USDOT Tier 1 University Transportation Center Final Report

NURail Project ID: NURail2013-UIUC-R08

Shared Rail Corridor Adjacent Track Accident Risk Analysis

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DISCLAIMER

Funding for this research was provided by the NURail Center, University of Illinois at Urbana - Champaign under Grant No. DTRT12-G-UTC18 of the U.S. Department of Transportation, Office of the Assistant Secretary for Research & Technology (OST-R), University Transportation Centers Program. The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the information presented herein. This document is disseminated under the sponsorship of the U.S. Department of Transportation's University Transportation Centers Program, in the interest of information exchange. The U.S. Government assumes no liability for the contents or use thereof.

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TECHNICAL SUMMARY

Title

Shared Rail Corridor Adjacent Track Accident Risk Analysis

Introduction

Safety is a high priority for any rail system. There are several safety concerns associated with operating passenger and freight trains on shared-use rail corridors (SRC). Adjacent track accident (ATA) is one of the most important concerns. ATA mainly refers to a train accident scenario where a derailed equipment intrudes adjacent tracks, causing operation disturbance and potential subsequent train collisions on the adjacent tracks. Other ATA scenarios include collisions between trains on adjacent tracks (raking), turnouts and railroad crossings. Limited literature is available that addresses the risk of ATA for shared-use rail corridors. This study presents a comprehensive risk assessment to identify and quantify the effect of factors affecting the likelihood and consequence of ATA. A discussion on how these factors affect the probability and consequence is provided. A semi-quantitative risk analysis model is developed to evaluate the ATA risk incorporating various factors affecting train accident rate, intrusion rate, train presence rate, and accident consequences. A case study with a hypothetical railroad network is presented to illustrate the potential application of the risk model. This research intends to depict a high-level overview of adjacent track accident risk and provides a basis for future quantitative risk analyses and risk mitigation.

Results

Fig. 1 depicts a typical sequence of events of an ATA. Under normal operations, when a train operates on a track, its equipment loading gauge (which defines the allowable height, width, and loads of rolling stock) stays within the clearance envelope of the track. When a train derails, the train's equipment loading gauge may intrude the clearance envelope of its own track. The train may also intrude the clearance envelope of the adjacent track(s). Furthermore, if there is another train on the adjacent track, the derailed equipment may collide with the train on the adjacent track. A derailment without intrusion may cause equipment damage, infrastructure damage, passenger casualties and system disturbance, while an intrusion may lead to more severe consequences. Passenger trains operating at higher speeds may increase the probability and severity of the subsequent collisions.

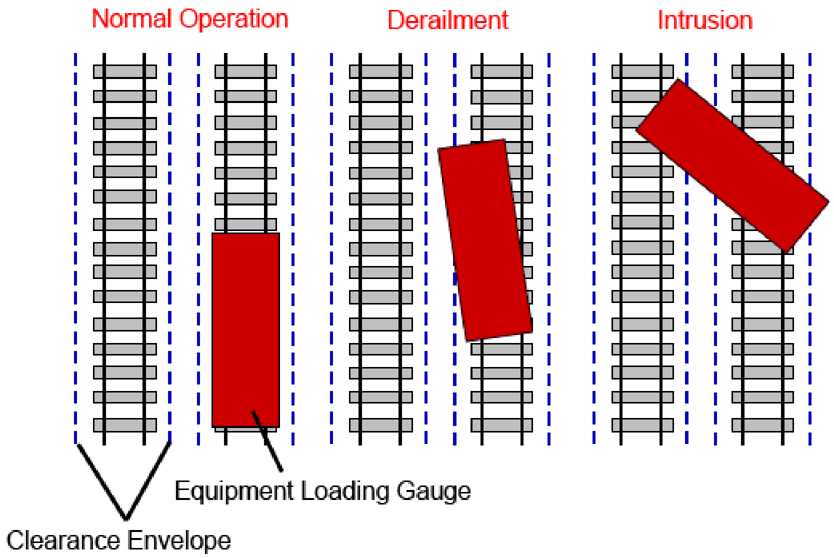

Fig. 1. A Typical Prequel for An ATA

Attached paper presents a semi-quantitative model to evaluate the probabilities associated with each event, the consequences, and the overall risk. Various factors affecting the initial accident, the intrusion, the presence of trains on adjacent tracks, as well as the consequences are identified and investigated. A case study with a hypothetical railroad network with SRC settings is also used to illustrate the ATA risk model.

Recommendations

The risk model enables comparisons of the relative ATA risks among different track sections along the same SRC. The model could also be used to locate the risk hotspots on a SRC where the ATA risk is high and risk mitigation is required. This research intends to depict a high-level overview of ATA, and provides a basis for future quantitative risk analyses and risk mitigation implementations.

Publications

Lin, C.Y. and M. R. Saat. Semi-quantitative risk assessment of adjacent track accidents on shared-use rail corridors. *Safety Science*, in-review. [Attached]

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Semi-quantitative risk assessment of adjacent track accidents on shared-use rail corridors

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ARTICLE INFO

Article history:

Keywords:
Accident
Adjacent Track
Rail
Semi-Quantitative Risk Analysis
Shared-Use Corridor

ABSTRACT

Safety is a high priority for any rail system. There are several safety concerns associated with operating passenger and freight trains on shared-use rail corridors. Adjacent track accident (ATA) is one of the most important concerns. ATA mainly refers to a train accident scenario where a derailed equipment intrudes adjacent tracks, causing operation disturbance and potential subsequent train collisions on the adjacent tracks. Other ATA scenarios include collisions between trains on adjacent tracks (raking), turnouts and railroad crossings. Limited literature is available that addresses the risk of ATA for shared-use rail corridors. The research described in this paper presents a comprehensive risk assessment to identify and quantify the effect of factors affecting the likelihood and consequence of ATA. A discussion on how these factors affect the probability and consequence is provided. A semi-quantitative risk analysis model is developed to evaluate the ATA risk incorporating various factors affecting train accident rate, intrusion rate, train presence rate, and accident consequences. A case study with a hypothetical railroad network is presented to illustrate the potential application of the risk model. This research intends to depict a high-level overview of adjacent track accident risk and provides a basis for future quantitative risk analyses and risk mitigation.

1. Introduction

1.1 Shared-Use Rail Corridor

A large number of developments of improved or expanded passenger rail service in the U.S. involves the use of existing railroad infrastructure or rights of way (*Saat and Barkan, 2013*). Shared or Mixed Use Rail Corridors (SRC) refer to different types of passenger and/or freight train operations using common infrastructure in one way or another (*Lin et al., 2013*). Fig. 1 shows three types of SRC: shared track, shared right-of-way and shared corridor, defined by the U.S. Department of Transportation, Federal Railroad Administration (FRA).

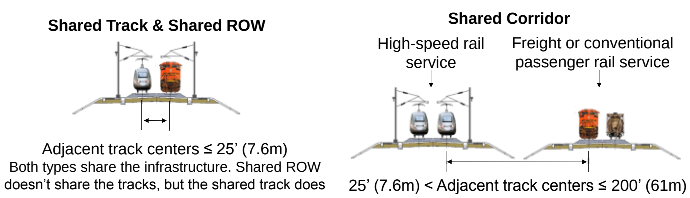


Fig. 1. Definition of SRC by FRA (*Resor, 2003*)

1.2 Adjacent Track Accident (ATA)

Various safety, infrastructure, equipment, planning, operational, economic and institutional challenges have been identified for the implementation of SRC (*Saat and Barkan, 2013*). Safety is a high priority for any rail system (Elvik and Voll, 2014), and there are several safety concerns associated with operating passenger and freight trains on SRC. Adjacent track accident is one of the most important concerns (*Saat and Barkan, 2013*). ATA mainly refers to a train accident scenario where a derailed railroad equipment intrudes adjacent tracks, causing operation disturbance and potential subsequent train collisions on the adjacent tracks. Other ATA scenarios include collisions between trains on adjacent tracks (raking between trains), turnouts, and railroad crossings.

Fig. 2 depicts a typical sequence of events of an ATA. Under normal operations, when a train operates on a track, its equipment loading gauge (which defines the allowable height, width, and loads of rolling stock) stays within the clearance envelope of the track. When a train derails, the train's equipment loading gauge may intrude the clearance envelope of its own track. The train may also intrudes the clearance envelope of the adjacent track(s). Furthermore, if there is another train on the adjacent track, the derailed equipment may collide with the train on the adjacent track. A derailment without intrusion may cause equipment damage, infrastructure damage, passenger casualties and system disturbance, while an intrusion may lead to more severe consequences. Passenger trains operating at higher speeds may increase the probability and severity of the subsequent collisions. Various ATA scenarios will be elaborated in the following section.

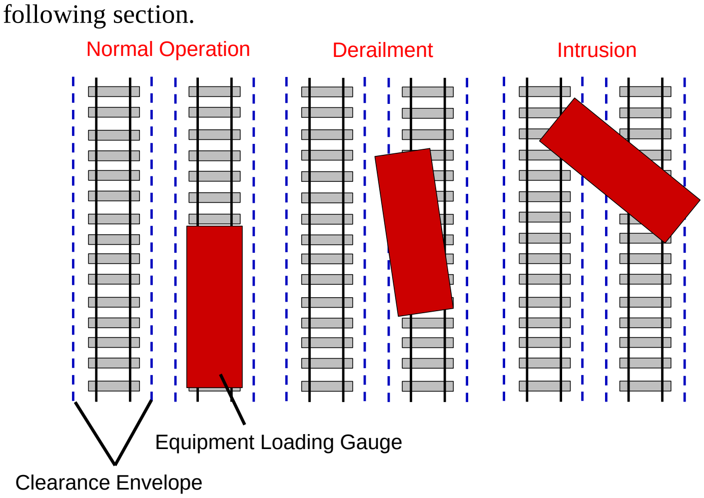


Fig. 2. A Typical Prequel for An ATA

1.3 Literature Review

North America has a long history of shared-use rail corridors. Thus, there has been plenty of research addressing the safety issue of SRC in the U.S. (*Hadden et al., 1992; Moyer et al., 1994; Ullman and Bing, 1995; Phraner and Roberts, 1999; Phraner, 2001; Chisholm, 2002; Nash, 2003; Resor, 2003; English et al., 2007; Rulens, 2008; Saat and Barkan, 2013; Lin et al., 2013; Chadwick et al., 2014*). However, few studies focused specifically on the risk of ATAs on SRC (*Hadden et al., 1992; Ullman and Bing, 1995*). These studies provide comprehensive analyses on ATAs either qualitatively or semi-quantitatively. However, some of these studies were conducted long time ago, and some of the assumptions may no longer be valid and the results may be different due to recent changes in operating conditions and advances in technologies. English et al. (2007) analyzed previous derailment data from FRA, National Transportation Safety Board (NTSB), and Transport Safety Board of Canada to understand the distribution of lateral and longitudinal displacements of derailed equipment. Rulens (*2008*) conducted an analysis on the intrusion protection between high-speed rail and adjacent transportation systems. Cockle (2014) conducted an analysis on the risk of a freight railroad adjacent to high-speed rail trackage. These studies provide details and insights on certain parts of the risk of ATAs. However, more general and comprehensive assessment of the risk of ATA is not well-understood. There are also studies regarding the safety issue of SRC outside the U.S. (*Phraner and Roberts, 1999; Phraner, 2001; Chisholm, 2002; Nash, 2003; Rulens, 2008*), but different characteristics of rail equipment, regulatory conditions, railroad culture, and different operational practices make the focus of SRC in other countries (mostly among different types of passenger trains) different from the focus of SRC in the U.S. (mostly between heavy-haul freight trains and lighter, and faster passenger trains).

1.4 Research Objectives

This paper presents a comprehensive risk assessment to identify factors affecting the likelihood and consequence of ATAs. A semi-quantitative risk analysis model is developed to evaluate the risk. An ATA is divided into a sequence of events, including the initial accident, the intrusion, the presence of trains on adjacent tracks, and the accident consequence. A semi-quantitative model is presented to evaluate the probabilities associated with each event, the consequences, and the overall risk. Various factors affecting the initial accident, the intrusion, the presence of trains on adjacent tracks, as well as the consequences are identified and investigated. A case study with a hypothetical railroad network with SRC settings is used to illustrate the ATA risk model.

2. Adjacent Track Accident (ATA) Scenarios

ATA is not a single event. It consists of a series of events that lead to different results based on the individual events. It is thus difficult to discuss the risk of ATA as a whole. Hence, in this paper, ATA is classified into different scenarios. Fig. 3 demonstrates the event tree of ATA. Based on the type of initial accident, ATA is classified into derailments and collisions. When a train derails, it could occur on single or multiple track sections. For the purpose of this study, only derailments on multiple track sections are considered. The derailment is then classified into two branches depending on whether or not the derailed equipment intrudes the adjacent track. If it does, it would become an intrusion and then the presence of another train on adjacent track would be examined, because this might result in a collision between derailed equipment and the train on the adjacent track. Likewise, collisions are also classified into two categories based on whether the section is a single or multiple track section. Only collisions on multiple track sections are considered. Some collision scenarios directly involve trains on different tracks, such as side collisions where two trains collide at turnout or raking collisions where two trains on different tracks collide with each other at non-turnout area. Fig. 4 illustrates specific ATA derailment and collision scenarios.

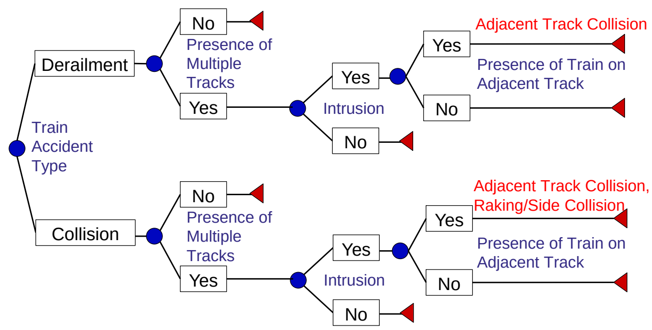
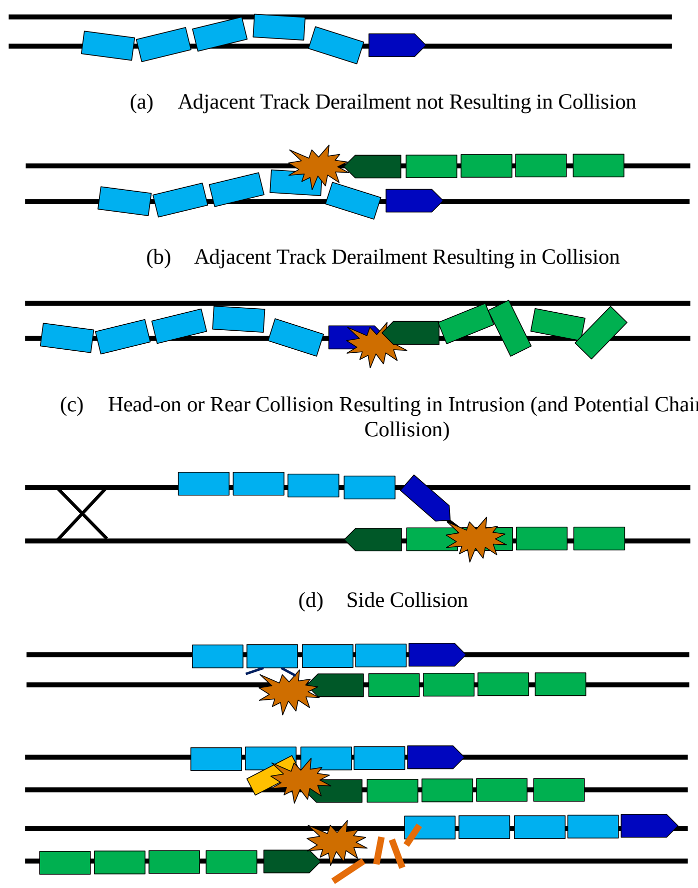


Fig. 3. Conceptual Framework for ATA



(a) Adjacent Track Derailment not Resulting in Collision

(b) Adjacent Track Derailment Resulting in Collision

(c) Head-on or Rear Collision Resulting in Intrusion (and Potential Chain Collision)

(d) Side Collision

(e) Raking Collision

Fig. 4. Specific ATA Derailment and Collision Scenarios

3. Semi-Quantitative Risk Analysis

3.1 Risk Model

A common definition of risk is the multiplication of the frequency of an event with the consequence of the event. In this study, the ATA risk index is defined as follows:

$$R = P(A) \times P(I|A) \times P(T|I) \times C \quad (1)$$

where

R: The risk index for an ATA

P(A): The probability of an initial derailment or collision on a multiple track section

P(I|A): Conditional probability of intrusion (CPI) given an initial derailment or collision

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

C: The consequence of an ATA

There are three probability components and one consequence component in the model. The three probability components correspond to the event tree shown in Fig. 3. The purpose of this model is to calculate and compare the relative ATA risks for different track sections in a SRC. To assess the risk for each track section, each component has five levels associated with their probabilities and consequences. These levels are assigned scoring values from 1 to 5. Higher numbers represent higher probability or more severe consequence. In the following subsections, the definitions for different levels of probability and consequence will be provided. Factors affecting each component will be identified, discussed and correlated with the level of probability and consequence.

3.2 Probability of Initial Accident, P(A), and Accident Factors

The initial accident is the first event of the ATA sequence. The probability of this event can be estimated by analyzing previous accident data. FRA publishes and maintains train accident databases which record reportable train accidents as well as annual traffic volume (*FRA, 2011*). Compared to other risk components, P(A) has the most sufficient information to conduct quantitative analysis. Therefore, the reference for defining levels of P(A) is mostly based on previous quantitative analyses on train accident rates (*Nayak et al., 1983; Ullman and Bing, 1995; Anderson and Barkan, 2004; Liu et al., 2011*). Five factors may affect the probability of initial accidents: method of operation, track quality, traffic density, type of equipment, and train defect detector. These factors will be discussed individually to understand their effects.

Method of Operation

Method of operation determines the presence of signaling systems as well as different types of train control systems. Previous research suggested that the accident rate in signaled track sections are lower than on non-signaled track sections (*Ullman and Bing, 1995, Liu, 2013*).

Track Quality

FRA classifies track quality into nine classes used by freight and passenger rail according to FRA Track Safety Standards (*FRA, 2011*). Previous research suggested that there is a relationship between FRA track class and accident rate. The latest research shows that the higher the track class, the lower the accident rate (*Nayak et al., 1983; Ullman and Bing, 1995; Anderson and Barkan, 2004; Liu et al., 2011).*

Traffic Density

Traffic density on a freight line (or a freight and passenger mixed traffic line), measured in annual million gross tonnage (MGT), may have an effect on the train derailment rate. The higher the traffic density, the lower the derailment rate. This may result from the more frequent maintenance and inspection rate and the installation of more wayside defect detection systems on heavy density traffic lines. Dedicated passenger lines usually have lower derailment rates due to higher track maintenance standards and inspection frequency. In addition, lighter passenger equipment deals cause less wear and damage to the track structure, reducing the potential risk of accidents due to track structure defects. Thus, it is assumed that dedicated passenger lines have low derailment rates (*Liu, 2013*).

Type of Equipment

Different designs of train equipment may result in different mechanical failure rates. Therefore, it is expected that different types of equipment would affect the accident rates. However, currently there is limited research providing any quantitative evidence.

Defect Detectors and Track Inspections

Defect detectors for train or track may reduce the accident rate. The train defect detector can identify flaws on train wheel or other part of the rail cars before they fail, protecting the car from derailing. This may improve the train performance and result in lower accident rate (*Ullman and Bing, 1995*). For example, Wheel Impact Load Detectors (WILDs) are used in the U.S. to identify wheel defects that could lead to a rolling stock failure (*Van Dyk et al., 2013; Hajibabai et al., 2012*). Track inspections can effectively reduce the infrastructure-related accidents, such as broken rail derailment (*Dick et al. 2003; Barkan et al. 2003; Liu et al. 2012, 2013a, 2013b, 2013c, 2014*). Similar to the type of equipment, the effect of defect detectors and track inspections on accident rates is not known and further research is required.

The accident factors described previously can be combined to create the level of initial accident probability, except type of equipment, defect detectors and track inspections because of data limitation. In order to properly assign the level of probability of initial accident to a track segment with specific combination of accident factors, Accident Factor Score (AFS) is created. For each factor, an AFS is assigned to different segment characteristics (Table 1). The higher the AFS score, the higher the increase in accident rate. For a track segment, all the AFS factor-specific scores will be multiplied together. Finally, based on the total AFS, a level of intrusion probability (from 1 to 5) will be assigned to the specific track segment (Table 2).

Table 1
Accident Factor Score Definitions

Accident Factor	Criteria	Accident Factor Score (AFS)
FRA Track Class	6 or above	1.0
	5	2.0
	4	4.0
	2, 3	8.0
	X, 1	16.0
Traffic Density	*Freight-Train only or Freight and Passenger Shared Lines:*	
	More than 60 MGT	1.0
	40 - 60 MGT	1.4
	20 - 40 MGT	2.0
	Less than 20 MGT	4.0
	Passenger-Train only Lines:	
	Dedicated Passenger Line	1.0
Method of Operation	Signaled	1.0
	Non-Signaled	1.5
		96.0
The highest score possible		**0**
The lowest score possible		**1.00**

Table 2
Level of P(A)

Total Accident Factor Score (AFS)	**Level of P(A)**
AFS ≤ 3	1
3 < AFS ≤ 10	2
10 < AFS ≤ 20	3
20 < AFS ≤ 45	4
AFS > 45	5

3.3 Conditional Probability of Intrusion, P(I|A), and Intrusion Factors

The conditional probability of intrusion is the second event in the ATA sequence. The CPI is more difficult to be quantified than the probability of initial accident because more uncertainties are involved in this event. The quantitative analysis done by English (*English et al., 2007*) can be used as a basis for CPI. However, there are some other factors that would affect the intrusion, such as track alignment, elevation differential, adjacent structure, containment, train speed, and point of derailment. These factors are discussed in a more qualitative manner and their evaluations involve more subjective engineering judgments.

Similar to the way P(A) is calculated, Intrusion Factor Score (IFS) is created for each intrusion factor. For each factor, an IFS is assigned to different route characteristics. The higher the IFS score, the higher the increase in CPI. For a track section, all the factor-specific IFS will be multiplied together. Finally, based on the total IFS, a level of intrusion probability (from 1 to 5) will be assigned to the track section.

The Distance between Track Centers

The distance between track centers directly affects the probability of intrusion because it is intuitive that the closer the adjacent tracks, the more probable a derailed equipment will intrude the adjacent tracks. Fig. 5 shows the maximum lateral travel distribution from the analysis by English et al. (*2007*). Data from 1978 to 1985 from NTSB were chosen. Our study classify the IFS for different track center spacings by selecting the 10^{th}, 25^{th}, 50^{th}, and 75^{th} percentile from the cumulative distribution of probability in Fig. 5. The result is summarized in Table 3.

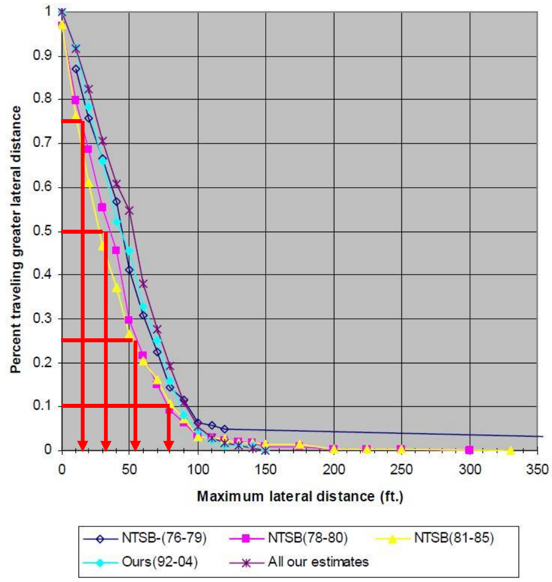


Fig. 5. Maximum Lateral Travel Distribution (*English et al., 2007*)

Table 3
Intrusion Factor Score Definitions for the Distance between Track Centers

Distance Between Track Centers, X in ft. (meters)	**Conditional Probability of Intrusion**	**Intrusion Factor Score**
X > 80 (24.4)	P(I|A) ≤ 0.10	1.0
55 (16.7) < X ≤ 80 (24.4)	0.10 < P(I|A) ≤ 0.25	1.5
30 (9.1) < X ≤ 55 (16.7)	0.25 < P(I|A) ≤ 0.50	2.0
15 (4.5) < X ≤ 30 (9.1)	0.50 < P(I|A) ≤ 0.75	3.0
X ≤ 15 (4.5)	P(I|A) > 0.75	5.0

Track Alignment

Track alignment considers whether the track is tangent or curved and whether the track is at level or on gradient. A tangent and level section is the base case which does not contribute much to CPI. A curved section will provide additional lateral force to trains, resulting in higher chance of lateral displacement given a derailment and thus higher CPI. A section on gradient will provide extra longitudinal force to rail cars (buff or tension depending on gradients). Although this force will not directly cause the rail car to move laterally, the longitudinal force may cause one rail car to push another and create accordion or "zig-zag" effect which will move the car laterally and rotate the car, which may intrude adjacent tracks. A curved and gradient section may result in more effect on the intrusion due to the additional lateral and longitudinal forces. Therefore, given all others are equal, a curved and gradient section has higher intrusion rate than a curved-only or gradient-only section. Table 4 shows the IFS for different combination of track alignment.

Table 4
Intrusion Factor Score Definitions for Track Alignment

Horizontal Alignment	**Vertical Alignment**	**Intrusion Factor Score**
Tangent	Level	1.0
Tangent	On Gradient	1.1
Curved	Level	1.5
Curved	On Gradient	1.7

Elevation Differential

The relative elevations between adjacent tracks may affect the CPI. As shown in Fig. 6, if the derailed equipment is on the high track, it may be more likely to intrude the adjacent track because of the additional gravity force induced by the elevation. On the other hand, if the derailed equipment is on the low track, it may be less likely to intrude the adjacent track because it may be contained by the embankment, given all others are equal. Table 5 shows the IFS for different elevation settings.

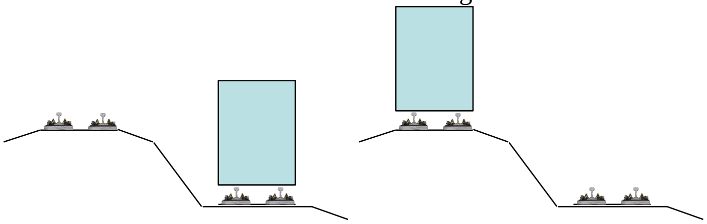


Fig. 6. Effect of Elevation Differential on CPI

Table 5
Intrusion Factor Score Definitions for Elevation Differential

The Track Where A Train Derails Is	Intrusion Factor Score
10 ft. lower than the adjacent track	0.7
Level with the adjacent track	1.0
10 ft. higher than the adjacent track	1.3

Adjacent Structure
Adjacent structures refer to the structures on the outside of the rail infrastructure as shown in Fig. 7. The concern associated with adjacent structures is the "rebound effect". When the adjacent structure is close enough to the tracks and large and heavy enough to redirect the derailment force, the movement of derailed equipment may be diverted toward adjacent tracks. Adjacent structures, depending on its shape and arrangement, can be classified into single or continuous structure. A single structure is an independent, self-supported structure. A highway bridge that crosses the railroad with its pillars is an example. A continuous structure, such as a noise barrier, locates alongside with the track. Densely constructed buildings along the track in the urban area can be considered as a continuous structure.

Assuming the adjacent structure is able to divert the direction of travel of derailed equipment, if there are more adjacent structures, it is more likely that the derailed equipment going outward would contact the structure and be diverted inward to adjacent tracks. Table 6 shows the IFS for different adjacent structure settings.

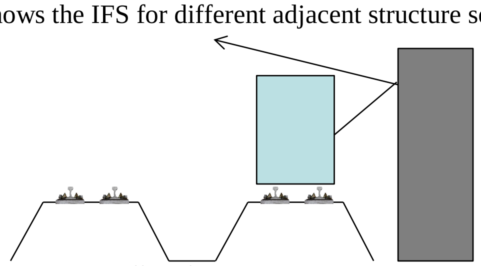


Fig. 7 Effect of Adjacent Structure on CPI

Table 6
Intrusion Factor Score Definitions for Adjacent Structure

Adjacent Structure	Intrusion Factor Score
No Structure	1.0
Single Structure	1.1
Continuous Structure	1.3

Containment
Containment is the structure located in between the adjacent tracks. The presence of containment can reduce the likelihood of intrusion by containing the derailed equipment, preventing it from intruding adjacent tracks. Containments can also reduce the consequence by absorbing the energy from derailed equipment (discussed in consequence part of this paper). Three types of containment which are currently used in high-speed rail system in Europe and Asia are discussed: guard rail, parapet, and physical barrier (*Hadden et al., 1992; Moyer et al., 1994; Ullman and Bing, 1995; Rulens, 2008*).

Guard rail (or check rail) is frequently used in turnouts to prevent trains from derailment. Guard rail can also be used to contain rail equipment within the track clearance and prevent it from intruding adjacent tracks. Installing guard rails in high-risk area is thus expected to reduce the CPI. Parapet has similar function to guard rail but is installed on the sides of the track structure. Physical barriers, such as concrete walls, are installed between two tracks to absorb the impact of train in a derailment and prevent the derailed equipment from intruding adjacent tracks (Fig. 8).
Table 7 shows the IFS for different containment settings. Note that the types of containment discussed are conceptual and general. Site-specific evaluations would be necessary to decide the effectiveness of each approach.

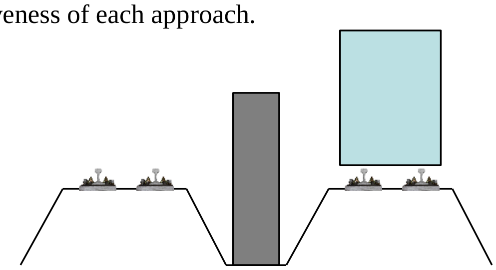


Fig. 8. Effect of Containment on CPI

Table 7
Intrusion Factor Score Definitions for Containment

Type of Containment	Intrusion Factor Score
All containments installed	0.5
Physical barrier and guard rail or parapet installed	0.6
Physical barrier installed only	0.7
Parapet and guard rail installed	0.8
Parapet or guard rail installed only	0.9
No containment	1.0

Train Speed
Speed of train may affect the CPI because the higher the train speed, the more the energy involved when a train derails, resulting in more opportunity for derailed equipment to move farther and foul adjacent track.

The train speed is assigned high, medium, or low to a track section, based on the average train speed of the track sections in the same shared-use corridor. The average speed on the track segment can be affected by various factors, including type of traffic (bulk freight, intermodal, passenger, etc.), track alignment, track class, and so on. Table 8 shows the IFS for different train speeds.

Table 8
Intrusion Factor Score Definitions for Train Speed

Train Speed	Intrusion Factor Score
Low (less than 40 mph)	1.0
Medium (40 mph to 70 mph)	1.2
High (more than 70 mph)	1.4

Point of Derailment (POD)
Point of derailment (POD) refers to the position-in-train of the first car derailed (*Anderson, 2005; Liu et al., 2013a*). The position of the first derailed car will affect the CPI because of the reaction forces at the coupler. If the first car derailed is the first or the last car of the train consist, it might drag other cars away from the track. Also, because the first and the last car 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. On the other hand, cars in the middle of the train consist are coupled at both ends, providing more restraining forces to the cars so that they won't easily rotate. However, there are situations where one car in the middle of train consist derails and drag other cars away from track, resulting in massive derailment and intrusion. Due to this level of uncertainty, the effect of POD would require further research to better understand the mechanism.

Besides, 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 occur. As such, it is difficult to pre-assign the IFS to this factor in the model.

Mostly based on engineering judgments, Table 9 summarized all the pre-accident intrusion factors and the associated IFS scores. The total IFS is calculated by multiplying the IFS from the six intrusion factors. Table 10 shows the relationship between total IFS and the corresponding levels of P(I|A). The higher the level, the more likely the occurrence of intrusion given an initial derailment or collision.

Table 9
Summary of All Intrusion Factor Score Definitions

Intrusion Factor	Criteria	Intrusion Factor Score (IFS)
Distance Between Track Centers, X, in feet (meters)	X > 80 (24.4)	1.0
	55 (16.7) < X ≤ 80 (24.4)	1.5
	30 (9.1) < X ≤ 55 (16.7)	2.0
	15 (4.5) < X ≤ 30 (9.1)	3.0
	X ≤ 15 (4.5)	5.0
Track Alignment	Tangent and level	1.0
	Tangent and on gradient	1.1
	Curved and level	1.5
	Curved and on gradient	1.7
Elevation Differential	Adjacent track is 10 ft. higher	0.7
	Adjacent track is level	1.0
	Adjacent track is 10 ft. lower	1.3
Adjacent Structure	No adjacent structure	1.0
	Single structure	1.1
	Discrete structure	1.2
	Continuous structure	1.3
Containment	All containments installed	0.5
	Physical barrier and guard rail or parapet installed	0.6
	Physical barrier installed only	0.7
	Parapet and guard rail installed	0.8
	Parapet or guard rail installed only	0.9
	No containment installed	1.0
Train Speed	Low (less than 40 mph)	1.0
	Medium (40 mph to 70 mph)	1.2
	High (more than 70 mph)	1.4
The highest score possible		**20.11**
The lowest score possible		**0.35**

Table 10
Total IFS and Level of CPI Definitions

Total Intrusion Factor Score (IFS)	Level of CPI
IFS ≤ 2	1
2 < IFS ≤ 3	2
3 < IFS ≤ 5	3
5 < IFS ≤ 10	4
IFS > 10	5

3.4 Conditional Probability of The Presence of Trains on Adjacent Tracks, P(T|I), and Train Presence Factors

The third component of the ATA risk model considers the presence of trains on adjacent tracks given an intrusion. One concern with ATA is that if the derailed equipment is struck by a train on the adjacent track, it would result in a collision and potentially more severe consequences. With the introduction of higher-speed passenger trains on SRC, the train on the adjacent track may not have enough time to stop before the debris of a derailed equipment. There are two scenarios for the presence of the train. One is that the train on the adjacent track presents at the time the intrusion occurs, and the other is that the train on the adjacent track is approaching the site where an intrusion occurs.

Although P(T|I) is a random variable and is harder to quantify for now than other two probability components in the model, there are factors affecting this probability that will be discussed. The train presence factors include intrusion detection and warning systems, traffic density, method of operation, train speed, and shunting problem.

Intrusion Detection and Warning System (IDW)
The IDW system detects intruding rail equipment when it derails and breaks the fences installed with detectors between tracks, and changes the signal on either side of the adjacent track to stop (*Hadden et al., 1992; Ullman and Bing, 1995; Saat and Barkan, 2013*). Trains on adjacent tracks beyond the next block would have enough time to stop short of the derailed equipment. However, IDW may not work if the train is already in the block where the intrusion occurs unless there is an advanced train control system that transmit the information directly to the train and force it to stop.

Traffic Density
Traffic density on adjacent track directly affects P(T|I) because the higher the traffic density, the more likely the presence of a train at the time intrusion occurs. The traffic density of a track section on a freight line or a freight and passenger shared line is assigned by annual million gross tons (MGT) to the section. The traffic density for dedicated passenger lines is assigned the highest level.

Method of Operation
Different train control systems have different accuracy of train location as well as the ability of communicating the information. For example, the traditional track circuit system can only identify a train's location by "block" but does not provide the exact

position of the train, whereas advanced train control systems can precisely locate the train. Representative systems include the European Rail Traffic Management System (ERTMS) in European countries and Advanced Train Administration & Communications System (ATACS) in Japan. Positive Train Control (PTC) is the proposed advanced train control technology in the U.S. Also, advanced train control systems can communicate information more efficiently than traditional oral communication between dispatchers and engineers. IDW can also be integrated with advanced control systems so that the intrusion warnings can be efficiently and instantly delivered to other trains in the same proximity (*Hadden et al., 1992; Ullman and Bing, 1995*).

In this study, train control systems are divided into three categories: advanced train control system, typical train control system, and dark territory. Advanced train control systems refer to the track sections with the installation of PTC compliant train control systems. Typical train control systems refer to track sections protected by track circuits. Dark territory refers to non-signaled track sections with no track circuit.

Train Speed

Train speed on adjacent tracks could affect P(T|I). If a train on an adjacent track is already in the block where initial accident and intrusion take place, the typical train control system may not be able to protect train from striking the derailed equipment. When the train speed is high, it may not be able to stop in time and may result in a collision. The train speed is assigned high, medium, or low to a track section, based on the average train speed of the adjacent track sections on the same SRC.

Shunting

Some concerns regarding loss of shunt problem in lighter passenger equipment is taken into consideration. This problem is relevant to the wheel load, wheel tread condition, and track circuit reliability (*Saat and Barkan, 2013*). If the train on adjacent track cannot be detected, the train control system may not be able to warn the train about the intrusion and fail to stop the train in time.

Compared with P(A) and P(I|A), P(T|I) contains more uncertainties because of the fact that it is difficult to predict whether or not there is a train running on adjacent tracks when an intrusion occurs. Therefore, the descriptions of the train presence factors are more qualitative. Based on engineering judgments, Train Presence Score (TPS) is assigned to train presence factors in Table 11. Shunting problem is not assigned any TPS because it is hard to predict when and where the shunting problem would occur. The total TPS in a specific track section is calculated by multiplying the TPS from individual train presence factor together. Table 12 shows the relationship between total TPS and corresponding level of P(T|I). The higher the level, the more likely the presence of train given an intrusion. Although not all the combinations are considered, the selected factor combinations are assumed to be representative to account for most of the circumstances.

Table 11
Train Presence Score Definitions

Train Presence Factors	Criteria	Train Presence Score (TPS)
IDW	Presence	1
	Absence	2
Traffic Density	*Freight or Freight and Passenger Shared Lines:*	
	Less than 20 MGT	1
	20 - 40 MGT	1.3
	40 - 60 MGT	1.6
	More than 60 MGT	2
	Passenger Lines:	
	Dedicated Passenger Line	2
Method of Operation	Advanced train control	1
	Typical train control system	2
	Dark territory	3
Average Train Speed	Low (less than 40 mph)	1
	Medium (40 mph to 70 mph)	2
	High (more than 70 mph)	3
The highest score possible		**36**
The lowest score possible		**1**

Table 12
Total TPS and Level of P(T|I) Definitions

Total Train Presence Factor (TPS)	Level of P(T|I)
TPS ≤ 3	1
3 < TPS ≤ 6	2
6 < TPS ≤ 12	3
12 < TPS ≤ 24	4
TPS > 24	5

3.5 Consequence, C, and Consequence Factors

Consequence is the accident impacts from an ATA. The major concern is the severe consequence resulted from the collision between derailed equipment and trains on adjacent track. Previous research shows the average casualties for passenger train collisions is higher than the average casualties for passenger train derailments (*Lin et al., 2013*). Because ATA may include both passenger train and freight train, the consequence of ATA includes multiple, possible types of impact as follows:

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

Casualties refer to passenger and non-passenger fatalities or injuries from accident impact, and/or casualties due to exposure to hazardous materials release in an ATA involving a freight train transporting hazardous materials. Equipment damage is the cost required to repair rail cars. Infrastructure damage is the cost required to replace damaged track structure. Non-railroad property damage includes the non-railroad structure damaged by the impact of derailed equipment or explosion. System disturbance and delay resulted from the derailment is measured by system shutdown time and the number of train affected. Environmental impact refers to environmental damage due to the release of fuel or any hazardous material. Economic loss refers to the damage or release of the lading being carried by freight cars. Several factors are identified to affect the severity of ATA accidents: speed of train, equipment strength, containment, and product being transported.

Equipment Strength
Equipment strength is a key factor for reducing the potential casualties on board from the derailment and/or collision impact. The crashworthiness analyses has been conducted for higher-speed passenger trains (Tier I standard) (*Carolan et al., 2011*) to understand how reinforced equipment can withstand larger collision impact and thus result in less consequence. The rolling stocks are classified into two categories: reinforced equipment and traditional equipment. Reinforced equipment refers to passenger rail cars that meet the FRA Tier I or higher crashworthiness regulations, or freight cars that are equipped with top fitting protection, jacket, and couplers that prevent rail cars from overriding other rail cars. Traditional equipment refers to railcars that do not meet the requirement stated previously.

Speed of Train
With higher speed, more energy will be involved when a derailment or collision occur. Research shows the train speed may affect the consequence of an accident (*Liu et al., 2011*). Therefore, it is expected to have more severe consequence if the train speed is higher.

Containment
The presence of containment may reduce the conditional probability of intrusion and also the consequence by absorbing the impact from the derailing equipment (*Hadden et al., 1992; Moyer et al., 1994; Ullman and Bing, 1995*).

Product Being Transported (Freight Train)
If the collision involves freight trains carrying hazardous material (or dangerous goods), then it may release the hazardous material and result in more severe consequences.

The definition of consequence level consists of the evaluation on equipment strength, speed, presence of containment, and whether or not hazardous material is transported in the track section. Similar to the conditional probability of intrusion, Consequence Factor Score (CFS) is assigned to different situations in each consequence factor as shown in Table 13. The total CFS is calculated by multiplying the CFS from individual consequence factor together. The total CFS is then related to the level of consequences in Table 14.

Table 13
CFS for Consequence Factor Score Definitions

Consequence Factor	**Criteria**	**Consequence Factor Score (CFS)**
Equipment Strength	Reinforced equipment	1
	Traditional equipment	2
Speed	Low (less than 40 mph)	1
	Medium (40 mph to 70 mph)	2
	High (more than 70 mph)	3
Containment	Containment Present	1
	No Containment	2
Product being transported	No Hazardous material	1
	Hazardous material	2
The highest score possible		**24**
The lowest score possible		**1**

Table 14
Level of Consequence Definitions

Consequence Factor Score	**Level of Consequence**
CFS ≤ 3	1
3 < CFS ≤ 6	2
6 < CFS ≤ 10	3
10 < CFS ≤ 15	4
CFS > 15	5

3.6 Overall Probability

The three probability levels can be combined into a single score to represent the overall probability by multiplying the value of the three probabilities:

$$P = P(A) \times P(I|A) \times P(T|I)$$

Based on the values of P, a level of overall probability will be assigned. Table 15 shows the relation between the value of P and the level of overall probability.
This level of overall probability will be multiplied with the consequence to obtain the ATA risk.

Table 15
Overall Probability Level Definitions

Multiplication of P(A), P(I|A), and P(T|I)	**Overall Probability Level, P**
1 < P ≤ 10	1
10 < P ≤ 20	2
20 < P ≤ 30	3
30 < P ≤ 50	4
P > 50	5

3.7 Model Application

The proposed semi-quantitative model enables the evaluation of ATA risk for different track segments or sites. Many of the factors discussed previously vary from site to site. For example, the distance of track centers of two main tracks on the corridor may change due to different terrain, passing passenger train station or freight yards, or the installation of containment. Also, if the track configuration changes, such as the presence of the third main track, or if another railroad corridor becomes close enough (track center distance less than 200 ft.) to the main corridor of interest, the overall ATA risk will also change. A segment is defined as a portion of the corridor with all the track alignment, nearby terrain, structures, infrastructure, and signals. A railroad corridor can be divided into hundreds or thousands of segments depending on the resolution and accuracy of analysis required. The segment length can vary from segment by segment depending on the site characteristics. The segment length will affect the ATA risk, but can be normalized to allow comparison. Proper segment division can account for important factors affecting the ATA risk and yield more precise analyses.

One of the complexity of evaluating ATA risk is the multiple risks being calculated on one segment of tracks. Fig. 9a shows a segment where two tracks, A and B, are adjacent to each other. The ATA risk for that segment is

$R_{AB}+R_{BA}$

where

R_{AB}: Risk A to B. The risk that a train on track A derails and intrudes track B.
R_{BA}: Risk B to A. The risk that a train on track B derails and intrudes track A.

In R_{AB}, track A is called "Initiating Track" because the initial accident occurs at that track, and track B is called "Intruded Track" because it is the track being intruded.
If three track are close to each other, the ATA risk will be calculated for each combination of tracks. For instance, in Fig. 9b, there are three tracks adjacent to each other. The ATA risk for this segment is

$R_{AB}+R_{BA}+R_{AC}+R_{CA}+R_{BC}+R_{CA}$

Fig. 9c shows n tracks. The ATA risk for this segment is

$$\sum_{i}^{n}\sum_{j}^{n}(R_{ij}+R_{ji})$$

where

$i < j \qquad \forall i$

Fig. 9d shows the interaction of a track with a railroad yard. Because there are usually many tracks in a yard, numerous calculations need to be done when the track passes by or through the yard. Yard and terminal tracks are usually maintained in lower track class than mainline tracks are, so the accident rate on yard and terminal tracks are higher than on mainline track. Also, in a busy yard or terminal there would be many switching operations and thus trains going back and forth in the yard, increasing the train presence rate. Therefore, it is necessary to consider the risk of adjacent yards and terminals. On the other hand, most of the train operations in yards and terminals are at low speed (mostly restrictive speed), which results in lower intrusion rate and consequence. For simplicity and the considerations above, the yard or terminal track which is the closest to the mainline represents the whole yard or terminal and the ATA risk between a mainline and a yard or terminal is:

$R_{AY}+R_{YA}$

where

R_{AY}: Risk A to Y. The risk that a train on track A derails and intrude the closest yard/terminal track Y.
R_{YA}: Risk Y to A. The risk that a train on the closest yard/terminal track Y derails and intrude track A.

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

$$R=\sum_{m=1}^{p}(\sum_{i}^{n}\sum_{j}^{n}R_{ij}+R_{ji})$$

where

$i < j \qquad \forall i$

R: The total ATA risk on the entire corridor
n: total number of track in a segment
i, j: tracks in the segment
m: track segment
p: total number of segments in the corridor

A case study will be provided in the next section to illustrate the risk model.

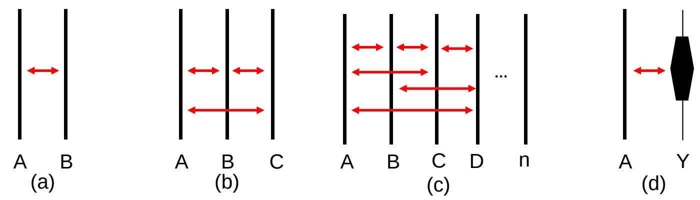


Fig. 9. Calculation of ATA Risk

4. Case Study

4.1 Hypothetical Shared-Use Rail Corridor Network

To demonstrate the potential application of the model, a hypothetical railroad network was constructed. This hypothetical network was illustrated in Fig. 10. The network consists of a 500-mile line with passenger train services from terminal A to terminal B. Terminal A is located in an industrial city that has only one railroad line serving passenger trains and a freight yard nearby the terminal. The terminal B, on the other hand, is located in a metropolitan and there are multiple passenger train systems in the vicinity.

The passenger train line, also denoted "trunk line" in this case study, starts from Terminal A and joins with the freight railroad (RR) F mainline coming out of the yard at milepost (MP) 002. The number 002 indicates that the point is 2 miles from the end point of rail in Terminal A. The two tracks share the same infrastructure and are connected with crossovers. The double track section ends at junction J (MP 300) where a connection track splits out from the junction and connects to another freight mainline. The track spacing between the two main tracks ranges from 15 feet to 35 feet. The trunk line becomes single track from MP 300 to 400 with 2-mile sidings and 10-miles siding spacing. The track spacing between mainline track and the siding ranges from 10 feet to 20 feet. There are freight trains running on this line. The trunk line then joins with the commuter train line from MP 400 all the way down to Terminal B (MP 500), but the two tracks only share the infrastructure. They do not share the trackage. The track center spacing ranges from 20 feet to 50 feet. In addition to the commuter line C, there is another freight railroad K mainline going through the city which is parallel to the trunk line and is 150 to 180 feet away from track center to center from MP 425 to 500. There are 10 intermediate passenger train stations along the trunk line.

Various types of hazardous material are transported through Section 1 of the trunk line, including chlorine and crude oil. The trunk line contains all three shared-use setting and is thus suitable for our analysis. The trunk line was divided into three sections based on different shared-use setting. Route characteristics for each section was summarized in Table 16. Note that the table only show the section characteristics, while some site-specific characteristics (for example, the relative elevation differential between two main tracks) were not listed in the table as they vary from site to site. These factors will be considered, however, in an example risk calculation in the next subsection.

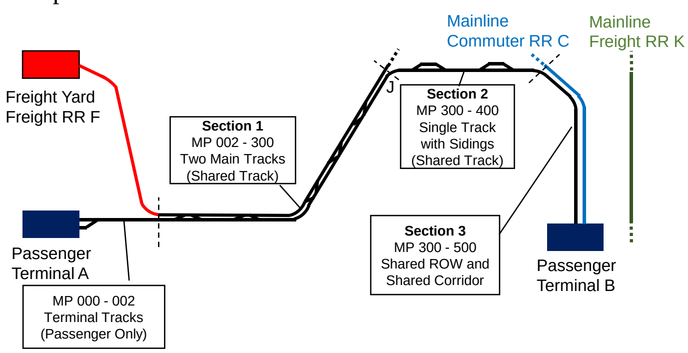


Fig. 10. Hypothetical Shared-Use Rail Corridor Network

Table 16
Section Characteristics of the Hypothetical Shared-Use Rail Corridor Network

Section		1	2	3
Milepost		MP 002-300	MP 300-400	MP 300-500
Type of SRC		Shared Track	Shared Track	Shared Track Shared ROW Shared Corridor
Method of Operation	Trunk Line	100 % CTC[1]	98% CTC 2% Non-Signaled	100% CTC
	Commuter Line			100% PTC
	Freight Line			95% CTC 4% ATC[3]/TWC[4] 1% Non-Signaled
Track Quality	Trunk Line	40% Class 7 50% Class 6 10% Class 5	35% Class 5 45% Class 4 20% Class 3	70% Class 6 20% Class 5 10% Class 4
	Commuter Line			Commuter RR: 80% Class 5 20% Class 4
	Freight Line			Freight RR K: 60% Class 4 30% Class 3 10% Class 2
Traffic Density	Trunk Line	65 MGT	45 MGT	45 MGT
	Commuter Line			50 trains per day
	Freight Line			10 MGT
Type of Equipment	Trunk Line	Traditional Equipment	Traditional Equipment	Traditional Equipment
	Commuter Line			Reinforced Equipment
	Freight Line			Traditional Equipment
Train Defect Detectors	Trunk Line	Presence	Absence	Presence
	Commuter Line			Absence
	Freight Line			Absence
Adjacent Structure	Trunk Line	60% None 40% Single	80% None 20% Single	30% Single 70% Continuous
	Commuter Line			30% Single 70% Continuous
	Freight Line			30% Single 70% Continuous
Containment	Trunk Line	100% No Barrier	100% No Barrier	100% Physical Barrier
	Commuter Line			100% Physical Barrier
	Freight Line			100% No Barrier
Average Train Speed	Trunk Line	45 mph	55 mph	55 mph
	Commuter Line			65 mph
	Freight Line			35 mph
IDW	Trunk Line	Presence	Absence	Presence
	Commuter Line			Presence
	Freight Line			Absence

[1] Centralized Traffic Control
[2] Positive Train Control
[3] Automatic Train Control
[4] Track Warrant Control
Note
1.The section MP 000 - 002 is not listed because it is not a shared-use section.

4.2 Risk Calculation and Comparison

In order to demonstrate the proposed risk analysis model, three sites from the hypothetical SRC network were chosen and the ATA risk of each site was evaluated and compared. The three sites were chosen from the three sections of the hypothetical network. Table 17 shows the locations and the risk calculations for each site. The ATA risk for a specific site considers the interactions of all railroad lines with regard to the line of interest (the Trunk Line). For example, Site 1 was chosen from Section 1 where two main tracks were shared by passenger trains and freight trains. The methodology of calculating the ATA risk discussed in Section 3.6 is applied for the three example segments.

Table 17
ATA Risk Calculation for the Three Sites in Hypothetical Network

	Site 1		Site 2		Site 3			
Milepost	132	132	355	355	486	486	486	486
Section	1	1	2	2	3	3	3	3
Length (feet)	3,000	3,000	3,000	3,000	3,000	3,000	3,000	3,000
Track in Analysis	Trunk Line Main 1 to Main 2	Trunk Line Main 2 to Main 1	Trunk Line Main Track to Siding	Trunk Line Siding to Main Track	Trunk Line to Commuter Line	Commuter Line to Trunk Line	Trunk Line to Freight Line K	Freight Line K to Trunk Line
P(A)								
FRA Track Class	1	2	1	8	1	2	1	4
Traffic Density (MGT)	1	1	1.4	2	1	1	1	4
Method of Operation	1	1	1	1	1	1	1	1.5
Total Accident Factor Score	1	2	1.4	16	1	2	1	24
Level of P(A)	**1**	**1**	**1**	**3**	**1**	**1**	**1**	**4**
Intrusion Factor Score								
Distance Between Track Centers (feet)	5.0	5.0	5.0	5.0	3.0	3.0	1.0	1.0
Track Alignment	1.5	1.5	1.0	1.0	1.1	1.1	1.1	1.1
Elevation Differential	1.3	0.7	1.0	1.0	0.7	1.3	1.0	1.0
Adjacent Structure	1.2	1.2	1.1	1.1	1.3	1.3	1.3	1.3
Containment	0.8	0.8	0.9	1.0	0.5	0.7	1.0	1.0
Train Speed (mph)	1.4	1.4	1.4	1.0	1.4	1.2	1.4	1.0
Total Intrusion Factor Score	13.1	7.1	6.9	5.5	2.1	4.7	2.0	1.4
Level of $P(I\mid A)$	**5**	**4**	**4**	**4**	**2**	**3**	**1**	**1**
Train Presence Score								
IDW	1	1	2	2	1	1	1	2
Traffic Density	2	2	1.6	1	1.6	2	2	1
Method of Operation	2	2	2	2	2	1	2	3
Average Train Speed	2	2	2	1	2	2	2	1
Total Train Presence Score	8	8	12.8	4	6.4	4	8	6
Level of $P(T\mid I)$	**3**	**3**	**4**	**2**	**3**	**2**	**3**	**2**
Consequence Factor Score								
Speed of Train	2	2	2	1	2	2	2	1
Equipment Strength	2	2	2	2	2	2	2	2
Containment	2	2	2	2	1	1	1	1
Product Being Transported	2	2	1	1	1	1	2	2
Total Consequence Factor Score	16	16	8	4	4	4	8	4
Level of Consequence	**5**	**5**	**3**	**2**	**2**	**2**	**3**	**2**
Multiplication of P(A), $P(I\mid A)$, and $P(T\mid I)$	**15**	**12**	**16**	**24**	**6**	**6**	**3**	**8**
Overall Level of Probability	**2**	**2**	**2**	**3**	**1**	**1**	**1**	**1**
ATA Risk Index	**10**	**10**	**6**	**6**	**2**	**2**	**3**	**2**

The overall ATA risk for a specific site is the sum of ATA risks on the site. The ATA risk for the three sites are:

Site 1: 20 (10+10)
Site 2: 12 (6+6)
Site 3: 9 (2+2+2+3)

The ATA risk of Site 1 is the highest among the three due to high consequence level. Site 2 does not have as high consequence level as Site 1, but it has higher overall probability level mostly because of the higher accident rate of the siding. The ATA risk of Site 3 is lower than Sites 1 and 2 because of its lower intrusion rate and consequence level. The lower intrusion rate is mainly due to the larger distances between tracks. The lower consequence mainly due to the presence of containment. However, note that the more railroad lines are around the trunk line, the more ATA risks would be incurred. If site 3 not only had the trunk line, commuter line and freight line but also had another main track or siding, the ATA risk would be significantly higher.

The ATA risks calculated for every segment along the same route can be compared with each other. Fig. 11 shows the frequency diagram for the ATA risks of the trunk line. The whole route was divided into 880 segments and the ATA risk for each segment was calculated. The x-axis shows all values of ATA risk on the route and the y-axis shows how many segments have the specific value of ATA risk. The figure shows risk index 8 is the most frequent one.

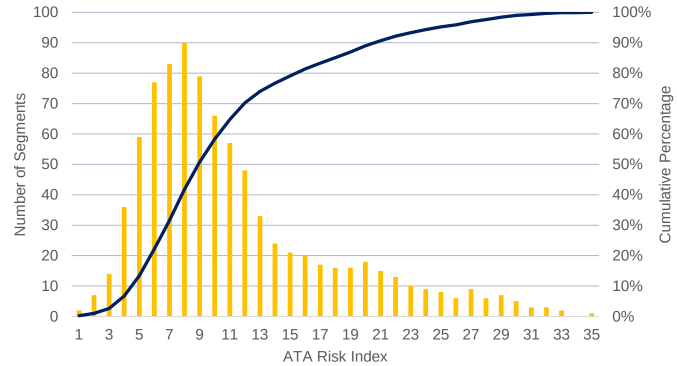


Fig. 11. Frequency of ATA Risk of the Trunk Line

The calculated ATA risk indices enable the identification of the segments with high ATA risk, or risk "hotspot", along the corridor of interest. An example is as shown in Fig. 12. Segment or route risk can be managed with proper risk communication and interpretation (*Kawprasert and Barkan, 2009*). Proper risk mitigation strategies can then be implemented to those segments. Another potential application of the ATA risk model is the evaluation of the effect of different risk mitigation strategies. By using the ATA model, one can calculate and compare the reduced risk before and after the risk mitigation strategy is applied. This can further be integrated into an optimization model considering the cost-effectiveness of the risk mitigation strategies on shared-use rail corridors.

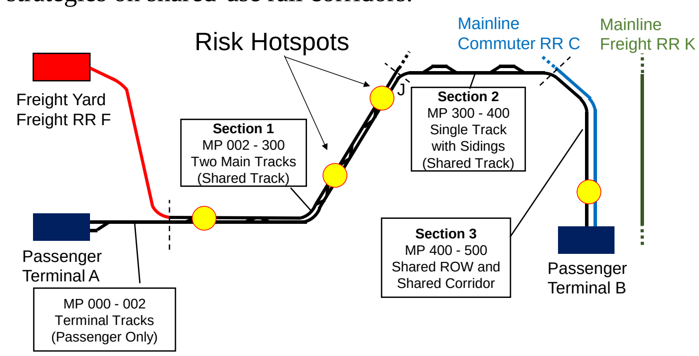


Fig. 12. Risk Hotspots of ATA Risk of the Trunk Line

5. Conclusion

The research described in this paper presents a comprehensive risk assessment to identify and quantify the effect of factors affecting the likelihood and consequence of an ATA. A semi-quantitative risk analysis is developed to evaluate the ATA risk. Levels of probability for each event and the consequences are defined. Various factors affecting the initial accident, the intrusion, the presence of trains on adjacent tracks, as well as the consequences are identified and investigated. The model enables comparisons of the relative ATA risks among different track sections along the same SRC. The model could also be used to locate the risk hotspots on a SRC where the ATA risk is high and risk mitigation is required. This research intends to depict a high-level overview of ATA, and provides a basis for future quantitative risk analyses and risk mitigation implementations.

Acknowledgements

This research was funded by the National University Rail (NURail) Center, a U.S. DOT University Transportation Center. The authors are grateful to the helpful comments from several anonymous reviewers.

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