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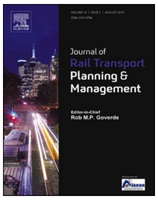

Semi-quantitative risk assessment of adjacent track accidents on shared-use rail corridors

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ABSTRACT

There are several safety questions associated with operating passenger trains and freight trains on shared-use rail corridors (SRCs). Among them are adjacent track accidents (ATA) in which derailed railroad equipment intrudes upon (“fouls”) adjacent tracks and is struck by another train on adjacent tracks. ATAs can occur in any multiple track territory, but they become more complex and potentially more hazardous on SRCs. ATAs can be broken down into three principal events: the initial derailment, an intrusion, and a train present on an adjacent track. Previous research established a foundation for addressing intrusion risk by qualitatively identifying the risk and potential mitigation measures and conducting preliminary quantitative intrusion probability analysis; however, a gap remains between current research on intrusion risk and a comprehensive risk assessment model for ATAs. This paper presents an index-based, semi-quantitative risk analysis framework to evaluate probability and consequence of ATAs. A new risk index system was developed to evaluate ATA risk by assigning levels of probability to the three principal events and the overall ATA consequence level to different track segments, thereby enabling comparison of relative ATA risk among these track segments. The levels of ATA probability and consequence are determined by various infrastructure, rolling stock, and operational factors identified in this research where each factor contributes risk scores that can be summed and converted to levels of probability and consequence. The magnitude of risk due to each factor is determined by their effect, i.e., whether it increases or decreases the probability and/or consequence. A case study based on a 320-km, modified real-world SRC is presented to demonstrate and validate the model. Higher operating speed, lack of containment or barriers, and higher initial derailment rate all significantly affect ATA risk. The model enables comparisons of the relative ATA risks among different track segments at a resolution not previously achieved. It can also be used to locate high-risk locations (risk hotspots) on a railroad corridor where ATA risk is high. This model also provides information pertinent to future improvements in quantification of ATA risk and research on mitigation measures.

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1. Introduction

1.1. Shared-use rail corridors (SRC)

Development of improved or expanded passenger rail service in the United States (U.S.) generally involves use of existing railroad infrastructure or right-of-way (ROW) (Bing et al., 2010; Peterman et al., 2013). Shared-use rail corridors (SRC) refer to trackage, ROW, and rail corridors that are used by more than one type of train, i.e., freight trains, rail transit, commuter trains, intercity passenger trains and high-speed rail (Ullman and Bing, 1995; Bing et al., 2010). The U.S. Department of Transportation (DOT), Federal Railroad Administration (FRA) defines three types of SRCs based on whether or not different types of trains share trackage, and if not, what the separation distance between adjacent tracks of different railroad systems is (Resor, 2003) (Fig. 1.) In Shared Track, passenger and freight trains operate on the same track(s). In both shared ROW and shared corridors, passenger and freight trains operate on separate adjacent tracks, but do not share track. In this case, the US DOT defines Shared ROW as passenger and freight rail lines with track centers less than 7.6 m (25 feet) apart, and Shared Corridors as track centers greater than or equal to 7.6 m (25 feet) and less than 61 m apart (200 feet).

SRCs offer advantages compared to the construction of new, dedicated passenger rail lines. These include lower capital costs, less economic, environmental and social impact, and easier accessibility to core urban areas (Nash, 2003). However, implementation of SRCs also poses challenges, including safety concerns due to more frequent and higher-speed operation of passenger trains in close proximity to freight trains and maintenance-of-way personnel, reduced line capacity due to heterogeneous traffic if tracks are shared, and a number of others discussed by Saat and Barkan (2013). Safety is the most important aspect of any railroad operation and one of the considerations of SRC implementation is the potential intrusion of derailed equipment onto adjacent railroad tracks. The intruding equipment may strike or be struck by another train operating on an adjacent track, resulting in a collision leading to more derailed equipment, infrastructure and rolling stock damage, and potentially, casualties and releases of hazardous materials. This type of collision is referred to as an adjacent track accident (ATA) and was identified by Saat and Barkan (2013) as one of the most important SRC safety issues.

1.2. Adjacent track accidents

Railroad equipment and infrastructure is designed so that in normal operations, the equipment is clear of equipment operating on an adjacent track (Fig. 2a). However, if a train derails, the derailed equipment's loading gauge will nearly always exceed its own track's clearance envelope (Fig. 2b). If the derailed equipment enters an adjacent track's clearance envelope, it is called an intrusion (Fig. 2c). When an intrusion occurs, there is a possibility that another train is running on the adjacent track, either next to, or approaching, the intrusion location. If so, the train on the adjacent track may collide with the derailed equipment (Fig. 2d). A collision resulting from the sequence of events described above is referred to as an adjacent track accident, or ATA (Lin et al., 2016).

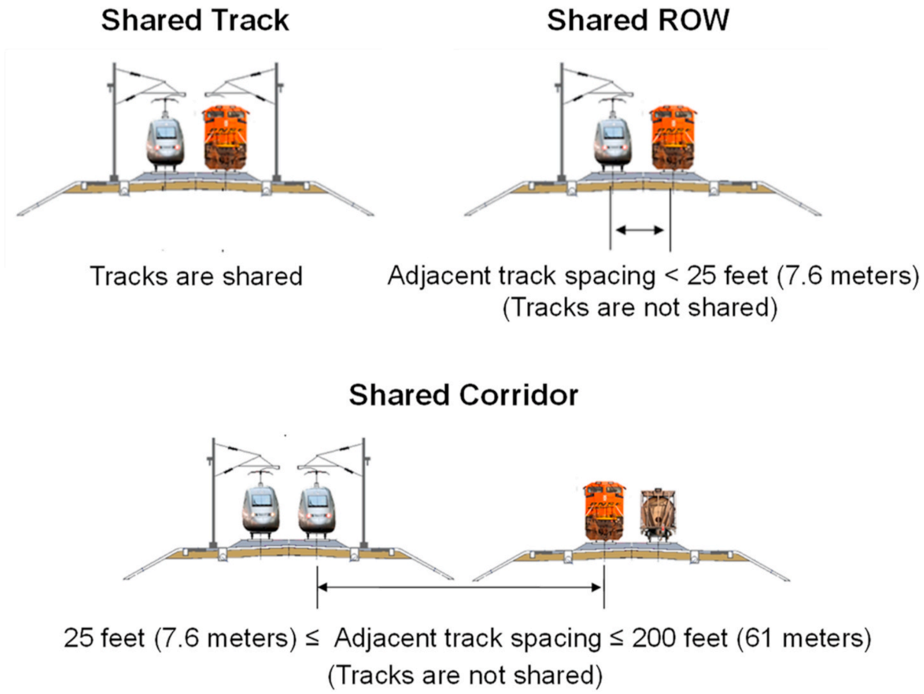

Fig. 1. Three types of shared-use rail corridors defined by the US DOT (Resor, 2003).

ATAs can occur in any multiple track territory, but they become more complex and potentially more hazardous on SRCs. As more high-speed and higher-speed passenger train services are introduced, the probability of an ATA increases, because, *ceteris paribus*, at higher speed, it takes more time and distance to stop a train if there is an intrusion ahead. Different speeds, frequencies, and other operational characteristics between passenger and freight trains increase the frequency of train meets and passes (Dingler et al., 2013), which also increases the probability of trains being close to an intrusion location should one occur. In addition, higher speed also implies greater kinetic energy in collisions, meaning more damage to rail equipment, infrastructure, and potential onboard passenger and crew casualties. Train operation by multiple operators on SRCs may also present more opportunities for communication errors, resulting in delayed or failed delivery of a warning to trains on adjacent tracks in a sufficiently timely manner to avoid a collision if an intrusion occurs. If hazardous materials are transported on an SRC, the potential consequences of an ATA are further increased if these materials are released in an accident.

2. Literature review

Intrusion risk was first formally identified in a study conducted by Booz Allen and Hamilton (1989) for the Washington Metropolitan Area Transit Authority. Since then Hadden et al. (1992) conducted a qualitative risk assessment of SRCs, including intrusion risk, and evaluated the effectiveness of risk mitigation measures. Barkan (1990) used data from the National Transportation Safety Board (NTSB) to quantify the distribution of lateral distance traveled by derailed equipment in train accidents. English et al. (2007) extended this work by incorporating data from the FRA and the Canadian Transportation Safety Board, in addition to the NTSB data, to develop a more sophisticated understanding of the lateral and longitudinal displacements of derailed equipment under various conditions. Clark et al. (2013) further developed an analytical tool based on English et al.‘s work to evaluate lateral distance traveled by derailed rail equipment and the effectiveness of prevention measures. Clark and Mosavi (2020) also discussed the use of physical barriers as a means of intrusion prevention.

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

The aforementioned studies established a foundation for addressing intrusion risk by qualitatively identifying the risk and potential mitigation measures and conducting preliminary quantitative intrusion probability analysis; however, a gap remains between current research on intrusion risk and a comprehensive risk assessment model for ATAs (Table 1). Specifically, development of a general intrusion probability model that can be used for all types of railroad systems and incorporating the intrusion probability model into a comprehensive ATA risk assessment model has not been addressed. Cockle's model is useful because it takes into account both the initial derailment rate and intrusion probability, but it does not account for the probability of train presence on adjacent tracks and the consequence of an adjacent track collision. It focuses on interactions between trains operating on conventional rail lines and high-speed trains on adjacent trackage and assumes that once an intrusion occurs, a collision between a conventional train and a high-speed train on adjacent tracks is inevitable and will result in unacceptable consequences. Cockle's model focuses on identifying

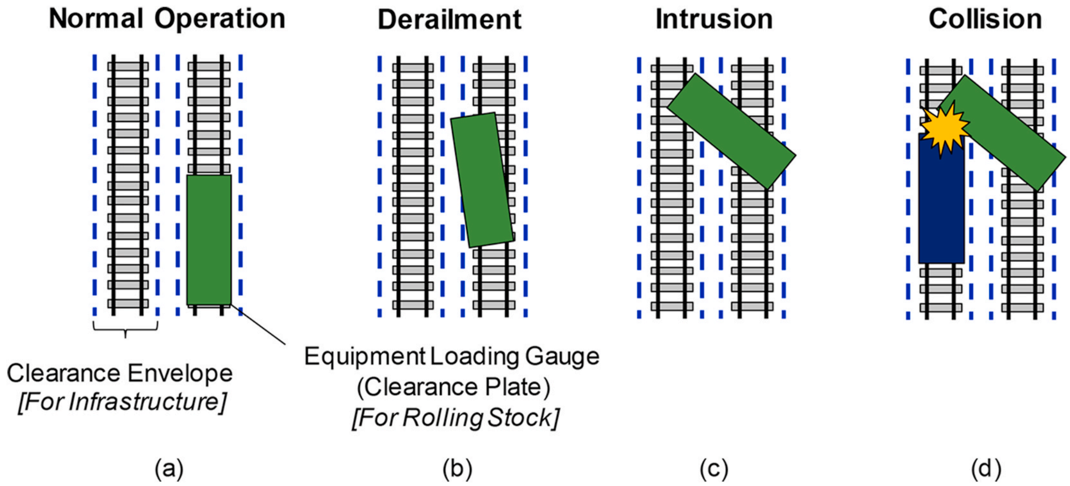

Fig. 2. A typical ATA event sequence (Lin et al., 2016).

Table 1
Summary of ATA literature review.

ATA Risk Topic	Risk Analysis Method		
	Qualitative	Semi-Quantitative	Quantitative
ATA risk identification	Hadden et al. (1992), Saat and Barkan (2013) and Clark and Mosavi (2020)	No research found	Ullman and Bing (1995)
Comprehensive ATA risk assessment model	Lin et al. (2016)	Cockle (2014)	No research found
Lateral displacement of rail equipment in derailments	N/A	N/A	Barkan (1990), English et al. (2007) and Clark et al. (2013)

factors affecting intrusion probability but does not delve into factors affecting the initial derailment rate.

Quantitative risk assessment (QRA) has been considered to address ATA risk, but a literature review found that there has only been preliminary progress developing such models. Lin et al. (2016) conducted a comprehensive fault tree analysis of ATA risk in which they identified all likely scenarios. The sequence of events leading to an ATA was divided into three principal events: initial derailment, intrusion, and adjacent train presence. Possible combinations of basic events were identified, and the corresponding probability calculations derived using Boolean algebra. Lin et al.'s model provided a foundation for ATA QRA and identified all salient elements; however, while there are quantitative models to address the initial train derailment probability, quantitative assessments of the other two probability components (intrusion and adjacent train presence) are more challenging due to lack of data. A comprehensive, risk-based decision-support tool to address ATA hazard on SRCs and to evaluate risk mitigation measures is needed. The results of the literature review suggested that the most effective pathway toward this objective is through a more sophisticated, semi-quantitative risk assessment approach.

A related problem exists in the field of highway engineering in terms of the risk of crashes involving vehicles traveling in adjacent or opposing lanes. We reviewed the pertinent literature in hopes there might be some potential application to address risk assessment questions regarding ATA. The most effective means of preventing "adjacent lane accidents" was installation of median barriers (AASHTO, 2011). The decision to install highway median barriers is primarily driven by highway traffic volume, posted speed limits, and median width (Miaou et al., 2005; AASHTO, 2011). There has been some quantitative assessment of the design of median barriers (Tarko et al., 2008; Ray et al., 2009; Fan et al., 2015) and their effect on crash severity (Donnell and Mason, 2006; Hu and Donnell, 2010; Martin et al., 2013; Russo and Savolainen, 2018); however, we were unable to find any published research that comprehensively addresses multi-factor, corridor and segment level adjacent-lane accident risk. Furthermore, various aspects of the railway ATA risk problem differ and are more complex, hence the need to delve deeper into the problem with this research.

3. Research objectives

In this paper, we identify critical factors that affect intrusion probabilities and how they can be incorporated in ATA risk assessment. Also identified are factors that affect the probability of initial derailment, train presence, and consequences of ATAs. We present a SQRA model framework that considers key factors affecting the probability and consequences of an ATA. We also develop a new risk index system that considers factors affecting all three probability components and consequences in an ATA thereby enabling comparison of relative ATA risk among different track segments in any type of railroad system. We then use a modified real-world railroad corridor to demonstrate how the SQRA model evaluates and compares ATA risk on different track segments and discuss the effects of each factor on such risk. The ATA SQRA model serves two purposes: 1) it is an interim step towards a comprehensive, fully quantitative ATA risk assessment framework, and 2) it can also serve as a stand-alone, screening-level ATA risk assessment tool to provide high-level evaluation to identify locations, track segments, or portions of railroad corridors that require more detailed, quantitative risk analysis.

4. Semi-quantitative risk analysis (SQRA)

Semi-quantitative risk analysis (SQRA) is a technique that uses numerical values to describe and evaluate risk (Gadd et al., 2003; Aven 2008). These numerical values may be order-of-magnitude risk estimates, some ordinal risk metric, or risk indices. Although these values do not reflect the actual probability and consequences of hazards, they can provide information regarding the relative scale of risk. SQRA is useful in relative risk comparison, especially when a full quantitative risk analysis is infeasible due to insufficient data to support a fully quantitative risk calculation. This is especially important to address new and emerging sources of risk due to the introduction of new or changed technologies and operations, as is the case for ATA risk assessment. In these instances, it can be used to: identify the most important factors contributing to system risk, the portion of a system with the greatest hazards, determine if more in-depth quantitative risk assessment is needed, prioritize the need for new research and data collection, and for which elements of the system it is needed (Modarres et al., 2010).

SQRA has been used in various fields of study including veterinary science (Delahay et al., 2007), food hygiene (Sumner and Ross, 2002), occupational safety (Jacinto and Silva, 2010), supply chain networks (Moonis et al., 2010), environmental threats (Tahar et al., 2017), health care (Kaya and Hocaoglu, 2020). And transportation safety (Reniers et al., 2010). In railroad applications, besides

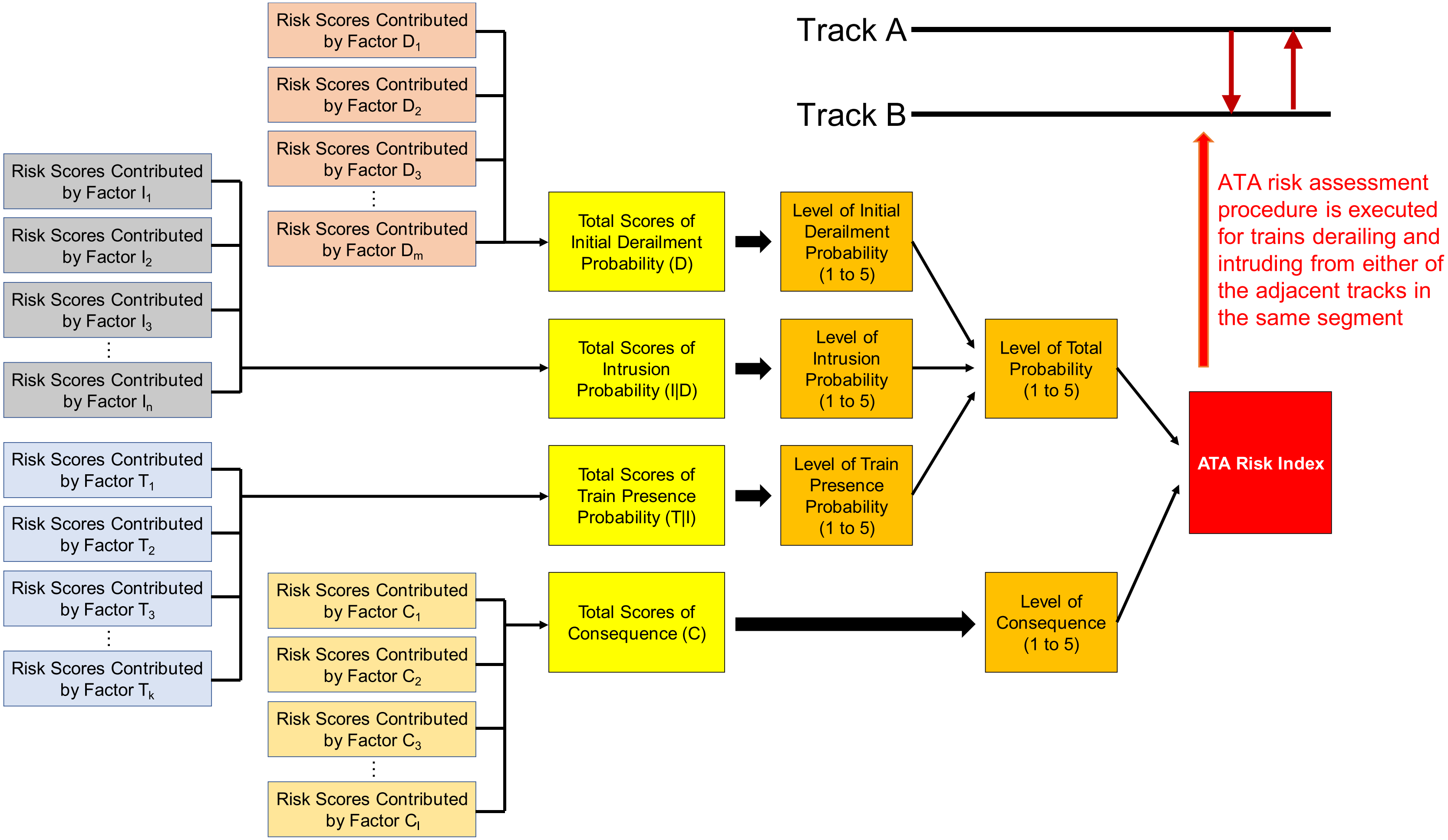

Fig. 3. Risk score, risk level and ATA risk index.

Cockle's model, Saat et al. (2015) used SQRA to address the risk of ballast projection (or "flight") on high-speed and higher-speed rail operations to identify and evaluate potential risk mitigation strategies. Internationally, Bepperling (2008) used SQRA to address railroad human factors on European railroads. The authors are unaware of any previous research that focused on general SQRA of ATAs.

A common definition of risk is the product of the probability of an event and the consequence of that event (Kushnir, 1985). This definition has been used in a wide range of railroad-related risk analyses (Barkan et al., 1992; Anand et al., 2005; Glickman and Erkut, 2007; Liu et al., 2013; Saat et al., 2014; Cheng et al., 2017). In the context of SQRA, the ATA risk is defined as:

$$\mathrm{R} = \mathrm{P} \times \mathrm{C} \tag{1}$$

Where:

R: Risk index of ATA for a track segment.

P: Level of probability of ATA for the track segment.

C: Level of consequence of ATA for the track segment.

The risk index is a unitless measure of the overall ATA risk for a track segment. The level of ATA probability, P, is also unitless and is divided into three components corresponding to the ATA event sequence described previously (Fig. 2). The resulting SQRA model for ATAs is thus defined as follows:

$$\mathrm{R} = \mathrm{P(D)} \times \mathrm{P(I|D)} \times \mathrm{P(T|I)} \times \mathrm{C} \tag{2}$$

where:

R: Risk index of ATA for a track segment.

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

$\mathrm{P(I|D)}$: Level of conditional probability of an intrusion given an initial derailment.

$\mathrm{P(T|I)}$: Level of conditional probability of the presence of a train on an adjacent track given an intrusion.

C: Level of consequence of an ATA if it occurs.

For a track segment ATA risk is calculated in two parts. Assuming there are two adjacent tracks, A and B, the ATA risk of a train on track A derailing and intruding onto track B and colliding with another train on track B is calculated, and then the ATA risk of a train on track B derailing and intruding onto track A and colliding with a train on track A is calculated, thereby accounting for the risk of a train derailing on either of the adjacent tracks.

The model uses a risk index system that is determined by the three probability components and the consequence component. Each component has five levels with corresponding values from one (lowest) to five (highest). To obtain the level for each component, various infrastructure, rolling stock, train operating characteristics, and any other relevant factors are considered. Each relevant characteristic or factor contributes "scores" to the level of specific model component(s), and based on the total score, component levels are determined. Using these levels, an ATA risk index is assigned (Fig. 3). In SQRA the probability and consequence portions are commonly divided into five to seven levels (Delahay et al., 2007; Moonis et al., 2010; Saat et al., 2015), and a five-level scale was used in this study. A railroad corridor can be divided into multiple segments and risk indices for each segment are calculated using equation (2). A summary of each factor and how it affects ATA risk is presented in the following subsections. More detailed descriptions of each factor and their effects can be found in Appendix A.

The affecting factors for each probability component and the consequence component are developed based on previous research (English et al., 2007; Cockle, 2014), and additional factors identified by detailed discussion with experts. Each factor is divided into several categories and assigned a score. The number of categories in a factor, the score for each category, the range of each category, and whether they contribute to the increase or decrease in the probability or consequence of ATA were determined and validated by expert judgment and domain knowledge through multiple brainstorming and discussion sessions.

The effect of changing individual factors on probability or consequence components cannot presently be quantified, and therefore the score system was used. Furthermore, it is uncertain which factors have greater effect on the probability or consequence components. SQRA literature (Delahay et al., 2007; Saat et al., 2015) suggests that use of a homogenous score-scale is a suitable approach under such circumstances, so we used a score-scale of 1–2 for each factor. This does not provide relative weights of different affecting factors, but it does enable qualitative comparison. If a track segment has more features that are likely to increase the probability and/or consequence of ATA risk than another track segment, its risk score will be higher and so will the overall ATA risk index. It is recognized that in SQRA a factor may affect several different probability and the consequence components. When this is the case, the factor will appear in the list of affecting factor of those components with scores. For example, if a factor F affects both P(D) and $\mathrm{P(I|D)}$, it will appear in the lists of affecting factors of both probability components so that when this factor is changed, it will affect the score, which may or may not affect the level, of both probability components. This approach best accounts for the effect of one factor on multiple components in SQRA. If a factor interacts with another (meaning that changing one factor will change the status of another) this interaction is accomplished by directly changing both factors before obtaining their scores. This is considered the best available approach to account for interaction effects of factors in SQRA (Reniers et al., 2010).

Development of the SQRA model requires expert judgment; therefore, the expert consultation process must be rigorous and unbiased to assure the reliability and accuracy of the resulting model (Reniers et al., 2010). In this study, a team of ten qualified experts were selected that included experienced safety advisors, risk managers, academics, and industry practitioners from major railroad organizations and government agencies who specialize in railroad transportation, engineering, safety, and risk assessment. We used the Reniers et al. (2010) criteria for choosing experts based on their knowledge pertinent to this study. This included reputation and years of experience in relevant fields, familiarity with uncertainty concepts, diversity in railroad background, balanced perspective, interest in the subject, expertise relevant to railroad safety and accident analysis, availability, and diversity of knowledge. All the participating experts were given the opportunity to contribute insights from their professional domain. The resulting expert-based risk index system and SQRA model can be regarded as having been qualitatively validated. Expert judgment in developing SQRA has been used in a number of previous studies in a variety of scientific fields (Sumner and Ross, 2002; Delahay et al., 2007; Moonis et al., 2010; Reniers et al., 2010; Tahar et al., 2017) and was adopted for use in this study along with suitable protocols.

For each track segment, the scores from each factor that affect a probability or consequence component are summed up to get the total score for the component. Then a conversion is made from the total score to a probability or consequence level. The additive property of scores for each factor to obtain the level of probability and consequence is recognized and has been used in other SQRA studies (Reniers et al., 2010; Saat et al., 2015; Tahar et al., 2017). Finally, the levels of probability and consequence are multiplied using Equation (2) to obtain the ATA risk index.

4.1. *Probability of initial derailment, P(D), and accident factors*

Five factors affecting the probability of initial derailment are identified and discussed below: method of operation, track quality, traffic density, traffic mix, and rolling stock defect detection and infrastructure inspection technologies.

4.1.1. *Method of operation*

In the context of this research, method of operation indicates the presence or absence of a wayside signal or automatic train control system. Train derailment rates on signaled track segments are lower than non-signaled track segments (Liu et al., 2017; Wang et al., 2020). If a Positive Train Control (PTC) system is implemented on the track segment certain types of derailments may be further be reduced (Zhang et al., 2018).

4.1.2. *Track standards*

Track segments are divided into five categories based on their FRA (2020) track classes. Track segments with higher FRA track classes have lower derailment rates than segments with lower track classes (Liu et al., 2017; Wang et al., 2020).

4.1.3. *Traffic density*

Traffic density refers to the total quantity of traffic transported over a track segment per year and in North America is commonly measured in millions of gross tons (MGT, converted to million gross tonnes in this paper). Derailment rates on higher density track segments are lower than on lower density segments (Liu et al., 2017; Wang et al., 2020). Studies have also found that average passenger train derailment rates are lower than freight trains and that dedicated passenger lines have the lowest derailment rates (Lin et al., 2019; Wang et al., 2020).

4.1.4. *Traffic mix*

Traffic mix refers to the relative proportion of passenger versus freight train traffic. Derailment rates on passenger-train-dominant

Table 2
Summary of factors affecting the initial derailment probability and AFS.

Accident Factor	Criteria Level	AFS
Method of Operation	Signaled and PTC	1.00
	Signaled	1.50
	Non-Signaled	2.00
FRA Track Class	6 or above	1.00
	5	1.25
	4	1.50
	2, 3	1.75
	X, 1	2.00
Traffic Density	*Freight-Train only or Freight and Passenger Shared Lines:*	
	More than 54.6 MGT	1.00
	36.4–54.6 MGT	1.33
	18.2–36.4 MGT	1.67
	Less than 18.2 MGT	2.00
	Passenger-Train only Lines:	
	Dedicated Passenger Line	1.00
Traffic Mix	80% or More Passenger Train Traffic	1.00
	Mixed Traffic	1.50
	80% or More Freight Train Traffic	2.00
Defect Detectors	Present	1.00
	Absent	2.00

track segments are generally lower than freight-train-dominant segments (Lin, 2019).

4.1.5. *Defect detectors and enhanced track inspection technologies and planning*

Wayside defect detection and track inspection technologies are used to identify incipient flaws in rolling stock and infrastructure components before they fail (Blevins et al., 2003; Edwards et al., 2007, 2009; Lagnebäck, 2007; Schlake et al., 2010). We assumed that track segments with defect detectors, improved track inspection technologies, and more frequent inspections have lower derailment rates than those without these enhancements (Liu et al., 2014; Liu and Dick, 2016).

The effects of altering features in different factors on the initial derailment probability may vary. For example, upgrading the FRA track class from 3 to 4 on a track segment may result in a different degree of reduction in derailment probability compared to converting the track segment from non-signaled to signaled. Also, the incremental difference in derailment probability between FRA track classes 3 and 4 may not be the same as the difference between classes 4 and 5. Some of these relationships can be addressed quantitatively, while others are less well understood. In this research, a linear approach for affecting factors is assumed in which each factor and each level within a factor have an equal effect on the initial derailment probability.

We assigned an Accident Factor Score (AFS) to each factor affecting initial derailment probability (Table 2). The AFS ranges from 1 to 2 for each factor where the base value is 1. The higher the AFS, the greater the increase in initial derailment probability. For a given track segment, the AFS values from all affecting factors are summed. The lowest possible total AFS is 5, and the highest total AFS is 10. Based on the total AFS, a level of initial derailment probability was assigned (Table 3). For purposes of consistency and simplicity, there are some underlying assumptions for the AFS: the effect of each factor is weighted equally, the AFS for each factor is equally divided by the number of categories for the factor, and the total AFS is equally divided into 5 levels.

4.2. *Conditional probability of intrusion, $P(I|D)$, and intrusion factors*

Seven factors affect intrusion probability: distance between track centers, track alignment and geometry, elevation difference, adjacent structures, containment, train speed, and the first derailed vehicle (FDV).

4.2.1. *Distance between track centers*

The horizontal distance between two adjacent track centers is divided into five ranges. The greater the horizontal track center distance, the lower the conditional probability of intrusion (English et al., 2007; Clark et al., 2013). If the track center distance is not uniform within a track segment, an average value is used.

4.2.2. *Track alignment and geometry*

Track alignment and geometry indicates whether a track segment is tangent, curved, level, or on a grade. Tangent track segments have lower intrusion probability than curved track segments, and level track segments have lower intrusion probability than track segments on a grade (Cockle, 2014). Effects of curvature and grade are assumed to be additive to the intrusion probability.

4.2.3. *Elevation difference between adjacent tracks*

If the top-of-rail elevations between two or more adjacent tracks in a track segment differ, a derailment occurring on the lower track has a lower intrusion probability than a derailment occurring on the higher track (Cockle, 2014). If two adjacent tracks have the same elevation, trains derailing on either track have the same intrusion probability.

4.2.4. *Adjacent structures*

Adjacent structures refer to structures alongside the track that may affect the intrusion probability. Track segments without any adjacent structure have lower intrusion probability than track segments with adjacent structures due to “rebound” effect in the latter case (Cockle, 2014). Structure type may also affect intrusion probability with more robust structures increasing the likelihood of intrusion.

4.2.5. *Containment*

Containment refers to structures between two tracks that prevent derailed equipment from intruding. Two types of containment, parapets and physical barriers (Hadden et al., 1992; Moyer et al., 1994; Ullman and Bing, 1995; Rulens, 2008), are considered. Track segments with containment have lower intrusion probability than track segments without containment. The effects of parapets and physical barriers are different and additive.

Table 3
Total AFS and level of initial derailment probability.

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

4.2.6. *Train speed*

Train speed is assigned low, medium, or high, based on the average speed on the segment. Intrusion probability is assumed to be directly correlated with average speed, with low speed segments having the lowest intrusion probability, and the highest speed segments the highest (English et al., 2007).

4.2.7. *First derailed vehicle*

First Derailed Vehicle (FDV) refers to the position of the first vehicle derailed in a train (Wang et al., 2020). For reasons described in Appendix A, this factor is not considered in the SQRA model.

Similar to AFS, an Intrusion Factor Score (IFS) was assigned for each intrusion factor except FDV (Table 4). The higher the IFS, the greater the increase in intrusion probability. Each factor has an IFS ranging from 1 to 2 where the base value is 1. For a track segment, the IFS values from all intrusion factors were summed with the lowest possible total IFS being 6 and the highest being 12. Based on the total IFS, a level of intrusion probability (from 1 to 5) was assigned (Table 5). The intrusion probability has the same assumption as the probability of initial derailment.

4.3. *Conditional probability of train presence, $P(T|I)$, and train presence factors*

The third probability component of the ATA risk model is the presence of trains on adjacent tracks given an intrusion. There are two variants for the presence of a train. One is that when an intrusion occurs, there is a train adjacent to the derailing equipment, and the other is that the train on the adjacent track is approaching the intrusion location. Factors affecting this probability include intrusion detection systems, traffic density, train control system, and train speed (Lin and Barkan, 2019).

4.3.1. *Intrusion detection and warning system*

This factor indicates whether an intrusion detection and warning (IDW) system is installed on a track segment. Track segments with IDW systems have a lower train presence probability than track segments without them (Hadden et al., 1992; Ullman and Bing, 1995; Saat and Barkan, 2013).

4.3.2. *Traffic density*

The higher the traffic density, the more likely it is that there will be a train at or near an intrusion location due to more frequent train meets and passes (Lin and Barkan, 2019). Train headway on a given track segment may not be homogeneous. It can be is affected by time of day, day of week, train type, operational plans, and other factors. Traffic density in this analysis is used to represent the average frequency of trains on the track. The traffic density for dedicated passenger lines is assigned the highest level, while on a mixed-traffic corridor, the traffic density of a track segment is measured using MGT. Track segments with lower MGT have lower train

Table 4
Summary of intrusion factors and IFS.

Intrusion Factor	Criteria (Level)	IFS
Distance Between Track Centers, X, in meters (feet)	$X > 24.4$ (80)	1.00
	16.7 (55) $< X \leq 24.4$ (80)	1.25
	9.1 (30) $< X \leq 16.7$ (55)	1.50
	4.3 (14) $< X \leq 9.1$ (30)	1.75
	$X \leq 4.3$ (14)	2.00
Track Alignment	Tangent and level	1.00
	Tangent and on gradient when traveling upward	1.13
	Tangent and on gradient when traveling downward	1.25
	Curved on outside track and level	1.38
	Curved on inside track and level	1.50
	Curved on inside track and on gradient when traveling upward	1.63
	Curved on outside track and on gradient when traveling upward	1.75
	Curved on outside track and on gradient when traveling downward	1.88
	Curved on inside track and on gradient when traveling downward	2.00
Elevation Differential	The track where a train derail is 3 m lower than adjacent track	1.00
	The track where a train derail is level with adjacent track	1.50
	The track where a train derail is 3 m higher than adjacent track	2.00
Adjacent Structure	No adjacent structure	1.00
	Single structure	1.33
	Discrete structure	1.67
	Continuous structure	2.00
Containment	Both containments installed	1.00
	Physical barrier installed only	1.33
	Parapet installed only	1.67
	No containment installed	2.00
Train Speed	Low (less than 48 kmph)	1.00
	Medium (48 kmph to 112 kmph)	1.50
	High (more than 112 kmph)	2.00

Table 5
Total IFS and level of intrusion probability.

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

presence probability than higher-MGT track segments.

4.3.3. Train control system

This factor specifies the type of train control system in use on a track segment. On track segments with advanced train control systems, it is more likely that an intrusion will be detected and an oncoming train stopped before an ATA occurs so these segments will have lower train presence probability than track segments with conventional train control systems (Hadden et al., 1992; Ullman and Bing, 1995). Track segments in dark territory have the highest train presence probability.

4.3.4. Train speed

Train speed for a track segment is assigned low, medium, or high based on the average speed on the adjacent track. Track segments with lower average train speed have a lower train presence probability (Lin and Barkan, 2019).

Lin (2019) developed a mathematical train presence probability model. Using the output of that model combined with the factors discussed above (more detailed information is presented in Appendix A), a Train Presence Score (TPS) was developed for each factor (Table 6). Similar to the initial derailment probability and intrusion probability, each train presence factor has a TPS ranging from 1 to 2 where the base value is 1. The total TPS for a specific track segment is calculated by summing the TPS from all train presence factors with the lowest total TPS being 4 and the highest being 8. Total TPS is then converted to levels of train presence (Table 7). The higher the level, the more likely the probability. Although not all the combinations are considered, the selected factors are assumed to be representative of most circumstances. TPS probability holds the same assumption as AFS and IFS.

4.4. Consequence, C, and severity factors

Consequence is the damage or harm resulting from an ATA. The major concern is the consequence of a collision between derailed equipment and trains on adjacent tracks. Previous research showed that the average casualties for passenger train collisions are greater than passenger train derailments (Lin et al., 2019). The consequences of ATAs include multiple types of impacts as follows:

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

Table 6
Train presence factors and TPS.

Train Presence Factors	Criteria (Level)	TPS
IDW	Presence	1.00
	Absence	2.00
	Freight or Freight and Passenger Shared Lines:	
Traffic Density	Less than 18.2 MGT	1.00
	18.2–36.4 MGT	1.33
	36.4–54.6 MGT	1.67
	More than 54.6 MGT	2.00
	Passenger Lines:	
	Dedicated Passenger Line	2.00
Train Control System	Advanced train control	1.00
	Typical train control system	1.50
	Dark territory	2.00
Average Train Speed	Low (less than 48 kmph)	1.00
	Medium (48 kmph to 112 kmph)	1.50
	High (more than 112 kmph)	2.00

Table 7
Total TPS and level of train presence probability.

Total TPS	Level of P(T|I)
TPS ≤4.8	1
4.8 < TPS ≤5.6	2
5.6 < TPS ≤6.4	3
6.4 < TPS ≤7.2	4
TPS >7.2	5

The factors affecting the severity of ATA accidents are discussed in the following subsections: equipment damage resistance, train speed, containment, and product being transported.

4.4.1. *Equipment damage resistance*

Equipment damage resistance is a key factor for reducing on-board casualties from the derailment and/or collision impact (Tyrell and Perlman, 2003). Carolan et al. (2011) conducted crashworthiness analyses for higher-speed passenger trains to understand how equipment with crash energy management (CEM) design can withstand greater collision impact force and result in less structural damage and fewer passenger casualties. Meran et al. (2016) developed a crush zone system to improve the crashworthiness characteristics of rail equipment used on the Turkish State Railway. Gao and Wang (2018) and Zhu et al. (2020) both conducted international review of CEM standards and methods to enhance CEM of rail equipment and reduce the consequence of train collisions. Rolling stock is classified into two categories in this study: CEM-designed equipment and conventional equipment. CEM-designed equipment refers to passenger cars that meet the FRA Tier I or higher crashworthiness regulations, and conventional equipment refers to rail cars that do not (Carolan et al., 2011).

4.4.2. *Train speed*

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

4.4.3. *Containment*

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

4.4.4. *Product being transported (freight train only)*

If a collision involves freight trains carrying hazardous materials, it may cause a release resulting in more severe consequences (Liu et al., 2013; Liu and Dick, 2016).

Each factor was assigned a Consequence Factor Score (CFS) (Table 8). CFS ranges from 1 to 2 where the base value is 1. For a given track segment, the total CFS is calculated by summing the individual CFS. The lowest possible total CFS is 4 and the highest is 8. The total CFS was converted to the level of consequence (Table 9).

5. ATA risk evaluation

Levels of probability for initial derailment, intrusion, and train presence can be multiplied using equation (2) to obtain the overall probability P and an overall probability is then assigned (Table 10). After obtaining the overall probability level, using equation (1), an ATA risk index, R, is obtained by multiplying this probability level P times the consequence level C. Note that the risk index is not a quantitative measure of ATA risk; instead, it indicates the relative risk of a track segment compared to other track segments.

The proposed SQRA model enables evaluation and comparison of ATA risk indices for a railroad corridor. A corridor is divided into multiple track segments, each characterized by its track, structures, and signal configuration. Segment length varies depending on these and other characteristics, as well as the desired resolution of the analysis. Evaluation of the ATA risk index is also affected by the

Table 8
Consequence factors and CFS.

Consequence Factor	Criteria (Level)	CFS
Equipment Strength	CEM-designed equipment	1.00
	Traditional equipment	2.00
Speed	Low (less than 48 kmph)	1.00
	Medium (48 kmph to 112 kmph)	1.50
	High (more than 112 kmph)	2.00
Containment	Containment Present	1.00
	No Containment	2.00
Product being transported	No Hazardous material	1.00
	Hazardous material	2.00

Table 9
Total CFS and level of consequence.

Total CFS	Level of Consequence
CFS = 4	1
4 < CFS ≤5	2
5 < CFS ≤6	3
6 < CFS ≤7	4
CFS >7	5

Table 10
Overall probability level definitions.

Multiplication of P(D), P(I|D), 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

number of adjacent tracks. In the simplest case there are two adjacent tracks, A and B (Fig. 4a), and the ATA risk index for the given segment is:

$$R_{\text{segment, 4a}} = R_{AB} + R_{BA=}P_{AB} \times C_{AB} + P_{BA} \times C_{BA} \tag{3}$$

where:

$R_{AB,}$ $P_{AB,}$ C_{AB}: the risk index, level of probability, and level of consequence of having an ATA where a train on track A derails and intrudes onto track B and strikes, or is struck by, a train on track B.

$R_{AB,}$ $P_{AB,}$ C_{AB}: the risk index, level of probability and level of consequence of having an ATA where a train on track B derails and intrudes onto track A and strikes, or is struck by, a train on track A.

Calculation of the ATA risk index becomes more complex when there are more than two adjacent tracks. For example, in a segment with three tracks (Fig. 4b) each pairwise combination of tracks has a distinct set of model input and ATA risk is calculated for each pair. The risk index for this segment is the sum of the risk indices from each pair:

$$R_{\text{segment, 4b}} = R_{AB} + R_{BA} + R_{AC} + R_{CA} + R_{BC} + R_{CA} \tag{4}$$

If there are n tracks adjacent to each other in a segment (Fig. 4c), the ATA risk index for this segment is calculated as follows:

$$R_{\text{segment,4c}} = \sum_{i}^{n} \sum_{j}^{n} \left(R_{ij} + R_{ji}\right) \tag{5}$$

where:

i and j represent any pair of the n adjacent tracks from 1, 2, 3, …, n, and $i < j \forall i,j$

The aforementioned calculations consider train interactions on adjacent main tracks. If there is a railroad yard or terminal in the track segment (Fig. 4d), the ATA risk between the mainline and yard tracks is calculated separately. Since there are usually multiple tracks in a yard, more calculations are required. Accident rates on yard and terminal tracks are higher than on mainline tracks (Anderson and Barkan, 2004). In a busy yard or terminal there are frequent switching operations with locomotives and railcars moving back and forth, thereby increasing the train presence rate as well. Counteracting these factors is that nearly all yard and terminal operations are at low speed (≤32.2 mph) resulting in lower intrusion rates and consequences. Furthermore, depending on the relative

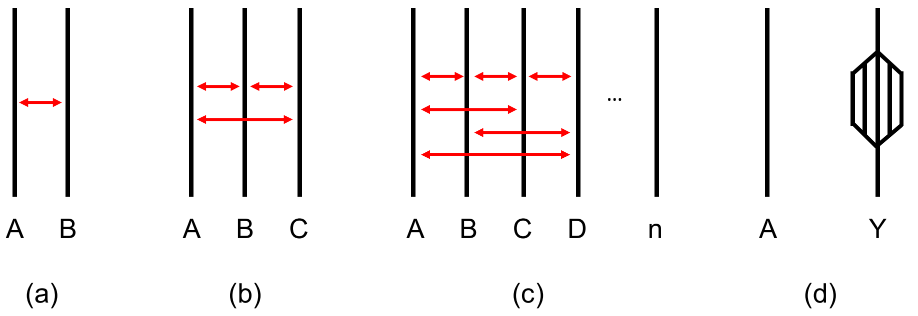

Fig. 4. ATA risk relevance among different adjacent tracks.

locations of mainline tracks and the yard/terminal, mainline tracks can be positioned around or through a yard/terminal, complicating the scenarios in ATA risk calculation involving yard or terminal tracks. For the purpose of the analysis described here we assumed that the ATA risk between the mainline track and the closest yard track is representative of the ATA risk between the mainline track and the whole yard at that location and is calculated as follows:

$$R_{\text{segment, 4d}} = R_{AY} + R_{YA} \tag{6}$$

where:

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

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

The total ATA risk index for the rail corridor is the sum of the risk indices on all segments:

$$R_{\text{corridor}} = \sum_{m=1}^{p} \left(\sum_{mi}^{n} \sum_{mj}^{n} R_{ij} + R_{ji} \right) \tag{7}$$

where:

n: total number of tracks in a segment

i and *j* represent any pair of the *n* adjacent tracks from 1, 2, 3, …, n in the segment m, and $i < j \forall i, j$

m: track segment

p: total number of track segments in the railroad corridor.

6. Model demonstration

To demonstrate the SQRA ATA model, a railroad corridor was developed based on an actual SRC in operation in the United States. The corridor is divided into track segments with different infrastructure, rolling stock, and operating characteristics, and the model was used to evaluate and compare ATA risk on different track segments. An important criterion required for the selected corridor is the inclusion of varying segment characteristics so that the effects of different factors can be detected by the SQRA model and reflected in the risk score, level of probabilities and consequence, and resulting risk indices. We were provided confidential, proprietary data on critical corridor characteristics and incorporated these into our analysis to ensure that the evaluation and comparison of ATA risk was

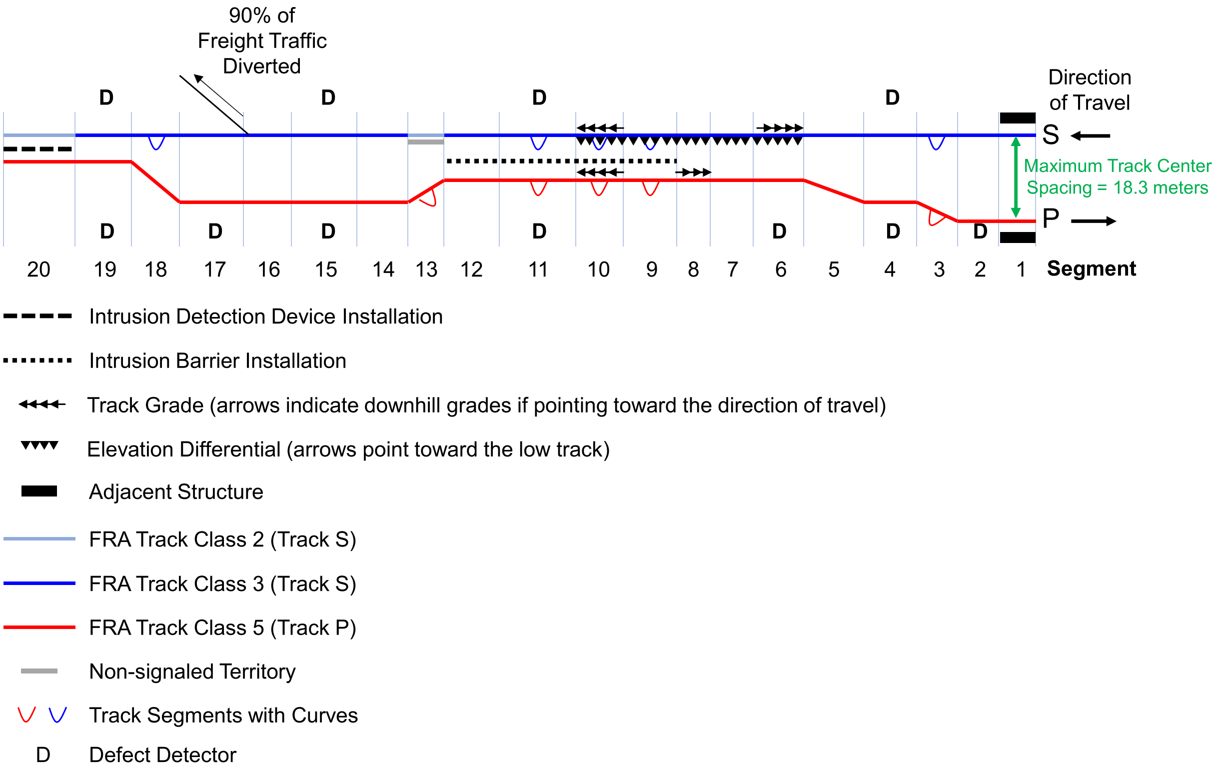

Fig. 5. SRC layout for case study.

as realistic and practical as possible. The model was validated by observing whether the ATA risks on each segment matched the expected effects of their infrastructure, rolling stock, and operational characteristics.

6.1. Corridor information

A 320-km SRC consists of two tracks: S and P (Fig. 5). Track S is shared by freight and passenger trains with 90% freight traffic (including hazardous materials) and 10% passenger traffic, with total annual traffic on track S of 54.6 MGT. Track P is a dedicated passenger line. Both railroad operators want to understand the ATA risk along the corridor. The corridor is divided into 20 segments based on infrastructure, rolling stock, and operational characteristics (Table 11). At the end of segment 16, much of the freight train traffic from track S is diverted to another route. Therefore, from segment 17 to 20, Track S has 50% freight train traffic and 50% passenger train traffic. The maximum track separation between tracks S and P is 18.3 m, making this a shared-ROW corridor (Resor, 2003).

6.2. Risk evaluation and comparison

Equations (1) through (7) are used to calculate ATA risk indices for each segment on the SRC. Because there are two tracks on this segment, the probability levels for P(D), P(I|D), P(T|I), and C are calculated separately for each track. The process is illustrated with Segment 12 using the following steps:

1. Track S on segment 12 is signaled with FRA track class 3, 54.6 MGT mixed traffic, and does not have a defect detection system. According to Table 2, the AFS of track S on segment 12 for this segment is 1.5 (signaled without PTC) + 1.75 (track class 3) + 1.33 (36.4–54.6 MGT) + 2 (80% or more freight train traffic) + 2 (no defect detectors) = 8.58. According to Table 3, this score is converted to P(D) level 4. Track P on segment 12 is signaled, with class 5 track, has only passenger traffic, and no defect detection system. According to Table 2, the AFS of track S on segment 12 for this segment is 1 (signaled with PTC) + 1.25 (track class 5) + 1 (dedicated passenger line) + 1 (80% or more passenger train traffic) + 2 (no defect detectors) = 6.25. According to Table 3, this score is converted to P(D) level 2.
2. The track center spacing on segment 12 is 4.57 m. Track S and P are both tangent and level tracks. There is no elevation differential between the two tracks and there is no adjacent structure. Parapet and intrusion barriers are installed between the two tracks. The train speed on track S is 47 kmph and on track P is 127 kmph. Using Table 5, the IFS for track S on segment 12 is 1.75 (track center

Table 11
Segment input for the SRC.

Segment	Track S							Track P								
	TC	G	C	S	TCS	AS	SD	TC	G	C	S	TCS	AS	SD	TS	ED
1	3	0	0	1	S	1	40	5	0	0	1	A	1	56	7.62	0
2	3	0	0	1	S	0	40	5	0	0	1	A	0	56	7.62	0
3	3	0	1	1	S	0	56	5	0	1	1	A	0	72	6.71	0
4	3	0	0	1	S	0	72	5	0	0	1	A	0	96	6.10	0
5	3	0	0	1	S	0	89	5	0	0	1	A	0	96	5.18	0
6	3	up	0	1	S	0	89	5	0	0	1	A	0	96	4.57	1
7	3	0	0	1	S	0	89	5	0	0	1	A	0	127	4.57	1
8	3	0	0	1	S	0	89	5	down	0	1	A	0	127	4.57	1
9	3	0	1	1	S	0	47	5	0	1	1	A	0	80	4.57	1
10	3	down	1	1	S	0	47	5	up	1	1	A	0	80	4.57	1
11	3	0	1	1	S	0	47	5	0	1	1	A	0	80	4.57	0
12	3	0	0	1	S	0	47	5	0	0	1	A	0	127	4.57	0
13	3	0	0	1	D	0	32	5	0	1	1	A	0	127	5.49	0
14	2	0	0	0	S	0	56	5	0	0	1	A	0	127	6.10	0
15	3	0	0	1	S	0	72	5	0	0	1	A	0	127	6.10	0
16	3	0	0	1	S	0	72	5	0	0	1	A	0	127	6.10	0
17	3	0	0	1	S	0	89	5	0	0	1	A	0	127	6.10	0
18	3	0	1	1	S	0	89	5	0	0	1	A	0	89	5.18	0
19	3	0	0	1	S	0	89	5	0	0	1	A	0	72	4.27	0
20	2	0	0	1	S	0	24	5	0	0	1	A	0	48	4.27	0

TC: FRA track class.
AS: presence of adjacent structure.
G: track grade.
TS: track spacing.
C: presence of curve.
ED: elevation differential.
S: presence of signaling system.
TCS: train control system (D: Dark Territory; S: Typical; A: Advanced).
SD: average operating speed.

spacing between 4.3 m and 9.1 m) + 1 (track alignment being tangent and level) + 1.5 (no elevation differential) + 1 (no adjacent structure) + 1 (physical barrier and parapet) + 1 (train speed less than 48 kmph) = 7.25. According to Table 5, this score is converted to P(I|D) level 2. The IFS for track P on segment 12 is 1.75 (track center spacing between 4.3 m and 9.1 m) + 1 (track alignment being tangent and level) + 1.5 (no elevation differential) + 1 (no adjacent structure) + 1 (physical barrier and parapet) + 2 (train speed greater than 112 kmph) = 8.25. According to Table 5, this score is converted to P(I|D) level 2.

3. Neither track on segment 12 has IDWs. According to Table 7, the TPS for track S is 2 (no IDWs) + 1.33 (36.4–54.6 MGT mixed traffic) + 1.5 (typical TCS) + 1 (train speed less than 48 kmph) = 5.83. According to Table 7, this score is converted to P(T|I) level 3. Likewise, the TPS for track P is 2 (no IDWs) + 2 (dedicated passenger line) + 1 (advanced TCS) + 2 (train speed greater than 112 kmph) = 7. According to Table 7, this score is also converted to P(T|I) level 4.
4. The total probability level of segment 12 can be obtained by multiplying the levels of P(D), P(I|D), and P(T|I):

$$P_{SP} = P(D)_S \times P(I|D)_S \times P(T|I)_P = 4 \times 2 \times 4 = 32$$

$$P_{PS} = P(D)_P \times P(I|D)_P \times P(T|I)_S = 2 \times 2 \times 3 = 12$$

Using Table 10, the probability level for track S is 4 (P_{SP12}) and the probability level for track P is 2 (P_{PS12}). It is important to mention that when calculating the probability of an ATA that initiates on track S, i.e. a train on track S derails, intrudes onto track P, and is struck by another train on track P, or P_{SP}, the probability levels of P(D) and P(I|D) on track S are used while the probability level of P(T|I) on the adjacent track is used. This is because the initial derailment and intrusion take place on track S, so it is the characteristics of track S that affect the initial derailment and intrusion probability. On the other hand, after the intrusion occurs, whether or not there is another train on the adjacent track (track P in this case) that potentially collides with the intruding train is affected by the characteristics of the adjacent track. The same logic applies to the probability of ATA that initiates on track P: the probability levels of P(D) and P(I|D) on track P are used while the probability level of P(T|I) on track S is used.

5. For consequence evaluation, the rolling stock used on track S is not CEM-designed but rolling stock used on track P is. Hazmat traffic carried on track S but not on track P. According to Table 8, the consequence score for track S is 2 (conventional equipment) + 1 (train speed less than 48 kmph) + 1 (containment) + 2 (carrying hazmat traffic) = 6. According to Table 9, this score is converted to C level 3 (C_{PS12}). The consequence score for track P is 1 (CEM-designed equipment) + 2 (train speed greater than 112 kmph) + 1 (no containment) + 1 (no hazmat traffic) = 5. According to Table 9, this score is converted to level 2 (C_{SP12}).
6. Finally, using equation (3), the ATA risk for segment 12 is:

$$R_{12} = R_{SP12} + R_{PS12} = P_{SP12} \times C_{SP12} + P_{PS12} \times C_{PS12} = 4 \times 3 + 2 \times 2 = 16$$

The risk of an ATA is calculated for all segments on the SRC (Table 12) and the levels of probabilities for the three principal events and consequence are visualized (Fig. 6). Segments 3, 5, 7, 8, 14, and 16 have the highest ATA risk due to high train presence and consequence levels. This is because the operating speed on both tracks on those segments is high, and there is no containment, intrusion barriers, or IDW to prevent or reduce the risk of ATAs. The suggested risk mitigation measures for these segments are installation of intrusion barriers and IDWs to reduce intrusion probability and consequences, and wayside defect detectors to reduce initial derailment probability. Segment 13 also has high ATA risk due to the high initial derailment rate. The suggested risk mitigation measure is to upgrade the track to higher FRA track class or install a signaling system for the segment. Segments 9, 10, 11, and 12 have low ATA risk mainly due to the presence of containment such as physical barriers and parapets.

Table 12
ATA risk indices output for the SRC.

Segment	$P(D)_S$	$P(D)_P$	$P(I\|D)_S$	$P(I\|D)_P$	$P(T\|I)_S$	$P(T\|I)_P$	P_{SP}	P_{PS}	C_{SP}	C_{PS}	R(ATA)
1	4	2	3	4	3	4	4	3	4	3	**25**
2	4	2	2	3	3	4	4	2	4	3	**22**
3	4	2	3	3	4	4	4	3	5	3	**29**
4	3	1	3	3	4	4	4	2	5	3	**26**
5	4	2	3	3	4	4	4	3	5	3	**29**
6	4	1	3	2	4	4	4	1	5	3	**23**
7	4	2	3	3	4	4	4	3	5	3	**29**
8	4	2	3	3	4	4	4	3	5	3	**29**
9	4	2	2	2	3	4	4	2	3	2	**16**
10	4	2	3	2	3	4	4	2	3	2	**16**
11	3	1	2	2	3	4	3	1	3	2	**11**
12	4	2	2	2	3	4	4	2	3	2	**16**
13	5	2	2	4	4	4	4	4	4	3	**28**
14	4	2	3	3	4	4	4	3	5	3	**29**
15	3	1	3	3	4	4	4	2	5	3	**26**
16	4	2	3	3	4	4	4	3	5	3	**29**
17	3	1	3	3	3	4	4	1	5	3	**23**
18	3	2	3	3	3	4	4	2	5	3	**26**
19	2	1	3	3	3	4	3	1	5	3	**18**
20	3	2	3	3	2	2	2	2	4	3	**14**

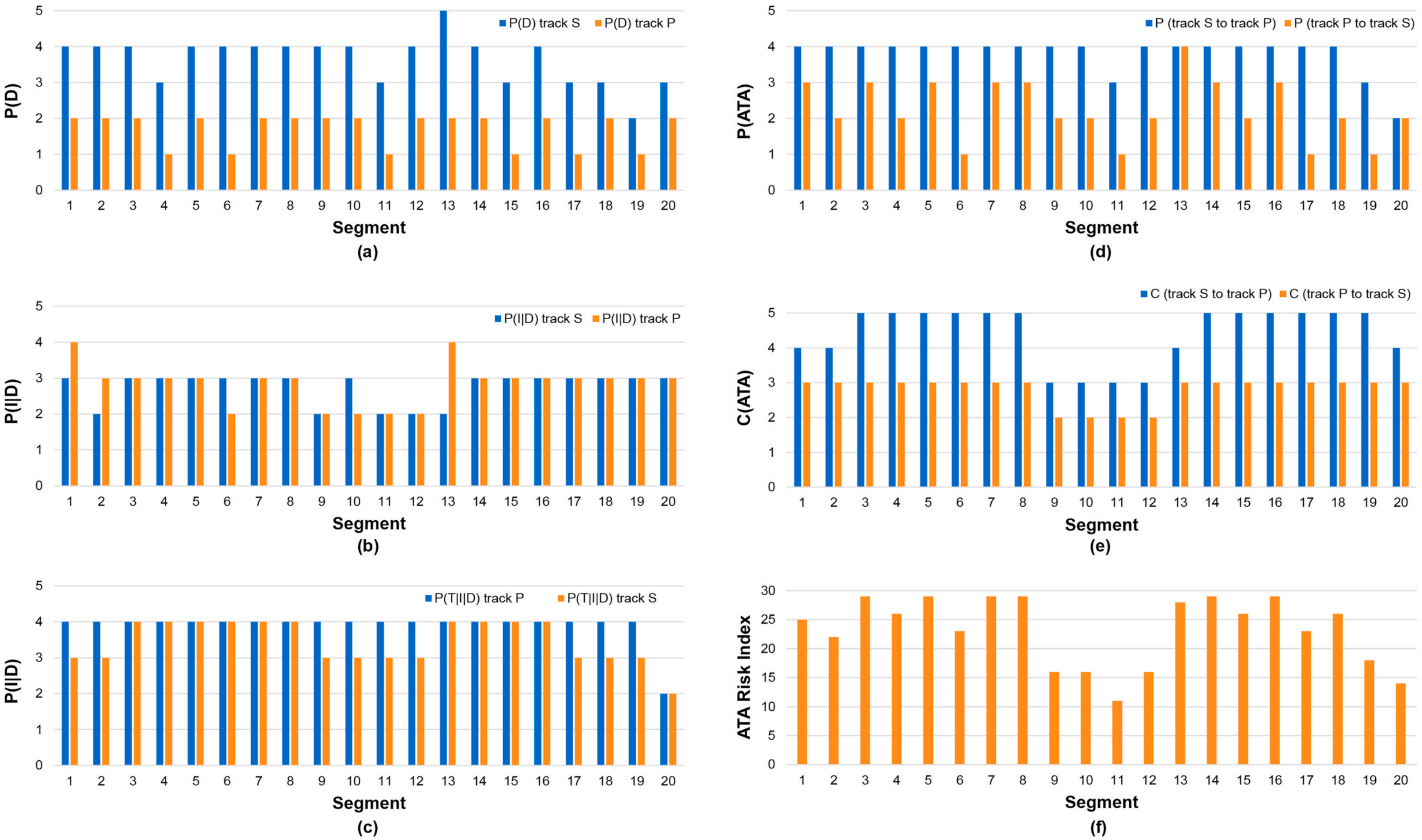

Fig. 6. Visualization of ATA risk evaluation for each track segment in the case study: (a) P(D), (b) P(I|D), (c) P(T|I|D), (d) overall probability level, P, (e) consequence level, C, and (f) ATA risk index.

7. Discussion

Several factors are identified that affect probability and consequence components in the SQRA ATA model. Train speed, for example, is identified to affect probability of intrusion, probability of train presence, and consequence. The main reason is the kinetic energy generated by operating trains at higher speed. This affects the lateral movement of derailed equipment, the time and distance required to stop the train on an adjacent track, and the severity of impact if a collision occurs. Reducing operating speed can reduce ATA risk, but it also reduces operating efficiency. Hence, other risk mitigation strategies such as installation of containment and IDWs could be considered on track segments where higher operating speed is necessary. Quantitatively addressing the effect of train speed on ATA risk is thus important in more accurately evaluating the risk and the effectiveness of risk mitigation measures.

Another factor affecting multiple model components is containment, which affects both the probability of intrusion and consequence. Intrusion barriers are among the most important risk mitigation measures for train intrusion and ATA, but the effect of these barriers has not been fully quantified. Construction of intrusion barriers can be costly and requires additional space on the ROW. They can also interfere with maintenance activities and evacuation processes in an emergency. Research is needed to quantify the effectiveness of intrusion barrier designs and their placement to reduce ATA risk.

8. Model limitations

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

The identification of factors and categorization of probability and consequence levels necessarily relies on expert judgment. This is because there has not been a general model that encompasses all the risk components, ($P(D)$, $P(I|D)$, $P(T|I)$, and C) nor motivation to quantify the factors affecting them. Another contribution of the SQRA model presented here is to structure the problem and identify the principal factors affecting ATA risk.

Despite the aforementioned model limitations, the SQRA model provides a foundation for addressing ATA risk that is applicable to current questions. In a complex system such as a SRC, the model can identify locations and track segments with higher risk so that users can allocate resources more effectively, and prioritize them for more in-depth quantitative risk assessment if appropriate. Although the model does not provide quantitative risk estimates of the absolute frequency and expected severity of an ATA, it does provide a practical tool to estimate relative ATA risk that has already been put to use (Shahtaheri, 2021).

Beyond its practical use, the current model structure and results provide insight into the most important information needed for a more accurate SQRA and potentially, a fully quantitative risk assessment model. In this way, the model helps focus research and data collection resources towards this end. As new technologies develop and operations change, it is not unusual for insufficient information to be available for a full, quantitative risk analysis. However, this does not diminish the importance of these potential new risks, nor should it discourage attempts to understand and manage it as effectively as possible until the requisite data are available. In these instances, a qualitative or semi-quantitative approach can be used to identify and prioritize the key factors and data needed to develop a more sophisticated and accurate risk assessment model (Elms, 2001). This process is often iterative; once quantitative data for each factor have been collected, the SQRA model can be used to re-evaluate the risk and identify the next highest risk locations. The model is also dynamic because as knowledge of additional relationships is developed new factors can be incorporated to enhance the model.

9. Conclusions

The research described here presents the first comprehensive assessment of the factors affecting ATA risk and an SQRA model was developed to fulfill this objective. Levels of probability and consequence, and various factors affecting the initial derailment, the intrusion, the presence of trains on adjacent tracks, and the consequences are defined. The model enables comparison of the relative ATA risks among different track segments. It can also be used to locate high-risk locations (risk hotspots) on a railroad corridor, thereby prompting more in-depth analyses and risk mitigation measures for these locations. Several opportunities for future research to develop a comprehensive, quantitative ATA risk assessment are discussed.

10. Future research

The development of the SQRA ATA model revealed several research questions that should be addressed to improve its accuracy and comprehensiveness, and also provide information for improved quantitative ATA risk assessment and other rail safety analyses in the future.

10.1. Passenger and freight train accident analysis

Passenger and freight trains differ in rolling stock, infrastructure, and operating characteristics, which affects their accident characteristics. When operating these types of trains on the same corridor these differences in rates, severity, and affecting factors should be accounted for in a comprehensive SRC risk analysis. The results can be used to derive quantitative estimates of initial derailment probability that can be incorporated into the SQRA model for more accurate analyses.

10.2. Quantitative analysis of intrusion probability

Presently, quantification of intrusion probability considers only track center spacing. Quantitative analysis of other factors identified in this research that affect intrusion probability should be addressed. Specifically, what are the effects of: curvature, grade, elevation differential, the presence of adjacent structures, and train speed. Train accident intrusion data are not commonly recorded so simulation and train accident modeling techniques (Birk et al., 1990; Kirkpatrick, 2009, 2013; Kirkpatrick et al., 2015; Wilson et al., 2011; Ling et al., 2016) should be used for this analysis and validated using data from actual accidents. Detailed quantitative analyses should be carried out to enable greater resolution of the effects of curvature and grades on intrusion probabilities.

10.3. Effect of intrusion barriers

Physical intrusion barriers can reduce intrusion probability and consequences; however, the relationship between the design of the barrier and the reduction in risk are poorly understood. Structural modeling of intrusion barriers and impacts of rail equipment would enable characterization and quantification of the effectiveness of intrusion barriers. This would improve the accuracy of this aspect of the SQRA model and provide important information regarding barrier design parameters and guidance in their use.

10.4. Quantitative train presence probability

If an intrusion occurs, the distance between the intruding train, the adjacent track, and a train running on that track are important parameters affecting the risk. If the tracks are sufficiently close and the train on the adjacent track is too close or passing at the time of the intrusion, a collision is inevitable. If, on the other hand, the trains are farther apart there is a chance that the train on the adjacent track may be able to stop in time to prevent a collision. The alerting system and braking capability of the train on the adjacent track both affect the likelihood of the collision. Addressing these questions involves the development of a quantitative model for train presence probability as part of the comprehensive ATA risk assessment (Lin, 2019). Understanding the relationships between these factors as well as other factors mentioned in this paper will improve the accuracy of the SQRA model.

Data availability statement

Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request (SQRA ATA risk calculator and data for the case study).

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Appendix A. Additional Information for Factors Affecting ATA Risk

Factors Affecting the Probability of Initial Derailment, P(D)

Method of Operation

Method of operation indicates whether a track segment has electric track circuits and wayside signals. Previous research found that train accident rate on signaled track segments is lower than non-signaled track segments. This may be due to enhanced detection of broken rails, which are among the leading causes of mainline derailments (Liu et al., 2017; Wang et al., 2020), but further research is needed to understand the underlying explanation.

Track Standards

The FRA (2020) classifies railroad track into nine classes based on maximum authorized speed and maintenance standards. Previous research has found an inverse relationship between FRA track class and train derailment rate (Nayak et al., 1983; Anderson and Barkan 2004; Liu et al., 2017; Wang et al., 2020). There are five principal track classes commonly used by US freight railroads, ranging from class 1 with the lowest maximum allowable train speed to class 5 with the highest. Track classes 6 and higher are grouped together because they are primarily used for passenger train operations. The authors are unaware of any quantitative analyses of derailment rates for FRA track classes higher than 5, but based on the research cited above, it is presumed that they are at least as low, and probably lower, than class 5.

Traffic Density

Annual railroad traffic density is commonly measured on North America railroads by the total gross tonnage traveling over a section of rail line. This metric includes the total weight of all locomotives, rolling stock, and lading. Higher traffic densities are correlated with lower derailment rates (Liu et al., 2017; Wang et al., 2020). The exact mechanism for this is not understood, but it may be due to the more frequent inspections, maintenance, and number of wayside defect detection systems characteristic of high-density freight and dedicated passenger rail lines. In addition, lighter axle loads of passenger equipment inflicts relatively less damage to the track structure, reducing derailment likelihood. Thus, it is assumed that, *ceteris paribus*, dedicated passenger lines have the lowest derailment rates followed by mixed freight and passenger traffic lines and freight-only lines.

Traffic Mix

Failures of wheels, axles, and other rolling stock components can cause derailments. Different component designs may have different failure rates; however, there is little quantitative data on how these may affect derailment rates. In this study, we assumed that passenger railroad equipment has higher reliability than freight rail equipment due to the more frequent and detailed equipment inspection and maintenance. This is also supported by comparing train accident rates due to mechanical failure between mainline passenger and freight train accidents (Liu, 2015; Lin et al., 2019; Wang et al., 2020). Future research on passenger and freight train accident rates and causes is needed to better understand the effect of equipment type on derailment rates.

Defect Detectors and Enhanced Track Inspection Technologies and Planning

The most common wayside defect detection technologies used by North American railroads are hot bearing detectors and dragging equipment detectors. These have been widely implemented on railroad main lines since the 1960s. Since then, a number of other, more advanced detection technologies have been developed and implemented including Wheel Impact Load Detectors (WILD) and Truck Performance Detectors (TPD). All of these technologies are used to identify component defects before they fail potentially leading to an equipment-caused derailment (Blevins et al., 2003; Johansson and Nielsen, 2003; Edwards et al., 2007; Lagnebäck, 2007; Stratman et al., 2007; Schlake et al., 2010; Hajibabai et al., 2012; Van Dyk et al., 2013). Similarly, various types of advanced track inspection technologies have been developed to identify defects in the track system before they lead to failure, thereby reducing the likelihood of infrastructure-related derailments (Dick et al., 2003; Edwards et al., 2009; Liu et al., 2014; Liu and Dick, 2016; Liu, 2017; Bin Osman et al., 2018). Planning and optimization of track inspection and maintenance scheduling also help to further reduce derailment risk while improving operation efficiency (Liu et al., 2014; Bin Osman et al., 2018; Farhangi et al., 2020). Although it stands to reason that these technologies and practices reduce derailment likelihood, the quantitative relationship between the use of a particular technology and its preventive effect has not been measured. Further research is needed to better understand and quantify the effect of wayside defect detectors and track inspections on derailment rate reduction.

Factors Affecting the Conditional Probability of Intrusion, $P(I|D)$

Distance Between Track Centers

Research by English et al. (2007) found an inverse relationship in the distance between track centers and probability of intrusion. The authors developed the distribution of maximum lateral distance traveled by derailed rolling stock (Fig. A1.) and found a gamma distribution was the best fit for the data. The parameters for the fitted gamma distribution were later updated by Clark et al. (2013). In the model described in this research, IFS for distance between track centers is assigned based on the 12th, 25th, 50th and 75th percentile from the probability distribution of lateral displacement from Clark et al.'s research.

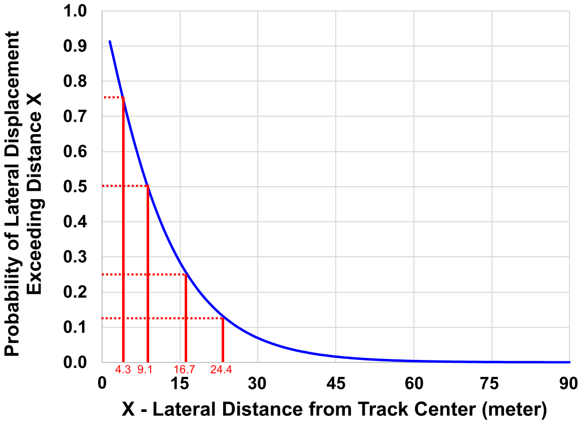

Fig. A1. Maximum lateral travel distribution (Clark et al., 2013).

Track Alignment and Geometry

Derailments on level, tangent track segments are believed to have the lowest likelihood of an intrusion and thus were considered the base case scenario. If a derailment occurs on a curved track segment, additional lateral forces may increase the intrusion probability, especially when the derailed train is on the inside track of the curve on multiple-track territory. A derailment on a grade affects longitudinal forces that indirectly affect intrusion probability. These longitudinal, in-train forces do not directly cause lateral movement of equipment; however, they may affect the extent that derailed rolling stock collides with other equipment in the train (Wu et al., 2013). These impacts may cause equipment to be moved laterally or rotate causing an intrusion on an adjacent track. When these two factors occur together, we assumed that, *ceteris paribus*, these track segments will have higher intrusion probability than curved-only or gradient-only sections. Between curved-only and gradient-only track segments, we assumed that curved segments have higher intrusion probability because the lateral forces generated on them can cause the derailed equipment to move laterally and thus increase its chance of intruding onto an adjacent track.

Elevation Difference Between Adjacent Tracks

If there is an elevation difference between two adjacent tracks, trains derailing on the higher track are more likely to intrude onto the lower track due to gravitational effects on derailed equipment (Fig. A2a). Conversely, derailed equipment on the lower track is less likely to intrude onto the higher adjacent track because of the constraining effects of gravity and the embankment (Fig. A2b).

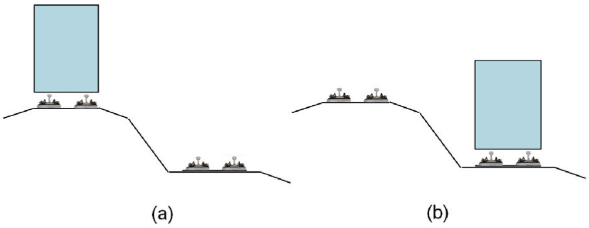

Fig. A2. Effect of elevation differential on intrusion probability.

Adjacent Structures

Adjacent structures along a railroad line may have a “rebound” effect (Fig. A3.) that alters the direction of travel of derailed equipment. If a structure is close enough to the railroad tracks and strong enough to redirect the movement of derailed equipment from “away from adjacent tracks” to “toward adjacent tracks”, then its presence could affect intrusion probability. Adjacent structures are classified into three types depending on their shape and density: single, discrete, and continuous structures. A single structure is an independent, self-supported structure such as a bridge abutment or pier. Discontinuous structures could be a series of separate buildings as commonly found in urban areas. Examples of a continuous structure are noise barriers or retaining walls located next to the track, or a single long building or closely spaced adjacent buildings such as in urban areas.

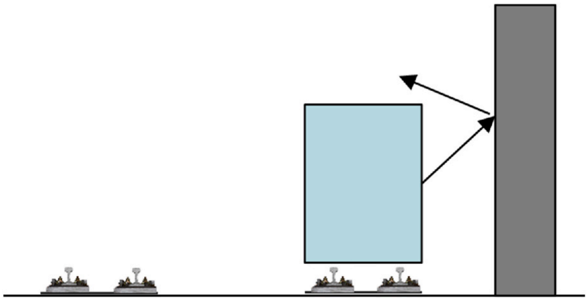

Fig. A3. Effect of adjacent structure on intrusion probability.

Containment

Two types of containment, parapet and physical barriers, are currently used in HSR systems in Europe and Asia (Hadden et al., 1992; Moyer et al., 1994; Ullman and Bing, 1995; Rulens, 2008). Parapets are reinforced railings or structures mounted adjacent to the track to contain derailed trucks (bogies), preventing them from intruding onto adjacent tracks (Fig. A4). Physical barriers can be earth berms or concrete walls (Fig. A5.) installed between adjacent tracks to absorb the impact forces of derailed equipment and prevent it from intruding onto adjacent tracks (Clark and Mosavi, 2020).

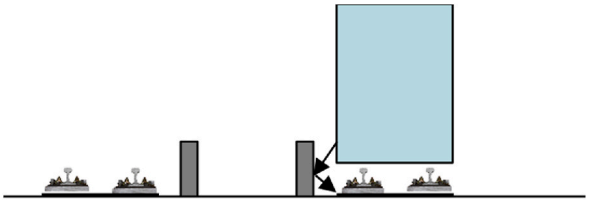

Fig. A4. Parapet contains the wheel set of derailed equipment and prevents the equipment from intruding into an adjacent track (Bae et al., 2018).

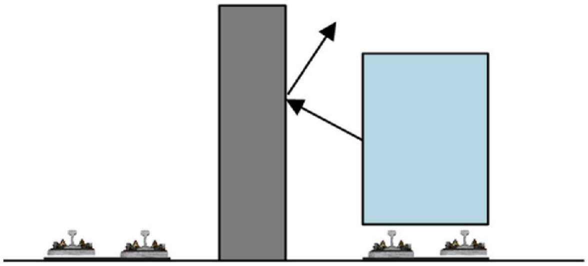

Fig. A5. A physical barrier absorbs the impact from derailed equipment and prevents it from intruding onto adjacent tracks (Clark and Mosavi, 2020).

Train Speed

Train speed may affect intrusion probability because the higher the speed, the more energy involved when a train derails, resulting in more opportunity for the derailed equipment to move farther and foul adjacent tracks (English et al., 2007). Train speed on a track segment is assigned high, medium, or low, based on the average speed for the segment. The average train speed is affected by various factors such as type of traffic (bulk freight, intermodal, passenger, etc.), traffic heterogeneity, track alignment, track class, and method of operation. Two speeds were selected for categorization: 48 km-per-hour (kmph), which is slightly higher than the average speed of freight trains on major railroads in the U.S. (35.4 kmph (BTS, 2017)), and 112 kmph which is slightly lower than the maximum authorized speed of passenger trains on most U.S. passenger and freight SRCs (112 kmph (Dick and Ruppert, 2019)). These speeds were selected to represent typical North American railroad operating conditions.

First Derailed Vehicle (FDV)

The first derailed vehicle may affect intrusion probability due to reaction forces at the coupler. Because the first and last vehicle are only coupled at one end, they are less restrained with regard to lateral movement and might have more chance to rotate and foul adjacent tracks in a derailment. Vehicles elsewhere in the train consist are coupled at both ends, providing greater restraining force. The most common situation is when a single vehicle in a train derails and causes other vehicles to derail, resulting in a larger derailment and intrusion. Due to this level of uncertainty, the effect of FDV is not known and will require further research to better understand the effect of this mechanism. Compared with other intrusion factors, FDV is a post-accident factor rather than a pre-accident factor. That is, we would not know which car in the train consist will derail before the derailment occurs. As such, it is difficult to pre-assign scores to this factor in the model.

Factors Affecting the Conditional Probability of Train Presence, $P(T|I)$

Intrusion Detection and Warning System

An intrusion detection and warning (IDW) system is installed on the fences between two adjacent tracks and detects intruding rail equipment when it strikes the fences (Hadden et al., 1992; Ullman and Bing, 1995; Saat and Barkan, 2013). If trains on adjacent tracks are a sufficient distance away from the intrusion location, the IDW system will alert the operator or dispatcher enabling them to stop or slow down before colliding with the intruding equipment.

Traffic Density

The reason to assign dedicated passenger lines the highest level of train presence probability is because on a railroad corridor with only passenger trains, these trains are likely to have similar operating patterns such as station stops and speed profiles; therefore, the capacity of the corridor increases, and more trains can be accommodated (Wang et al., 2017). On the other hand, a railroad with mixed traffic encounters differing schedules and patterns between passenger and freight trains, meaning that traffic heterogeneity is high, resulting in more train conflicts and consequent delay and reduction in traffic density (Dingler et al., 2009; Shih et al., 2015; Sogin et al., 2016).

Train Control System

Train control systems have differing levels of precision in determining train location. They also vary in their ability to communicate the information between engineers (train drivers) and dispatchers. For example, under a typical Centralized Traffic Control (CTC) system, train presence at “control points” which define the boundary of the movement authority of trains, is identified, but the system generally does not know the location of trains in intermediate blocks between control points. More advanced train control systems are capable of identifying the trains’ location more precisely. In the US, PTC systems permit greater precision in train location (Zhang et al., 2018) and elsewhere in the world systems such as the European Rail Traffic Management System and the Advanced Train Administration & Communications System in Japan, provide similar capability (Noboru, 2013; Cunha and Macedo, 2020). An IDW system can be integrated with these advanced train control systems so that intrusion warnings could automatically be delivered to dispatchers, and drivers of other nearby trains (Hadden et al., 1992; Ullman and Bing, 1995; Saat and Barkan, 2013).

Train Speed

If train speed is high enough, a train approaching an intrusion location may not be able to stop before striking the derailed equipment fouling the track, given the same braking capability of the train (Lin and Barkan, 2019).

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