Proceedings of the 2014 Joint Rail Conference
JRC2014
April 2-4, 2014, Colorado Springs, CO, USA

JRC2014-3773

SEMI-QUANTITATIVE RISK ASSESSMENT OF ADJACENT TRACK ACCIDENTS ON SHARED-USE RAIL CORRIDORS

Chen-Yu Lin
Rail Transportation and Engineering Center
Department of Civil and Environmental Engineering
University of Illinois at Urbana-Champaign
Urbana, Illinois, USA
clin69@illinois.edu

Mohd Rapik Saat
Rail Transportation and Engineering Center
Department of Civil and Environmental Engineering
University of Illinois at Urbana-Champaign
Urbana, Illinois, USA
mohdsaat@illinois.edu

ABSTRACT

Safety is a high priority for any rail system, and 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 refers to train accident scenarios 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 addressed the risk of ATA for shared-use rail corridors. The research described in this paper presents a comprehensive risk assessment to identify factors affecting the likelihood and consequence of adjacent track accidents. A discussion on how these factors affect the probability, consequence, and how individual factor relates to each other are provided. A semi-quantitative risk analysis is developed to investigate various factors affecting train accident rate, intrusion rate, and accident consequences. This research intends to depict a high-level overview of adjacent track accidents and provides a basis for future quantitative risk analyses and risk mitigation implementations.

NOMENCLATURE

ATA: Adjacent Track Accident
CFS: Consequence Factor Score
FRA: Federal Railroad Administration
IFS: Intrusion Factor Score
NTSB: National Transportation Safety Board
SRC: Shared (or Mixed) Use Rail Corridor
TPS: Train Presence Score

INTRODUCTION

Shared-Use Rail Corridor

A large number of developments of improved or expanded passenger rail service in the U.S. involve the use of existing railroad infrastructure or rights of way (*1*). 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 (*2*). Figure 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).

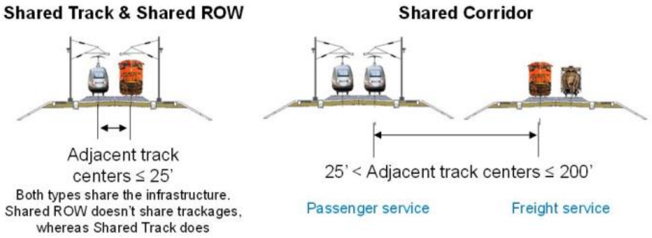


Figure 1 Definition of SRC by FRA (*3*)

Adjacent Track Accident (ATA)

A number of safety, infrastructure, equipment, planning, operational, economic and institutional challenges have been identified for the implementation of SRC (*1*). Safety is a high priority for any rail system, 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 (*1*). ATA refers to train accident scenarios 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.

Figure 2 depicts a typical prequel before an ATA. Under normal operation, when a train operates on a track, its equipment loading gauge 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. However, if the train not only intrudes the clearance envelop of its own track, but also intrudes on the clearance envelope of the adjacent track(s), this would result in an intrusion. Furthermore, if there happens to be another train on the adjacent track, the derailed equipment may collide with the train. A derailment without intrusion may cause equipment damage, infrastructure damage, passenger casualties and system disturbance, while an intrusion may lead to more severe consequences, such as a colliding with another train on the adjacent track, resulting in potentially more damage and casualties. Passenger trains operating at higher speed may increase the probability and severity of the subsequent collisions. Various ATA scenarios will be elaborated on in a later section.

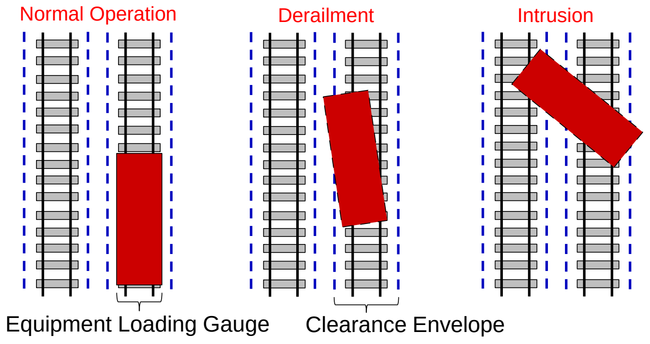


Figure 2 A Typical Prequel for an ATA

Literature Review

North America has a long history of shared-use rail corridors. There has been plenty of research addressing the safety issue of SRC in the U.S. (*1-12*). However, limited studies focused specifically on the risk of ATAs on SRC (*4, 5, 6*) during 1990s. These studies provide comprehensive analyses on ATAs either qualitatively or semi-quantitatively. However, these studies were conducted more than 20 years 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. (*7*) in 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 (*8*) conducted an analysis on the intrusion protection between high-speed rail and adjacent transportation systems. These studies provide details and insights on the risk of ATAs. However, the general and comprehensive risk assessment of the risk of ATA is not well-understood. There are also studies regarding the safety issue of SRC outside the U.S. (*8-12*), but different characteristics of rail equipment, regulatory conditions, railroad culture, and different philosophies in 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).

Research Objectives

This paper presents a comprehensive risk assessment to identify factors affecting the likelihood and consequence of ATAs. A semi-quantitative risk analysis is developed to evaluate the risk. An ATA is divided into a sequence of events, namely 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 probability associated with each event 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. This paper also discusses how these factors affect the ATA probability and consequence, and how individual factor relates to each other.

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 divided into different scenarios. Figure 3 demonstrates the event tree of ATA. Based on the type of initial accident, ATA is divided into derailments and collisions. When a train derails, it could occur on sections with single or multiple tracks. For the purpose of this study, only derailments on multiple track sections are considered. The derailment is further divided 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 divided 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. Figure 4 illustrates specific ATA derailment and collision scenarios.

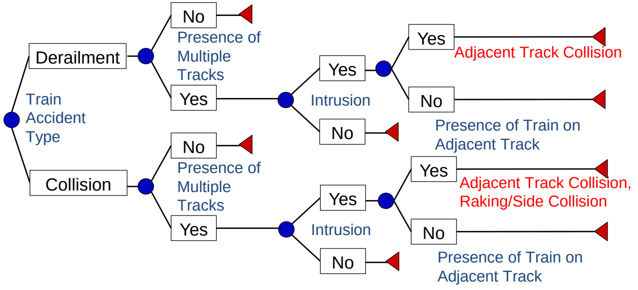
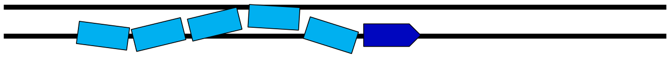
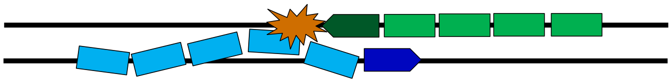


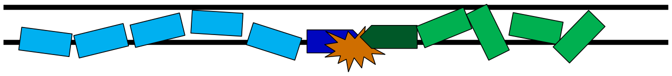
Figure 3 Conceptual Framework for ATA



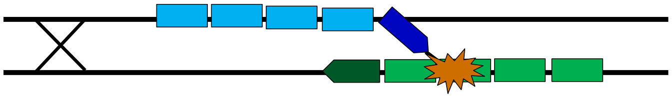
(a) Adjacent Track Derailment not Resulting in Collision



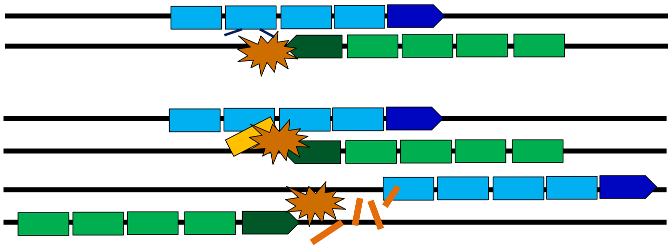
(b) Adjacent Track Derailment Resulting in Collision



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



(d) Side Collision



(e) Raking Collision

Figure 4 Specific ATA Derailment and Collision Scenarios

SEMI-QUANTITATIVE RISK ANALYSIS

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:

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

where

R: The risk index for ATA
P(A): The probability of initial derailment or collision on multiple track section
P(I|A): Conditional probability of intrusion (CPI) given an initial derailment or a collision
P(T|I): Conditional probability of the presence of a train on adjacent track given an intrusion
C: The Consequence

There are three probability components and one consequence component in the model. The three probability components correspond to the event tree shown in Figure 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 will have five levels associated with their probability and consequence. These levels are assigned 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 stated. Factors affecting each component will be identified, discussed and correlated with the level of probability and consequence. The levels of the three probability components will be combined into an overall probability. Finally, a risk assessment matrix is presented with different levels of ATA risk according to the level of the overall probability and consequence.

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 (*13*). 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 (5, 14, 16-19). 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 (*5*, *14*).

Track Quality

FRA classifies track quality into nine classes used by freight and passenger rail according to FRA Track Safety Standards (*15*). 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 (*5*, *14*, *16-19*).

Traffic Density

Previous research suggested that the traffic density on a line, measured in annual gross tonnage, has an effect on the train accident rate. The higher the traffic density, the lower the accident rate due to the higher level of maintenance (*14*).

Type of Equipment

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

Train Defect Detectors

The train defect detector can identify flaws on train wheel or other part of the rail cars before they fail, protecting the car from derailment. This may improve the train performance and result in lower accident rate (*5*). 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 (*20*, *21*).

The accident factors described previously can be combined to create the level of initial accident probability, except type of equipment and train defect detectors because of data limitation. The level of initial accident rates are divided into five levels from 1 to 5 which is summarized in Table 1 based on different combinations of the accident factors. The higher the level, the higher the probability of the initial accident.

Table 1 Level of P(A)

FRA Track Class	Traffic Density	Method of Operation	Level of P(A)
Track Class 1-3	low	Non-Signaled	5
Track Class 1-3	low	Signaled	4
Track Class 1-3	high	Non-Signaled	4
Track Class 1-3	high	Signaled	3
Track Class >3	low	Non-Signaled	3
Track Class >3	low	Signaled	2
Track Class >3	high	Non-Signaled	2
Track Class >3	high	Signaled	1

Conditional Probability of Intrusion (CPI) 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 (*7*) 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 engineering judgments.

In order to properly assign the level of CPI to a track section with specific combination of intrusion factors, Intrusion Factor Score (IFS) is created. 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 IFS will be multiplied together. Finally, based on the total IFS, a level of intrusion probability (from 1 to 5) will be assigned.

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. Figure 5 shows the maximum lateral travel distribution from the analysis by English et al. (*7*). Data from 1978 to 1985 from NTSB are chosen because they account for the majority of data. Our study classify the IFS for different track center spacing by selecting the 10th, 25th, 50th, and 75th percentile from the cumulative distribution of probability in Figure 5. The result is summarized in Table 2.

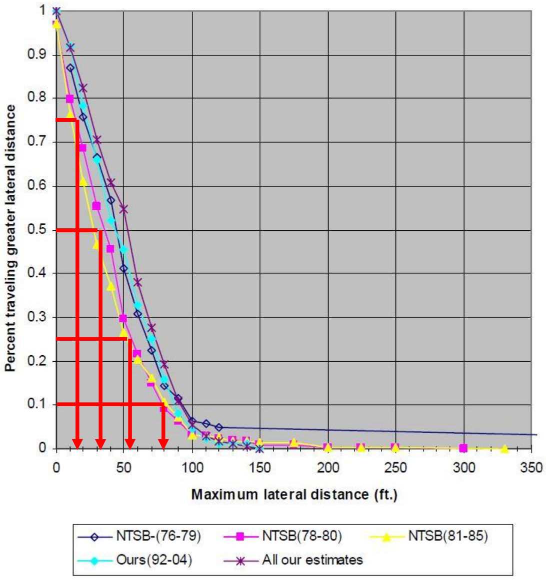


Figure 5 Maximum Lateral Travel Distribution (*7*)

Table 2 Intrusion Factor Score (IFS) for the Distance between Track Centers

Distance Between Track Centers, X (ft.)	Conditional Probability of Intrusion	Intrusion Factor Score
X > 80	P(I|A) ≤ 0.10	1.0
55 < X ≤ 80	0.10 < P(I|A) ≤ 0.25	1.5
30 < X ≤ 55	0.25 < P(I|A) ≤ 0.50	2.0
15 < X ≤ 30	0.50 < P(I|A) ≤ 0.75	3.0
X ≤ 15	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 3 shows the IFS for different combination of track alignment.

Table 3 Intrusion Factor Score 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 Figure 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 4 shows the IFS for different elevation settings.

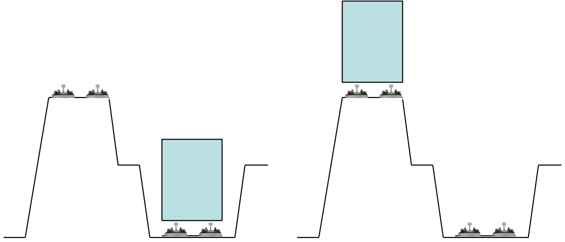


Figure 6 Effect of Elevation Differential on CPI

Table 4 Intrusion Factor Score 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 Figure 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, discrete, 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 discrete structure refers to a series of structures that are close to each other so that these structures form a “fence” instead of a single point that could divert the derailment force. For example, an industrial complex. A continuous structure, such as a noise barrier, locates alongside with the track. Buildings 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 5 shows the IFS for different adjacent structure settings.

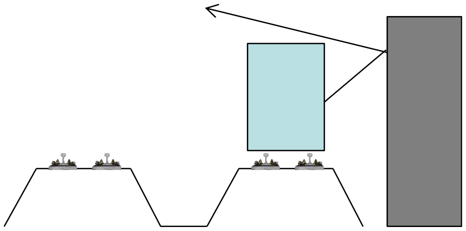


Figure 7 Effect of Adjacent Structure on CPI

Table 5 Intrusion Factor Score for Adjacent Structure

Adjacent Structure	Intrusion Factor Score
No Structure	1.0
Single Structure	1.1
Discrete Structure	1.2
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 (*4-6, 8*).

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 (Figure 8).

Table 6 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.

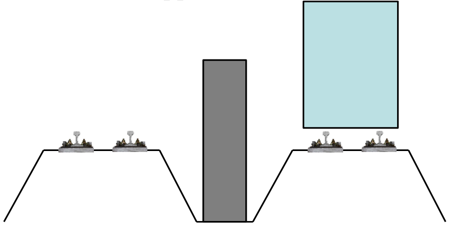


Figure 8 Effect of Containment on CPI

Table 6 Intrusion Factor Score 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 further 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. Table 7 shows the IFS for different train speed.

Table 7 Intrusion Factor Score for Train Speed

Train Speed	Intrusion Factor Score
Low	1.0
Medium	1.2
High	1.4

Point of Derailment (POD)

Point of derailment (POD) refers to the position-in-train of the first car derailed (*22*). The position of the first derailed car might 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.

Based on engineering judgment, Table 8 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 9 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 8 IFS for Selected Intrusion Factors

Intrusion Factor	Criteria	Intrusion Factor Score (IFS)
Distance Between Track Centers, X, in feet	$X > 80$	1.0
	$55 < X \leq 80$	1.5
	$30 < X \leq 55$	2.0
	$15 < X \leq 30$	3.0
	$X \leq 15$	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	1.0
	Medium	1.2
	High	1.4
The highest score possible		**20.11**
The lowest score possible		**0.35**

Table 9 Total IFS and Level of CPI

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

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, there are factors affecting this probability. 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 break the fences installed with detectors between tracks, and changes the signal on either side of the adjacent track to stop (*1, 4, 5*). 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 is assigned high, medium, or low to a track section, based on the relative traffic density of the track sections on the same SRC.

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 specific "block" but does not provide the exact position of the train, whereas advanced train control systems can precisely locate the train location. 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 (*4,5*).

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 Problem

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 (*1*). 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 relatively qualitative. Based on engineering judgment, Train Presence Score (TPS) is assigned to train presence factors in Table 10. 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 11 shows the relationship between total TPS and corresponding level of P(T|I). The higher the level, the more likely the occurrence of intrusion given an initial derailment or collision. Although not all the combinations are considered, the selected factor combinations are assumed to be representative to account for most of the circumstances.

Table 10 TPS for Selected Train Presence Factors

Train Presence Factors	Criteria	Train Presence Score (TPS)
IDW	Absence	2
	Presence	1
Traffic Density	High	3
	Medium	2
	Low	1
Method of Operation	Dark territory	3
	Typical train control system	2
	Advanced train control	1
Average Train Speed	High	3
	Medium	2
	Low	1
The highest score possible		**54**
The lowest score possible		**1**

Table 11 Total TPS and Level of P(T|I)

Total Train Presence Factor (TPS)	Level of P(T|I)
TPS > 36	5
24 < TPS ≤ 36	4
12 < TPS ≤ 24	3
6 < TPS ≤ 12	2
TPS ≤ 6	1

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 (*2*). Because ATA may include both passenger train and freight train, the consequence of ATA includes multiple 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, 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.

Speed of Train

With higher speed, more energy will be involved when a derailment or collision occur. Research shows the train speed would affect the consequence of an accident (*19*). Therefore, it is expected to have more severe consequence if the train speed is higher.

Equipment Strength

Equipment strength is a key factor for reducing the potential casualties on board from the derailment and/or collision impact. The crashworthiness has been conducted for higher-speed passenger trains (Tier I standard) (*23*). The reinforced equipment can withstand larger collision impact and thus result in less consequence.

Containment

The presence of containment can not only reduce the conditional probability of intrusion but also reduce the consequence by absorbing the energy (*4-6*).

Product Being Transported (Freight Train)

If the collision involves freight trains carrying hazardous material, 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, 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 12. 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 13.

Table 12 CFS for Consequence Factors

Consequence Factor	Criteria	Consequence Factor Score
Equipment strength	Conventional equipment	3
	Tier I compliant equipment	2
	Tier II compliant equipment	1
Containment	No containment	2
	Containment present	1
Product being transported	Hazardous material	2
	No hazardous material	1
The highest score possible		**12**
The lowest score possible		**1**

Table 13 Level of Consequence

Consequence Factor Score	Level of Consequence	Description
$CFS > 8$	5	Catastrophic
$6 < CFS \leq 8$	4	Severe
$4 < CFS \leq 6$	3	Medium
$2 < CFS \leq 4$	2	Minor
$CFS \leq 2$	1	Negligible

CALCULATION OF THE ATA RISK INDEX

The ATA risk components and their associated factors as defined in Equation 1 were discussed in the previous sections. In order to create a risk assessment matrix the levels of the three probability components are multiplied together to a single value, and this value represents the overall probability level, P. Table 14 shows the conversion of the multiplication of the three probability components and the overall probability level.

Table 14 Level of Overall Probability Level, P

Multiplication of $P(A)$, $P(I\|A)$, and $P(T\|I)$, P	Overall Probability Level	Description
$P > 100$	5	Frequent
$60 < P \leq 100$	4	Very Likely
$30 < P \leq 60$	3	Likely
$10 < P \leq 30$	2	Unlikely
$1 < P \leq 10$	1	Very Unlikely

The overall probability (Table 14) and the consequence (Table 13) are combined into a risk assessment matrix showing the risk tolerance for each combination of degree of probability and consequence, as shown in Table 15. Five types of risk tolerances are defined in this study as follows:

I: The risk is tolerable and there is no risk mitigation measurement required at the current level. However, the current situation should be monitored constantly.

II: The risk is tolerable but should be carefully reviewed and the current situation should be monitored so that the risk would not become higher. The risk mitigation strategies should be planned and applied in the future to reduce the risk.

III: The risk is high. Although no immediate action is required, the system should prioritize the risk mitigation strategies to reduce the risk to tolerable levels.

IV: The risk is very high and the system should address this problem and reduce the risk level as soon as possible.

V: The risk is too high and the system should not operate before proper risk mitigations are applied and the risk is reduced below this level right away.

By using the ATA model and the risk assessment matrix, it is feasible to calculate and compare the relative ATA risk of different track sections along the same SRC. One of the important applications of the model is locating the risk hotspots on a SRC where the ATA risk is high and risk mitigation is required.

Table 15 ATA Risk Assessment Matrix

Overall Probability, P		**Consequence Level, C**				
		Negligible	Minor	Medium	Severe	Catastrophic
		1	2	3	4	5
Frequent	5	III	IV	IV	V	V
Very Likely	4	II	III	IV	IV	V
Likely	3	II	II	III	IV	II
Unlikely	2	I	II	II	III	IV
Very Unlikely	1	I	I	II	II	III

CONCLUSIONS

The research described in this paper presents a comprehensive risk assessment to identify factors affecting the likelihood and consequence of an ATA. A semi-quantitative risk analysis is developed to evaluate the 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.

ACKNOWLEDGMENTS

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

REFERENCES

1. Saat, M.R., and Barkan, C.P.L. (2013). Investigating Technical Challenges and Research Needs Related to Shared Corridors for High-Speed Passenger and Railroad Freight Operations. Publication DOT/FRA/ORD-13-29. FRA, U.S. Department of Transportation, Washington, D.C.
2. Lin, C.Y., Saat, M. R., Barkan, C.P.L. (2014). Causal Analysis of Passenger Train Accident on Shared-Use Rail Corridor, Proceedings of 93rd Transportation Research Board, Washington, D.C.
3. Resor, R.R. (2003). Catalog of “Common Use” Rail Corridors. Publication DOT/FRA/ORD-03-16. Federal Railroad Administration, U.S. Department of Transportation, Washington, D.C.
4. Hadden, J., Lewalski, W., Kerr, D., Ball, C. (1992) Safety of High-Speed Guided Ground Transportation Systems: Shared Right-of-Way Safety Issues. Publication DOT/FRA/ORD-92-13. Federal Railroad Administration, U.S. Department of Transportation, Washington, D.C.
5. Ullman, K.B., and Bing, A.J. (1995). High Speed Passenger Trains in Freight Railroad Corridors: Operations and Safety Considerations. Publication DOT/FRA/ORD-95-05. Federal Railroad Administration, U.S. Department of Transportation, Washington, D.C.
6. Moyer, P.D., James, R.W., Bechara, C.H., Chamberlain, K.L. (1994). Safety of High Speed Guided Ground Transportation Systems Intrusion Barrier Design Study. Publication DOT/FRA/ORD-95-04. Federal Railroad Administration, U.S. Department of Transportation, Washington, D.C.
7. English, G.W., Highan, G., Bagheri, M. (2007). Evaluation of Risk Associated with Stationary Dangerous Goods Railroad Cars. TranSys Research Ltd.
8. Rulens, D. (2008). Rolling Stock and Vehicle Intrusion Protection for High-Speed Rail and Adjacent Transportation Systems TM 2.1.7. Parsons Brinckerhoff.
9. Phraner, S. D., and Roberts, R.T. (1999) Joint Operation of Light Rail Transit or Diesel Multiple Unit Vehicles with Railroads. Transit Cooperative Research Program (TCRP) Report 52. U.S. Department of Transportation, Washington, D.C.,
10. Phraner, S. D. (2001) Supplementing and Updating TCRP Report 52: Joint Operation of Light Rail Transit or Diesel Multiple Unit Vehicles with Railroads. TCRP Research Results Digest 42. U.S. Department of Transportation, Washington, D.C.
11. Chisholm, G. (2002) Germany’s Track-Sharing Experience: Mixed Use of Rail Corridors. TCRP Research Results Digest 47. U.S. Department of Transportation, Washington, D.C.
12. Nash, A. (2003) Best Practice in Shared-Use High-Speed Rail Systems. Publication ORNL-6973. Oak Ridge National Laboratory, Oak Ridge, Tennessee.
13. Federal Railroad Administration (FRA). (2011). FRA Guide for Preparing Accident/Incident Reports, U.S. Department of Transportation, Washington, D.C.
14. Liu, X. (2013). Optimal Strategies to Improve Railroad Train Safety and Reduce Hazardous Materials Transportation Risk. PhD Dissertation. University of Illinois at Urbana-Champaign, Urbana, IL.
15. Federal Railroad Administration (FRA). (2011). FRA Track Safety Standard, U.S. Department of Transportation, Washington, D.C.
16. Nayak, P.R., Rosenfield, D.B., Hagopian, J.H., (1983). Event Probabilities and Impact Zones for Hazardous Materials Accidents on Railroads. Publication

DOT/FRA/ORD-83/20. U.S. Department of Transportation, Washington, D.C.

17. Treichel, T.T. and Barkan, C.P.L. (1993). Working Paper on Mainline Freight Train Accident Rates. Unpublished Report to the Association of American Railroads.
18. Anderson, R. and Barkan, C.P.L. (2004). Railroad Accident rates for use in rail transportation risk analysis. Transportation Research Record - Journal of the Transportation Research Board 1863: 88-98.
19. Liu, X, Barkan, C.P.L., Saat, M.R. (2011). Analysis of Derailments by Accident Cause: Evaluating Railroad Track Upgrades to Reduce Transportation Risk. Transportation Research Record - Journal of the Transportation Research Board 2261: 178-185.
20. Van Dyk, B.J., Dersch, M.S., Edwards, J.R., Ruppert, Jr., C.R., Barkan, C.P.L. (2013). Quantifying Shared Corridor Wheel Loading Variation Using Wheel Impact Load Detectors. Proceedings of the 2013 ASME Joint Rail Conference, Knoxville, Tennessee.
21. Hajibabaia, H., Saat, M.R., Ouyang, Y., Barkan, C.P.L., Yang, Z., Bowling, K., Somani, K., Lauro, D., and Li, X. (2012). Wayside Defect Detector Data Mining to Predict Potential WILD Train Stops. Presented at the Annual Conference and Exposition of the American Railway Engineering and Maintenance-of-Way Association (AREMA), Chicago, Illinois.
22. Anderson, R.T. (2005). Quantitative Analysis of Factors Affecting Railroad Accident Probability and Severity. M.S. Thesis. University of Illinois at Urbana-Champaign, Urbana, Illinois.
23. Carolan, M., Jacobsen, K., Llana, P., Severson, K., Perlman, B., Tyrell, D. (2011) Technical Criteria and Procedure for Evaluating the Crashworthiness and Occupant Protection Performance of Alternatively Designed Passenger Rail Equipment for Use in Tier I Service. Publication DOT/FRA/ORD-11/22. U.S. Department of Transportation, Washington, D.C.