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Shared Rail Corridor Adjacent Track Accident Risk Analysis – Part 2

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DISCLAIMER

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TECHNICAL SUMMARY

Title

Shared Rail Corridor Adjacent Track Accident Risk Analysis – Part 2

Introduction

Shared or mixed use corridors refer to different types of passenger and freight trains using common infrastructure in one way or another. Different characteristics from different types of operation may result in complicated operating environments. A high priority for any rail system is operating safety, and there are several questions associated with operating passenger and freight trains on shared-use corridors. Adjacent track accidents (ATA) are one of the challenges that has been identified. ATA refers to train accident scenarios where a derailed rail equipment intrudes onto adjacent tracks, disrupting operation and potentially causing a train collision with a train on the adjacent track. Other ATA scenarios include collisions between trains on adjacent tracks (raking), turnouts, and railroad crossings. The main objective of this project is development of a new, quantitative model to calculate the probability of ATAs by identifying the major probability components in the ATA event sequence: initial train derailments, intrusion of derailed rail vehicles, and collisions between a train on an adjacent track with derailed equipment. This project is the continuation of the project titled “Shared Rail Corridor Adjacent Track Accident Risk Analysis (NURail2013-UIUC-R08)”.

Approach and Methodology

A three-phase, comprehensive and quantitative risk assessment model will be developed to address the ATA risk. Three models will be developed to address the probabilities of initial derailment, intrusion and train presence on adjacent tracks. Affecting factors for each model will be identified and their effects will be quantified into those models. This project will involve a comprehensive risk assessment for ATAs on shared-use corridor, providing a basis for risk comparison, evaluation of risk mitigation strategy, and a decision-making process in the future. In summary, the step-by-step procedure of this project as follows:

1) Quantify the probability of initial train derailments on SRCs for different types and combinations of train traffic by conducting statistical and causal train accident analyses

2) Identify factors that affect the probability of train intrusions in derailment scenarios and investigate their effects

3) Identify and quantify the factors that affect the probability of train presence on adjacent tracks when an intrusion occurs

4) Develop an ATA probability assessment model by combining probabilities of initial derailment, train intrusion, and train presence on adjacent tracks.

5) Develop a procedure and guidance for ATA probability assessment

Findings

A comprehensive, quantitative model was developed to address ATA risk. The model consists of three parts: the initial derailment probability, conditional probability of intrusion, and conditional probability of train presence given an intrusion. Factors affecting one or more of the three parts were identified and accounted for in the models. The model presents ATA probability in two forms: a quantitative probability value and a qualitative risk indicator showing additional intrusion risk.

Conclusions

A generic ATA probability assessment model is developed. The model calculates ATA probability by dividing a railroad corridor into different segments and evaluating the ATA probability for each segment by its infrastructure, rolling stock, and operational characteristics. This model evaluates the ATA probability by providing a quantitative ATA probability and a risk indicator showing additional or potentially reduced ATA probability. The main contribution of this model is to provide a standard procedure and guidance for evaluating the ATA probability on an existing or newly planned railroad corridor and to manage ATA risk more effectively and efficiently. The model provides the first comprehensive attempt at an ATA risk assessment framework. With appropriate quantitative data and statistics, this model has the flexibility to be extended or modified to improve the accuracy of probability evaluation.

Recommendations

The following future research opportunities were identified, with the development of the ATA risk assessment model, that can improve the accuracy of the model or extend the range and utility of the models: common cause failure analysis of ATA, human factor analysis, full quantification of intrusion probability, component reliability analysis, consequence of ATA, and evaluation of ATA risk mitigation measures.

Publications

Lin, C-Y., M.R. Saat, and C.P.L. Barkan. 2020. Quantitative causal analysis of mainline passenger train accidents in the United States. *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, DOI: 10.1177/0954409719876128.

Lin, C-Y., M.R. Saat, and C.P.L. Barkan. 2020. Semi-quantitative risk assessment of adjacent track accidents on shared-use rail corridors. *Safety Science (Under Review)*.

Lin, C-Y., M.R. Saat, and C.P.L. Barkan. 2020. Hazards associated with shared-use rail corridors in the United States – literature review and research needs. *Safety Science (Under Review)*.

Lin, C-Y., M.R. Saat, and C.P.L. Barkan. 2020. A Risk Management Tool to Evaluate Adjacent Track Accidents on Shared-Use Rail Corridors. In: *Proceedings of the American Railway Engineering and Maintenance-of-way Association (AREMA) 2020 Annual Conference*, Dallas, Texas, USA.

Lin, C-Y. and C.P.L. Barkan. 2019. Modeling the Probability of Train Presence on Adjacent Tracks in Railway Vehicle Intrusion Scenarios. In: *Proceedings of the 2019 World Congress of Railway Research*, Tokyo, Japan.

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

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SECTION 1. INTRODUCTION

1.1. Shared-use Rail Corridors

Increasing demand for passenger rail transport in the United States has led to the growth of faster and more frequent passenger rail services. Two approaches are being used to undertake these passenger rail projects and initiatives: incremental upgrade of existing railroad infrastructure and construction of new, dedicated passenger rail lines (Peterman, 2013). Both approaches lead to the development of SRCs where passenger trains share track, right-of-way (ROW) or railroad corridors with freight trains and other types of passenger trains (Ullman and Bing, 1995; Bing et al., 2010). The United States Department of Transportation (USDOT) Federal Railroad Administration (FRA) defines three types of SRCs based on whether or not different types of trains share trackage and the separation distance between adjacent tracks of different railroad systems (Resor, 2003). SRC safety is a topic of growing importance as new and expanded passenger rail and transit corridors develop. Many of these new or expanded train services are operating on existing freight railroad trackage or corridors. While providing economic, environmental, and societal benefits, and reducing capital cost and construction time (Nash, 2003), SRCs present certain potential risks related to changes in infrastructure configuration, rolling stock, operating practices (Saat and Barkan, 2013). Among them is the potential intrusion of derailed rail equipment onto adjacent railroad tracks. The intruding equipment may strike or be struck by another train running on an adjacent track, resulting in a collision leading to more derailed equipment, infrastructure and rolling stock damage, and potential casualties and releases of hazardous material. This type of collision is referred to as an adjacent track accident (ATA) (Lin, 2019).

1.2. Adjacent Track Accidents

Railroad equipment and infrastructure is designed so that, in normal operations, the equipment is well clear of equipment operating on an adjacent track (Figure 1.1a). However, if a train derails, the derailed equipment's loading gauge, which is a series of standards that define the maximum height and width of locomotives and rolling stock (including lading if it is a freight car), will nearly always exceed its own track's clearance envelope, which is the height and width limits of railroad structures to assure safe passage of trains without any possibility of impacting elements of the infrastructure above, below, or beside the track (Hay, 1982) (Figure 1.1b). If the derailed equipment enters an adjacent track's clearance envelope, it is called an intrusion (Figure 1.1c). When an intrusion occurs, there is a possibility that another train is running on the adjacent track, either next to, or approaching, the intrusion location. If so, there is a chance that the train on the adjacent track will collide with the derailed equipment (Figure 1.1d), resulting in an ATA (Lin et al., 2016).

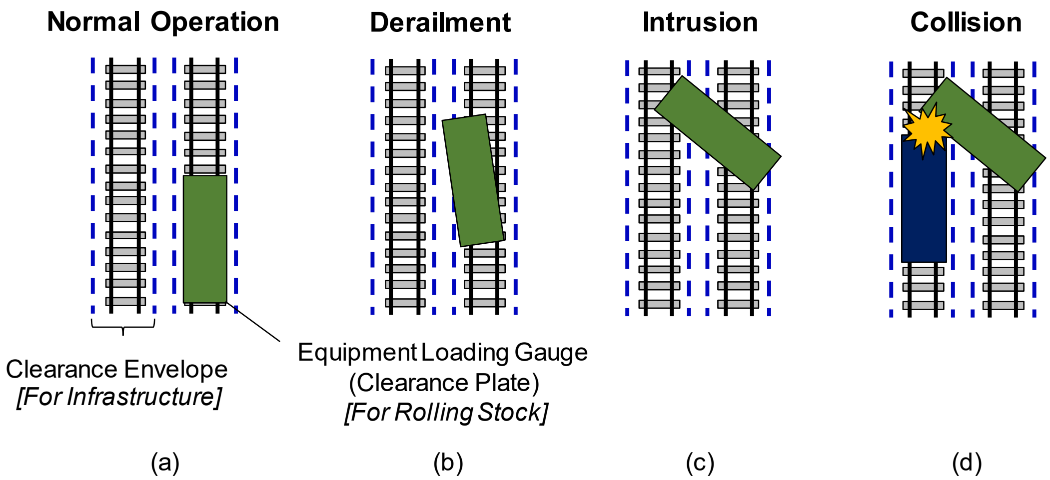


Figure 1.1: A typical ATA Event Sequence

There has been a limited amount of previous research addressing ATA risk. Cockle (2014) developed a semi-quantitative risk model to evaluate ATA risk associated with operating high-speed rail (HSR) trains adjacent to conventional railroad tracks. As the first part of the NURail project addressing ATA risk, Lin et al. (2014) developed a generalized, semi-quantitative risk assessment model for ATAs by considering factors affecting the probability of train derailment, intrusion, train presence on adjacent tracks, and consequences. Lin et al. (2016) also developed a quantitative risk assessment framework for ATAs by conducting a fault-tree analysis. These studies described the fundamental elements needed to address probabilities for different events in an ATA, but there is a need to integrate these models into a holistic risk assessment framework.

1.3. Research Objectives

In this project, a risk management framework for ATAs initiated by passenger or freight trains operating on SRCs is developed. The framework defines ATA risk and identifies affecting factors. Then, a new, quantitative model to calculate the probability of ATAs by assessing three major probability components in an ATA event sequence: initial train derailments, intrusion of derailed rail vehicles, and collisions between a train on an adjacent track with derailed equipment, is developed.

SECTION 2. METHODOLOGY

2.1. Probability Assessment Framework

The ATA risk assessment framework consists of three probability models for initial train derailment, conditional probability of intrusion, and conditional probability of train presence as described in the typical ATA event sequence. The model evaluates the probability of an ATA and each probability model is affected by different infrastructure, rolling stock, and operational factors (Figure 2.1). These factors are divided into two groups: quantitative factors affecting the probability values of ATA, and qualitative factors that affect ATA probability, but whose degree of influence is not quantified. A qualitative factor can become a quantitative factor when sufficient information is available and proper quantification analyses are conducted. This risk assessment framework can incorporate and adapt the quantification of these qualitative factors by modifying and extending the model using probabilistic risk assessment (PRA) methodology.

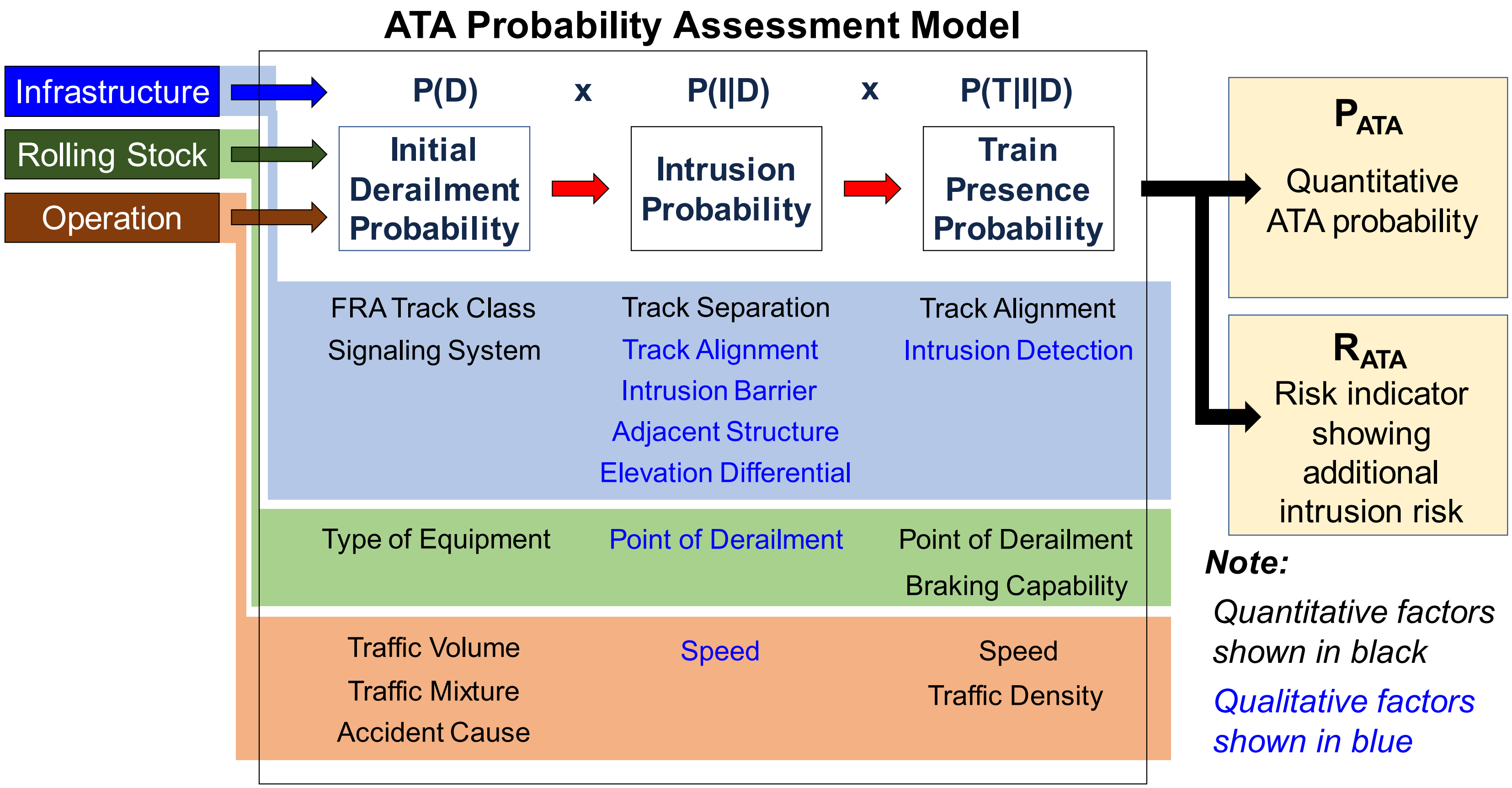


Figure 2.1: ATA probability Assessment Framework

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

2.2. Initial Derailment Probability, P(D)

The initial train derailment probability is expressed as number of train derailments divided by traffic exposure (Nayak et al., 1983; Anderson and Barkan, 2004; Liu et al., 2011; 2017). The two general types of trains considered are freight trains and passenger trains. Previous studies found that freight train derailment rates are correlated with the track class defined by the United States Department of Transportation (USDOT) Federal Railroad Administration (FRA), method of operation, and traffic density (Liu et al., 2017). A derailment rate matrix based on these factors was developed using USDOT FRA train accident data and railroad operating data. That matrix has recently been updated by Wang et al. (2020). The derailment rate varies with infrastructure, traffic, and method of operation. Accident-cause-specific freight train derailment rate analysis and estimation has also been conducted (Barkan et al., 2003; Liu et al., 2012; 2017, Liu, 2017a; b). A general statistical and causal analysis for passenger train accidents and evaluated passenger train derailment rate using the USDOT FRA train accident data was referenced (Lin et al., 2020).

Derailment rate varies with different types of train operations due to differing types and composition of rolling stock, infrastructure, and operational protocols implemented for the specific type of train operation. To account for different types of train operation on the same track, a weighted derailment rate based on the proportion of traffic from different types of railroad operation is developed:

$$P(D) = \frac{\sum R_i \times T_i}{\sum T_i} \tag{1}$$

where:
$P(D)$: the probability of initial train derailment
R_i: probability of train derailment for the i^{th} type of rail operation
T_i: the traffic of the i^{th} type of rail operation

2.3. Intrusion Probability, P(I|D)

The conditional probability of intrusion given a train derailment was determined by the likelihood lateral displacement of derailed rail vehicles and the presence and effectiveness of intrusion barriers or containment. The lateral displacement of derailed equipment is represented by a gamma distribution based on previous research on train accident data (Barkan, 1990; English et al., 2007; Clark et al., 2013). The distribution of displacement of derailed equipment is expressed as:

$$Gamma(X;\alpha,\beta) = \frac{1}{\beta^{\alpha}\Gamma(\alpha)} \times X^{\alpha-1} \times e^{\frac{-X}{\beta}} \qquad (2)$$

where:
Gamma (X; α, β): the probability where the maximum lateral displacement of derailed equipment is X feet
X: maximum lateral displacement of derailed equipment
Γ(α): the gamma function
α: shape parameter
β: scale parameter

The values of $\alpha = 1.2$ and $\beta = 33.0$ were selected as the parameters for the gamma distribution based on NTSB data (*24*). The probability of intrusion can be calculated by obtaining the cumulative probability function where $x \geq X$, given that no intrusion barrier is present (Figure 2.2):

$$P(\mathrm{x} \geq \mathrm{X}) = 1 - F(X;\ \alpha,\beta) \qquad (3)$$

where:
P(x ≥ X): the probability of intrusion for a track segment
F(X; α, β): the cumulative gamma function given track center spacing X

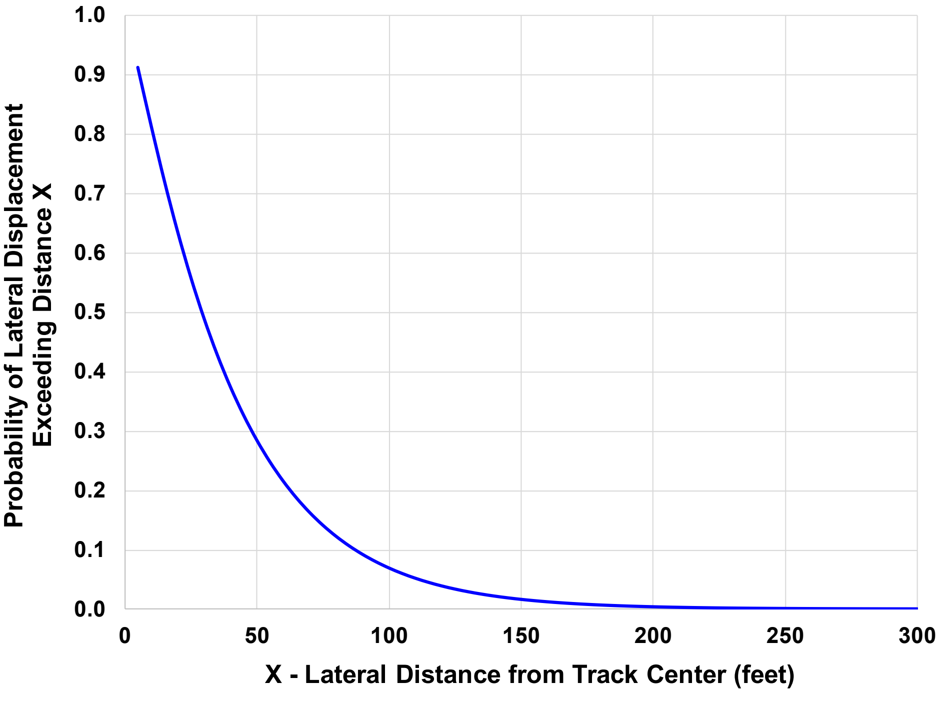


Figure 2.2: Probability Function for the Lateral Displacement of Derailed Equipment Exceeding Certain Distance X (Clark et al., 2013)

Another important factor is the presence and reliability of intrusion barriers or containment such as a crash wall, containment, or intrusion barrier. These structures are installed between adjacent tracks to contain derailing equipment and prevent it from intruding onto adjacent tracks. The design of these structures has been studied using computer simulations (Moyer et al., 1994;

Layden, 2014, Bae et al., 20218a; b) and implemented in the California High-Speed Rail project (Abtahi, 2013). The authors are unaware of any empirical studies of the efficacy of these intrusion barriers, and thus their reliability is unknown. In the model described here, it is assumed that the presence of an intrusion barrier is 100% effective, i.e., that it would always contain derailed equipment and prevent it from intruding onto an adjacent track. The model can account for lower effectiveness if suitable data are available. The probability of crash wall failure is defined in the following way:

$P_{CF} = 1$ if no intrusion barrier is installed
and
$P_{CF} = \lambda$ if an intrusion barrier is installed
where λ is the failure rate of the intrusion barrier

Although there is currently no reliable value for λ, its inclusion in the risk assessment model enables sensitivity analysis of its effect on ATA risk. This may provide guidance for target levels of effectiveness and consequent design parameters for intrusion barriers. Combining this probability with the probability of lateral displacement of derailed equipment exceeding track center spacing (equation 3), the conditional probability of intrusion given a train derailment can be expressed as follows:

$$P(I|T) = \mathrm{P}_{CF} \times P(\mathrm{x} \geq \mathrm{X})$$

2.4. Train Presence Probability, P(T|I|D)

When an intrusion occurs, the most undesired consequence is that the derailed equipment on an adjacent track strikes or is struck by another train. There are several factors affecting the probability of these adjacent track collisions. The first is the frequency of train meets and passes on adjacent tracks, and the is the distance between the intruding rail vehicle and the oncoming train on the adjacent track.

To evaluate collision probability between trains on adjacent tracks, the terms train “meet” and “pass” are defined. A train meet (TM) occurs when two trains traveling on adjacent tracks in opposite directions go past one another (Figure 2.3a), and a train pass (TP) occurs when one train overtakes another on an adjacent track (Figure 2.4b) (Lamorgese and Mannino, 2015). The more TM and TP activities occurring on a track segment, the higher the probability of having an adjacent track collision. TM and TP event identification has been analyzed using econometrics (Oh et al., 2004; Gorman, 2009; Şahin, 2017; Sørensen et al., 2017) and simulation methods (White, 2005; D’Ariano et al., 2007; Shih et al., 2017). In this research, the train conflict screening tool developed by Shih et al. (2017) was used to identify the number of TM and TP events. The output of this model is the average number of events on track segments along a railroad corridor, given their characteristics.

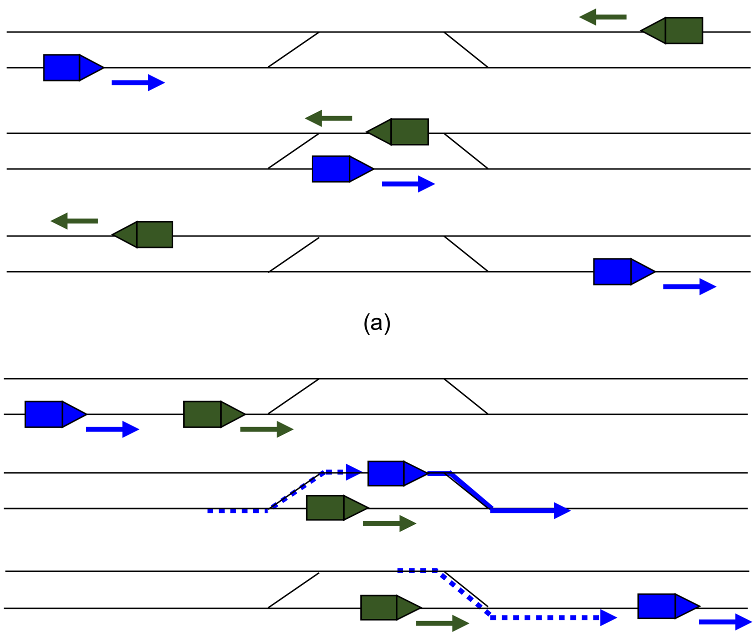


Figure 2.3: Typical (a) Train Meet (TM) and (b) Train Pass (TP) Scenarios

When two trains on adjacent tracks meet or pass within a certain distance of each other when an intrusion occurs, a collision may result. The maximum distance between two trains on adjacent tracks posing potential collision risk to each other is defined as "Critical Distance (CD)". In other words, any distance greater than CD will not result in an adjacent track collision even if the front of the intruding train derails and fouls the adjacent track, given everything else functioning normally. CD is crucial in train presence probability calculation because it bounds the collision probability distribution.

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

$$D_{brake} = 0.7333 \times \frac{V^2}{b+0.008\times R+0.2\times G} \tag{5}$$

where:
D_{brake} = train braking distance (feet)
V = initial speed of the train (miles per hour)
b = train deceleration rate (miles per hour per second)
R = curvature (degree)
G = grade (percent; positive value indicates ascending grades and negative value indicates descending grades)

CD defines the maximum distance where two trains pose risk to one another. If the front of a train derails and intrudes onto the adjacent track, and the two trains are within their CD when the intrusion occurs, a collision is inevitable. However, the first derailed vehicle may not be the front of the train consist. If it is further back in the train, there will be additional distance for the adjacent train to apply brakes and avoid a collision. The first derailed vehicle (FDV) which refers to the position of the first vehicle derailed in a train thus plays a key role in train presence probability assessment (Anderson, 2005; Liu et al., 2013). Understanding the probability distribution of FDV enables more accurate estimation of the probability of an adjacent track collision.

Trains vary in the number of cars and consequent length. The normalized first derailed vehicle (NFDV) was developed to account for this variation (Saccomanno and El-Hage, 1989; 1991). Previous research found that NFDV is affected by accident causes (Liu et al., 2014). Derailment causes affect probability distributions for NFDV. Liu et al. (2014) found that a beta distribution provided the best fit for the FDV and NFDV probability distributions for most derailment causes. In this research, a beta distribution ($\alpha = 0.6793$, $\beta = 0.8999$) for the probability distribution of NFDV is used based on Liu et al.'s work (2014). Given train length L, the probability that the FDV is at the nth position in a train, P(n), follows the equation:

$$P(n) = F\left(\frac{n}{L}\right) - F\left(\frac{n-1}{L}\right) \tag{6}$$

where:
P(n): probability of FDV being at the nth car of a train
F: the cumulative density distribution of the fitted beta distribution

Consider two trains B and A running at speed V_B and V_A in opposite directions towards each other on Main Track (track M) and Adjacent Track (track J), respectively (Figure 2.4a). This is a TM scenario. When the distance between the front of the two trains, D_{avail}, is greater than their CD, there is no risk of an adjacent track collision. When D_{avail} = CD (Figure 2.4b), they will just make contact if train B derails and intrudes its front end onto track J, and the engineer of train A immediately applies the brakes. The collision probability where D_{avail} being CD is set to zero. When D_{avail} is less than CD (Figure 2.4c), the probability of collision can be expressed as:

$$\mathrm{P}_{collision,TM} = \sum_{n=1}^{K} P(n) \tag{7}$$

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

$$\sum_{k=1}^{K} l_k > (D_{brake} - D_{avail}) \tag{8}$$

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

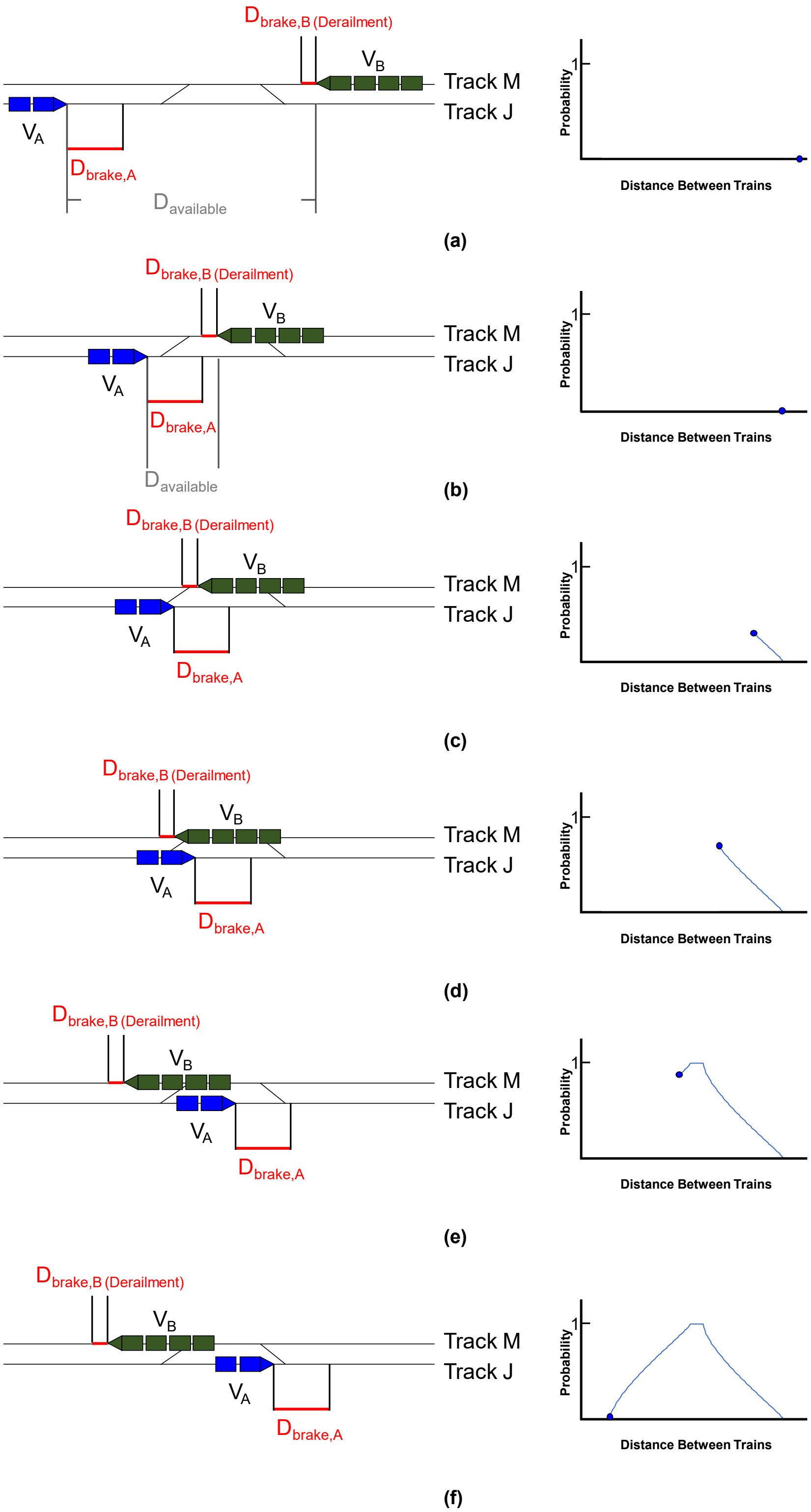


Figure 2.4: Adjacent Track Collision Probability for a TM scenario when (a) $D_{avail} > CD$, (b) $D_{avail} = CD$, (c) $D_{avail} < CD$, (d) Two Trains Start Passing Each Other, (e) Two Trains Are Passing Each Other, and (f) Two Trains Completely Pass Each Other

As two trains approach each other, the distance between them diminishes, resulting in increasing collision probability (Figure 2.4d). After the rear end of train A passes the front end of train B (Figure 2.4e), it is assumed that the portion of train B passed by train A will not pose any threat to train A if it derails. For example, if the end of train A has passed the 14th car of train B (counting from the front) while the FDV of train B is at the 8th car, this situation will not lead to an adjacent track collision Therefore, the collision probability can be modified as:

$$\mathrm{P}_{collision,TM} = \sum_{n=1}^{K} P(n) - \sum_{n=1}^{S} P(n) \qquad (9)$$

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

The possibility of collision exists until the two trains pass each other completely and the probability of collision returns to zero (Figure 2.4f). the sum of CD and the total length of two trains is called "Collision Zone (CZ)", because the risk of an adjacent track collision is greater than zero when two trains are within this distance.

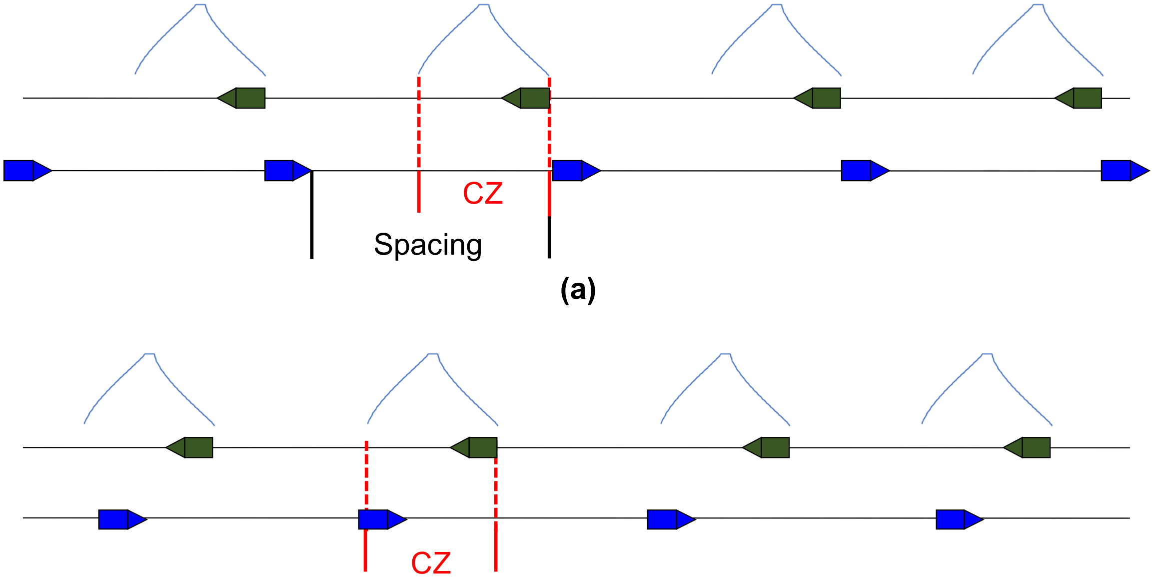
To obtain the adjacent track collision probability given an intrusion, the frequency of TM and TP events on a track segment was investigated. If TMs and TPs are frequent, then it is more likely that another train will be at, or approaching, the intrusion location, and the collision risk high. The concept of average spacing was used to obtain adjacent track collision probability on a track segment. Average spacing means the average distance between trains. Two types of average spacing are developed: average spacing for TM events and average spacing for TP events. Average spacing for TM events, denoted as S_M, is the average distance between trains that will meet each other, and the average spacing for TP events, denoted as S_P, is the average distance between trains that will pass one another.

When an intrusion occurs, two trains can be any distance away within average spacing. If this distance is within CZ, then the risk of adjacent track collisions exists. Therefore, CZ is considered as a proportion of the average train spacing to calculate the probability that the distance between two trains on adjacent tracks is within CZ (Figure 2.5a). When the distance between two trains on adjacent tracks is within CZ, the average collision probability from the derived distribution is used to calculate the adjacent track collision probability for the track segment, assuming the probability of the distance between two trains on adjacent tracks is uniformly distributed within the average spacing (Figure 2.5b).

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

$$P_T = \frac{CZ}{S} \times E(P_{collision}) \qquad (10)$$

where:
P_T: the probability of train presence given an intrusion on a track segment
CZ: collision zone in feet
S: average spacing (S_M or S_P) based on TM or TP scenarios in feet
$E(P_{collision})$: the mean of the probability of adjacent track collisions



(a)

(b)

Figure 2.5: Illustration of (a) the Proportion of CZ to the Average Spacing and (b) Distance Between Trains on Adjacent Tracks at Any Given Point

The conditional probability of train presence given an intrusion consists of two parts: base train presence probability and failure to apply train brakes due to equipment failure or human errors. Train presence probability on a track segment is derived as follows:

$$1 - \prod_i \left(1 - P_{T,TM_i}\right) \times \prod_j \left(1 - P_{T,TP_j}\right) \tag{11}$$

where:
P_{T,TM_i}: adjacent track collision probability for the ith TM activities
P_{T,TP_j}: adjacent track collision probability for the jth TP activities
i: total number of TM in the track segment
j: total number of TP in the track segment

The base train presence probability assumes the train's brakes are applied and function properly. This may not always be the case because brake components may malfunction, or the engineer might not operate the brakes properly. There are only a few studies regarding the reliability of certain train brake system and components (Yang et al., 2016; Cai et al., 20218). They focus on specific brake systems or particular braking components. Consequently, the results are not general enough to be implemented in the ATA risk assessment model. The methods introduced in these studies can be applied when appropriate data are available.

There has been considerable research on human error in railroad operations (Wilson and Norris, 2005; Reinach and Viale, 2006; Wilson et al., 2007; Baysari et al., 2008; Madigan et al., 2016;

Zhan et al., 2017; Kyriakidis et al., 2018); however, no previous study has focused on human error in train brake operations. The probability of braking system failure is defined as follows:

$$P_{FB} = 1 - (1 - \lambda_{EB}) \times (1 - \lambda_{HB}) \quad (12)$$

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

Although there is currently no reliable value for λ_{EB} and λ_{HB}, its inclusion in the risk assessment enables sensitivity analysis of its effect on train presence probability and ATA risk. Combining this probability with the probability of train presence on adjacent tracks (Equation 11), the conditional probability of train presence given an intrusion can be expressed as follows:

$$1 - \prod_i((1 - P_{T,TM_i}) \times (1 - P_{FB,TM_i})) \times \prod_j((1 - P_{T,TP_j}) \times (1 - P_{FB,TP_j})) \quad (13)$$

2.5. Qualitative Factors

Factors that are not quantified in the models but affect ATA probability are considered qualitatively as risk indicators (Table 2.1). The presence of each factor adds one point to the risk indicator if it increases the ATA probability and subtracts one point from the risk indicator if it reduces the ATA probability. The higher the risk indicator points the greater the likelihood of an ATA. Given the same quantitative value of ATA probability, track segments with positive points in the risk indicator have a higher chance of having an ATA; if the risk indicator points are negative for a track segment, it means that the ATA probability is reduced.

Table 2.1: Qualitative Factors and Risk Indicator

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

SECTION 3. ATA RISK ASSESSMENT GUIDANCE

The framework described in this report provides a generic method to calculate ATA risk. There are several assumptions and simplifications for the model configuration, input parameters and probability calculations due to the lack of certain quantitative data. These assumptions can be removed or modified to improve the accuracy of the risk assessment model if proper quantitative data are available. Models in the ATA risk assessment framework can also be modified or customized to best suit the needs of the users. The following subsections provide guidance for use of the ATA risk assessment framework.

3.1. Initial Derailment Rate

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

Train Derailment Data
The default initial train derailment rate in the ATA risk assessment framework is calculated using historical national train accident data developed by the USDOT FRA. If train derailment data specific to the railroad corridor of interest, or for corridors with similar characteristics to the corridor of interest are available, a more representative set of train derailments can be used to calculate the initial derailment rate.

Traffic Data
The default traffic data used to calculate the initial derailment rate are the national traffic from the Class I railroads and Amtrak in the US. If specific traffic data for the corridor of interest, or corridors that have similar train, track, and operational characteristics to the corridor of interest are available, these can be used instead. The default unit of traffic data is train-mile because it is applicable to both passenger and freight train traffic. The use of different units for traffic data is possible, but the selected units should make sense and be consistent for all types of trains operating on the corridor.

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

3.2. Conditional Probability of Intrusion

Track Center Spacing
The current intrusion probability model uses track center spacing as the only quantitative factor to evaluate the probability. If empirical or simulation data are available to account for the effect of

other factors, such as curvature, grade, or the presence of an intrusion barrier, then the model can be modified to obtain a more accurate intrusion probability.

Reliability of Intrusion Barriers and Containment Systems
Currently the ATA Probability Assessment Model does not specify a default value for the failure rate of intrusion barriers and containment. If a track segment lacks these, or they are only installed on a portion of the corridor, the failure rate of intrusion barriers or containment of segments without them should be set to one. For segments that have intrusion barriers completely installed, an estimated failure rate for the intrusion probability calculation could be based on expert judgement for their design and location.

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

3.3. Conditional Probability of Train Presence Given an Intrusion

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

Train Meet and Pass Activities
If trains on the corridor of interest follow scheduled operation, direct calculation of the number and average spacing of TM and TP activities is preferable. If trains are running with unscheduled operation or there are multiple types of trains on the corridor with a more complicated operating schedule, the method described by Shih et al. (*2017*) can be used.

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

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

Reliability of Braking System and Human Brake Operations

Currently the ATA risk assessment model does not specify default values for the failure rate of braking systems due to either human error or mechanical failures. Depending on the resolution of the analysis desired, model users can specify the failure rates for braking systems due to these factors based on their best knowledge.

Other Qualitative Factors

A qualitative factor that could affect train presence probability but is not quantified is the presence of an intrusion detection system. Model users should document the presence and type of detection system in place at locations along the corridor. When quantitative data about the reliability and effectiveness of these detection systems are available, their effects can be quantitatively evaluated using a revised and updated ATA risk assessment model.

SECTION 4. CONCLUSION

In this project, a generic ATA probability assessment model is introduced. The model consists of three probability models to address derailment, intrusion, and train presence probability. Segment-level ATA probability is evaluated using a combination of quantitative probability values and qualitative risk indicators. Additional guidance is provided for users to customize the model to best suit their particular circumstances and requirements. The ATA risk assessment model provides the first comprehensive attempt at a ATA risk assessment framework. With appropriate quantitative data and statistics, this model has the flexibility to be extended or modified to improve the accuracy of probability evaluation.

REFERENCES

Abtahi, A. 2013. *Rolling Stock and Vehicle Intrusion Protection for High-Speed Rail and Adjacent Transportation Systems*. Parsons Brinckerhoff Report TM 2.1.7. San Francisco, CA, USA.

Anderson, R.T. 2005. *Quantitative Analysis of Factors Affecting Railroad Accident Probability and Severity*. Master's Thesis, University of Illinois at Urbana-Champaign, Department of Civil and Environmental Engineering. Urbana, IL, USA.

Anderson, R.T. and C.P.L. Barkan. 2004. Railroad accident rates for use in transportation risk analysis. *Transportation Research Record: Journal of Transportation Research Board,* 1863: 88 – 98.

Bae, H-U, K-M. Yun, J. Moon, and N-H. Lim. 2018a. Impact force evaluation of the derailment containment wall for high-speed train through a collision simulation. *Advances in Civil Engineering*. DOI: 10.1155/2018/2626905.

Bae, H-U, K-M. Yun, and N-H Lim. 2018b. Containment capacity and estimation of crashworthiness of derailment containment walls against high-speed trains. *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, 232(3): 680 – 696.

Barkan, C.P.L. 1990. *Distance from Track Center of Railroad Equipment in Accidents. Memorandum*. Association of American Railroads, Washington, DC, USA.

Barkan, C.P.L., C.T. Dick, and R.T. Anderson. 2003. Analysis of railroad derailment factors affecting hazardous materials transportation risk. *Transportation Research Record: Journal of Transportation Research Board,* 1825: 64 – 74.

Baysari, M.T., A.S. Mclntosh, and J.R. Wilson. 2008. Understanding the human factors contribution to railway accidents and incidents in Australia. *Accident Analysis and Prevention*, 40: 1750 – 1757.

Bing, A.J., E.W. Beshers, M. Chavez, D.P. Simpson, E.S. Horowitz, and W.E. Zullig Jr. 2010. *Guidebook for Implementing Passenger Rail Service on Shared Passenger and Freight Corridors*. Transportation Research Board Report NCHRP 657. Washington, DC, USA.

Cai, G., Y. Wang, Q. Song, and C. Yang. 2018. RAMS analysis of train air braking system based on GO-Bayes method and big data platform. *Complexity*. DOI: 10.1155/2018/5851491.

Clark, S.L., S. Moulton, S. McCabe, and J. Kubo. 2013. Analytical method to calculate risk-based track separation distances for high speed tracks in freight corridors. In: *Proceedings of the American Railway Engineering and Maintenance-of-way Association Annual Conference*, Indianapolis, IN, USA.

Cockle, J. 2014. Freight railroads adjacent to high-speed rail – assessing the risk. In: *Proceedings of the 2014 Joint Rail Conference*, Colorado Springs, CO, USA.

D'Ariano, A., M. Pranzo, and I.A. Hansen. 2007. Conflict resolution and train speed coordination for solving real-time timetable perturbations. *IEEE Transactions on Intelligent Transportation Systems*, 8(2): 208 – 222.

English, G.W., G. Highan, and M. Bagheri. 2007. *Evaluation of Risk Associated with Stationary Dangerous Goods Railroad Cars*. TranSys Research Ltd., ON, Canada.

European Railway Agency (ERA). 2014. *Introduction to ETCS Braking Curves*. European Railway Agency, Valenciennes, France.

Gorman, M.F. 2009. Statistical estimation of railroad congestion delay. *Transportation Research Part E: Logistics and Transportation Review*, 45(3): 446 – 456.

Hay, W.W. 1982. *Railroad Engineering*, 2nd ed. John Wiley & Sons, New York, NY, USA.

Institute of Electrical and Electronics Engineers (IEEE). 2009. *IEEE Guide for the Calculation of Braking Distances for Rail Transit Vehicles*. IEEE, New York, NY, USA.

Kyriakidis, M., A. Majumdar, and W.Y. Ochiend. 2018. The human performance railway operational index—a novel approach to assess human performance for railway operations. *Reliability Engineering and System Safety*, 170: 226 – 243.

Layden, G. 2014. Development of crash wall design loads from theoretical train impact. In *Proceedings of the 2014 American Railway Engineering and Maintenance-of-way Association Annual Conference*, Chicago, IL, USA.

Lamorgese, L. and C. Mannino. 2015. An exact decomposition approach for the real-time train dispatching problem. *Operation Research*, 63(1): 48 – 64.

Lin, C-Y. 2019. *Probabilistic Risk Assessment of Railroad Train Adjacent Track Accidents*. Doctoral Thesis, University of Illinois at Urbana-Champaign, Department of Civil and Environmental Engineering. Urbana, IL, USA.

Lin, C-Y. and M.R. Saat. 2014. Semi-quantitative risk assessment of adjacent track accidents on shared-use rail corridors. In: *Proceedings of the 2014 Joint Rail Conferences, Colorado Springs*, Colorado, CO, USA.

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

Lin, C-Y., M.R. Saat, and C.P.L. Barkan. 2019. Quantitative causal analysis of mainline passenger train accidents in the United States. Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit. DOI: 10.1177/0954409719876128.

Liu, X. 2017a. Optimizing rail defect inspection frequency to reduce the risk of hazardous materials transportation by rail. *Journal of Loss Prevention in the Process Industries*, 48: 151 – 161.

Liu, X. 2017b. Statistical causal analysis of freight-train derailments in the United States. *Journal of Transportation Engineering, Part A: Systems*, 143(2). DOI: 10.1061/JTEPBS.0000014.

Liu, X., C.P.L. Barkan, and M.R. Saat. 2011. Analysis of derailments by accident cause: evaluating railroad track upgrades to reduce transportation risk. *Transportation Research Record: Journal of Transportation Research Board*, 2261: 178 – 185.

Liu, X., M.R. Saat, and C.P.L. Barkan. 2013. Analysis of U.S. freight-train derailment severity using zero-truncated negative binomial regression and quantile regression. *Accident Analysis and Prevention*, 59: 87 – 93.

Liu, X., M.R. Saat, and C.P.L. Barkan. 2014. Probability analysis of multiple-tank-car release incidents in railway hazardous materials transportation. *Journal of Hazardous Materials*, 276: 442 – 451.

Liu, X., M.R. Saat, and C.P.L. Barkan. 2017. Freight-train derailment rates for railroad safety and risk analysis. *Accident Analysis and Prevention*, 98: 1 – 9.

Liu, X., M.R. Saat, and C.P.L. Barkan. 2012. Analysis of causes of major train derailment and their effect on accident rates. *Transportation Research Record: Journal of Transportation Research Board*, 2289: 154 – 163.

Madigan, R., D. Golightly, and R. Madders. 2016. Application of Human Factors Analysis and Classification System (HFACS) to UK rail safety of the line incidents. *Accident Analysis and Prevention*, 97: 122 – 131.

Moyer, P.D., R.W. James, C.H. Bechara, and K.L. Chamberlain. 1994. *Safety of High Speed Guided Ground Transportation Systems Intrusion Barrier Design Study*. U.S. Department of Transportation Report DOT/FRA/ORD-95/04. Washington, DC, USA.

Nash, A. 2003. *Best Practices in Shared-Use High-Speed Rail Systems*. Mineta Transportation Institute Report MTI 02-02. San Jose, CA, USA.

Nayak, P.R., D.B. Rosenfield, and J.H. Hagopian. 1983. *Event Probabilities and Impact Zones for Hazardous Materials Accidents on Railroads*. U.S. Department of Transportation Report DOT/FRA/ORD-83/20. Washington, DC, USA.

Oh, S.M., S.H. Hong, and I.C. Choi. 2004. Railway conflict detection and resolution in the Korea railway system. *Computers in Railway IX*. DOI: 10.2495/CR040681.

Peterman, D.R., J. Frittelli, and W.J. Mallett. 2013. *The Development of High Speed Rail in the United States: Issues and Recent Events.* Congressional Research Service Report R42584. Washington, DC, USA.

Reinach, S. and A. Viale. 2006. Application of a human error framework to conduct train accident/incident investigations. *Accident Analysis and Prevention*, 38(2): 396 – 406.

Resor, R.R. 2003. *Catalog of "Common Use" Rail Corridors*. U.S. Department of Transportation Report DOT-FRA-03-16. Washington, DC, USA.

Saat, M.R. and C.P.L. Barkan. 2013. *Investigating Technical Challenges and Research Needs Related to Shared Corridors for High-Speed Passenger and Railroad Freight Operations*. U.S. Department of Transportation Report DOT/FRA/ORD-13/29. Washington DC, USA.

Saccomanno, F.F. and S.M. El-Hage. 1989. Minimizing derailments of railcars carrying dangerous commodities through effective marshaling strategies. *Transportation Research Record: Journal of Transportation Research Board*, 1245: 34 – 51.

Saccomanno, F.F. and S.M. El-Hage. 1991. Establishing derailment profile by position for corridor shipment of dangerous goods. *Canadian Journal of Civil Engineering*, 18(1): 67 – 75.

Şahin, I. 2017. Markov chain model for delay distribution in train schedules: Assessing the effectiveness of time allowances. *Journal of Rail Transport Planning & Management*, 7(3): 101 – 113.

Shih, M-C., C.T. Dick, D. Mussanov, and C.P.L. Barkan. 2017. A parametric model of the train delay distribution based on traffic conflicts. In: *Proceedings of the 7th International Conference on Railway Operating Modelling and Analysis*, Lille, France.

Sørensen, A.Ø., A.D. Landmark, N.O.E. Olsson, and A.A. Seim. 2017. Method of analysis for delay propagation in a single-track network. *Journal of Rail Transport Planning & Management*, 7(1-2): 77 – 97.

Thurston, D.F. 2011. Statistical safe braking analysis. In: *Proceedings of the ASME/ASCE/IEEE 2011 Joint Rail Conference*, Pueblo, CO, USA.

Ullman, K.B. and A.J. Bing. 1995. *High Speed Passenger Trains in Freight Railroad Corridors: Operations and Safety Considerations*. U.S. Department of Transportation Report DOT/FRA/ORD-95/05. Washington, DC, USA.

Wang, B.Z., C.P.L. Barkan, and M.R. Saat. 2020. Quantitative Analysis of Changes in Freight Train Derailment Causes and Rates. *Journal of Transportation Engineering, Part A: Systems*. DOI: 10.1061/JTEPBS.0000453.

White, T. 2005. Alternatives for railroad traffic simulation analysis. *Transportation Research Record: Journal of Transportation Research Board*, 1916, 34 – 41.

Wilson, J.R. and B.J. Norris. 2005. Rail human factors: past, present and future. *Applied Ergonomics*, 36(6): 649 – 660.

Wilson, J.R., T. Farrington-Darby, G. Cox, R. Bye, and R.J. Hockey. 2007. The railway as a socio-technical system: human factors at the heart of successful rail engineering. *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, 221(1): 101 – 115.

Yang, J., C. Zhao, A. Zhu, D. Yao, and H. Wu. 2016. Reliability estimation for the braking systems of high-speed electric multiple units based on Bayes inference and the GO method. *Journal of Computational and Theoretical Neuroscience*, 13(2): 1314 – 1322.

Zhan, Q., W. Zheng, and B. Zhao. 2017. A hybrid human and organizational analysis method for railway accidents based on HFACS-Railway Accidents (HFACS-RAs). *Safety Science*, 91: 232 – 250.