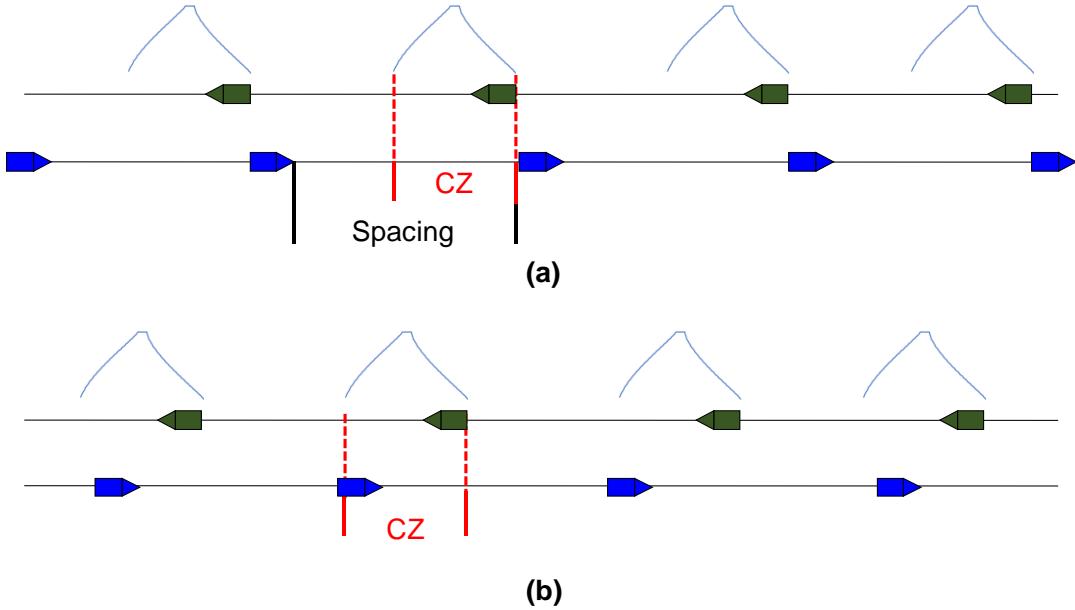


Figure 5.7: Illustration of (a) the proportion of CZ to the average spacing and (b) distance between trains on adjacent tracks at any given point.

Hence, for a track segment, given the average spacing of trains on adjacent tracks and the number of TM and TP events, the overall adjacent track collision probability is calculated by:

$$1 - \prod_i (1 - P_{T,TM_i}) \times \prod_j (1 - P_{T,TP_j}) \quad (5.9)$$

where:

P_{T,TM_i} : adjacent track collision probability for the i th TM event

P_{T,TP_j} : adjacent track collision probability for the j th TP event

i: total number of TM events in the track segment

j: total number of TP events in the track segment

If we want to calculate the probability of adjacent track collisions on the track segment with a given spacing, S , between trains on adjacent tracks, the following equation applies:

$$1 - \prod_i \left(1 - P_{\text{collision},TM_i}(S)\right) \times \prod_j \left(1 - P_{\text{collision},TP_j}(S)\right) \quad (5.10)$$

where:

$P_{\text{collision},TM_i}(S)$: the probability of an adjacent track collision in TM scenario given spacing S

$P_{\text{collision},TP_j}(S)$: the probability of an adjacent track collision in TP scenario given spacing S

S: spacing between trains in feet

i: total number of TM events in the track segment

j: total number of TP events in the track segment

5.2.4.4 Exposure Time and Exposure Distance

In addition to collision probability calculation, it may also be important to understand the area or distance along a corridor, and the length of time that two trains on adjacent tracks are exposed to the risk of an adjacent track collision. Exposure Time is defined as the time required for two trains on adjacent tracks to complete a TM or TP, and Exposure Distance is the distance required to do so. The Exposure Time and Exposure Distance for TM scenarios are:

$$ET_{TM} = \frac{CZ_{TM}}{(V_A + V_D)} \quad (5.11)$$

$$ED_{TM} = CZ_{TM} \quad (5.12)$$

where:

ET_{TM} : Exposure Time for TM scenarios (seconds)

ED_{TM} : Exposure Distance for TM scenario (feet)

CZ: Critical Zone (feet)

V_A : speed of the approaching train (feet per second)

V_D : speed of the derailing train (feet per second)

The Exposure Time and Exposure Distance for TP scenarios are:

$$ET_{TP} = \frac{CZ_{TP}}{(V_A - V_D)} \quad (5.13)$$

$$ED_{TP} = \frac{CZ_{TP}}{(V_A - V_D)} \times V_D \quad (5.14)$$

where:

ET_{TP}: Exposure Time for TP scenarios (seconds)

ED_{TP}: Exposure Distance for TP scenario (feet)

Exposure Time and Exposure Distance provide additional information regarding the adjacent track collision risk. An important aspect is the relative speed of the derailing and approaching trains. The greater the relative speed between the derailing train and approaching train, the more quickly the two trains will travel through the CZ, and the shorter the time that the trains are exposed to adjacent track collision risk. This is true for both TM and TP scenarios. The Exposure Distance for TM scenarios is CZ, regardless of the relative speed of the two trains. For TP scenarios, the Exposure Distance depends on the relative speed of the two trains. If the approaching train is traveling at a much higher speed than the derailing train, it will overtake the train quickly and therefore the distance traveled while the two trains are exposed to an adjacent track collision is short; in some scenarios as short as two thousand feet. Conversely, if the approaching train is traveling just slightly faster than the derailing train resulting in a small relative speed difference between two trains, it may take several miles or more to complete the TP, meaning that the two trains are exposed to the risk of adjacent track collision for a long distance.

From a risk management perspective, this means that if a TM or TP takes place in a short time and distance, then it may be possible to implement risk mitigation measures at specific locations or track segments where TMs or TPs are most likely to occur; however, if most of the TMs or TPs take place with long Exposure Distance and Exposure Time, these risk mitigation measures would need to be implemented on more extensive sections of track. Understanding Exposure Distance and Exposure Time assists model users in interpreting the results of the collision probability assessment and decision making regarding the implementation of risk mitigation measures.

5.3 Model Demonstration

5.3.1 Case Study

In this section, I provide an example of an adjacent-track collision probability calculation on a two-track segment with pre-defined train and traffic information (Table 5.1). This is accomplished by calculating the collision probability of the freight train derailing and intruding onto the adjacent track where a passenger train is running.

Table 5.1: Input for a sample adjacent track collision probability calculation

	Train Characteristics	
	Passenger Train	Freight Train
Speed (mph)	79	59
Deceleration Rate (mphps)	2.00	1.48
Number of Locomotives and Rail Cars	15	80
Average Length of Rail Equipment (ft.)	85	60
Train Length (ft.)	1,275	4,800
Average Spacing of TM (ft.)		26,400
Average Spacing of TP (ft.)		26,400
Total Number of TM on the Track Segment		2
Total Number of TP on the Track Segment		1

Using equation 5.1, I calculate the minimum braking distance for the passenger train and the freight train:

$$D_{brake(pass.)} = 0.7333 \times \frac{79^2}{2 + 0.008 \times 0 + 0.2 \times 0} = 2,283.3 \text{ ft.}$$

$$D_{brake(frei.)} = 0.7333 \times \frac{59^2}{2 + 0.008 \times 0 + 0.2 \times 0} = 1,724.7 \text{ ft.}$$

Since this is a TM scenario, the CD will be the sum of the two braking distances:

$$CD_{TM} = D_{brake(pass.)} + D_{brake(frei.)} = 2,283.3 + 1,724.7 = 4,013.0 \text{ ft.}$$

The total lengths of the two trains are:

$$L_{freight} = 80 \times 60 = 4,800 \text{ ft.}$$

$$L_{passenger} = 15 \times 85 = 1,275 \text{ ft.}$$

Using equations 5.2 through 5.5, the collision probability is derived (Figure 5.8). On the vertical axis is the probability of an adjacent track collision and on the horizontal axis is the distance between the trains. The reference point (distance = 0) is when the head ends of the two trains meet.



Figure 5.8: Collision probability distribution for TM scenario

The collision probability increases as the two trains approach each other and eventually reaches one. Then the probability begins to decrease as the rear end of the passenger train passes the front end of the freight train because the portion of freight train passed by the passenger train no longer pose collision risk to the passenger train. An asymmetric probability distribution is observed because the distribution of POD is also asymmetric in a train consist.

If the two trains are running in the same direction, and the passenger train is passing the freight train on the adjacent track, then using equation 5.6 and equation 5.7, I derive the adjacent track collision distribution accordingly (Figure 5.9). A similar pattern is shown except that the increasing and decreasing curve of collision probability is reversed, because the distribution of the freight train's NPOD is reversed for the TP

scenario. The CD for the TP scenario is just the minimum braking distance of the passenger train, which is less than the CD in the TM scenario. This is because the braking distance for the freight train (the train that derails and intrudes onto an adjacent track) is not counted towards the total CD for the reason stated in subsection 5.2.2.

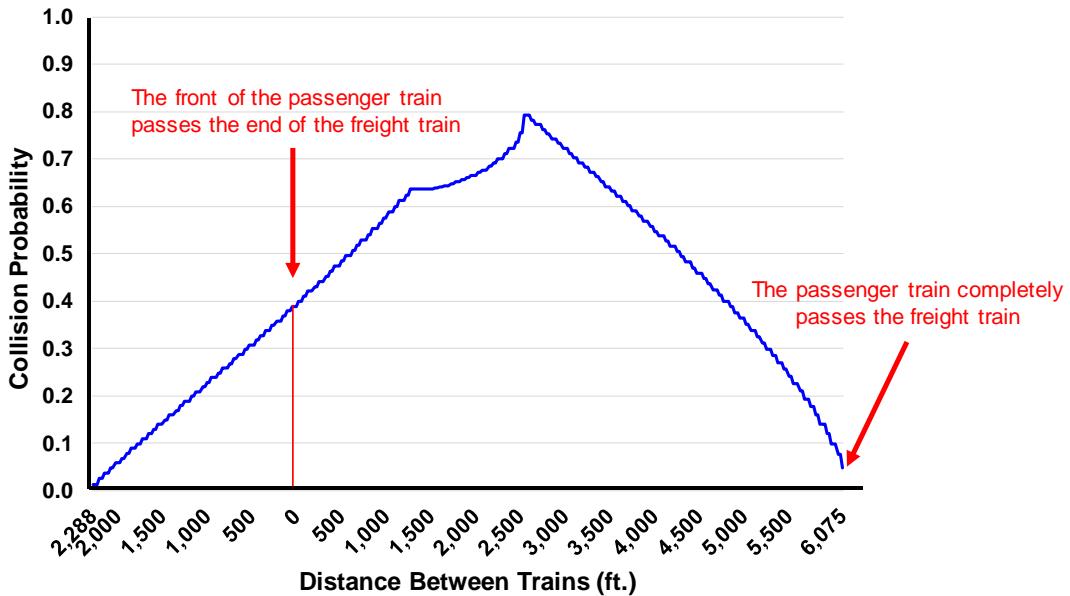


Figure 5.9: Collision probability distribution for TP scenario

The CZs for TM and TP are calculated respectively:

$$CZ_{TM} = 4,800 + 1,724.7 + 1,275 + 2,288.3 = 10,088$$

$$CZ_{TP} = 4,800 + 3,356 + 2,288.3 = 8,363.3$$

Given the average spacing of five miles (26,400 feet), the proportion of CZ to the averaging spacing for TM and TP scenarios are:

$$\frac{CZ_{TM}}{S_{TM}} = \frac{10,088}{26,400} = 0.3821$$

$$\frac{CZ_{TP}}{S_{TP}} = \frac{8,363}{26,400} = 0.3168$$

Using equation 5.8, the probabilities of an adjacent track collision in a TM and TP scenario on this track segment are:

$$P_{T,TM} = \frac{CZ_{TM}}{S_{TM}} \times E(P_{collision,TM}) = 0.3821 \times 0.5339 = 0.2040$$

$$P_{T,TP} = \frac{CZ_{TP}}{S_{TP}} \times E(P_{collision,TP}) = 0.3168 \times 0.4347 = 0.1377$$

Since there are two TM events and one TP event on this track segment, the average adjacent track collision probability can be calculated using equation 5.9:

$$1 - \prod_i (1 - P_{T,TM_i}) \times \prod_j (1 - P_{T,TP_j}) \\ = 1 - ((1 - 0.2040) \times (1 - 0.2040) \times (1 - 0.1377)) = 0.4537$$

Using equation 5.10, the adjacent track collision probability when two trains are at a certain distance away, for example, 2,000 feet, the probability can be calculated:

$$\begin{aligned}
P(\text{collision}, S = 2,000) &= 1 - \prod_i \left(1 - P_{s,\text{collision},TM_i}(2,000)\right) \times \\
&\quad \prod_j \left(1 - P_{s,\text{collision},TP_j}(2,000)\right) = 1 - (1 - P_{s,\text{collision},TM_1}(2,000)) \times \\
&\quad \left(1 - P_{s,\text{collision},TM_2}(2,000)\right) \times \left(1 - P_{s,\text{collision},TP_1}(2,000)\right) = 0.5789
\end{aligned}$$

Using equations 5.11 through 5.14, the Exposure Time and Exposure Distance for TM and TP scenarios can be calculated as follows:

$$ET_{TM} = \frac{CZ_{TM}}{(V_{\text{passenger}} + V_{\text{freight}})} = \frac{10,088}{(115.9 + 86.5)} = 50 \text{ seconds}$$

$$ED_{TM} = CZ_{TM} = 10,088 \text{ feet} = 1.91 \text{ miles}$$

$$ET_{TP} = \frac{CZ_{TP}}{(V_A - V_D)} = \frac{8,363.3}{(115.9 - 86.5)} = 285 \text{ seconds}$$

$$ED_{TP} = \frac{CZ_{TP}}{(V_A - V_D)} \times V_D = 285 \times 86.5 = 24,652.5 \text{ feet} = 4.67 \text{ miles}$$

The speeds of the passenger and freight train are converted from mph to feet per second for the calculations. Given the same input, the Exposure Time and Exposure Distance for the TP scenario are both greater than those in an otherwise similar TM scenario due to the smaller relative speed between the approaching and derailing trains.

5.3.2 Analysis of the Effects of Train Length and Train Speed

In this subsection, I describe analyses to understand the effects of train length and train speed on the probability of adjacent track collisions. To analyze the effect of train length, a set of input variables were chosen to perform the analyses (Table 5.2). Four

combinations of train length were compared: long derailing train and long approaching train, long derailing train and short approaching train, short derailing train and long approaching train, and short derailing train and short approaching train. All other input variables remain the same in all scenarios. The analysis was conducted for both TM and TP situations.

Table 5.2: Input for comparing the effect of train length on collision probability

Long Derailing Train		Short Derailing Train	
Long Approaching Train		Long Approaching Train	
Derailing Train	Approaching Train	Derailing Train	Approaching Train
Speed (mph*)	49	79	49
Deceleration Rate (mphps**)	1.48	2.00	1.48
Train Length (feet)	6,000	8,500	1,200
Track Grade (%)	0	0	0
Track Curvature (degree)	0	0	0

Short Derailing Train		Long Derailing Train	
Short Approaching Train		Short Approaching Train	
Derailing Train	Approaching Train	Derailing Train	Approaching Train
Speed (mph*)	49	79	49
Deceleration Rate (mphps**)	1.48	2.00	1.48
Train Length (feet)	1,200	1,275	6,000
Track Grade (%)	0	0	0
Track Curvature (degree)	0	0	0

In the TM scenario, a long derailing train and long approaching train have the longest CZ (Figure 5.10) because the total train length is the longest of the four scenarios. When the derailing train is long, the slope of the increasing and decreasing portions of the collision probability distribution are shallower. This is because the longer the derailing train, the more distance is required for the combined braking distances of both trains to reach the later part of the derailing train. More distance is also required for the approaching train to fully pass the derailing train. By contrast, if the length of the

derailing train is short, there is a steep increase and then decrease in the collision probability distribution. This is because the combined braking distance of the two trains can reach the end of the derailing train quickly, therefore resulting in a collision probability of one. After the front of the approaching train passes the end of the derailing train, the collision probability decreases quickly because it takes less distance for the approaching train to fully pass the derailing train.

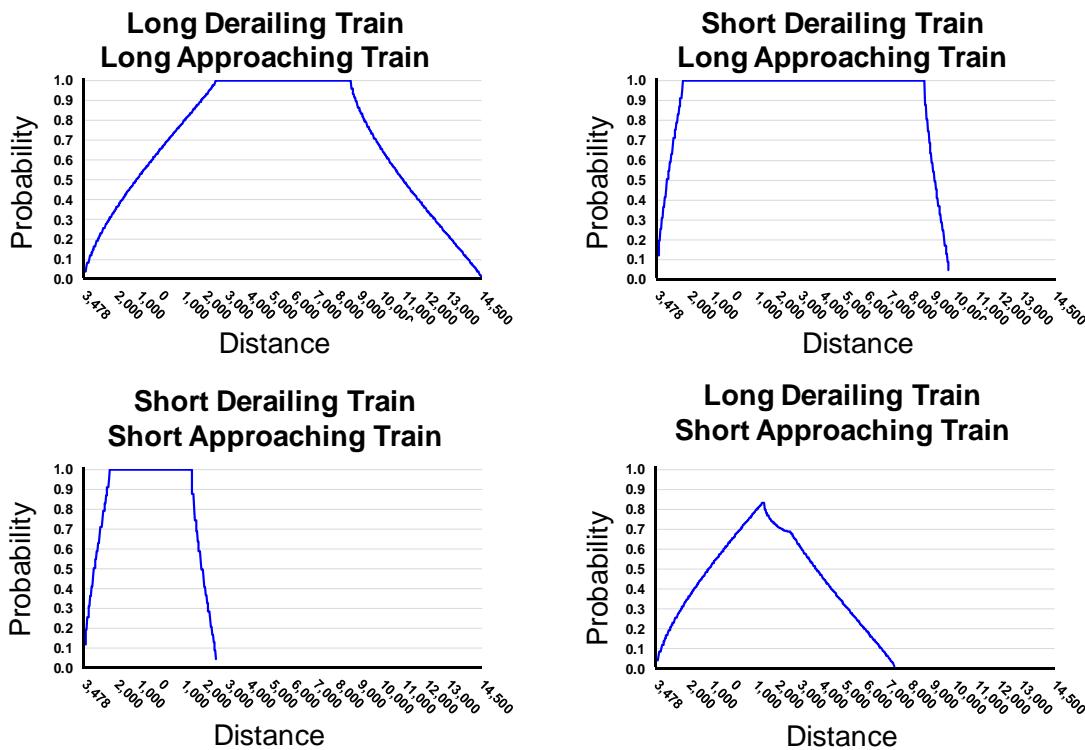


Figure 5.10: Collision probability distribution of the four combinations of train length for TM scenario

In the long derailing train and short approaching train scenario, there are discontinuities at certain distances. These occur when the rear end of the approaching train passes the front of the derailing train and when the combined braking distance of the

two trains reaches the end of the approaching train. The long derailing train and short approaching train scenario also demonstrates a lower average collision probability.

The same analysis and comparisons were performed for the TP scenarios (Figure 5.11) and the results are similar to the TM scenarios. The CDs are less than those in the TM scenarios because by definition the TM CDs are longer than those in the TP scenarios. The shape of each TP scenario tends to mirror to the corresponding TM scenario. This is due to the reverse use of the POD distribution in the probability calculation, as the approaching trains in TP scenarios are catching up and overtaking the derailing trains from their rear end instead of their front end.

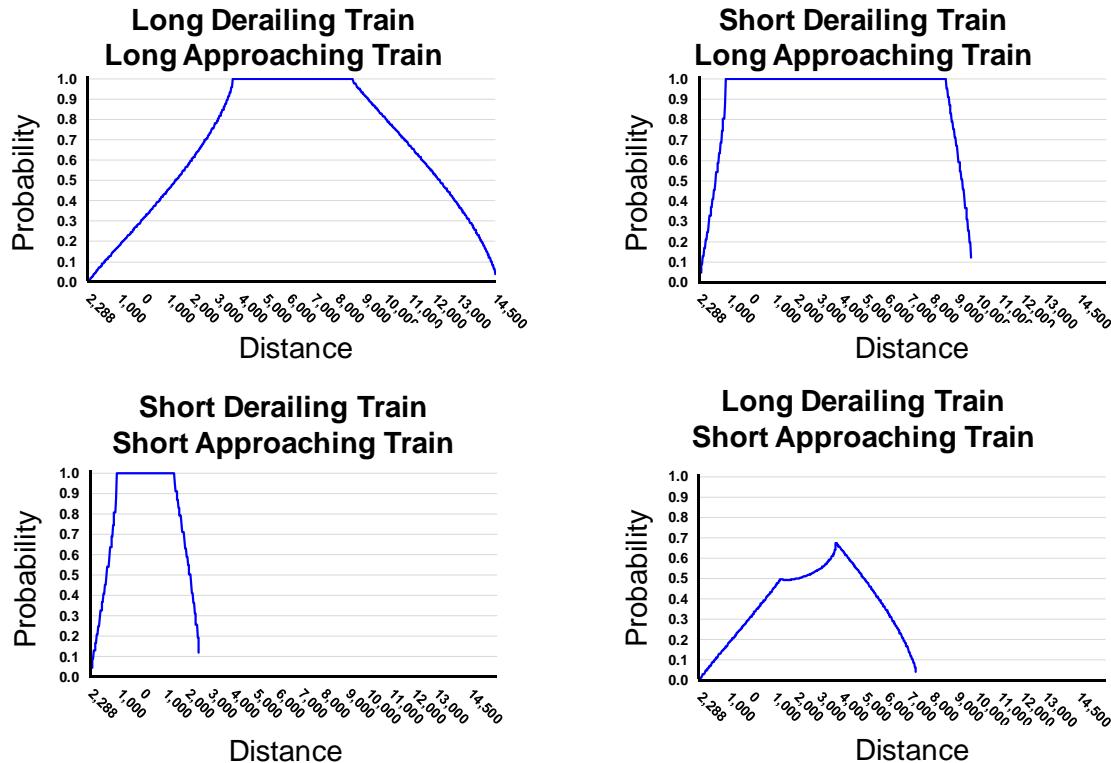


Figure 5.11: Collision probability distribution of the four combinations of train length for TP scenarios

I conducted another set of analyses to understand the effect of the relative speed of derailing (Figure 5.12) and approaching trains (Figure 5.13). In each set of scenarios, I held the speed of the approaching or derailing train constant (79 mph and 49 mph, respectively) and varied the speed of the corresponding derailing or approaching trains. As expected, the higher the relative speed, the greater the CD.

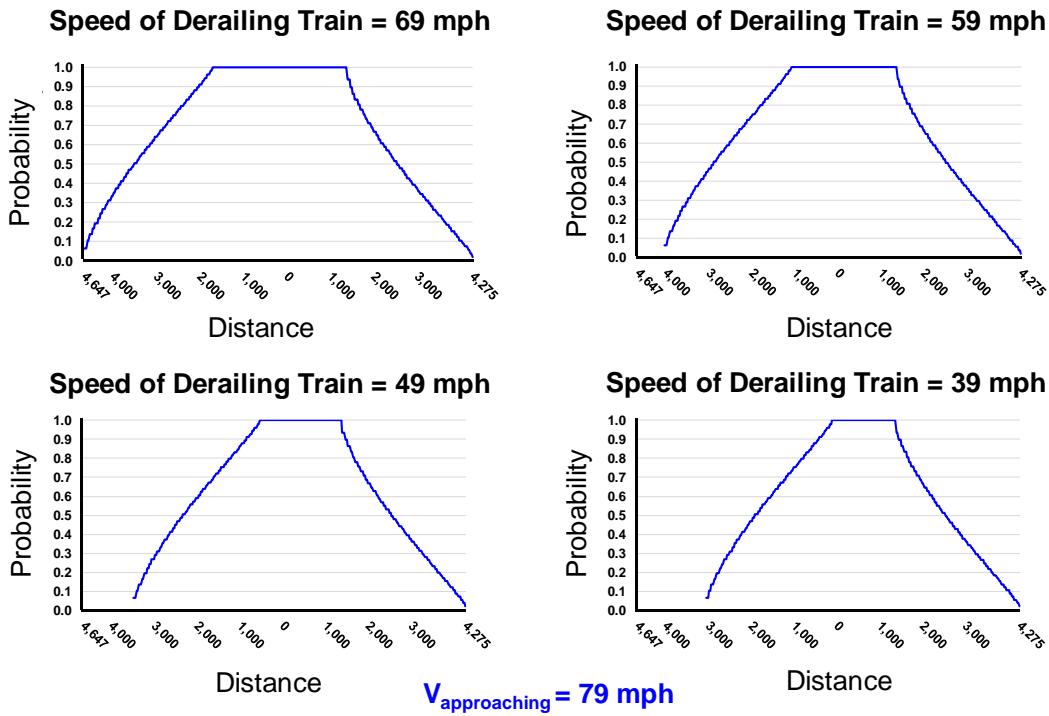


Figure 5.12: Collision probability distribution due to different speeds of the derailing train

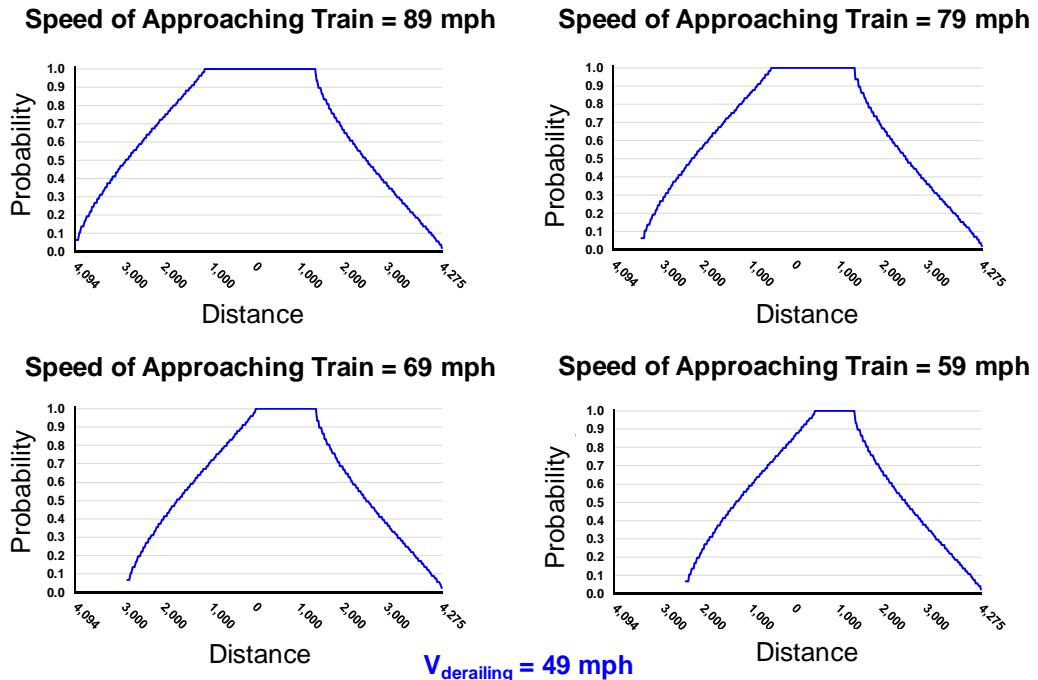


Figure 5.13: Collision probability distribution due to different speeds of the approaching train

5.4 Conclusions

In this chapter, I developed a quantitative model to evaluate the probability of train presence on an adjacent track when an intrusion occurs. The critical distance where two trains on adjacent tracks pose potential risk to each other and the factors affecting this distance were investigated. I developed a probability distribution for a single adjacent track collision in train meet and train pass scenarios based on train and derailment characteristics. I also investigated the effects of relative train length and relative train speed on collision probability. Segment-level train-presence probability was derived based on the frequency and average headway of train meet and pass events. I calculated the Exposure Time and Exposure Distance for adjacent track collisions to understand the duration and distances over which two trains on adjacent tracks are exposed to the risk. I

also provided sample calculations to demonstrate the model's behavior. This model also serves as an important part of the comprehensive adjacent track accident model that I introduce in the next chapter.

CHAPTER 6

DEVELOPMENT OF ADJACENT TRACK ACCIDENT PROBABILITY ASSESSMENT MODEL

6.1 Introduction

Development of an adjacent track accident (ATA) probability assessment model requires comprehensive understanding of the event sequence of an ATA (Figure 2.2) and factors affecting the probability of each event stage of an ATA event (Figure 2.5). In previous chapters, I investigated factors affecting the probability of: initial train derailments (Chapter 3), intrusion (Chapter 4), and train presence (Chapter 5) and developed models for each probability components. In this chapter, I introduce the Adjacent Track Accident Probability Assessment Model (ATAPAM) combining the risk analysis results and models developed in previous chapters to provide a comprehensive risk assessment tool to evaluate the probability of an ATA. The factors affecting probability components identified previously are incorporated in the model. The ATAPAM presents ATA probability in two forms: a quantitative probability value and a qualitative risk indicator showing additional intrusion risk. I demonstrate the ATAPAM with a case study showing how the model works and can be used to evaluate ATA probability. Finally, I develop an ATA probability assessment procedure and guidance for model users to customize the ATAPAM to best suit their needs.

6.2 Adjacent Track Accident Probability Assessment Model (ATAPAM)

The ATAPAM consists of three probability models for initial train derailment, conditional probability of intrusion, and conditional probability of train presence. The model evaluates the probability of an ATA as defined in the Fault Tree Analysis (FTA) in chapter 2, and the probabilities of basic events in the fault tree are calculated in the ATAPAM. Each probability model is affected by different infrastructure, rolling stock, and operational factors (Figure 6.1). These factors are divided into two groups: quantitative factors affecting the probability values of ATA, and qualitative factors that affect ATA probability, but whose degree of influence is not quantified.

Some factors affect more than one probability model. For instance, track alignment, point of derailment, and train speed affect both intrusion probability and train presence probability. They affect one probability model in a quantitative manner and qualitatively affect another model. Track alignment qualitatively affects intrusion probability but quantitatively affects train presence probability. This is because track alignment characteristics such as curvature and grade, are believed to contribute to intrusion probability, but their effect is not presently quantifiable. In train presence probability assessment, these track characteristics affect train resistance and braking performance, and these effects are quantified in the model. A qualitative factor can become a quantitative factor when sufficient information is available and proper quantification analyses are conducted. The ATAPAM can incorporate and adapt the quantification of these qualitative factors by modifying and extending the model using probabilistic risk assessment (PRA) methodology.

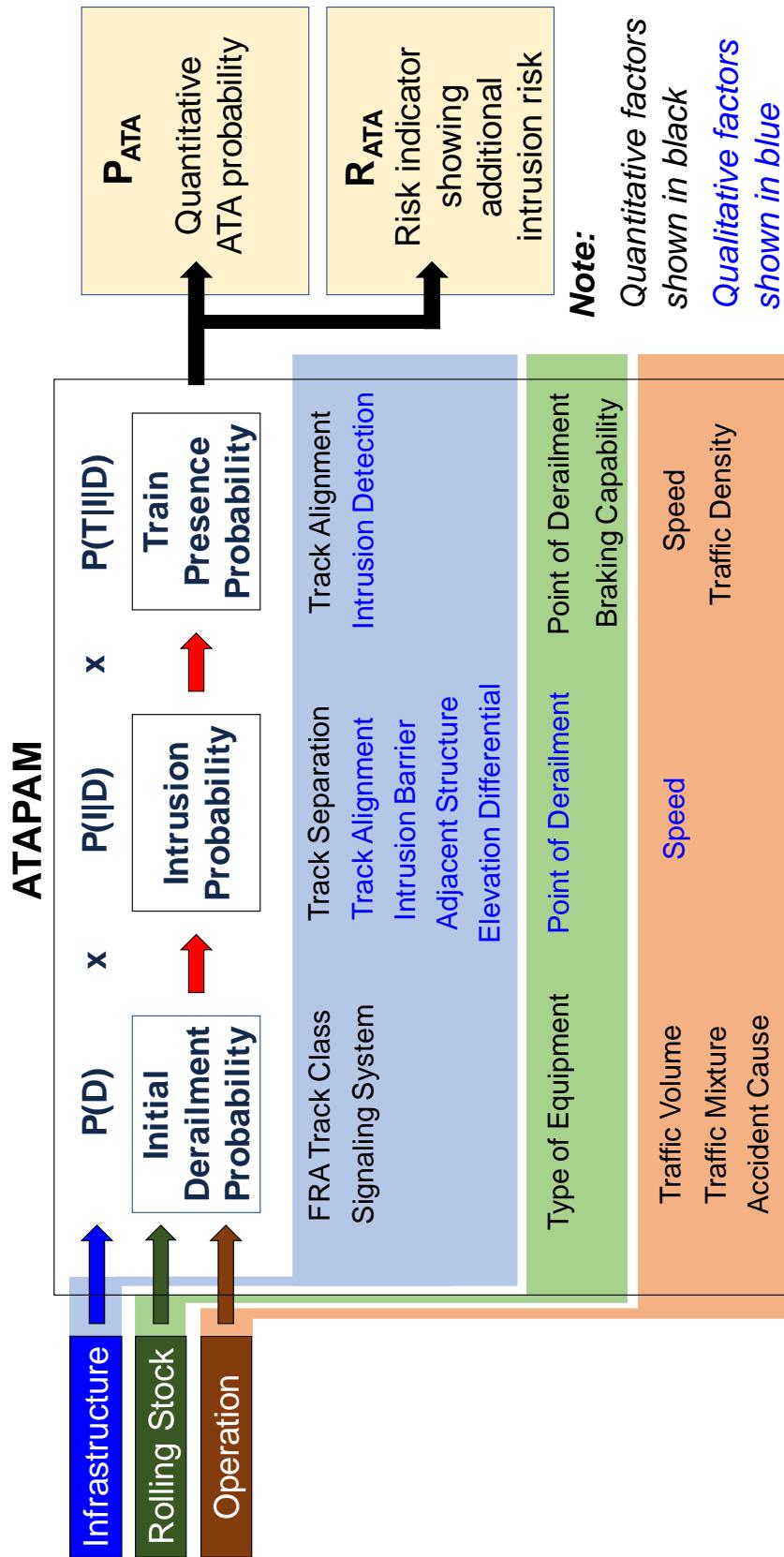


Figure 6.1: ATAPAM framework

The ATAPAM produces two outputs: a quantitative probability value for an ATA, and a qualitative risk indicator representing additional ATA risk. The quantitative probability value, denoted as P_{ATA} , is the multiplication of initial train derailment probability, intrusion probability, and train presence probability. The qualitative risk indicator, denoted as R_{ATA} , is a numerical value acknowledging the presence of factors that can increase or reduce overall ATA probability. Although their actual quantitative effect is not known, they provide useful information for model users in risk assessment and decision-making processes when managing ATA risk.

The ATA probability is evaluated by track segment. A railroad corridor is divided into segments based on different infrastructure, rolling stock, and operational characteristics. ATA probabilities and risk indicators for each track segment are evaluated by the ATAPAM. In the following subsections, I describe each probability model and discuss how the risk indicator is evaluated by qualitative factors.

6.2.1 Initial Train Derailment Probability, $P(D)$

The initial train derailment probability is expressed as number of train derailments divided by traffic exposure (Nayak et al., 1983; Anderson and Barkan, 2004; Liu et al., 2011; 2017). In the ATA fault tree, the initial derailment event is divided into different accident causes as basic events (Figure 2.5), because these causes explain which part of the railroad system failed resulting in a derailment. In terms of probability measurement, there are multiple approaches depending on data and methods available. In the following

paragraph, I describe how I evaluate the probability of initial derailment for different types of trains.

The two general types of trains considered are freight trains and passenger trains. Previous studies found that freight train derailment rates are affected by the track class defined by the United States Department of Transportation (USDOT) Federal Railroad Administration (FRA), method of operation, and traffic density (Liu et al., 2017). The authors developed a derailment rate matrix based on those factors using USDOT FRA train accident data. That matrix has been updated by Wang et al. (2019) (Table 6.1). The derailment rate matrix does not explicitly show derailment rates by accident causes; however, the differences in the rates in different infrastructure, traffic, and method of operation categories implicitly account for the probability of derailments caused by different accident causes. For example, a track with higher FRA track class has a lower derailment rate. This is probably because there are fewer derailments caused by infrastructure defects due to more frequent track maintenance and more stringent track standards. Accident-cause-specific freight train derailment rate analysis and estimation has also been conducted (Barkan et al., 2003; Liu et al., 2011; 2012; Liu, 2017a; b). The derailment matrix used in the ATAPAM provides an aggregated, more general probability that applies to most freight railroad corridors in the United States. That said, the ATAPAM can adapt to the results generated from these causal analyses and specific railroad corridors as well if appropriate data are available.

With regard to passenger train derailment rate, in chapter 3, I presented a general statistical and causal analysis for passenger train accidents and evaluated passenger train derailment rate using the USDOT FRA train accident data (Table 3.2). The aggregated derailment rate provides a national average for general risk assessment use, while cause-specific derailment rates are also available if we need to obtain the probability of ATA caused by a specific accident cause. (Table 3.5).

Table 6.1: Estimated Mainline Derailment (per billion ton-miles) for the Time Period 2011 – 2015 (Wang et al., 2019)

Traffic Density (MGT)	Method of Operation (MO)	FRA Track Class					Total
		1	2	3	4	5	
<20	Non-Signaled	1.399	0.552	0.292	0.167	n/a	0.316
	Signaled	2.083	0.557	0.230	0.119	0.208	0.199
≥20	Non-Signaled	0.238	0.169	0.061	0.082	0.000	0.089
	Signaled	0.326	0.187	0.074	0.041	0.022	0.043
		4.047	1.466	0.657	0.408	0.230	0.647

* There was no traffic for <20 MGT, non-signaled, class 5 track

Derailment rate varies with different types of train operations due to differing types of rolling stock, infrastructure, and operational protocols implemented for the specific type of train operation. To account for different types of train operation on the same track, I developed a weighted derailment rate based on the proportion of traffic from different types of railroad operation. On a shared-use rail corridor (SRC), for example, train derailment rate is the weighted average of freight train derailment rate and passenger train derailment rate based on the proportion of each type of traffic:

$$P(D) = \frac{\sum R_i \times T_i}{\sum T_i} \quad (6.1)$$

where:

P(D): the probability of initial train derailment

R_i: probability of train derailment for the ith type of rail operation

T_i: the traffic of the ith type of rail operation

The reason I use the weighted average for train derailments is because accident characteristics change with traffic composition. For example, on a freight-dominant railroad corridor, broken rail and weld is the most frequent accident cause (Liu, 2017b), while on a passenger-dominant corridor, turnout defects and failure to obey or display signal are the most frequent (Table 3.5). More sophisticated methods such as multivariate analysis can be performed to obtain more accurate relationships between traffic composition and derailment rate, accounting for other variables that also affect train derailment rate. If sufficient accident data are collected for the railroad corridor of interest, use of the weighted average derailment is unnecessary because the probability of derailment rate can be directly calculated.

6.2.2 Intrusion Probability, P(I/D)

The conditional probability of intrusion given a train derailment is determined by the likelihood of excessive lateral displacement of derailed rail vehicle and the presence and reliability of intrusion barriers or containment as illustrated in the ATA fault tree (Figure 2.5). The following subsections discuss each of these elements.

6.2.2.1 Lateral Displacement of Derailed Equipment

As discussed in chapter 4, a gamma distribution was found to provide the best fit for the data on lateral displacement of derailed rail vehicle. The probability distribution of lateral displacement of derailed equipment can be expressed as:

$$\text{Gamma}(X; \alpha, \beta) = \frac{1}{\beta^\alpha \Gamma(\alpha)} \times X^{\alpha-1} \times e^{\frac{-X}{\beta}} \quad (6.2)$$

where:

Gamma ($X; \alpha, \beta$): the probability where the maximum lateral displacement of derailed equipment is X feet

X : maximum lateral displacement of derailed equipment

$\Gamma(\alpha)$: the gamma function

α : the shape parameter

β : the scale parameter

The values of $\alpha = 1.2$ and $\beta = 33.0$ were selected as the fitted parameters for the gamma distribution based on NTSB data (Clark et al., 2013). The probability of intrusion for a track segment can be calculated by obtaining the cumulative probability function where $x \geq X$, given that no intrusion barrier is present (Figure 6.2):

$$P(x \geq X) = 1 - F(X; \alpha, \beta) \quad (6.3)$$

where:

$P(x \geq X)$: the probability of intrusion for a track segment

$F(X; \alpha, \beta)$: the cumulative gamma function given track center spacing X

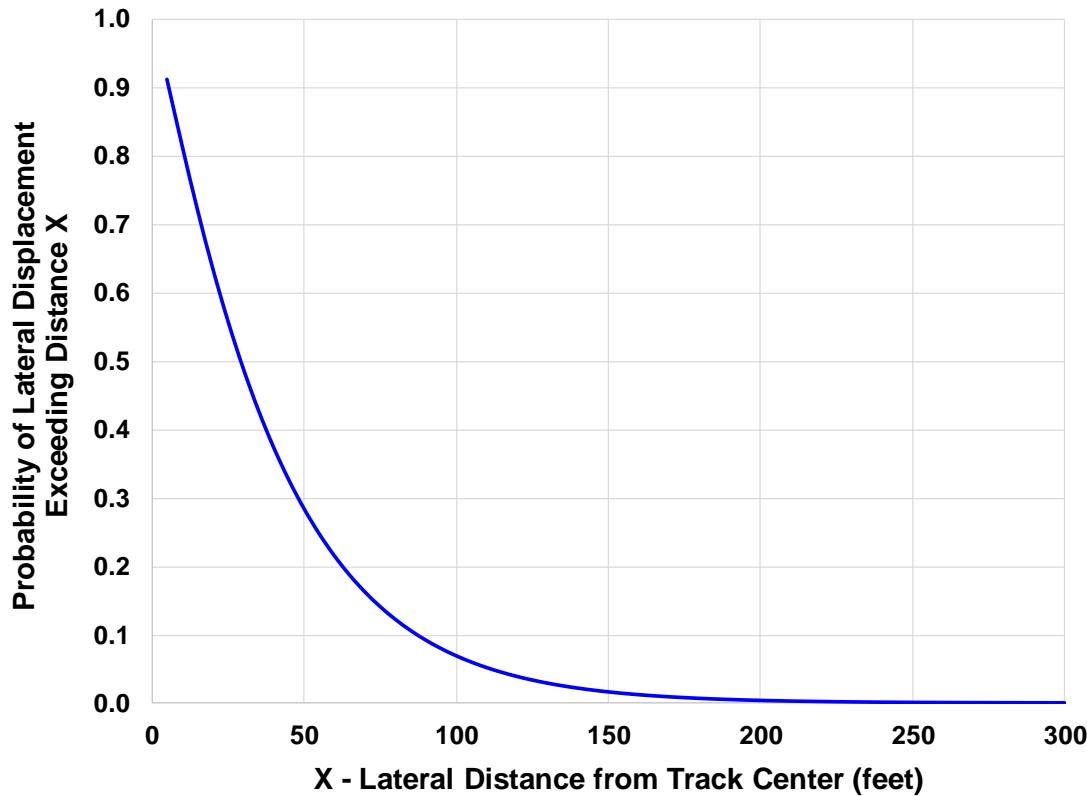


Figure 6.2: Probability function for the lateral displacement of derailed equipment exceeding distance x (Clark et al., 2013)

6.2.2.2 Crash Wall and Containment Failure

A crash wall, containment, or intrusion barrier are structures installed between adjacent tracks to contain derailing trains and prevent derailed equipment from intruding onto adjacent tracks. The design of these structures has been studied using computer simulations (Moyer et al., 1994; Layden, 2014; Bae et al., 2018a; b) and implemented in the California High-Speed Rail project (Abtahi, 2013). Previous studies focused on the design of intrusion barriers so that their strength will meet the maximum possible impact forces. I am unaware of any empirical studies of the efficacy of these intrusion barriers, and thus their reliability is unknown. In the ATAPAM, I assume that the presence of an

intrusion barrier in a track segment is 100% effective, i.e., that it would always contain derailed equipment and prevent it from intruding onto an adjacent track. The ATAPAM can account for lower effectiveness of intrusion barriers if proper data are available. The probability of crash wall failure is defined in the following way:

$P_{CF} = 1$ if no intrusion barrier is installed

and

$P_{CF} = \lambda$ if an intrusion barrier is installed

where λ is the failure rate of the intrusion barrier

Although there is currently no reliable value for λ , its inclusion in the ATAPAM enables sensitivity analysis of its effect on intrusion probability and ATA risk. This in turn may provide guidance for target levels of effectiveness and consequent design parameters for intrusion barriers. The notation P_{CF} corresponds to the event notation in the ATA fault tree (Figure 2.5). Combining this probability with the probability of lateral displacement of derailed equipment exceeding track center spacing (equation 6.3), the conditional probability of intrusion given a train derailment can be expressed as follows:

$$P(I|T) = P_{CF} \times P(x \geq X) \quad (6.4)$$

6.2.3 Train Presence Probability, $P(T|I/D)$

The conditional probability of train presence given an intrusion consists of two parts: base train presence probability and failure to apply train brakes due to equipment failure or human errors (Figure 2.5).

6.2.3.1 Base Train Presence Probability

Train presence probability on a track segment is derived in chapter 5 as follows:

$$1 - \prod_i (1 - P_{T,TM_i}) \times \prod_j (1 - P_{T,TP_j}) \quad (6.5)$$

where:

P_{T,TM_i} : adjacent track collision probability for the ith TM activities

P_{T,TP_j} : adjacent track collision probability for the jth TP activities

i: total number of TM in the track segment

j: total number of TP in the track segment

Details regarding derivations of adjacent track collision probability are described in subsection 5.2. This model considers track alignment, point of derailment, train speed, traffic density, and braking capability as quantitative factors.

6.2.3.2 Failure to Apply Train Brakes

The base train presence probability assumes the train's brakes are applied and function properly. This may not always be the case because brake components may malfunction, or the engineer might not operate the brakes properly. There are only a few studies regarding the reliability of certain train brake system and components (Yang et

al., 2016; Cai et al., 2018). They focus on specific brake systems or particular braking components. Consequently, the analysis results are not general enough to be implemented in the ATAPAM. The methods introduced in these studies can be applied when appropriate data are available.

There has been considerable research on human error in railroad operations (Wilson and Norris, 2005; Reinach and Viale, 2006; Wilson et al., 2007; Baysari et al., 2008; Wilson, 2014; Madigan et al., 2016; Zhan et al., 2017; Kyriakidis et al., 2018; Zhou and Lei 2018); however, no previous study has focused on human error in train brake operations.

The probability of braking system failure is defined as follows:

$$P_{FB} = 1 - (1 - \lambda_{EB}) \times (1 - \lambda_{HB})$$

where λ_{EB} is the failure rate of the train braking system, and λ_{HB} is the failure rate of brake application due to human error.

Although there is currently no reliable value for λ_{EB} and λ_{HB} , its inclusion in the ATAPAM enables sensitivity analysis of its effect on train presence probability and ATA risk. The notation P_{FB} corresponds to the event notation in the ATA fault tree.

Combining this probability with the probability of train presence on adjacent tracks (equation 6.5), the conditional probability of train presence given an intrusion can be expressed as follows:

$$1 - \prod_i ((1 - P_{T,TM_i}) \times (1 - P_{FB,TM_i})) \times \prod_j ((1 - P_{T,TP_j}) \times (1 - P_{FB,TP_j})) \quad (6.6)$$

6.2.4 Qualitative Factors

Factors that are not quantified in the models but affect ATA probability are considered qualitatively as risk indicators (Table 6.2). The presence of each factor adds one point to the risk indicator if it increases the ATA probability and subtracts one point from the risk indicator if it reduces the ATA probability. The higher the risk indicator points the greater the likelihood of an ATA. Given the same quantitative value of ATA probability, track segments with positive points in the risk indicator have a higher chance of having an ATA; if the risk indicator points are negative for a track segment, it means that the ATA probability is reduced.

Table 6.2: Qualitative factors and risk indicator

Factor	Risk Indicator Point Description
Curvature	Add 1 point if the track segment is in a curve
Grade	Add 1 point if the track segment is on a grade
Adjacent Structure	Add 1 point if there are adjacent structures along the track segment
Elevation Differential	Add 1 point if the track where the intruding train is running on is higher in altitude than the adjacent track; subtract 1 point if the track where the intruding train is running on is lower in altitude than the adjacent track
Train Speed	Add 1 point if the maximum speed of trains on the adjacent track is greater than 60 mph; subtract 1 point if the maximum speed of trains on the adjacent track is less than 30 mph.
Intrusion Detection	Subtract 1 point if intrusion detection device/system is installed

6.3 Case Study

6.3.1 Hypothetical Corridor

The hypothetical rail corridor consists of a 200-mile SRC with four tracks: S1, S2, P1 and P2 (Figure 6.3). Tracks S1 and S2 are two main tracks with 90% freight train traffic and 10% passenger traffic; Tracks P1 and P2 are two main tracks with pure passenger traffic. Assume that there is a concern for potential ATA risk between track S2 and P1, and the railroad operators on both tracks want to understand where along the corridor has high ATA risk, especially the probability of ATA where trains on Track S2 derail and intrude onto Track P1, and either strike, or are struck, by trains on Track P1. There is also ATA risk between track pair S1/S2, P1/P2, S1/P1, S2/P2, and S1/P2, but for the purpose of model demonstration, I specifically evaluate the ATA probability between tracks S2 and P1.

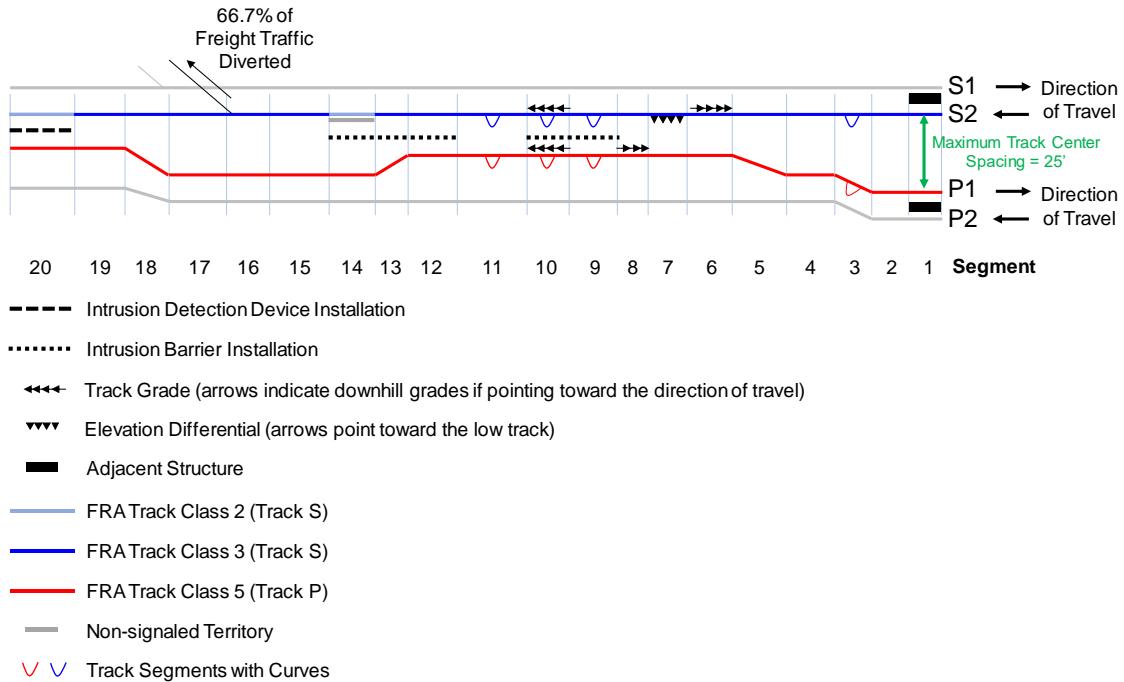


Figure 6.3: Hypothetical SRC layout

The average TM frequency between freight trains on Track S2 and passenger trains on Track P1 is four; the average TM frequency between passenger trains on Track S2 and passenger trains on Track P1 is one. The average TM spacing is five miles (26,400 feet). Assume tracks S2 and P1 are not connected so there is no TP event possible between these two tracks. The maximum track separation between tracks S2 and P1 is 25 feet, making this a shared-ROW corridor.

The corridor is divided into 20 segments based on infrastructure, rolling stock, and operational characteristics (Table 6.3). At the end of segment 16, two thirds of the freight train traffic from track S2 is diverted to another route. Therefore, from segment 17 to segment 20, Track S2 has 75% freight train traffic and 25% passenger train traffic. The average TM frequency is thus reduced to one.

Table 6.3: Segment input for the hypothetical SRC

Segment	Track S2							Track P1							TS	ED
	TC	G	C	S	AS	MSF	MSP	TC	G	C	S	AS	MS			
1	3	0	0	1	1	20	40	5	0	0	1	1	50	25	0	
2	3	0	0	1	0	25	45	5	0	0	1	0	55	25	0	
3	3	0	1	1	0	25	45	5	0	1	1	0	55	22	0	
4	3	0	0	1	0	39	59	5	0	0	1	0	79	20	0	
5	3	0	0	1	0	39	59	5	0	0	1	0	79	17	0	
6	3	+1	0	1	0	39	59	5	0	0	1	0	79	15	+1	
7	3	0	0	1	0	30	55	5	0	0	1	0	79	15	+1	
8	3	0	0	1	0	39	59	5	+1	0	1	0	79	15	+1	
9	3	0	1	1	0	39	59	5	0	1	1	0	79	15	0	
10	3	-1	1	1	0	39	59	5	-1	1	1	0	79	15	0	
11	3	0	1	1	0	39	59	5	0	1	1	0	79	15	0	
12	3	0	0	1	0	39	59	5	0	0	1	0	79	15	0	
13	3	0	0	1	0	30	45	5	0	0	1	0	79	18	0	
14	2	0	0	0	0	20	29	5	0	0	1	0	79	20	0	
15	3	0	0	1	0	30	45	5	0	0	1	0	79	20	0	
16	3	0	0	1	0	39	59	5	0	0	1	0	79	20	0	
17	3	0	0	1	0	30	59	5	0	0	1	0	79	20	0	
18	3	0	0	1	0	25	50	5	0	0	1	0	75	17	0	
19	3	0	0	1	0	20	40	5	0	0	1	0	60	14	0	
20	2	0	0	0	0	15	25	5	0	0	1	0	40	14	0	

TC: FRA track class

AS: presence of adjacent structure

G: track grade

TS: track spacing

C: presence of curve

ED: elevation differential

S: presence of signaling system

MSF: maximum operating speed for freight train (track S2)

MS: maximum operating speed for passenger train (track S2)

MS: maximum operating speed for passenger train (track P1)

I selected track segment 11 to perform an example calculation using following steps:

1. The freight train derailment rate is 0.074 per billion gross-ton-miles, which is converted to 0.264 derailments per million freight-train-miles using the average gross tons per train load (AAR, 2016). The passenger train derailment rate is 0.126 per million passenger-train-mile (Table 3.2). The initial derailment on track S2 for this segment is calculated using equation 6.1:

$$P(D) = \frac{\sum R_i \times T_i}{\sum T_i} = \frac{0.264 \times 0.9 + 0.126 \times 0.1}{0.9 + 0.1} = 0.2498$$

2. The intrusion rate is calculated using equation 6.3:

$$\begin{aligned} P(I|D) &= P_{CF} \times P(x \geq X) = 1 \times (1 - F(X; \alpha, \beta)) = 1 \times (1 - F(15; 1.2, 33.0)) \\ &= 0.7228 \end{aligned}$$

The failure rate of the intrusion barrier, P_{CF} , is assumed to be one because there is no intrusion barrier or containment installed on this track segment.

3. The train presence rate for a TM between a freight train on Track S2 and a passenger train on Track P1 is 0.3584; the train presence rate for a TM between a passenger train on Track S2 and a passenger train on Track P1 is 0.3831. The train presence probability for this segment is calculated using equation 6.6, assuming there is no braking failure due to human errors or mechanical failure ($P_{FB} = 0$):

$$\begin{aligned} P(T) &= 1 - \prod_i \left((1 - P_{T,TM_i}) \times (1 - P_{FB,TM_i}) \right) \times \prod_j \left((1 - P_{T,TP_j}) \times (1 - P_{FB,TP_j}) \right) \\ &= 1 - ((1 - 0.2203) \times (1 - 0))^4 \times ((1 - 0.2512) \times (1 - 0)) \\ &= 0.7233 \end{aligned}$$

4. The quantitative probability value of ATA (number of ATAs per million train mile) for this segment is:

$$P_{ATA, \text{ segment } 11} = P(D) \times P(I|D) \times P(T|I|D) = 0.2498 \times 0.7228 \times 0.7233 = 0.1306$$

5. There is only one qualitative factor in this segment, curvature, which is expected to increase intrusion rate. Therefore, the risk indicator for this segment, $R_{ATA,11}$, is +1.
6. The ATA probability for track segment 11, P_{11} , is:

$$(P_{ATA}, R_{ATA}) = (0.1306, +1)$$

The probability of an ATA is calculated for all segments on the SRC (Table 6.4). Segment 14 has the highest ATA probability mainly due to high initial derailment rate. There is already an intrusion barrier installed in the segment, so the overall ATA probability can be reduced based on how the intrusion barrier can absorb the impact from derailed equipment and prevent it from intruding onto the adjacent track. Segment 20 also has high ATA risk due to the high initial derailment rate. The suggested risk mitigation measure is to upgrade the track to higher track class or install a signaling system for the segment. Segments 6 through 12 all have the same initial derailment and intrusion probability due to similar infrastructure characteristics and track spacing, but their ATA probabilities differ because of different track alignment resulting in different train

presence probabilities. Segments with high train presence probability are usually associated with high maximum operating speed. The effect of grade and curve on train presence probability is relatively less. Intrusion probability is a direct function of track spacing, but as mentioned in chapter 6, this could change once the reliability data for intrusion barriers are available.

Table 6.4: ATA risk calculation output for the hypothetical SRC

Segment	P(D)	P(I D)	P(T I D)	P(ATA)	R(ATA)
1	0.2498	0.5600	0.4665	0.0653	1
2	0.2498	0.5600	0.5164	0.0722	0
3	0.2498	0.6054	0.5155	0.0780	1
4	0.2498	0.6373	0.7251	0.1154	0
5	0.2498	0.6876	0.7251	0.1246	0
6	0.2498	0.7228	0.7152	0.1291	2
7	0.2498	0.7228	0.7000	0.1264	1
8	0.2498	0.7228	0.7494	0.1353	1
9	0.2498	0.7228	0.7233	0.1306	0
10	0.2498	0.7228	0.7155	0.1292	1
11	0.2498	0.7228	0.7233	0.1306	0
12	0.2498	0.7228	0.7251	0.1309	-1
13	0.2498	0.6705	0.6881	0.1153	-1
14	0.5544	0.6373	0.6551	0.2315	-1
15	0.2498	0.6373	0.6881	0.1095	0
16	0.2498	0.6373	0.7251	0.1154	0
17	0.6459	0.6373	0.4046	0.1666	0
18	0.6459	0.6876	0.3627	0.1611	0
19	0.6459	0.7408	0.2738	0.1310	0
20	1.5062	0.7408	0.1801	0.2009	-1

6.4 ATA Probability Assessment Procedure and Guidance

The ATAPAM provides a generic ATA probability assessment framework. There are several assumptions and simplifications for the model configuration, input parameters and probability calculations due to the lack of certain quantitative data. These

assumptions can be removed or modified to improve the accuracy of ATAPAM if proper quantitative data are available. Models in the ATAPAM can also be modified or customized to best suit the needs of the users. The following paragraphs provide guidance for use of the ATAPAM.

6.4.1 Initial Derailment Rate

The calculation of initial derailment rate can vary due to available data and the resolution of the analysis. Proper selection of accident and traffic data is important, and the following paragraphs provide guidance on choosing and use of these data.

Train derailment data: The default initial train derailment rate in the ATAPAM is calculated using historical national train accident data developed by the United States Department of Transportation (USDOT) Federal Railroad Administration (FRA). If train derailment data specific to the railroad corridor of interest, or for corridors with similar characteristics to the corridor of interest are available, a more representative set of train derailments can be used to calculate the initial derailment rate.

Traffic data: The default traffic data used to calculate the initial derailment rate are the national traffic from the Class I railroads and Amtrak in the US. If specific traffic data for the corridor of interest, or corridors that have similar train, track, and operational characteristics to the corridor of interest are available, these can be used instead. The default unit of traffic data is train-mile because it is applicable to both passenger and

freight train traffic. The use of different units for traffic data is possible, but the selected units should make sense and be consistent for all types of trains operating on the corridor.

Initial derailment rate evaluation: The ATAPAM provides a weighted average for initial derailment rate on a SRC using nation-wide average passenger and freight train derailment rates. This is based on the assumption that derailment rate is proportional to the different types of traffic. If train derailment and traffic data are available for a particular corridor, a more accurate initial derailment rate can be developed without using the weighted average equation.

6.4.2 Conditional Probability of Intrusion

Track center spacing: The current intrusion probability model uses track center spacing as the only quantitative factor to evaluate the probability. If empirical or simulation data are available to account for the effect of other factors, such as curvature, grade, or the presence of an intrusion barrier, then the model can be modified to obtain a more accurate intrusion probability.

Reliability of intrusion barriers and containment systems: Currently the ATAPAM does not specify a default value for the failure rate of intrusion barriers and containment. If a track segment lacks these, or they are only installed on a portion of the corridor, the failure rate of intrusion barriers or containment of segments without them should be set to one. For segments that have intrusion barriers completely installed, an

estimated failure rate for the intrusion probability calculation should be based on expert judgement for the particular design and location.

Other qualitative factors: While dividing a railroad corridor of interest into segments, model users should document the factors that would qualitatively affect the intrusion probability in each segment, including track alignment (grade and curvature), train speed, elevation differential, and the presence of adjacent structures. These factors are evaluated qualitatively for now, but will be incorporated into the quantitative probability assessment when proper data are available.

6.4.3 Conditional Probability of Train Presence Given an Intrusion

When using the train presence model, users should define the resolution of the adjacent track collision analysis they want to conduct. For example, will each train be considered as an individual input, or will an average set of values be used for a group or type of train operation as presented in the case study.

Train meet and pass activities: If trains on the corridor of interest follow scheduled operation, direct calculation of the number and average spacing of TM and TP activities is preferable. If trains are running with unscheduled operation or there are multiple types of trains on the corridor with a more complicated operating schedule, the method described in chapter 5 can be used.

Braking capability: Braking capability is an important input as it determines the critical distance (CD) in an adjacent track collision scenario (see subsection 5.2.2). Model users may want to group trains with similar braking characteristics and develop a representative braking distance to be used for trains in each group. This will simplify the process of calculating the CDs and adjacent track collision probabilities for interactions between different types of trains operating on the corridor. The braking capability should also account for infrastructure characteristics such as track curvature and grade.

Train deceleration rate: The train deceleration rate, b, used in the braking distance calculation can be customized for different types of trains (see subsection 5.2.2). Depending on the resolution of the analysis, a general deceleration rate for the various different types of passenger and freight trains can be used, or model users can calculate customized deceleration rates for each specific type of train on the corridor.

Reliability of braking system and human brake operations: Currently the ATAPAM does not specify default values for the failure rate of braking systems due to either human error or mechanical failures. Depending on the resolution of the analysis desired, model users can specify the failure rates for braking systems due to these factors based on their best knowledge.

Other qualitative factors: A qualitative factor that could affect train presence probability, but is not quantified is the presence of an intrusion detection system. Model users should document the presence and type of detection system in place at locations

along the corridor. When quantitative data about the reliability and effectiveness of these detection systems are available, their effects can be quantitatively evaluated using a revised and updated ATAPAM.

6.5 The Semi-Quantitative ATA Risk Assessment Model and ATAPAM

In chapter 4, I introduced a semi-quantitative risk assessment model for ATAs that provides a screening-level risk assessment tool using a risk index system to rank and identify track segments on a railroad corridor that has high ATA risk and may require a more detailed quantitative risk assessment. Use of ATAPAM can provide this sort of analysis by incorporating more detailed track, train, and operational inputs.

Deciding whether to use the semi-quantitative ATA risk assessment model or ATAPAM will depend on the scope and resolution of the risk analysis needed. The semi-quantitative risk model can be used for preliminary risk assessment to identify the portions of a rail corridor that appear to have relatively high ATA risk. These locations may in turn require more detailed risk assessment and possible mitigation. For these segments, ATAPAM can be used to conduct quantitative assessments to evaluate the probability of an ATA, identify the factors or characteristics contributing most to the ATA risk on those segments, and to evaluate the effectiveness of possible risk reduction measures.

6.6 Conclusions

In this chapter, I described a generic ATA probability assessment model, ATAPAM. The model consists of three probability models to address derailment, intrusion, and train presence probability. I evaluate segment-level ATA probability using a combination of quantitative probability values and qualitative risk indicators. A case study is presented to demonstrate the use of the ATAPAM with a step-by-step procedure. Additional guidance is provided for users to customize the model to best suit their particular circumstances and requirements. ATAPAM provides the first comprehensive attempt at a ATA risk assessment framework. With appropriate quantitative data and statistics, the ATAPAM has the flexibility to be extended or modified to improve the accuracy of probability evaluation.

CHAPTER 7

CONCLUSIONS AND FUTURE WORK

7.1 Introduction

In this dissertation, I describe the development and application of a probabilistic model to address the probability of adjacent track accidents (ATAs). Using probabilistic risk assessment (PRA) methodology, I construct an ATA risk assessment framework consisting of three probability models and identify factors influencing these models and their effects. I develop a step-by-step procedure and guidance for evaluating the ATA probability and present a case study as an example demonstration and usage of the comprehensive risk assessment model. My work has led to a number of conclusions and contributions that I summarize below.

7.2 Conclusions

7.2.1 Event Tree and Fault Tree Analysis for Adjacent Track Accidents

Event tree analysis and Fault Tree Analysis (FTA) are used to develop a comprehensive understanding of ATAs and a novel approach to address its probability. Basic events leading to the occurrence of an ATA are identified and their logical relationship is investigated. The overall probability of an ATA can be evaluated using the fault tree. Using this PRA process I developed a risk assessment framework to conduct more detailed risk analyses to address each probability component of an ATA, which leads to probability analyses on train derailment, intrusion, and train presence on adjacent tracks.

7.2.2 Passenger Train Accident Analysis

I investigated passenger train accidents in the United States using statistical and causal analysis, to understand the general trend in rates of different types of passenger train accidents. Derailments and collisions have higher consequences than other accident types and are also more relevant to ATAs. I conducted a causal analysis for those derailments and collisions and identify the most important accident causes leading to more frequent or more severe train derailments and collisions. The results I obtained provide passenger derailment rates needed for the initial train derailment probability calculation in the ATA risk assessment model.

7.2.3 Train Intrusion Analysis

I identified the factors affecting the intrusion probability of rail equipment in derailments and investigated their effects. Track center spacing is quantified to evaluate intrusion probability while track alignment, adjacent structures, speed, elevation differential and intrusion barrier are identified as qualitative factors. Their effects can be quantified when proper data are available and analyzed or simulations performed. I develop a semi-quantitative risk assessment model to provide a risk assessment tool to evaluate ATA probability as an intermediate step towards developing a more comprehensive risk ATA assessment model.

7.2.4 Train Presence Analysis

I develop a novel approach to quantify the probability of collision between a train intruding onto an adjacent track while another train operates on that track. I investigate common practices of train meet and pass activities on railroad corridors and calculate the frequency of these events. Factors affecting the train presence probability are identified, including train spacing, track alignment, point of derailment, speed and braking capability. I then develop a probabilistic model to calculate the train presence probability accounting for those factors and traffic density.

7.2.5 ATA Probability Assessment Model

I develop the Adjacent Track Accident Probability Assessment Model (ATAPAM) combining the three probability models I previously developed. The ATAPAM calculates ATA probability by dividing a railroad corridor into different segments and evaluating the ATA probability for each segment by its infrastructure, rolling stock, and operational characteristics. This model evaluates the ATA probability by providing a quantitative ATA probability and a risk indicator showing additional or potentially reduced ATA probability. The main contribution of this model is to provide a standard procedure and guidance for evaluating the ATA probability on an existing or newly planned railroad corridor and to manage ATA risk more effectively and efficiently.

7.3 Future Work

The research I present in this dissertation improves our understanding of ATAs and allows the evaluation and comparison of ATA probability based on infrastructure,

rolling stock and operation characteristics. With the comprehensive risk assessment framework developed and described in this dissertation, I summarize future research opportunities that can improve the accuracy of the ATAPAM or extend the range and utility of the model.

7.3.1 Common Cause Failure Analysis of ATA

In the ATA fault tree, I assumed that all of the basic events are independent of each other. In other words, the probability of one basic event does not affect the probability of other basic events. This assumption can change because some basic events may have dependencies that are not within the original design of the system, such as common environmental factors or human interactions. Common cause failures (CCFs) are dependencies among basic events that are not explicitly modeled by PRA logic such as FTA (Mosleh et al., 1988; 1998; Sakurahara et al., 2019). For example, initial derailment is deducted into train accident causes as basic events in the ATA fault tree (Figure 2.5). I assumed that each train derailment is assigned a unique accident cause based on the way the train accident data I use are structured, and thus all accident causes are treated as basic events independent of each other. However, some accident causes may contribute to the occurrence of other accident causes, and train accidents can be caused by a combination of multiple accident causes. CCFs are important in system reliability engineering and addressing CCFs in ATAPAM can improve its accuracy in probability evaluation.

7.3.2 Human Factor Analysis

Many of the elements in the ATA probability directly or indirectly involve human factors. For example, some initial derailments are caused by human factors, and there might be human errors associated with the reliability of train brake systems and applications. Hence, it is an important future research direction to incorporate more extensive human factors analysis into the ATA risk assessment.

7.3.3 Full Quantification of Intrusion Probability

Current constraints in data availability prevent me from developing a fully quantitative intrusion probability model. There are two methods to collect more data for the quantification of this probability. The first is investigating more recent train derailments that resulted in an intrusion and obtaining the lateral displacement of derailed equipment. By so doing one could update the intrusion probability distribution and account for more factors if a sufficient amount of data is collected to perform statistical analysis. The second method is using train derailment simulation software to estimate rail equipment motion in derailment scenarios (Simon and Kirkpatrick, 1999; Kirkpatrick et al., 2001). Using derailment simulation, one could produce data on the distribution of the amount of lateral displacement of derailed equipment under different circumstances (different track curvature and grade, for example) and the interactions between intrusion barriers and derailed equipment. These data will help to develop the fully quantitative intrusion probability model.

7.3.4 Component Reliability Analysis

One of the assumptions in the ATAPAM is that components or devices in the systems will all function if present. For example, when evaluating the train presence probability, I assumed that the train brakes always function properly without considering the possible range in braking performance that might occur. Another example is that in the intrusion probability evaluation, I assume that when a barrier is present it will always function properly and reduce intrusion probability. This may not always be true because intrusion barriers can fail for a number of reasons. When data are available, consideration of those and other components that play a role in the ATAPAM would further improve the utility and accuracy of the model.

7.3.5 Consequence for ATA

Risk consists of probability and consequence. In my dissertation research I develop the probability estimation for ATAs, but the consequence of ATAs is equally important to address total risk. Casualties, infrastructure damage, rolling stock damage, environmental damage, and other impacts of ATAs are important in the risk assessment process and should be the subject of further research.

7.3.6 Evaluations of ATA Risk Mitigation Measures

The ATAPAM developed in my dissertation research can be used to evaluate the effectiveness of risk mitigation strategies. Model users can then determine the most effective and efficient risk mitigation measures for specific track segments by combining the results with a decision analysis framework that includes cost-benefit analysis. The

effectiveness of these risk mitigation measures can be compared to their implementation and maintenance costs to determine the most cost-effective options and allocations of risk reduction resources. If suitable data are available, an optimization framework using operations research methodologies to identify the best solutions may be feasible.

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APPENDIX A: FRA ACCIDENT CAUSE CODES AND ADL CAUSE GROUPINGS

FRA Accident Cause Group	ADL Cause Subgroup	FRA Train-Accident Cause Code	Accident Cause Code Description
Roadbed Defects	01T	T001	Roadbed Settled or Soft
		T099	Other Roadbed Defects
Infrastructure Damage Causes	02T	T002	Washout/rain/slide/flood/snow/ice damage to track
		T401	Bridge Misalignment or Failure
		T402	Flangeway Clogged
		T403	Engineering Design or Construction
Wide Gauge	03T	T110	Wide Gage (due to defective or missing crossties)
		T111	Wide Gage (due to defective or missing spikes or other rail fasteners)
		T112	Wide Gage (due to loose, broken, or defective gage rods)
		T113	Wide Gage (due to worn rails)
Track Geometry (excl. Wide Gauge)	04T	T101	Cross Level of Track Irregular (at joints)
		T102	Cross Level of Track Irregular (not at joints)
		T103	Deviation from Uniform Top of Rail Profile
		T104	Distributed Ballast Selection
		T105	Insufficient Ballast Selection
		T106	Superelevation Improper, Excessive, or Insufficient
		T107	Superelevation Runoff Improper
		T108	Track Alignment Irregular (other than buckled/sunkink)
		T199	Other Track Geometry Defects
Buckled Track	05T	T109	Track Alignment Irregular (buckled/sunkink)
Rail Defects at Bolted Joint	06T	T201	Broken Rail - Bolt hole crack or break
		T211	Broken Rail - Head and web separation (within joint bar limits)
		T213	Joint bar broken (compromise)
Joint Bar Defects	07T	T214	Joint bar broken (insulated)
		T215	Joint bar broken (noninsulated)
		T216	Joint bolts, broken, or missing
Broken Rails or Welds	08T	T202	Broken Rail - Base
		T203	Broken Rail - Weld (plant)
		T204	Broken Rail - Weld (field)
		T207	Broken Rail - Detail fracture from shelling or head check
		T208	Broken Rail - Engine burn fracture
		T210	Broken Rail - Head and web separation (outside joint bar limits)
		T212	Broken Rail - Horizontal split head
		T218	Broken Rail - Piped rail
		T219	Rail defect with joint bar repair
		T220	Broken Rail - Transverse/compound fissure
		T221	Broken Rail - Vertical split head
Other Rail and Joint Defects	09T	T299	Other rail and joint bar defects (Provide detailed description in narrative)
Turnout Defects - Switches	10T	T307	Spring/power switch mechanism malfunction
		T308	Stock rail worn, broken or disconnected
		T309	Switch (hand operated) stand mechanism broken, loose, or worn
		T310	Switch connecting or operating rod is broken or defective
		T311	Switch damaged or out of adjustment
		T312	Switch lug/crank broken
		T313	Switch out of adjustment because of insufficient rail anchoring
		T314	Switch point worn or broken
		T315	Switch rod worn, bent, broken, or disconnected
		T319	Switch point gapped (between switch point and stock rail)
Turnout Defects - Frogs	11T	T304	Railroad crossing frog, worn or broken
		T316	Turnout frog (rigid) worn, or broken
		T317	Turnout frog (self guarded), worn or broken
		T318	Turnout frog (spring) worn, or broken
Misc. Track and Structure Defects	12T	T404	Catenary System Defect
		T205	Defective or missing crossties (use code T110 if results in wide gage)
		T206	Defective spikes or missing spikes or other rail fasteners (use code T111 if results in wide gage)
		T217	Mismatched rail-head contour
		T222	Worn rail
		T223	Rail Condition - Dry rail, freshly ground rail
		T224	Rail defect originating from bond wire attachment (Provide description in narrative)
		T301	Derail, defective
		T302	Expansion joint failed or malfunctioned
		T303	Guard rail loose/broken or mislocated
		T305	Retarder worn, broken, or malfunctioning
		T306	Retarder yard skate defective
		T399	Other frog, switch and track appliance defects (Provide detailed description in narrative)
		T499	Other way and structure defect (Provide detailed description in narrative)
Train Operation Human Factor (H)	Brake Operation (Main Line)	H510	Automatic brake, insufficient (H001) -- see note after cause H599
		H511	Automatic brake, excessive (H002)
		H512	Automatic brake, failure to use split reduction (H003)
		H513	Automatic brake, other improper use (H004)
		H514	Failure to allow air brakes to fully release before proceeding (H005)
		H515	Failure to properly cut-out brake valves on locomotives (H006)
		H516	Failure to properly cut-in brake valves on locomotives (H007)
		H517	Dynamic brake, insufficient (H009)
		H518	Dynamic brake, excessive (H010)
		H519	Dynamic brake, too rapid adjustment (H011)
		H520	Dynamic brake, excessive axles (H012)
		H521	Dynamic brake, other improper use (H013)
		H525	Independent (engine) brake, improper use (except actuation) (H023)
		H526	Failure to actuate off independent brake (H024)

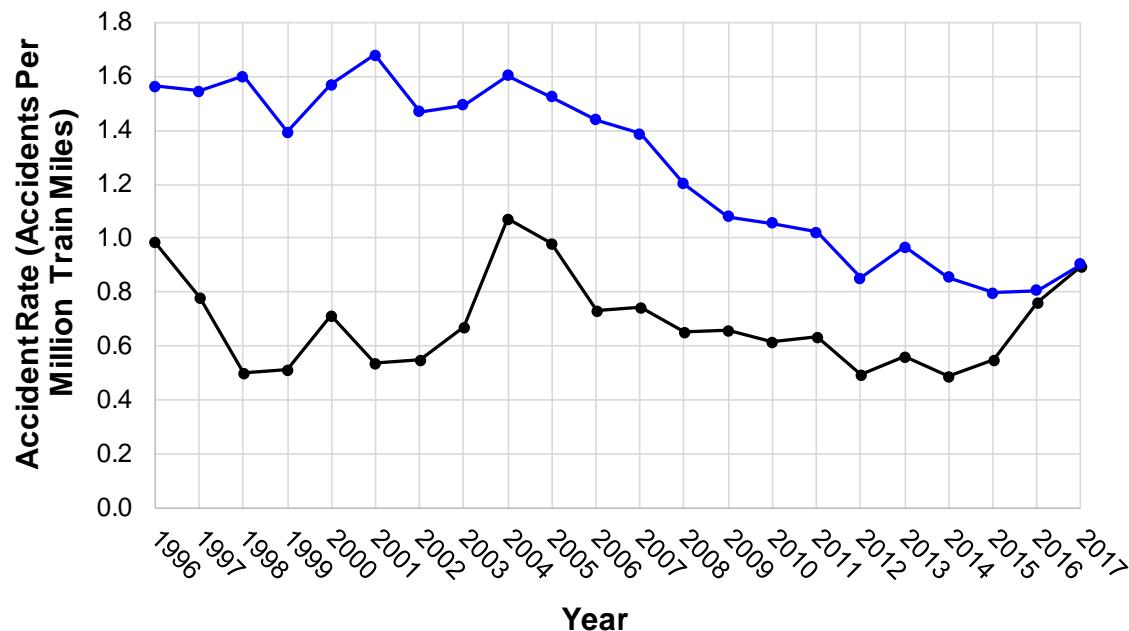
FRA Accident Cause Group	ADL Cause Subgroup	FRA Train-Accident Cause Code	Accident Cause Code Description	
Handbrake Operations	02H	H017	Failure to properly secure engine(s) (railroad employee)	
		H018	Failure to properly secure hand brake on car(s) (railroad employee)	
		H019	Failure to release hand brakes on car(s) (railroad employee)	
		H020	Failure to apply sufficient number of hand brakes on car(s) (railroad employee)	
		H021	Failure to apply hand brakes on car(s) (railroad employee)	
	03H	H022	Failure to properly secure engine(s) or car(s) (non railroad employee)	
		H025	Failure to control speed of car using hand brake (railroad employee)	
		M504	Failure by non-railroad employee, e.g., industry employee, to control speed of car using hand brake	
		H008	Improper operation of train line air connections (bottling the air)	
		H099	Use of brakes, other (Provide detailed description in narrative)	
Employee Physical Condition	04H	H101	Impairment of efficiency or judgment because of drugs or alcohol	
		H102	Incapacitation due to injury or illness	
		H103	Employee restricted in work or motion	
		H104	Employee asleep	
		H199	Employee physical condition, other (Provide detailed description in narrative)	
Failure to Obey/Display Signals	05H	H201	Blue Signal, absence of	
		H202	Blue Signal, improperly displayed	
		H204	Fixed signal, failure to comply	
		H205	Flagging, improper or failure to flag	
		H206	Flagging signal, failure to comply	
		H207	Hand signal, failure to comply	
		H208	Hand signal improper	
		H209	Hand signal, failure to give/receive	
		H215	Block signal, failure to comply	
		H216	Interlocking signal, failure to comply	
Train Operation Human Factor (H)	06H	H217	Failure to observe hand signals given during a wayside inspection of moving train	
		H218	Failure to comply with failed equipment detector warning or with applicable train inspection rules.	
		H219	Fixed signal (other than automatic block or interlocking signal), improperly displayed.	
		H220	Fixed signal (other than automatic block or interlocking signal), failure to comply.	
		H221	Automatic block or interlocking signal displaying a stop indication - failure to comply.*	
		H222	Automatic block or interlocking signal displaying other than a stop indication - failure to comply.*	
		H299	Other signal causes (Provide detailed description in narrative)	
		H210	Radio communication, failure to comply	
		H211	Radio communication, improper	
		H212	Radio communication, failure to give/receive	
Switching Rules	07H	H405	Train orders, track warrants, direct traffic control, track bulletins, radio, error in preparation, transmission or delivery	
		H301	Car(s) shoved out and left out of clear	
		H302	Cars left foul	
		H303	Derail, failure to apply or remove	
		H304	Hazardous materials regulations, failure to comply	
		H305	Instruction to trainyard crew improper	
		H306	Shoving movement, absence of man on or at leading end of movement	
		H307	Shoving movement, man on or at leading end of movement, failure to control	
		H308	Skate, failure to remove or place	
		H309	Failure to stretch cars before shoving	
Mainline Rules	08H	H310	Failure to couple	
		H311	Moving cars while loading ramp/hose/chute/cables/bridge plate, etc., not in proper position	
		H312	Passed couplers (other than automated classification yard)	
		H313	Retarder, improper manual operation	
		H314	Retarder yard skate improperly applied	
		H315	Portable derail, improperly applied	
		H316	Manual intervention of classification yard automatic control system modes by operator	
		H317	Humping or cutting off in motion equipment susceptible to damage, or to cause damage to other equipment	
		H318	Kicking or dropping cars, inadequate precautions	
		H399	Other general switching rules (Provide detailed description in narrative)	
Train Handling (excl. Brakes)	09H	H401	Failure to stop train in clear	
		H402	Motor car or on-track equipment rules, failure to comply	
		H403	Movement of engine(s) or car(s) without authority (railroad employee)	
		H404	Train order, track warrant, track bulletin, or timetable authority, failure to comply	
		H406	Train orders, track warrants, direct traffic control, track bulletins, written, error in preparation, transmission or delivery	
		H499	Other main track authority causes (Provide detailed description in narrative)	
		H501	Improper train make-up at initial terminal	
		H502	Improper placement of cars in train between terminals	
		H503	Buffing or slack action excessive, train handling	
		H504	Buffing or slack action excessive, train makeup	
Train Speed	10H	H505	Lateral drawbar force on curve excessive, train handling	
		H506	Lateral drawbar force on curve excessive, train makeup	
		H507	Lateral drawbar force on curve excessive, car geometry (short car/long car combination)	
		H508	Improper train make-up	
		H509	Improper train inspection	
		H522	Throttle (power), improper use (H014)	
		H523	Throttle (power), too rapid adjustment (H015)	
Train Speed	10H	H524	Excessive horsepower (H016)	
		H599	Other causes relating to train handling or makeup (Provide detailed description in narrative)	
		H601	Coupling speed excessive	
		H602	Switching movement, excessive speed	
Train Speed		H603	Train on main track inside yard limits, excessive speed	
		H604	Train outside yard limits, in block signal or interlocking territory, excessive speed	
		H605	Failure to comply with restricted speed in connection with the restrictive indication of a block or interlocking sign	
		H606	Train outside yard limits in nonblock territory, excessive speed	
		H607	Failure to comply with restricted speed or its equivalent not in connection with a block or interlocking signal.	
Train Speed		H699	Speed, other (Provide detailed description in narrative)	

FRA Accident Cause Group	ADL Cause Subgroup	FRA Train-Accident Cause Code	Accident Cause Code Description
Train Operation Human Factor (H)	Use of Switches	11H	H701 Spring Switch not cleared before reversing H702 Switch improperly lined H703 Switch not latched or locked H704 Switch previously run through H705 Moveable point switch frog improperly lined H706 Switch improperly lined, radio controlled H707 Radio controlled switch not locked effectively (Human Error) H799 Use of switches, other (Provide detailed description in narrative)
			H821 Automatic cab signal, failure to comply H822 Automatic cab signal cut out H823 Automatic train-stop device cut out H824 Automatic train control device cut out
			H899 Other causes relating to cab signals (provide detailed description in narrative)
			H991 Tampering with safety/protective device(s)
			H992 Operation of locomotive by uncertified/unqualified person
			H993 Human Factor – track
	Misc. Human Factors	12H	H994 Human Factor - Signal installation or maintenance error (field) H995 Human Factor - Motive power and equipment H996 Oversized loads or Excess Height/Width cars, misrouted or switched. H997 Motor car or other on-track equipment rules (other than main track authority) - Failure to Comply. H999 Other train operation/human factors (Provide detailed description in narrative)
			H99A Human Factor - Signal - Train Control - Installation or maintenance error (shop). H99B Human Factor - Signal - Train Control - Operator Input On-board computer incorrect data entry. H99C Human Factor - Signal - Train Control - Operator Input On-board computer incorrect data provided H99D Computer system design error (non vendor) H99E Computer system configuration/management error (non vendor)
Mechanical and Electrical Factors (E)	Air Hose Defect (Car)	01E	E00C Air hose uncoupled or burst
	Brake Rigging Defect (Car)	02E	E07C Rigging down or dragging
	Handbrake Defects (Car)	03E	E08C Hand brake (including gear) broken or defective E0HC Hand brake linkage and/or connections broken or defective
	UDE (Car or Loco)	04E	E05C Brake valve malfunction (undesired emergency) E05L Brake valve malfunction (undesired emergency) (LOCOMOTIVE)
	Other Brake Defect (Car)	05E	E01C Hydraulic hose uncoupled or burst E02C Broken brake pipe or connections E03C Obstructed brake pipe (closed angle cock, ice, etc.) E04C Other brake components damaged, worn, broken, or disconnected E06C Brake valve malfunction (stuck brake, etc.) E09C Other brake defects, cars (Provide detailed description in narrative)
			E20C Body bolster broken or defective E21C Center sill broken or bent E22C Draft sill broken or bent
			E23C Center plate broken or defective E24C Center plate disengaged from truck (car off center) E25C Center pin broken or missing E26C Center plate attachment defective E27C Side sill broken E29C Other body defects, (CAR) (Provide detailed description in narrative)
			E30C Knuckle broken or defective E31C Coupler mismatch, high/low E32C Coupler drawhead broken or defective E33C Coupler retainer pin/cross key missing
			E34C Draft gear/mechanism broken or defective (including yoke) E35C Coupler carrier broken or defective
	Coupler Defects (Car)	07E	E36C Coupler shank broken or defective (includes defective alignment control) E37C Failure of articulated connectors E39C Other coupler and draft system defects, (CAR) (Provide detailed description in narrative)
	Truck Structure Defects (Car)	08E	E44C Truck bolster broken E45C Side frame broken
	Sidebearing, Suspension Defects (Car)	09E	E40C Side bearing clearance insufficient E41C Side bearing clearance excessive E42C Side bearing(s) broken E43C Side bearing(s) missing E47C Defective snubbing (including friction and hydraulic) E48C Broken, missing, or otherwise defective springs (including incorrect repair and/or installation)
	Bearing Failure (Car)	10E	E52C Journal (plain) failure from overheating E53C Journal (roller bearing) failure from overheating
	Other Axle/Journal Defects (Car)	11E	E51C Broken or bent axle between wheel seats E54C Journal fractured, new cold break E55C Journal fractured, cold break, previously overheated E59C Other axle and journal bearing defects (CAR) (Provide detailed description in narrative)
	Broken Wheels (Car)	12E	E60C Broken flange E61C Broken rim E62C Broken plate E63C Broken hub E6AC Thermal crack, flange or tread
	Other Wheel Defects (Car)	13E	E64C Worm flange E65C Worm tread E66C Damaged flange or tread (flat) E67C Damaged flange or tread (build up) E68C Loose wheel E69C Other wheel defects (CAR) (Provide detailed description in narrative)
	TOFC/COFC Defects	14E	E11C Broken or defective tiedown equipment E12C Broken or defective container E13C Broken or defective trailer E19C Other trailer or container on flat car defects (Provide detailed description in narrative)

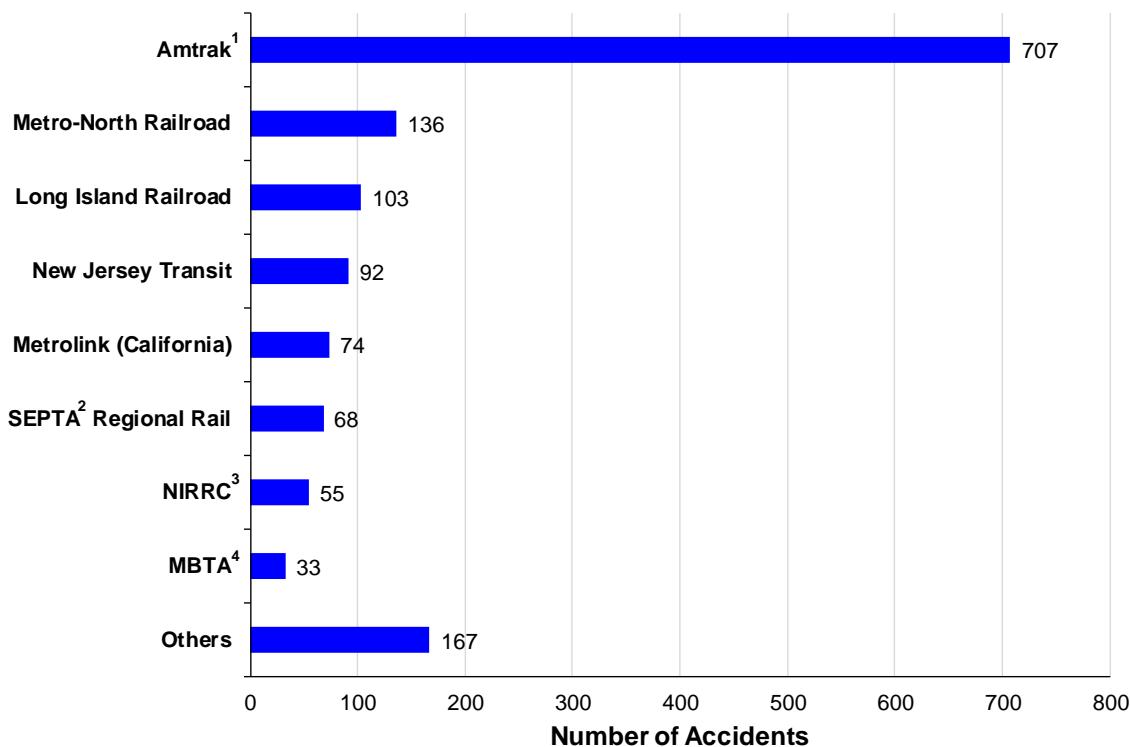
FRA Accident Cause Group	ADL Cause Subgroup	FRA Train-Accident Cause Code	Accident Cause Code Description	
Loco Trucks/Bearings/ Wheels	15E	E07L	Rigging down or dragging (LOCOMOTIVE)	
		E40L	Side bearing clearance insufficient (LOCOMOTIVE)	
		E41L	Side bearing clearance excessive (LOCOMOTIVE)	
		E42L	Side bearing(s) broken (LOCOMOTIVE)	
		E43L	Side bearing(s) missing (LOCOMOTIVE)	
		E44L	Truck bolster broken (LOCOMOTIVE)	
		E45L	Side frame broken (LOCOMOTIVE)	
		E46L	Truck bolster stiff, improper lateral or improper swiveling (LOCOMOTIVE)	
		E47L	Defective snubbing (LOCOMOTIVE)	
		E48L	Broken, missing, or otherwise defective springs (LOCOMOTIVE)	
		E49L	Other truck component defects, (LOCOMOTIVE) (Provide detailed description in narrative)	
		E4TL	Truck hunting (LOCOMOTIVE)	
		E51L	Broken or bent axle between wheel seats (LOCOMOTIVE)	
		E52L	Journal (plain) failure from overheating (LOCOMOTIVE)	
		E53L	Journal (roller bearing) failure from overheating- LOCOMOTIVE	
		E54L	Journal fractured, new cold break (LOCOMOTIVE)	
		E55L	Journal fractured, cold break, previously overheated (LOCOMOTIVE)	
		E59L	Other axle and journal bearing defects (LOCOMOTIVE) (Provide detailed description in narrative)	
		E60L	Broken flange (LOCOMOTIVE)	
		E61L	Broken rim (LOCOMOTIVE)	
		E62L	Broken plate (LOCOMOTIVE)	
		E63L	Broken hub (LOCOMOTIVE)	
		E64L	Worn flange (LOCOMOTIVE)	
		E65L	Worn tread (LOCOMOTIVE)	
		E66L	Damaged flange or tread (flat) (LOCOMOTIVE)	
		E67L	Damaged flange or tread (build up) (LOCOMOTIVE)	
		E68L	Loose wheel (LOCOMOTIVE)	
		E69L	Other wheel defects (LOCOMOTIVE) (Provide detailed description in narrative)	
		E6AL	Thermal crack, flange or tread (LOCOMOTIVE)	
		E70L	Running gear failure (LOCOMOTIVE)	
		E77L	Broken or defective swing hanger or spring plank (LOCOMOTIVE)	
		E78L	Pantograph defect (LOCOMOTIVE)	
		E7BL	Third rail shoe or shoe beam (LOCOMOTIVE)	
Loco Electrical and Fires	16E	E71L	Traction motor failure (LOCOMOTIVE)	
		E72L	Crank case or air box explosion (LOCOMOTIVE)	
		E73L	Oil or fuel fire (LOCOMOTIVE)	
		E74L	Electrically caused fire (LOCOMOTIVE)	
		E76L	Remote control equipment inoperative (LOCOMOTIVE)	
		E7AL	On-board computer - failure to respond (LOCOMOTIVE)	
Mechanical and Electrical Factors (E)		E00L	Air hose uncoupled or burst (LOCOMOTIVE)	
		E01L	Hydraulic hose uncoupled or burst (LOCOMOTIVE)	
		E02L	Broken brake pipe or connections (LOCOMOTIVE)	
		E03L	Obstructed brake pipe (closed angle cock, ice, etc.) (LOCOMOTIVE)	
		E04L	Other brake components damaged, worn, broken, or disconnected (LOCOMOTIVE)	
		E06L	Brake valve malfunction (stuck brake, etc.) (LOCOMOTIVE)	
		E08L	Hand brake (including gear) broken or defective (LOCOMOTIVE)	
		E09L	Other brake defects. (Provide detailed description in narrative) (LOCOMOTIVE)	
		E0HL	Hand brake linkage/Connections broken/defective (LOCOMOTIVE)	
		E10L	Computer controlled brake communication failure (LOCOMOTIVE)	
		E20L	Body bolster broken or defective (LOCOMOTIVE)	
		E21L	Center sill broken or bent (LOCOMOTIVE)	
		E22L	Draft sill broken or bent (LOCOMOTIVE)	
		E23L	Center plate broken or defective (LOCOMOTIVE)	
		E24L	Center plate disengaged from truck unit/off center (LOCOMOTIVE)	
		E25L	Center pin broken or missing (LOCOMOTIVE)	
		E26L	Center plate attachment defective (LOCOMOTIVE)	
		E27L	Side sill broken (LOCOMOTIVE)	
		E29L	Other body defects, (LOCOMOTIVE) (Provide detailed description in narrative)	
		E30L	Knuckle broken or defective (LOCOMOTIVE)	
		E31L	Coupler mismatch, high/low (LOCOMOTIVE)	
		E32L	Coupler drawhead broken or defective (LOCOMOTIVE)	
		E32L	Coupler drawhead broken or defective (LOCOMOTIVE)	
		E33L	Coupler retainer pin/cross key missing (LOCOMOTIVE)	
		E34L	Draft gear/mechanism broken/defective (including yoke) (LOCOMOTIVE)	
		E35L	Coupler carrier broken or defective (LOCOMOTIVE)	
		E36L	Coupler shank broken or defective (includes defective alignment control) (LOCOMOTIVE)	
		E37L	Failure of articulated connectors (LOCOMOTIVE)	
		E39L	Other coupler and draft system defects, (LOCOMOTIVE) (Provide detailed description in narrative)	
		E79L	Other locomotive defects (Provide detail description in narrative)	
		E99L	Other mechanical and electrical failures, (LOCOMOTIVE) (Provide detailed description in narrative)	
All Other Locomotive Defects	17E	E4AC	Gib Clearance (lateral motion excessive)	
		E49C	Other truck component defects, including mismatched side frames (CAR) (Provide detailed description in narrative)	
		E80C	Box car plug door open	
		E81C	Box car plug door, attachment defective	
		E82C	Box car plug door, locking lever not in place	
		E83C	Box car door, other than plug, open	
		E84C	Box car door, other than plug, attachment defective	
		E85C	Bottom outlet car door open	
		E86C	Bottom outlet car door attachment defective	
		E89C	Other car door defects (Provide detail description in narrative)	
All Other Car Defects	18E	E99C	Other mechanical and electrical failures, (CAR) (Provide detailed description in narrative)	
		E4BC	Truck bolster stiff (failure to slew)	
		E46C	Truck bolster stiff, improper swiveling	
Stiff Truck (Car)	19E	E4TC	Truck hunting	
Track/Train Interaction (Hunting) (Car)	20E	E75L	Current collector system (LOCOMOTIVE)	
Current Collection Equipment (Loco)	21E			

FRA Accident Cause Group	ADL Cause Subgroup	FRA Train-Accident Cause Code	Accident Cause Code Description
Signal and Communication (S)	Signal Failures 01S	S001	Automatic cab signal displayed false proceed
		S002	Automatic cab signal inoperative
		S003	Automatic train control system inoperative
		S004	Automatic train-stop device inoperative
		S005	Block signal displayed false proceed
		S006	Classification yard automatic control system switch failure
		S007	Classification yard automatic control system retarder failure
		S008	Fixed signal improperly displayed (defective)
		S009	Interlocking signal displayed false proceed
		S010	Power device interlocking failure
		S011	Power switch failure
		S012	Radio communication equipment failure
		S013	Other communication equipment failure
		S014	Computer system design error (vendor)
		S015	Computer system configuration/management error (vendor)
		S016	Classification yard automatic control system - Inadequate or insufficient control (e.g., automatic cycling, other sc
		S099	Other signal failures (Provide detailed description in narrative)
		S101	Remote control transmitter defective
		S102	Remote control transmitter, loss of communication
		S103	Radio controlled switch communication failure
		S104	Radio controlled switch not locked effectively (Equipment Failure)
Obstructions	01M	M101	Snow, ice, mud, gravel, coal, sand, etc. on track
		M402	Object or equipment on or fouling track (motor vehicle - other than highway-rail crossing)
		M403	Object or equipment on or fouling track (livestock)
		M404	Object or equipment on or fouling track - other than above (for vandalism, see code M503)
Grade Crossing Collisions	02M	M301	Highway user impairment because of drug or alcohol usage (as determined by local authorities, e.g., police)
		M302	Highway user inattentiveness
		M303	Highway user misjudgment under normal weather and traffic conditions
		M304	Highway user cited for violation of highway-rail grade crossing traffic laws
		M305	Highway user unawareness due to environmental factors (angle of sun, etc.)
		M306	Highway user inability to stop due to extreme weather conditions (dense fog, ice or snow packed road, etc.)
		M307	Malfunction, improper operation of train activated warning devices
		M308	Highway user deliberately disregarded crossing warning devices
		M309	Suicide (Highway-Rail Grade Crossing Accident)
		M310	Attempted Suicide (Highway-Rail Grade Crossing Accident)
		M399	Other causes (Provide detailed description in narrative)
Lading Problems	03M	M201	Load shifted
		M202	Load fell from car
		M203	Overloaded car
		M204	Improperly loaded car
		M206	Trailer or container tiedown equipment improperly applied
		M207	Overloaded container/trailer on flat car
		M208	Improperly loaded container/trailer on flat car
		M299	Miscellaneous loading procedures (Provide detailed description in narrative)
		M409	Objects such as lading chains or straps fouling switches
		M410	Objects such as lading chains or straps fouling wheels
Miscellaneous (M)	04M	M405	Interaction of lateral/vertical forces (includes harmonic rock off)
		M401	Emergency brake application to avoid accident
		M406	Fire, other than vandalism, involving on-track equipment
		M407	Automatic hump retarder failed to sufficiently slow car due to foreign material on wheels of car being humped
		M408	Yard skates slid and failed to stop cars
		M411	Passed couplers (automated classification yard)
		M501	Interference (other than vandalism) with railroad operations by non-railroad employee
		M502	Vandalism of on-track equipment, e.g., brakes released
		M503	Vandalism of track or track appliances, e.g., objects placed on track, switch thrown, etc.
		M505	Cause under active investigation by reporting railroad (Amended report will be forwarded when reporting railroad)
Other Miscellaneous	05M	M506	Track damage caused by non-railroad interference with track structure
		M507	Investigation complete, cause could not be determined (When using this code, the narrative must include the reason)
		M509	Suicide (Other Miscellaneous)
		M510	Attempted suicide (Other Miscellaneous)
		M599	Other miscellaneous causes (Provide detailed description in narrative)
		M103	Extreme environmental condition - FLOOD
Extreme Weather	06M	M104	Extreme environmental condition - DENSE FOG
		M105	Extreme environmental condition - EXTREME WIND VELOCITY
		M199	Other extreme environmental conditions (Provide detailed description in narrative)

**APPENDIX B: FRA-REPORTABLE MAINLINE PASSENGER AND FREIGHT
TRAIN ACCIDENT RATES, 1996 – 2017**



APPENDIX C: NUMBER OF FRA-REPORTABLE MAINLINE PASSENGER TRAIN ACCIDENTS BY RAILROADS, 1996 – 2017



Note:

1. National Railroad Passenger Corporation
2. Southeastern Pennsylvania Transportation Authority
3. Northeast Illinois Regional Commuter Railroad Corporation
4. Massachusetts Bay Transportation Authority