U.S. Department of
Transportation

Federal Railroad Administration

Hazards Associated with HSR Operations Adjacent to Conventional Tracks – Enhanced Literature Review Part II: Draft Guidance Document

Office of Research, Development
and Technology
Washington, DC 20590

DOT/FRA/ORD-19/28

Final Report
August 2019

REPORT DOCUMENTATION PAGE			*Form Approved* *OMB No. 0704-0188*
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.			
1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE August 2019		3. REPORT TYPE AND DATES COVERED Technical Report April 1, 2014-June 21, 2014
4. TITLE AND SUBTITLE Hazards Associated with HSR Operations Adjacent to Conventional Tracks – Enhanced Literature Review Part II: Draft Guidance Document			5. FUNDING NUMBERS DTFR53-12-D-00002 Task Order 2
6. AUTHOR(S) M. R. Saat, C.P.L. Barkan			
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) University of Illinois at Urbana-Champaign Rail Transportation and Engineering Center–RailTEC Department of Civil and Environmental Engineering 205 N. Mathews Ave Urbana, IL 61801			8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) U.S. Department of Transportation Federal Railroad Administration Office of Railroad Policy and Development Office of Research, Development and Technology Washington, DC 20590			10. SPONSORING/MONITORING AGENCY REPORT NUMBER DOT/FRA/ORD-19/28
11. SUPPLEMENTARY NOTES COR: Francesco Bedini Jacobini			
12a. DISTRIBUTION/AVAILABILITY STATEMENT This document is available to the public through the FRA website.			12b. DISTRIBUTION CODE
13. ABSTRACT (Maximum 200 words) The Federal Railroad Administration (FRA) set out to develop a guidance document, which provides information on the design considerations and potential risk mitigations for high-speed rail (HSR) systems adjacent to and sharing corridors with existing conventional railway operations. The objective of this project is to provide input to and support the development of the guidance document by conducting a comprehensive literature review of the 11 hazards associated with HSR operations adjacent to conventional tracks that were identified by FRA. This report is the second part of the three-part project that consists of the following: the general hazard assessment, which provides a general risk framework and procedures to identify, evaluate, and mitigate the risk of any potential hazard of HSR operations on shared-use rail corridors; and the detailed hazard assessment, which provides guidance to perform a risk assessment of the potential hazards.			
14. SUBJECT TERMS Shared corridor, high-speed rail, conventional railroad			15. NUMBER OF PAGES 84
			16. PRICE CODE
17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI
Std. 239-18
298-102

METRIC/ENGLISH CONVERSION FACTORS

ENGLISH TO METRIC

LENGTH (APPROXIMATE)

1 inch (in)	=	2.5 centimeters (cm)
1 foot (ft)	=	30 centimeters (cm)
1 yard (yd)	=	0.9 meter (m)
1 mile (mi)	=	1.6 kilometers (km)

AREA (APPROXIMATE)

1 square inch (sq in, in^2)	=	6.5 square centimeters (cm^2)
1 square foot (sq ft, ft^2)	=	0.09 square meter (m^2)
1 square yard (sq yd, yd^2)	=	0.8 square meter (m^2)
1 square mile (sq mi, mi^2)	=	2.6 square kilometers (km^2)
1 acre = 0.4 hectare (he)	=	4,000 square meters (m^2)

MASS - WEIGHT (APPROXIMATE)

1 ounce (oz)	=	28 grams (gm)
1 pound (lb)	=	0.45 kilogram (kg)
1 short ton = 2,000 pounds (lb)	=	0.9 tonne (t)

VOLUME (APPROXIMATE)

1 teaspoon (tsp)	=	5 milliliters (ml)
1 tablespoon (tbsp)	=	15 milliliters (ml)
1 fluid ounce (fl oz)	=	30 milliliters (ml)
1 cup (c)	=	0.24 liter (l)
1 pint (pt)	=	0.47 liter (l)
1 quart (qt)	=	0.96 liter (l)
1 gallon (gal)	=	3.8 liters (l)
1 cubic foot (cu ft, ft^3)	=	0.03 cubic meter (m^3)
1 cubic yard (cu yd, yd^3)	=	0.76 cubic meter (m^3)

TEMPERATURE (EXACT)

[(x-32)(5/9)] □F = y □C

METRIC TO ENGLISH

LENGTH (APPROXIMATE)

1 millimeter (mm)	=	0.04 inch (in)
1 centimeter (cm)	=	0.4 inch (in)
1 meter (m)	=	3.3 feet (ft)
1 meter (m)	=	1.1 yards (yd)
1 kilometer (km)	=	0.6 mile (mi)

AREA (APPROXIMATE)

1 square centimeter (cm^2)	=	0.16 square inch (sq in, in^2)
1 square meter (m^2)	=	1.2 square yards (sq yd, yd^2)
1 square kilometer (km^2)	=	0.4 square mile (sq mi, mi^2)
10,000 square meters (m^2)	=	1 hectare (ha) = 2.5 acres

MASS - WEIGHT (APPROXIMATE)

1 gram (gm)	=	0.036 ounce (oz)
1 kilogram (kg)	=	2.2 pounds (lb)
1 tonne (t)	=	1,000 kilograms (kg)
	=	1.1 short tons

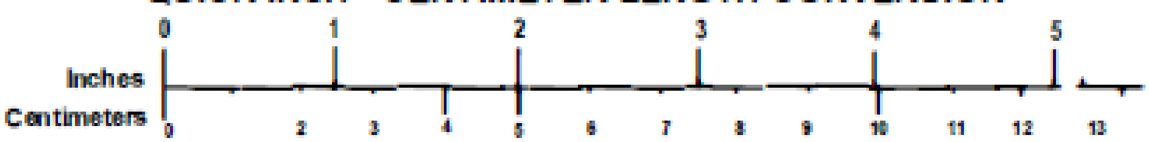
VOLUME (APPROXIMATE)

1 milliliter (ml)	=	0.03 fluid ounce (fl oz)
1 liter (l)	=	2.1 pints (pt)
1 liter (l)	=	1.06 quarts (qt)
1 liter (l)	=	0.26 gallon (gal)
1 cubic meter (m^3)	=	36 cubic feet (cu ft, ft^3)
1 cubic meter (m^3)	=	1.3 cubic yards (cu yd, yd^3)

TEMPERATURE (EXACT)

[(9/5) y + 32] □C = x □F

QUICK INCH - CENTIMETER LENGTH CONVERSION



QUICK FAHRENHEIT - CELSIUS TEMPERATURE CONVERSIO

°F	-40°	-22°	-4°	14°	32°	50°	68°	86°	104°	122°	140°	158°	176°	194°	212°
°C	-40°	-30°	-20°	-10°	0°	10°	20°	30°	40°	50°	60°	70°	80°	90°	100°

For more exact and or other conversion factors, see NIST Miscellaneous Publication 286, Units of Weights and Measures. Price $2.50 SD Catalog No. C13 10286

11

Contents

Illustrations

Tables

Executive Summary

Between April and June 2014, the Federal Railroad Administration (FRA) tasked Booz Allen Hamilton (Booz Allen) and the Rail Transportation and Engineering Center (RailTEC) in the Department of Civil and Environmental Engineering at the University of Illinois at Urbana-Champaign (UIUC) to assist in the development of a guidance document which provides information on the design considerations and potential risk mitigations for high-speed rail (HSR) systems adjacent to and sharing corridors with existing conventional railway operations. With the increasing demand for HSR operations, the potential hazards between HSR tracks and adjacent conventional tracks became more pronounced and needed to be considered. The objective of this project is to provide input to and support the development of the guidance document by conducting a comprehensive literature review of the following hazards associated with HSR operations adjacent to conventional tracks:

- Derailment on adjacent tracks
- Shifted load on adjacent tracks
- Aerodynamic interaction between trains on adjacent tracks
- Ground-borne vibration and its effect on HSR track geometry
- Intrusion of maintenance-of-way staff and equipment working on the adjacent track
- Obstruction hazard resulting from an adjacent track (non-derailment and grade-crossing collisions)
- Drainage problem affecting either the HSR track or the adjacent track
- Evacuation of passengers from trains on the adjacent track
- Hazardous materials on the adjacent track
- Fire on the adjacent track
- Electromagnetic interference between trains and wayside equipment on adjacent tracks

An additional, detailed literature review on specific hazards that FRA deems as requiring more information, as well as train accident analyses to identify train accident causes that are relevant to shared corridor operations, enhanced the initial literature review. Booz Allen and RailTEC then developed a draft guidance document based on the enhanced literature review and additional risk analyses. The entire project consists of three parts: 1) a summary report that defines the scope of the literature review and summarizes the results from the comprehensive literature review; 2) a draft guidance document for understanding, addressing and mitigating the risk of HSR systems adjacent to and sharing corridors with existing conventional railway operations using qualitative and quantitative risk management approaches; and 3) a complete and enhanced literature review of mitigating the risk of HSR systems adjacent to and sharing corridors with existing conventional railway operations.

This report presents Part II of the project, consisting of two parts: the general hazard assessment that provides a general risk framework and procedures to identify, evaluate, and mitigate the risk of any potential hazard of HSR operations in shared-use rail corridors. A risk register for a

specific set of hazards will be provided. The second part, a detailed hazard assessment, provides guidance to perform risk assessments of the potential hazards. Supplemental materials in the appendices include the fault-tree analysis for the specified hazards, an example semi-quantitative risk assessment of adjacent track accidents on shared-use rail corridors, and causal analysis of passenger train accident analyses.

Introduction

The following paragraphs give the overview of this summary report, including the background and objective of the literature review, approaches used to conduct the literature review, scope of this study, and the organization of the report.

1.1 Background

The Federal Railroad Administration (FRA) set out to develop a guidance document which provides information on the design considerations and potential risk mitigations for high-speed rail (HSR) systems adjacent to and sharing corridors with existing conventional railway operations. With the increasing demand for HSR operations, the potential hazards between HSR tracks and adjacent conventional tracks became more pronounced and needed to be considered. The objective of this project is to provide input to and support the development of the guidance document by conducting a comprehensive literature review of the following hazards associated with HSR operations adjacent to conventional tracks:

- Derailment on adjacent tracks
- Shifted load on adjacent tracks
- Aerodynamic interaction between trains on adjacent tracks
- Ground borne vibration and its effect on HSR track geometry
- Intrusion of maintenance of way staff and equipment working on the adjacent track
- Obstruction hazard resulting from an adjacent track (non-derailment and grade-crossing collisions)
- Drainage problem affecting either the HSR track or the adjacent track
- Evacuation of passengers from trains on the adjacent track
- Hazardous materials on the adjacent track
- Fire on the adjacent track
- Electromagnetic interference (EMI) between trains and wayside equipment on adjacent tracks

1.2 Objectives

This report provides guidance and procedures for the risk assessment of potential hazards for high-speed rail (HSR)[1] systems adjacent to and sharing corridors with existing conventional railway operations. The corridors where HSR is adjacent to or sharing corridors with conventional railway systems are also referred to as "shared-use rail corridors." With the increasing demand for high-speed rail operations, the potential hazards between HSR tracks and

[1] For brevity, the term HSR throughout the document will refer to both high-speed rail (HSR) and higher-speed rail (HrSR). Although some hazard assessments are more relevant to HSR than HrSR, this guidance document intends to provide more general and comprehensive shared-use rail risk assessment procedure. Per definition from FRA, HSR refers to express systems that run trains at 150 mph or above; HrSR refers to HSR and regional and emerging HSR systems that run trains between 90 mph and 150 mph.

adjacent conventional tracks became more pronounced and needed to be considered. The hazards identified in this document include those that pose potential risk to HSR operations due to adjacent conventional railroad operations and those that pose potential risk to conventional railroad operations due to adjacent HSR operations. The development of this guidance considered, among others, the following issues:

- Minimum track and right-of-way (ROW) spacing between adjacent railroad tracks without the use of additional protection
- Use of intrusion detection or protection devices and proper system characteristics and installation locations
- Use of physical barriers or crash walls; what conditions warrant use and basic design characteristics

Other relevant considerations include aerodynamics, effects of grading and track heights, and protection from activities along ROWs.

Overall Approach

This guidance consists of two parts. The first part, the general hazard assessment, provides a general risk framework and procedures to identify, evaluate, and mitigate the risk of any potential hazard of HSR operations in shared-use rail corridors. A risk register for a specific set of hazards will be provided. The second part, a detailed hazard assessment, provides guidance to perform risk assessment of the potential hazards. Supplemental materials in the appendices include:

- The fault-tree analysis (FTA) for the specified hazards
- An example semi-quantitative risk assessment of adjacent track accidents on shared-use rail corridors
- Causal analysis of passenger and freight train accident analyses

Scope

The scope of this research focuses on the development of risk assessment procedures and guidance document of safety issues of operating HSR adjacent to conventional railroad corridors.

Organization of the Report

Section 2 presents a general risk assessment framework and procedure. Section 3 presents a detailed risk assessment by applying qualitative and quantitative risk assessment techniques. Section 4 presents conclusions based on previous risk assessments.

General Hazard Assessment

Risk Management

Risk, as defined by the Project Management Body of Knowledge Guide (PMBOK Guide) (Project Management Institute, 2013), is "an uncertain event or condition that, if it occurs, has a positive or negative effect on a project's objectives." The two key elements of the risk are the uncertainty (usually known as "probability" or "likelihood") and the effect on the project's objectives (usually known as "consequence," "severity," or "impact"). In order to properly and comprehensively address the risk, a risk management plan is essential in achieving this goal. Risk management is defined by the PMBOK Guide as "the processes concerned with conducting risk management planning, risk identification, risk analysis, risk responses (risk mitigations), and risk control. A risk management plan identifies and prioritizes risks and mitigation strategies, and includes clear and consistent procedures and processes to carry out risk management." Although the risk could be positive or negative, in this guidance document the major objective of the risk management plan is to decrease the probability and/or the consequences of the hazards associated with HSR operations adjacent to and sharing corridors with conventional railroad systems.

The structure of risk management processes are organized in the following order:

- Risk Management Planning: Define the scope and objective of the risk assessment; define risk thresholds, tolerances, and the assessment framework.
- Risk Identification: Expose, prioritize and document all potential risks; develop risk register to identify potential locations of hazards, influencing factors and risk mitigation strategies.
- Qualitative Risk Analysis: Gain understanding of individual risks, considering various characteristics such as causes, probability, consequence and relationships with other risks.
- Quantitative Risk Analysis: Numerically analyze the effect of identified risks, including the quantitative assessment of probability and consequence. Probabilistic risk assessment (PRA) can be performed to gain further insight of prioritized risks.
- Risk Mitigation Strategies: Propose and evaluate potential risk mitigation strategies for the risks and integrate them into a comprehensive risk mitigation framework.

The follow sub-sections will discuss risk management planning and risk identification; the detailed risk assessment section will discuss the qualitative risk analysis, quantitative risk analysis, and risk mitigation strategies.

Risk Management Planning

The scope and objective of the risk assessment is mentioned above. Other items that need to be addressed in the risk management planning include:

2.1.1.1 Risk Thresholds and Tolerances

It is essential to have clear risk thresholds that define the acceptable risk level. The risk thresholds can be determined by the users of this guidance document based on qualitative or quantitative risk assessment.

2.1.1.2 Iterative and Dynamic Process

The nature of risk involves uncertainty. Thus, to ensure the effectiveness and quality of risk management, the risk assessment should be revisited periodically, and the progress on risk response actions should be monitored and adjusted if appropriate. The objective of the risk assessment is to address all potential risks, recognizing that some risks may be unknown in the beginning and may emerge later in a project. The emergent nature of risk requires the risk assessment processes to be iterative in order to find risks which were not evident earlier.

Risk Identification

The purpose of risk identification is to identify as many potential risks as possible. The techniques for risk identification include historical review, information gathering, and expert judgments. Historical review includes document literature review and practical experiences from previous projects. Information gathering includes brainstorming, industry surveys, and root cause/precursor analyses. Expert judgment included surveys and interviews. In preparation of this guidance document researchers conducted an intensive literature review, expert interviews, domestic and international stakeholder outreach, and industry surveys to collect and identify potential hazards associated with HSR operation adjacent to and sharing corridors with conventional railway systems.[2] Based on the results, the following 11 hazards were identified and defined:

1. Derailment on adjacent tracks: Derailments on adjacent tracks (or adjacent track accidents [ATA]) refers to train accident scenarios where derailed rail equipment intrudes adjacent tracks, causing operation disturbance and potential subsequent train collisions on the adjacent tracks. Other ATA scenarios include collisions between trains on adjacent tracks (raking collisions), turnouts, and railroad crossings.
2. Shifted load on an adjacent track: Unbalanced or improperly secured load or lading on freight cars may result in the derailment of freight cars, and may also lead to the intrusion of the load or lading from the freight cars onto adjacent tracks.
3. Aerodynamic interaction between trains on adjacent tracks: Train aerodynamics may influence the stability of two trains passing each other so that when two trains pass each other, the suction force induced by the aerodynamics may drag the train toward each other, resulting in train instability or raking collisions.
4. Ground-borne vibration and its effect on HSR track geometry: Ground-borne vibration is the vibration energy created by the train wheels rolling on the rails. The vibration waves propagate through the various soil and rock to the foundations of adjacent tracks, which may cause subgrade problems and thus track geometry problems.
5. Intrusion of maintenance-of-way (MOW) staff and equipment working on the adjacent track: The intrusion of MOW staff or vehicles on the adjacent track may result in the

[2] The completed literature review is available in Part III, "Literature Review of Hazards Associated with HSR and Conventional Tracks."

collision between the MOW staff or vehicle and a conventional or high-speed train. This may cause roadway worker casualties, equipment damage, system disturbance (train delay), train derailments, and passenger casualties.

6. Obstruction hazard resulting from an adjacent track (non-derailment and grade-crossing collisions): The obstructions fouling the HSR track from the adjacent track can result from the shifted load of railroad cars or from the collision of a train and a road vehicle. This collision can result from the grade crossing on conventional tracks or from non-grade-crossing areas.
7. Drainage problem affecting either the HSR track or the adjacent track: Poor drainage may cause the instability of the railroad roadbed, a track geometry irregularity, ballast fouling, and other substructure problems. These substructure defects may then lead to more severe crosstie deterioration, shorter life for track components, slow orders, and safety concerns.
8. Evacuation of passengers from trains on the adjacent track: When there is a derailment, a collision, or a fire on a train, an evacuation is needed to protect passengers. An ineffective and unsafe evacuation process may potentially lead to passenger injuries or fatalities.
9. Hazardous materials on the adjacent track: Transporting hazardous materials (or dangerous goods) on the railroad adjacent to HSR tracks poses additional risk to the HSR track due to the potential risk of the release of hazardous material from the freight cars on the conventional tracks, given an accident.
10. Fire on the adjacent track: Fire scenarios on trains could be the direct cause of accidents, including engine fire, pantograph fire, and human-caused fire. Other fire scenarios could be the consequences of the hazards mentioned previously, such as fire resulting from derailments, collisions, leaked fuel, and released hazardous materials. Fire may directly cause passenger casualties, equipment and/or infrastructure damage, and lading loss. High temperature, smoke inhalation, or injuries due to the collapse of structure could also occur. Fire on the adjacent track may result in the hindrance of visibility, potential casualties of passengers on the adjacent train, damage to the equipment, and chain fire or explosion.
11. EMI between trains and wayside equipment on adjacent tracks: EMI is the electromagnetic field generated by a source (e.g., a HSR train or a high-voltage power tower) that negatively affects the electrical or magnetic devices. EMI in this document specifically refers to the ones that adversely affect the operation of HSR by the wayside equipment on adjacent tracks.

Note that although this guidance document identified several potential hazards, there may be other hazards for specific HSR systems or new projects. Therefore, the users of this guidance document should treat these 11 hazards as a basis and follow the risk assessment process framework depicted previously to conduct a comprehensive risk identification process to identify additional, potential hazards.

2.1.2.1 Risk Register

The primary output from risk identification process is a risk register. Per PMBOK definition, a risk register is “a document where the results of risk identification, preliminary influencing factor analysis and proposed risk responses are recorded.” In this document, for each identified hazard, the potential locations where the hazard may occur are documented, and factors that may affect the probability and/or consequence of the identified hazard, as well as proposed risk mitigation strategies for the hazard, are recorded. The actual effects of these influencing factors and risk mitigation strategies are further discussed in the qualitative and quantitative risk analyses sections. Whenever a new hazard is identified, the risk register elements for the hazard should be developed and documented accordingly as demonstrated by the 11 identified hazards. This process is essential, as it provides the basis for further analyses and documentation for revision and update in the future.

2.1.2.2 Potential Location of Hazards

Different hazards occur at different places, and understanding where each hazard may occur is important for engineers and planners to appropriately address the potential risk when designing or planning a shared-use rail operation. Based on the previous literature review, expert interviews and industry surveys, the locations along a shared-use rail corridor where HSR operations are adjacent to or sharing corridors with conventional railway systems were determined. Table 2.1 summarizes the general locations along a shared-use rail corridor where each hazard is eminent. These locations can be revised and updated when further risk analyses are conducted and more information is available.

Table 2.1 General Locations Where Each Hazard Is Eminent

	Hazard	Location
1	Derailment on adjacent tracks	Along a shared-use rail corridor with multiple tracks
2	Shifted load on adjacent tracks	Along a shared-use rail corridor with freight train services
3	Aerodynamic interaction between trains on adjacent tracks	Along a shared-use rail corridor with multiple tracks, tunnels, and stations where trains operate at high speed
4	Ground-borne vibration and its effect on HSR track geometry	Along a shared-use rail corridor where trains operating at high speed, especially at locations with subgrade and track infrastructure conditions susceptible to vibrations, and at special track locations (e.g., switches and turnouts)
5	Intrusion of maintenance of way staff and equipment working on adjacent tracks	Along a shared-use rail corridor where track maintenance activities frequently take place and locations with limited clearances (e.g., bridges, tunnels)
6	Obstruction hazard resulting from adjacent tracks (non-derailment collisions)	Along a shared-use rail corridor close to other rail or highway vehicles (e.g., yards, grade crossings)
7	Drainage problem affecting either the HSR track or adjacent tracks	Along a shared-use rail corridor, especially in areas with high precipitation/snow, vegetation, and insufficient drainage systems
8	Evacuation of passengers from trains on adjacent tracks	Along a shared-use rail corridor with multiple tracks
9	Hazardous material transportation on adjacent tracks	Along a shared-use rail corridor with freight trains transporting hazardous materials
10	Fire on adjacent tracks	Along a shared-use rail corridor with freight trains transporting flammable liquids and/or gases, and other locations near fuel-based activities (e.g., power stations, gas stations)

	Hazard	Location
11	EMI between trains and wayside equipment on adjacent tracks	Along a shared-use rail corridor where high-voltage overhead catenary wires present

2.1.2.3 Influencing Factors

There are different factors that could affect an individual hazard. Identifying these factors could help to quantify and evaluate the risk of the hazard. Identified major factors include track center spacing between HSR tracks and conventional tracks, train speed (the maximum authorized speed for HSR and conventional rail systems), track geometry (curvature, elevation, maintenance standard, etc.), train equipment design, rail infrastructure, and human factors. A specific influencing factor may affect multiple hazards. One important tool to identify influencing factors is FTA. FTA is a technique frequently used in safety engineering and reliability engineering to reveal the underlying causes of a hazard. With a top-down failure analysis combined with Boolean logic, FTA is able to reveal the root events and their logic that led to the hazard. Appendix A in this guidance document demonstrates the FTA for the 11 hazards associated with HSR operations adjacent to and sharing with conventional railway systems. Table 2.2 summarizes the key influencing factors for each hazard.

Table 2.2 Key Influencing Factors for Each Hazard

	Hazard	Key Influencing Factors
1	Derailment on adjacent tracks	Track center spacing, train speed, human factors, track geometry, type of rail infrastructure, train control systems
2	Shifted load on adjacent tracks	Track center spacing, train speed, human factors, track geometry, train control systems
3	Aerodynamic interaction between trains on adjacent tracks	Track center spacing, train speed, train equipment design, wind condition
4	Ground-borne vibration and its effect on HSR track geometry	Track center spacing, train speed, track geometry, type of rail infrastructure, soil foundation/subgrade characteristics
5	Intrusion of maintenance of way staff and equipment working on adjacent tracks	Track center spacing, train speed, human factors
6	Obstruction hazard resulting from adjacent tracks (non-derailment collisions)	Track center spacing, train speed, human factors, track geometry, train control systems
7	Drainage problem affecting either the HSR track or adjacent tracks	Track center spacing, soil foundation/subgrade characteristics, track geometry, type of rail infrastructure
8	Evacuation of passengers from trains on adjacent tracks	Track center spacing, train equipment design, human factors
9	Hazardous material transportation on adjacent tracks	Track center spacing, train equipment design, hazardous materials traffic volume
10	Fire on adjacent tracks	Track center spacing, train equipment design, human factors, flammable product traffic volume
11	EMI between trains and wayside equipment on adjacent tracks	Train equipment design, type of rail infrastructure, train control systems

In addition, results from causal analysis of passenger and freight train accident analyses in Appendix B can be used to identify conventional train accident causes that may be relevant to future HSR operations adjacent to conventional tracks.

2.1.2.4 Potential Risk Mitigation

The ultimate goal of assessing the risk of each hazard is to be able to prevent or reduce the risk of the hazard in the shared-use rail operation. Based on the literature review, expert interviews and industry surveys identified general locations where each hazard is eminent, and the associated influencing factors. Table 2.3 summarizes several potential risk mitigation strategies and describes them in Appendix C. These risk mitigation strategies can be revised and updated when further risk analyses are conducted and more information is available for specific HSR systems or new projects.

Table 2.3. Potential Risk Mitigation Strategies for Each Hazard

	Hazard	Potential Risk Mitigation Strategies
1	Derailment on adjacent tracks	Proper track center spacing, installation of intrusion detection systems, building physical barriers, improved employee training, temporal separation
2	Shifted load on adjacent tracks	Proper track center spacing, installation of intrusion detection systems, building physical barriers, improved employee training on cargo securement, temporal separation
3	Aerodynamic interaction between trains on adjacent tracks	Proper track center spacing, installation of intrusion detection systems, building physical barriers, reduced train speed, temporal separation
4	Ground borne vibration and its effect on HSR track geometry	Proper track center spacing, reduced train speed
5	Intrusion of maintenance of way staff and equipment working on adjacent tracks	Proper track center spacing, installation of intrusion detection systems, building physical barriers, improved employee training, reduced train speed, temporal separation
6	Obstruction hazard resulting from adjacent tracks (non-derailment collisions)	Proper track center spacing, installation of intrusion detection systems, building physical barriers, improved employee training, grade crossing protection
7	Drainage problem affecting either the HSR track or adjacent tracks	Proper track center spacing, soil improvement, improved drainage
8	Evacuation of passengers from trains on adjacent tracks	Proper track center spacing, installation of intrusion detection systems, building physical barriers, improved employee training on safe passenger evacuation, enhanced rail equipment design
9	Hazardous material transportation on adjacent tracks	Proper track center spacing, building physical barriers, temporal separation, enhanced rail car design to prevent hazardous material release, temporal separation
10	Fire on adjacent tracks	Proper track center spacing, building physical barriers, temporal separation, enhanced rail equipment design
11	EMI between trains and wayside equipment on adjacent tracks	Improved employee training, better rail equipment design to prevent or reduce EMI

Detailed Hazard Assessment

After the risk identification, a detailed hazard assessment can be performed to prioritize the risk, qualitatively or quantitatively evaluate the risk, and analyze the effectiveness of potential risk mitigation strategies. In this chapter, qualitative risk assessment, quantitative risk assessment and risk mitigation will be introduced and discussed.

Qualitative Risk Assessment

Qualitative risk assessment evaluates the general characteristics of individual risks or hazards. The purpose of qualitative risk assessment is to prioritize the hazards by comparing the relative probability of occurrence and the consequence. The general procedure for conducting a qualitative risk assessment is:

- Defining risk characteristics that define the importance of the hazards
- Collecting and analyze any relevant data
- Prioritizing hazards by their relative probability and consequence levels or other qualitative criteria

The qualitative risk analysis tools or techniques should be able to distinguish important hazards from those that are less important. The criteria of importance are determined in advance and implemented in the techniques. The data collection and evaluation techniques may include interviewing, surveys, workshops, literature reviews and expert judgment.

Risk Prioritization of the Hazards Associated with HSR Operation Adjacent to and Sharing Corridors with Conventional Railway Systems

In order to assist the prioritization of the aforementioned hazards associated with HSR operation adjacent to conventional railway, a brief industry survey was conducted. The main objective of the survey was to determine which hazards were most important and in need of further in-depth research. The American Railway Engineering and Maintenance-of-Way Association (AREMA), Committee 17—High Speed Rail Systems, solicited the participants to the survey via email. In addition, although it was optional for the survey participants to provide names and contact information, the list and additional communication show that key contacts provided perspectives from the California High-speed Rail Project, Amtrak's Northeast Corridor, at least one Class I freight railroad, and multiple state rail planners.

Survey participants were asked to rate the 11 hazards on scale of 1 to 5, with 5 reflecting high importance or potentially high risk and 1 being the lowest importance or potentially low risk. Final scores for each hazard were computed by averaging the scores from all participants.

Based on the survey, the completed literature review and expert opinion, the following top-priority hazards were identified (listed in decreasing order of importance):

1. Derailment on adjacent tracks
2. Shifted load on adjacent tracks
3. Obstruction hazard resulting from adjacent tracks (including non-derailment and grade-crossing collisions)

4. Intrusion of MOW staff and equipment working on adjacent tracks
5. Hazardous materials on the adjacent track

Identified key factors affecting the severity of the high-priority hazards include:

- Track and ROW spacing between adjacent railroad tracks
- Speeds of both the HSR and conventional operations
- FRA track class (representing track quality and maintenance standard)
- Train control and signaling systems
- Existence of adjacent structures
- Use of physical barriers or containment

Ideally, risk assessments of specific HSR systems or new projects should at least evaluate the risk of the top-priority hazards. In addition, data related to the key factors should be collected to support potential quantitative risk assessments, if deemed necessary.

Regarding track and ROW spacing between adjacent railroad tracks, sufficient track and ROW spacing between adjacent railroad tracks is necessary for several reasons. The spacing should be large enough so that the clearances of the two adjacent tracks will not interfere each other and the aerodynamic effects of two trains will not affect the stability of either train. One of the most important reasons is the potential lateral displacement of a derailed railcar. When a train derails on one track, there is a possibility that one or more derailed cars move laterally far enough and intrude the adjacent track, causing traffic delays and potential collisions.

For other key factors, e.g., speeds of both the HSR and conventional operations, FRA track class, train control and signaling systems, existence of adjacent structures, and use of physical barriers or containment, a detailed inventory at track-segment-specific locations is needed. This information could be used to develop a more sophisticated model for appropriate track spacing and the decision making of the installation of barriers and/or containments. Table 3.1 provides an example of the track-segment inventory.

Table 3.4 Track-Segment Inventory Example

Key Factors	Input	Key Factors	Input
Location	HSR Main St. Segment	**Adjacent Railroad**	Railroad A
HSR Stationing	MP 21+00 – MP 85+00	**RR Mileposts**	231.2 – 232.3
Length	6,400 feet	**RR Derailment Rate (per million train mile)**	0.000002034
HSR Max. Authorized Speed	200 mph	**RR Track Class**	4
Existing Adjacent Structure	None	**RR Signaling System**	CTC
Physical Barriers	None	**RR Max. Authorized Speed**	60 mph (freight), 80 mph(passenger)
Horizontal Alignment	Tangent	**RR Number of Tracks**	2
Vertical Alignment	Level	**Highway Grade Crossing**	None

Quantitative Risk Assessment

Quantitative risk assessment provides numerical estimates of the probability and consequence of hazards. Results from a quantitative risk analysis can be used to determine risk thresholds and tolerances and check whether an estimated risk level is acceptable and if any risk mitigation strategy is necessary. The most important part of quantitative risk assessment is data collection. A quantitative risk analysis can only be carried out when there is high-quality and unbiased data for the analysis. The procedures for conducting quantitative risk analysis may include:

- Collecting numerical data for quantitative analysis
- Using appropriate model to evaluate the probability and consequence
- Addressing the interrelationships between risks in quantitative risk analysis
- Setting the quantitative risk threshold and tolerance upon agreement
- Comparing the estimated risks with the threshold and tolerance to determine whether risk mitigation is necessary

Stochastic approaches are usually considered, such as PRA, to perform a quantitative risk analysis. Sometimes, due to data availability and quality issues, a fully quantitative risk analysis is not feasible, and a semi-quantitative risk assessment could be implemented. Appendix D in this guidance document provides an example of a semi-quantitative risk assessment for one of the most important hazards identified, adjacent track derailments.

An alternative to quantitatively evaluating the risk of derailments on adjacent tracks is to address the probability of the lateral displacement of derailed railcars. English, Highan, and Bagheri (2007) analyzed the historical dispersion of railcars in mainline accidents (Figure 3.1).

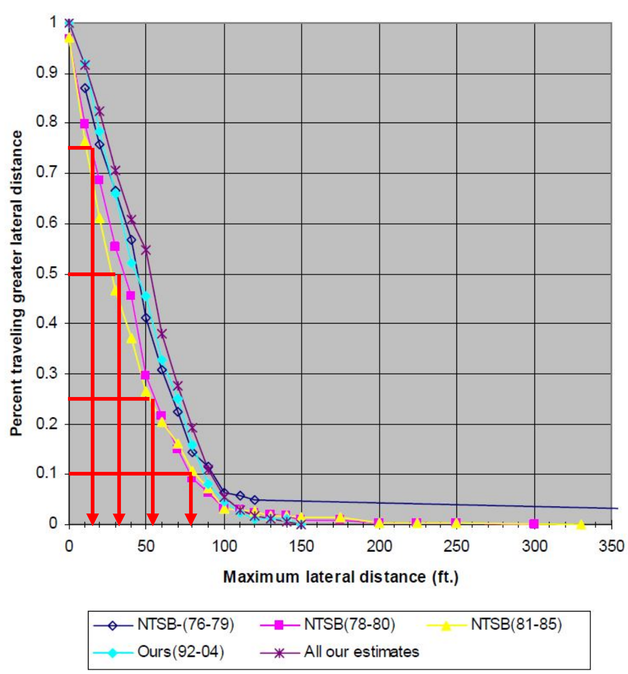


Figure 3.1 Maximum Lateral Travel Distribution (English, Highan, & Bagheri, 2007)

English, Highan, and Bagheri (2007) proposed a model to analyze the relationship between the lateral displacement with train speed. The model uses a gamma distribution function to estimate the probability of different lateral dispersion distances:

$$P(D) = \frac{1}{\beta\Gamma(\alpha)} \times D^{\alpha-1} \times e^{\frac{-D}{\beta}}$$

where:

P(D) = the probability the maximum dispersion is D in ft.

D = the maximum dispersion (with separate values for each side)

Γ = the gamma function

β = scale parameter of the distribution

α =the shape by the parameter of the distribution

The parameters α and β are related to the mean (μ) and standard deviation (σ) of the dispersion data in the following way:

$\beta = \sigma^2 / \mu$

$\alpha = \mu^2 / \sigma^2$

The mean lateral travel, μ, and standard deviation of lateral travel, σ, is then related to the train speed, V in mph:

$\mu = 30.7 + 0.29\ V$

$\sigma / \mu = 0.52 + 0.004\ V$

The English, Highan, and Bagheri model can be used to identify the minimum track spacing required based on the train speed on adjacent tracks. The model was developed using the lateral displacement data from the National Transportation Safety Board (NTSB) between 1975 and 1985. Since the NTSB has not recorded and maintained the lateral displacement data since 1985, the data available for the analysis was old. In addition, the result may not reflect the current improvement of track infrastructure and rolling stock technologies. Also, this model may not accurately measure the lateral displacement of a derailed railcar at a very high speed (e.g., HSR), as such operations did not exist during the time span of the data. Very high speed may cause larger and longer-distance railcar dispersion in an accident. Accident dynamic analysis using computer simulations may be able to address these limitations.

Risk Mitigation Strategies

Risk mitigation strategies, when implemented, can reduce the probability and/or consequence for one or more risks. Once risks are identified, analyzed, and prioritized, risk mitigation strategies should be developed if the risk is prioritized and the quantitative risk analysis shows that the risk exceeds tolerance thresholds. The procedures for implementing risk mitigation strategies may include:

- Identifying risk mitigation strategies

- Selecting proper risk mitigation strategies
- Evaluating the effectiveness of risk mitigation strategies
- Based on the resource constraint, prioritizing the implementation of risk mitigation strategies
- Updating risk register
- Reviewing the predicted effectiveness of risk mitigation strategies and residual risk and check whether the residual risk is acceptable

Table 2.1 summarizes potential risk mitigation strategies for the identified hazards associated with HSR operations adjacent to conventional tracks, and this also described in Appendix C.

Conclusion

This report is the second part of the three-part project that consists of two parts: the general hazard assessment, which provides a general risk framework and procedures to identify, evaluate, and mitigate the risk of any potential hazard of HSR operations on shared-use rail corridors, and a detailed hazard assessment, which provides guidance to perform a risk assessment of the potential hazards. In potential next phase of the study, a more detail guidance document of how to address hazards of HSR operations on shared-use rail corridors will be developed.

References

English, G. W., Highan, G., and Bagheri, M. (2007). *Evaluation of risk associated with stationary dangerous goods railroad cars*. Glenburnie, ON: TranSys Research, Ltd.

Project Management Institute. (2013). A guide to project management body of knowledge (5th ed.). Newtown Square, PA.

Appendix A. Fault-Tree Analysis for the Identified Hazards

In order to better understand the risk of potential hazards associated with high-speed rail (HSR) operation adjacent to conventional tracks, a fault tree analysis was performed for each of the 11 identified hazards. The objective of the fault tree analysis was to comprehend the mechanism and identify potential influencing factors of each hazard. The development of each fault tree helps to explore all possible scenarios that may cause a certain hazard and all influencing factors that may contribute to creating the hazard. This could provide the foundation for subsequent risk analysis and risk mitigation of each hazard for specific HSR systems or new projects.

General Risk Framework

Figure A-1 shows the general risk framework for the overall risk of operating HSR adjacent to conventional tracks. Each of the previously studied 11 hazards is categorized first by whether it is an intrusion hazard, meaning that the hazard may have resulted in the intrusion of rail equipment, personnel, or objects. The intrusions are important risks to address, since they may result in a subsequent collision between the trains on HSR tracks or conventional tracks and intruded objects, which may cause fatalities, injuries, and other serious consequences.

The intrusion hazards are further categorized into whether it specifically involves a freight train. Intrusion hazards involving at least one freight train include shifted load on adjacent tracks and hazardous material transportation on adjacent tracks. Intrusion hazards involving all train types include adjacent track derailment, obstruction hazard from adjacent tracks, evacuation of passengers on adjacent tracks, intrusion of MOW staff and equipment on adjacent tracks, and aerodynamic interaction between trains. Non-intrusion hazards are also important because they may result either in a derailment of a train, which may also foul the adjacent tracks, or the interference of the adjacent railroad systems. Non-intrusion hazards include electromagnetic interference (EMI), fire on adjacent tracks, drainage problem affecting track geometry, and ground-borne vibration.

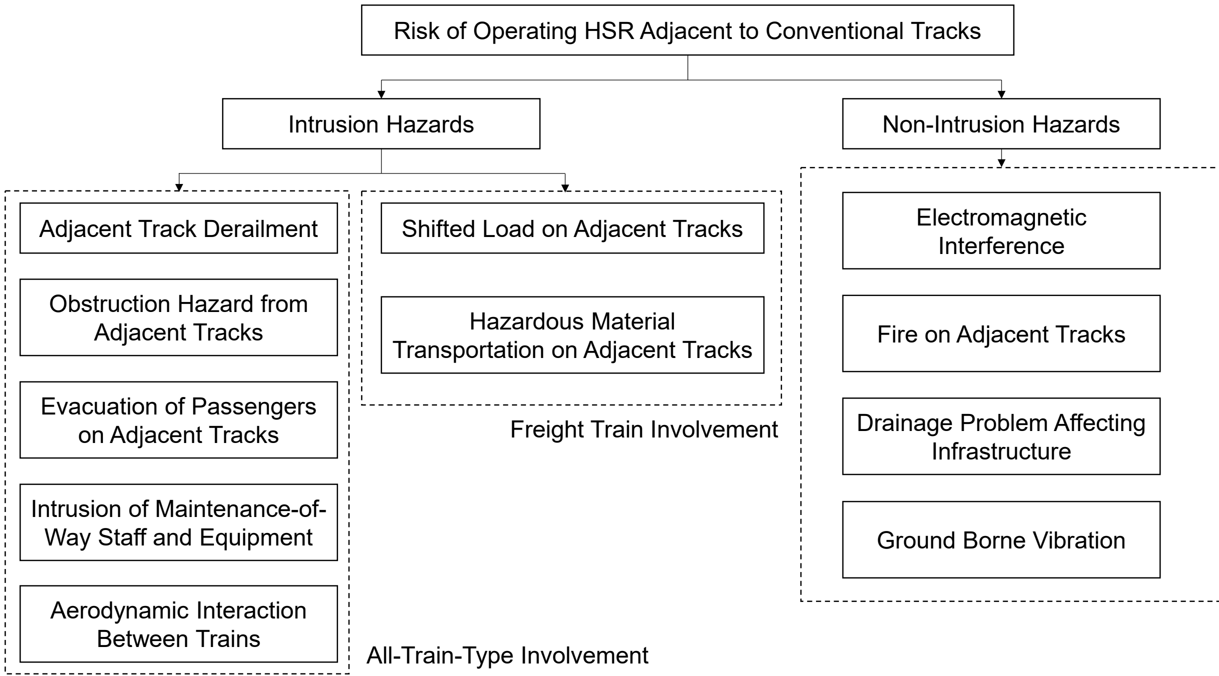


Figure A-1: General Risk Framework

Fault Tree Analyses for Individual Hazards

Derailment on Adjacent Tracks

Figure A-2 shows the fault tree for an adjacent track derailment scenario. An adjacent track derailment consists of a series of events: an initial derailment, an intrusion, and the presence of another train on the adjacent track. Each event is affected by certain influencing factors. Initial derailments may result from any of the following factors: infrastructure quality, method of operation, traffic density, and the presence of a train defect detector. An intrusion is assumed to occur only if there is an initial derailment. A couple of influencing factors including track center distances, train speed, track alignment, geographic conditions, elevation differential, containment, derailment mechanism, and adjacent structure affect the likelihood of an intrusion. Once an intrusion occurs, if there is another train on the adjacent track, it may lead to a collision. A number of factors affect the likelihood of the presence of another train on adjacent tracks.

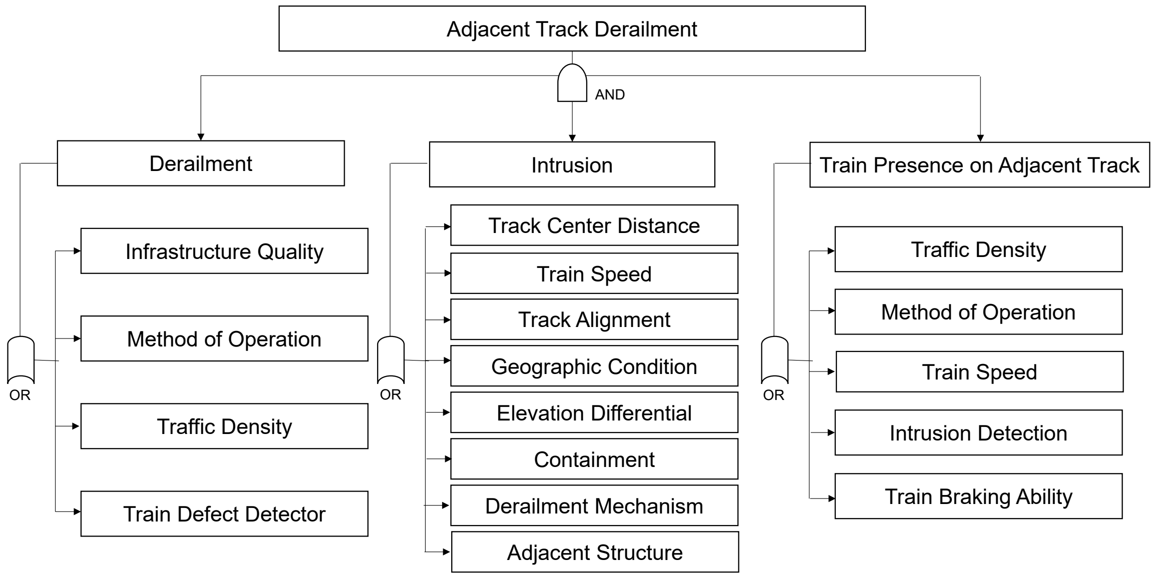


Figure A-2: Fault Tree for Adjacent Track Derailment

Shifted Load on Adjacent Tracks

Two major components that lead to a shifted load are poor secured cargo and excessive lateral force. Poorly secured cargo can be caused by improper loading procedure, including human error on the securing process. The amount of lateral force depends on infrastructure quality, rail car design, and train handling. Figure A-3 shows the fault tree for a shifted load on adjacent tracks scenario.

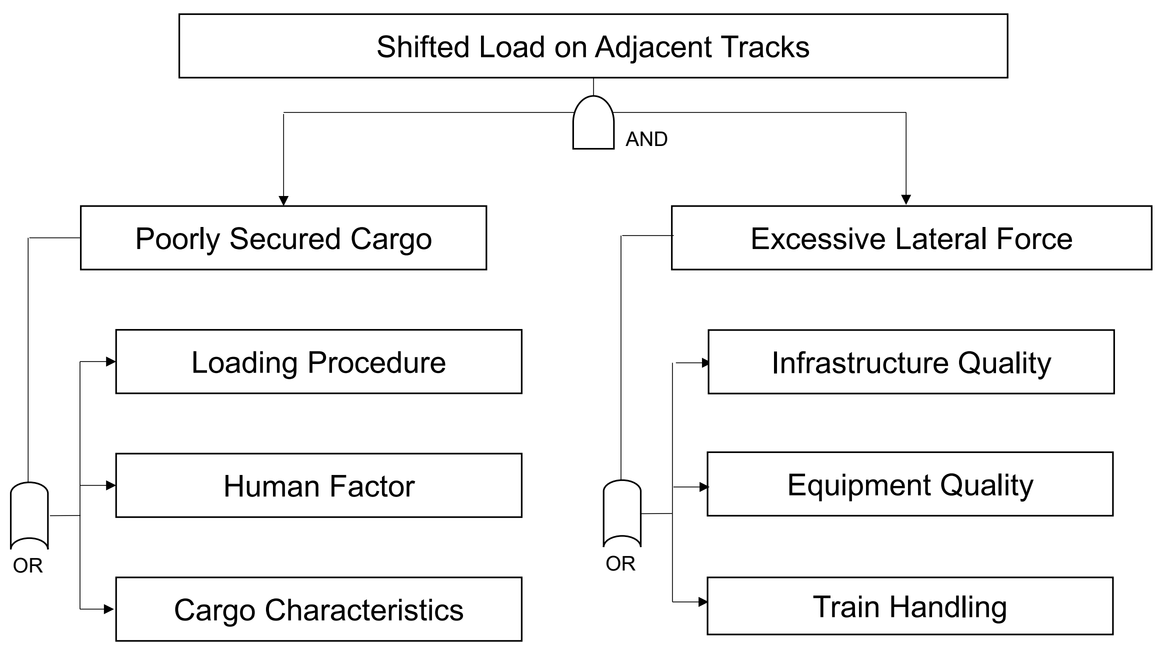


Figure A-3: Fault Tree for Shifted Load on Adjacent Tracks

Aerodynamic Interaction between Trains on Adjacent Tracks

Train characteristics and wind conditions are the two major factors that lead to an aerodynamic effect. Train speed, speed differential between trains, distance between trains, trains' directions, rolling-stock design, wind speed, and wind direction are the influencing factors. Figure A-4 shows the fault tree for a aerodynamic interaction between trains on adjacent tracks scenario.

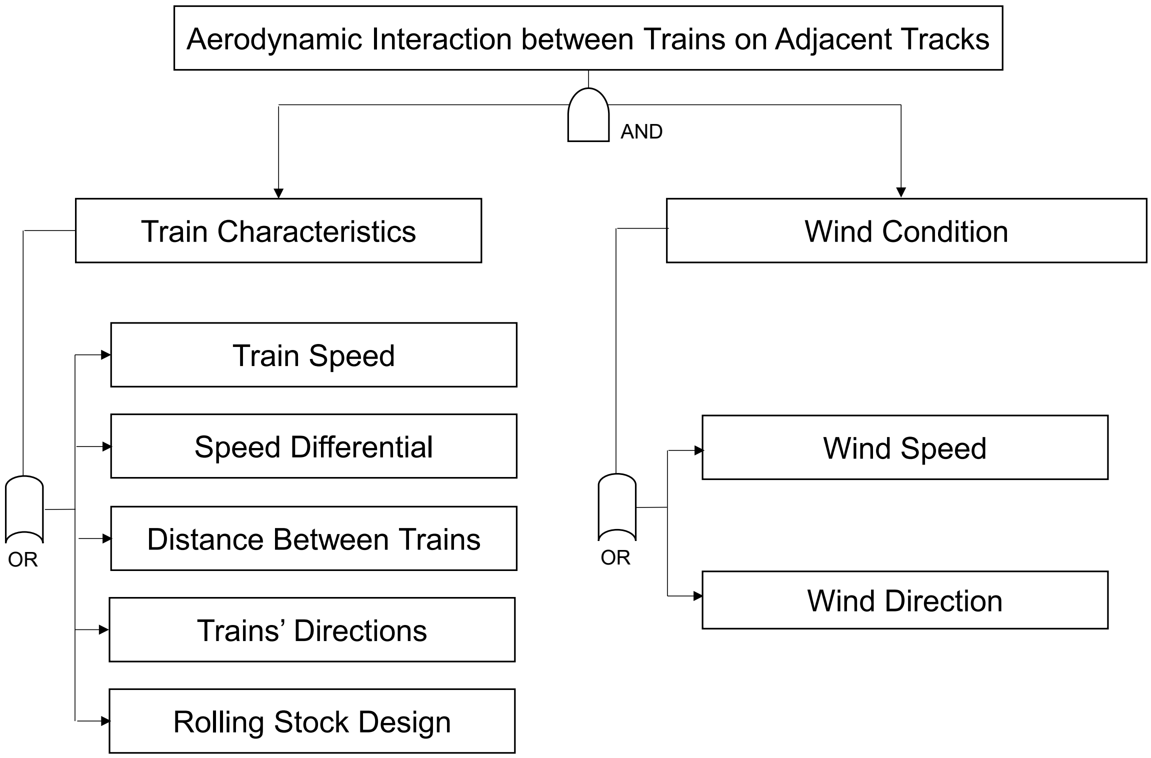


Figure A-4: Fault Tree for Aerodynamic Interaction between Trains on Adjacent Tracks

Ground-Borne Vibration

Ground-borne vibration is mostly affected by train speed and soil characteristics. Figure A-5 shows the fault tree for a ground-borne vibration scenario.

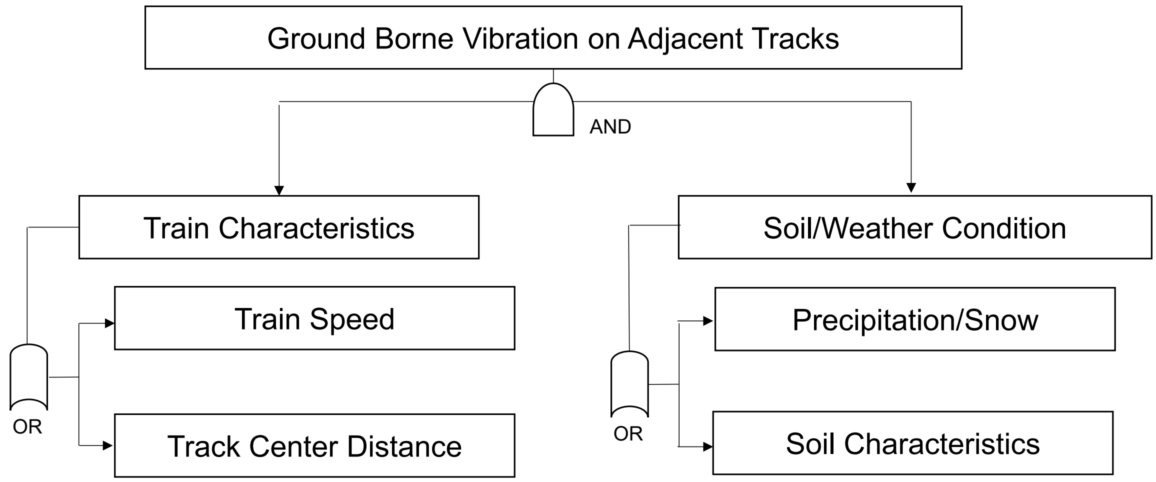


Figure A-5: Fault Tree for Ground Borne Vibration on Adjacent Tracks

Intrusion of Maintenance-of-Way Staff and Equipment from Adjacent Tracks

Two major scenarios lead to the intrusion of maintenance-of-way (MOW) staff and equipment: the fouling of track clearance by maintenance personnel or by maintenance equipment. Figure A-6 shows the fault tree for an intrusion of MOW staff and equipment scenario.

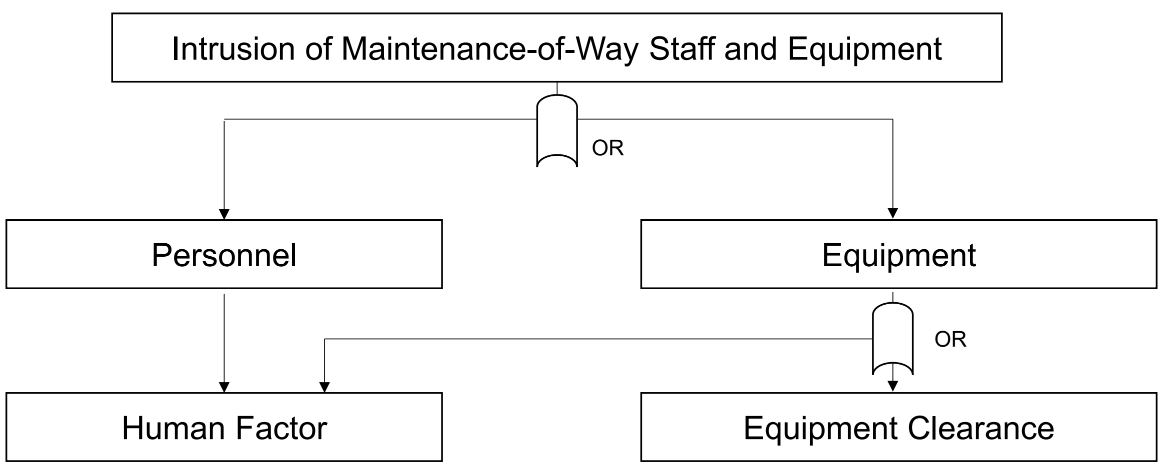


Figure A-6: Fault Tree for Ground Borne Vibration on Adjacent Tracks

Obstruction Hazard Resulting from Adjacent Tracks

Two types of obstructions are considered: an obstruction from another train, or an obstruction from a grade crossing. Figure A-7 shows the fault tree for an obstruction hazard resulting from adjacent tracks scenario.

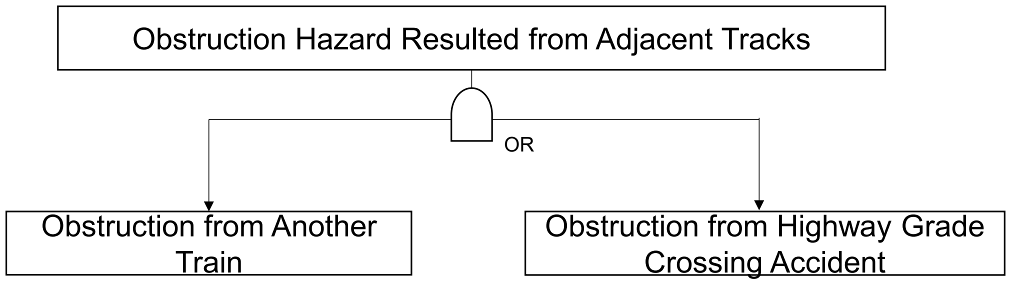


Figure A-7: Fault Tree for Obstruction Hazard Resulting from Adjacent Tracks

Drainage Problem Affecting Infrastructure

Drainage refers mainly to a drainage facility. Figure A-8 shows the fault tree for a drainage problem affecting infrastructure scenario.

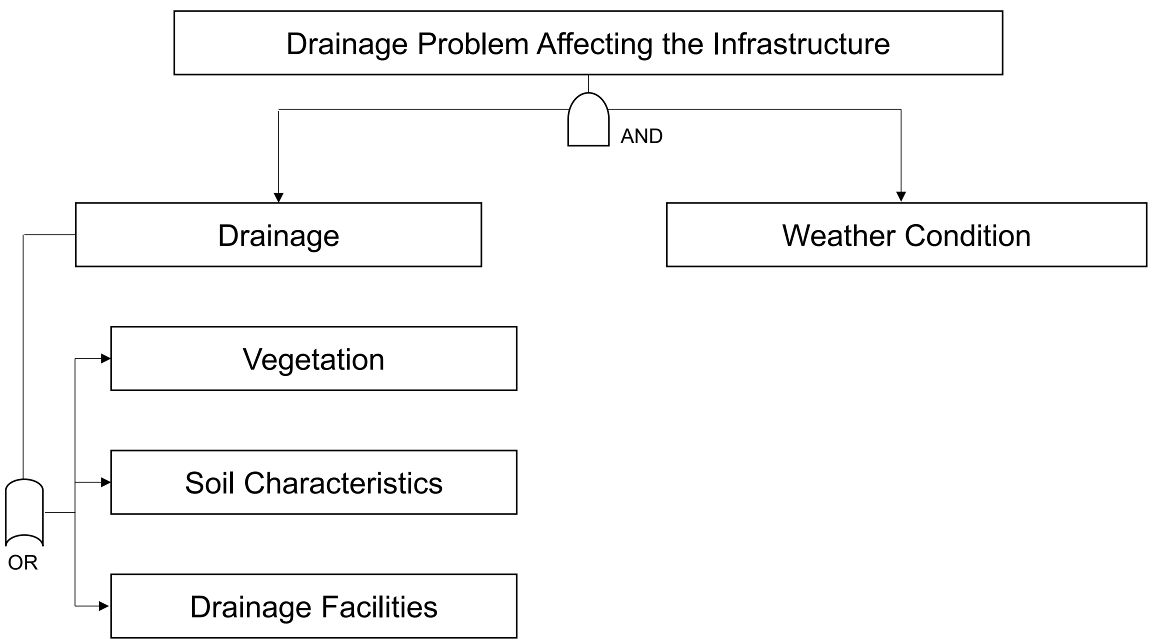


Figure A-8: Fault Tree for Drainage Problem Affecting Infrastructure

Evacuation of Passengers on Adjacent Tracks

The evacuation of passengers requires interaction between the passenger and employees or emergency responders. The rail equipment also plays an important role. Figure A-9 shows the fault tree for an evacuation of passenger on adjacent tracks scenario.

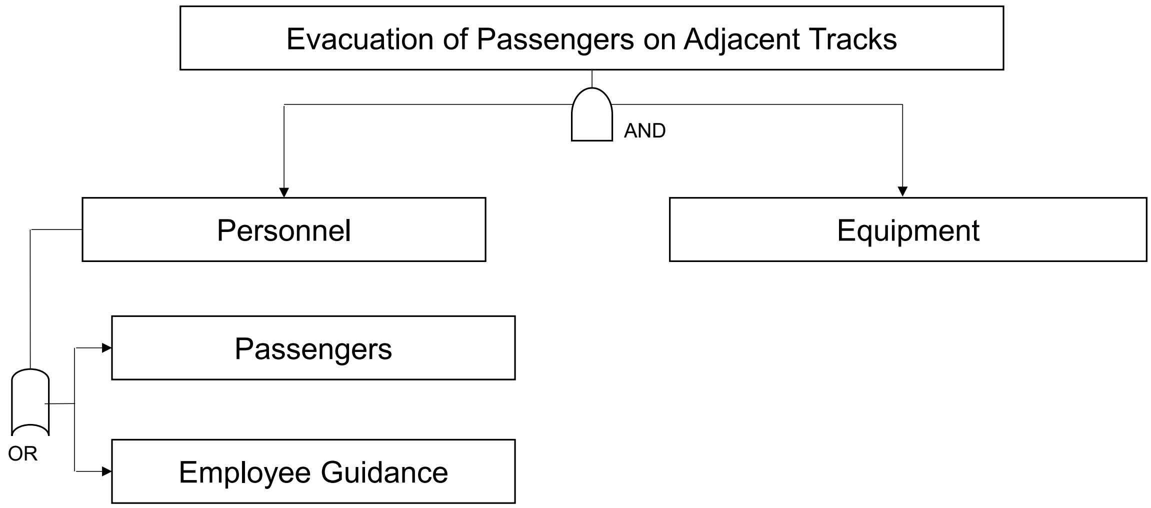


Figure A-9: Fault Tree for Evacuation of Passengers on Adjacent Tracks

Hazardous Material Transportation on Adjacent Tracks

Similar to adjacent track derailment, hazardous materials transportation hazards consist of multiple events. After an initial derailment, there may be a release; the probability is affected by the factors presented in the fault tree analysis illustrated in Figure A-10.

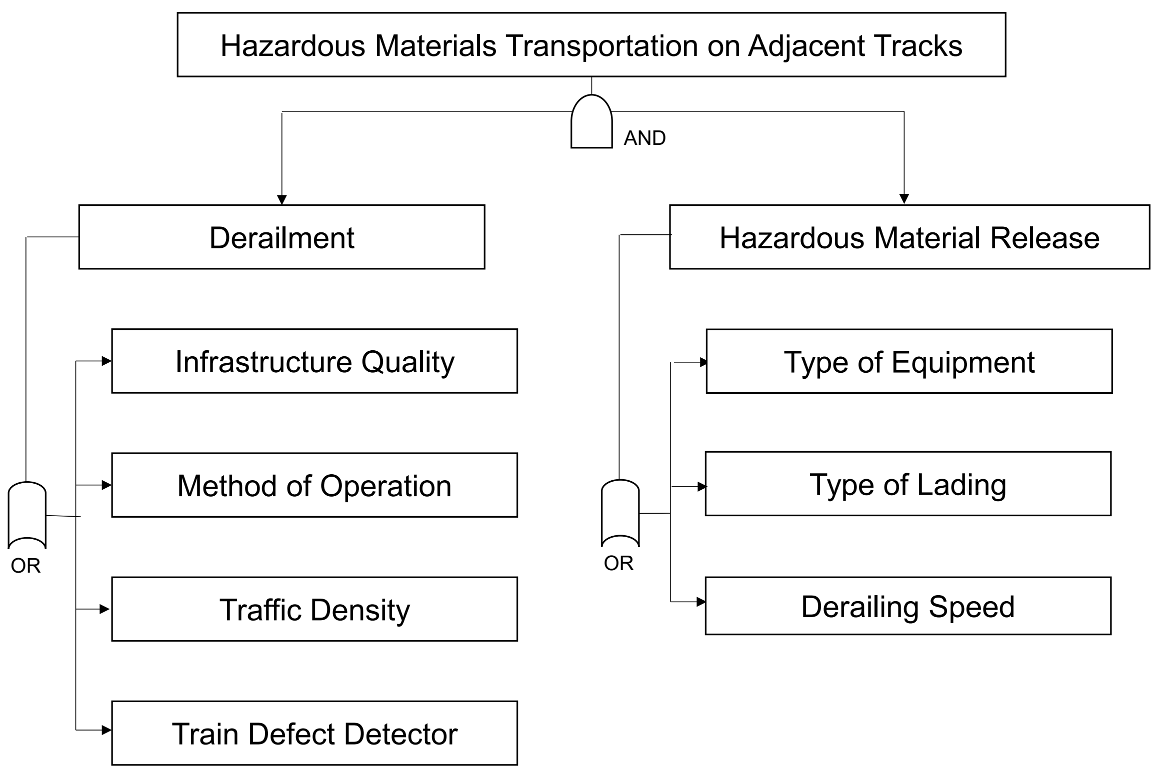


Figure A-10: Fault Tree for Hazardous Material Transportation on Adjacent Tracks

Fire on Adjacent Tracks

Fire on adjacent tracks is mainly affected by equipment failure (on fire) and/or improper human actions. Figure A-11 shows the fault tree for a fire on adjacent tracks scenario.

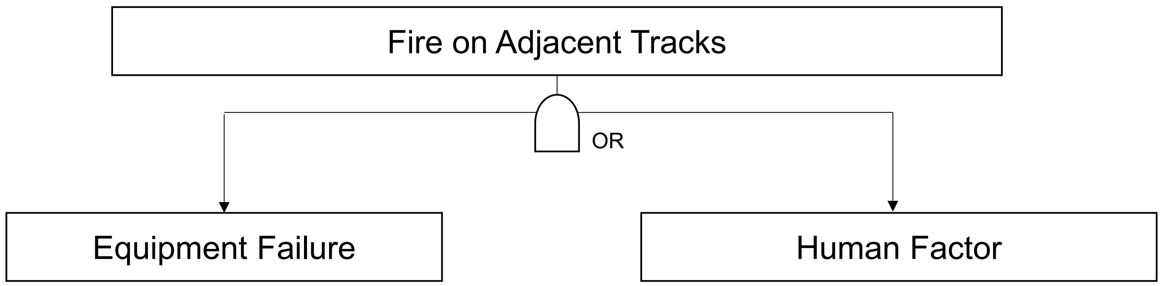


Figure A-11: Fault Tree for Fire on Adjacent Tracks

Electromagnetic Interference

The major source of electromagnetic interference is the presence of an overhead catenary system and the use of a pantograph. Figure A-12 shows the fault tree for an EMI scenario.

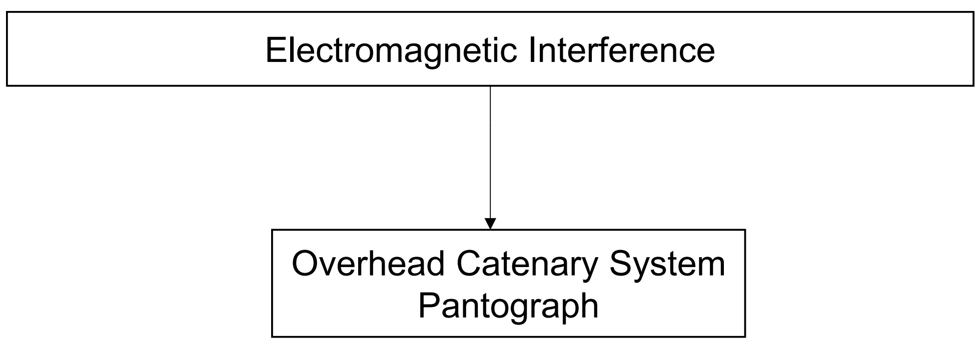


Figure A-12: Fault Tree for Electromagnetic Interference

Appendix B. Causal Analysis of Passenger and Freight Train Accident Analysis

Train accident data between 1999 and 2013 from the Federal Railroad Administration (FRA) rail equipment accident database were analyzed to examine the effects of different accident causes on conventional passenger and freight train accidents. The FRA database does not have sufficient information regarding accident locations to identify shared-use corridors. However, the majority of passenger trains run on freight owned infrastructures, and most of them are on shared trackage. Therefore, it is reasonable to assume that all the mainline passenger train accidents are on shared-use rail corridors. Although not all freight train accidents occur on shared-use rail corridors, due to the large sample size of accidents, analyzing all them still help to identify more relevant accident causes (the relatively more frequent and/or more severe causes).

In these analyses the frequency of an accident is represented by the accident rate per unit distance traveled. While several metrics could be used to represent the severity of an accident (e.g., cost, casualty, number of cars derailed), number of cars derailed was selected as it is expected to affect the cars' dispersion distance away from a track to potentially intrude other tracks on a shared rail corridor. The multiplication of the frequency and severity of an accident was used to represent the risk.

Over the 15-year interval from 1999 to 2013, there were 907 mainline passenger train accidents, including 441 grade-crossing accidents, 264 obstruction accidents, 141 derailments, 49 collisions, and 12 miscellaneous accidents. Figure B-1 shows the mainline passenger train accident rate over the 15-year interval sorted by five types of accidents: grade crossing, derailment, collision, obstruction, and miscellaneous. Over this period, grade-crossing accidents have been the most frequent type of passenger train accident, followed by obstructions and then derailments. On freight side, there were 8,947 mainline accidents, including 6,286 derailments, 1,876 grade-crossing accidents, 379 collisions, 265 obstructions, and 141 miscellaneous accidents. Figure B-2 shows mainline freight train accident rate over the 15-year interval sorted by five types of accidents: grade crossing, derailment, collision, obstruction, and miscellaneous. Derailments have been the most frequent accidents, followed by grade-crossing accidents and collisions. Passenger train accident rates have been consistently lower than freight train accident rates.

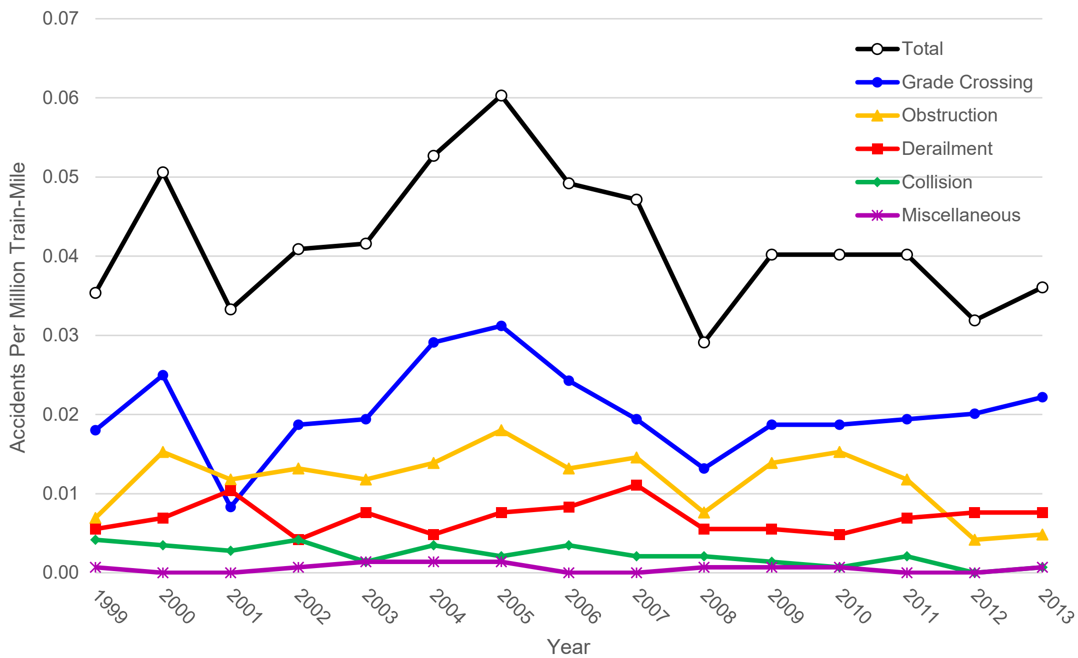


Figure B-1: Mainline Passenger Train Accident Rates by Type of Accidents, 1999–2013

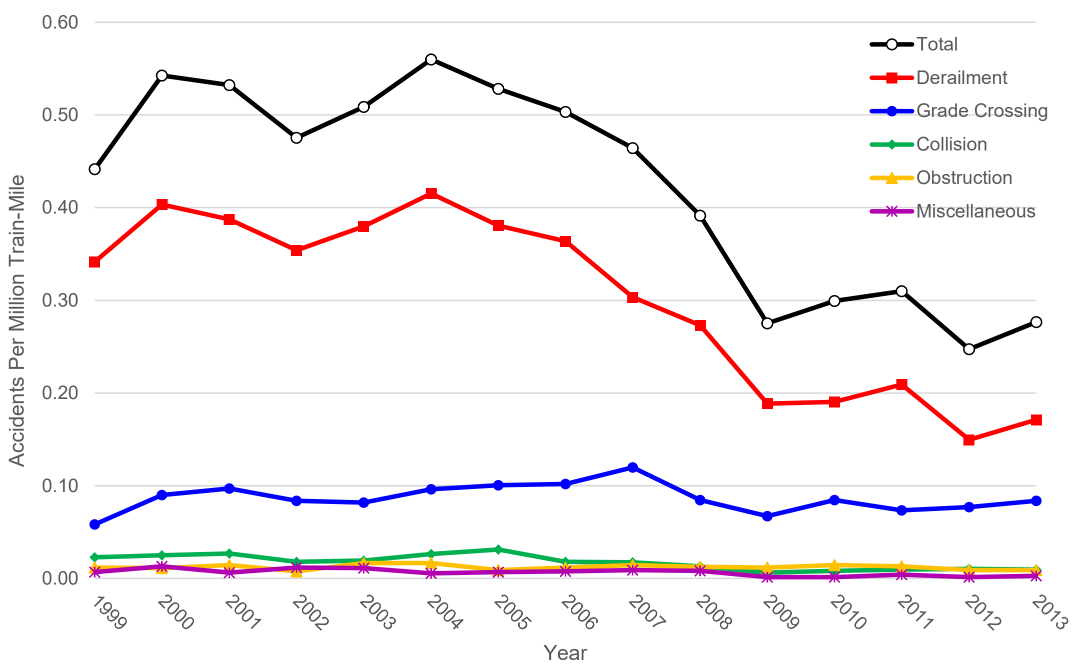


Figure B-2: Mainline Freight Train Accident Rates by Type of Accidents, 1999–2013

To measure the risk from different types of accidents, researchers plotted the number of accidents per unit train travel to represent the accident frequency versus the average severity of mainline passenger train accidents (Figure B-3) and freight train accidents (Figure B-4) by accident type. The graph is divided into four quadrants on the basis of the average frequency and severity along each axis. It enables easy comparison of the relative frequency and severity of different accident types. Accident types in the upper-right quadrant would be the most likely to pose the greatest risk because they are both more frequent and more severe than the average. The data indicate that the types of train accident most likely to result in high-number-of-cars-derailed incidents are derailments and collisions. Although they account for only about 21 percent of all passenger train accidents, derailments and collision, combined, resulted in about 68 percent of total number of cars derailed (Table B-1). For freight train accidents, derailments are both frequent and severe and thus fall in the upper-right quadrant of the graph. Collisions and derailments are still the most severe accidents among all accident types. Although grade-crossing accidents are the most common type of accident, they are among the least severe in their consequences. Collisions and derailments are caused by the interaction of two or more trains and motivate concern in shared-use corridors regarding passenger train collisions with a derailed freight train, or vice versa. Therefore, the next section of this paper examines mainline passenger and freight derailments and collisions in more detail.

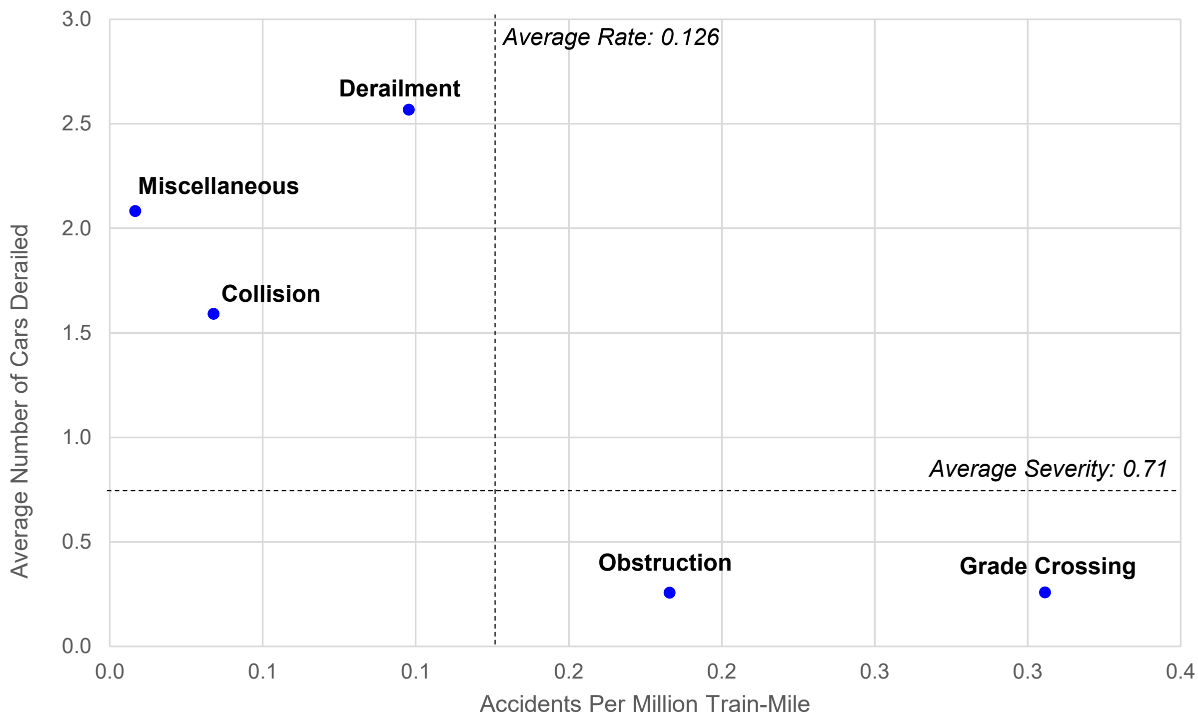


Figure B-3: Frequency and Severity Graph of Mainline Passenger Train Accidents by Type of Accident, 1999–2013

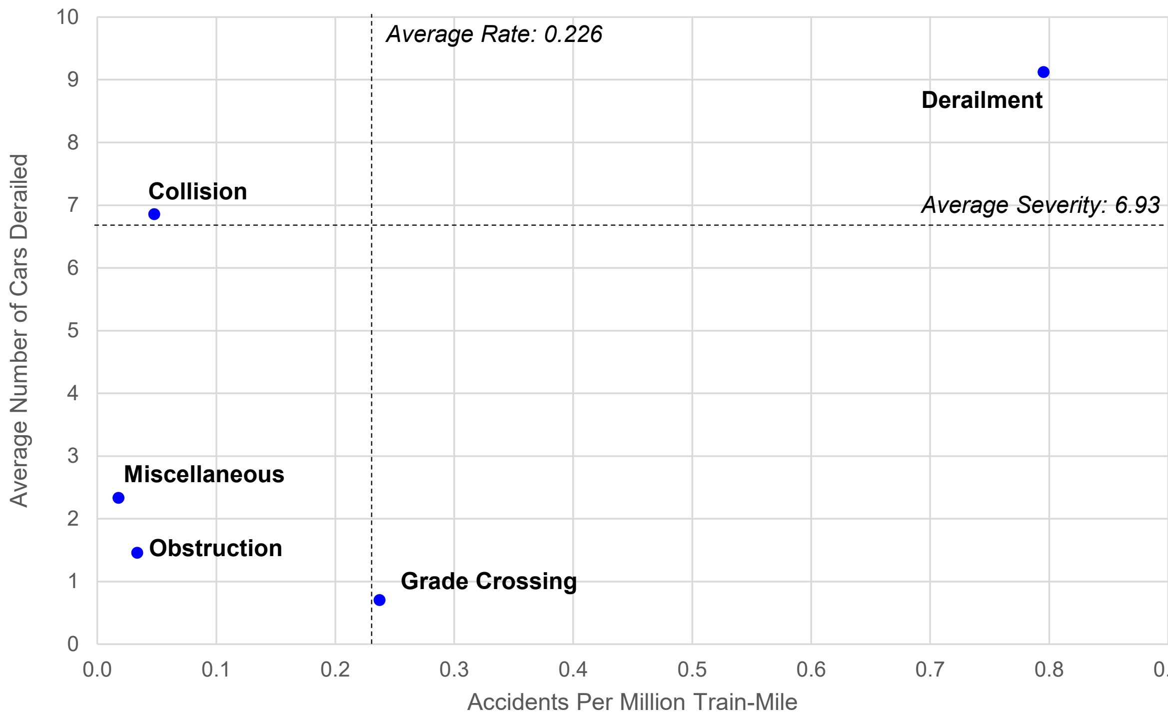


Figure B-4: Frequency and Severity Graph of Mainline Freight Train Accidents by Type of Accident, 1999–2013

Table B-1: Mainline Passenger Accident Frequency and Severity by Type of Accident, Sorted by Frequency

	Frequency	Percentage	Average Accident Rate	Total Cars Derailed	Percentage	Average Cars Derailed
Grade Crossing	441	48.6%	0.306	114	17.6%	0.26
Obstruction	264	29.1%	0.183	68	10.5%	0.26
Derailment	141	15.5%	0.098	362	56.0%	2.57
Collision	49	5.4%	0.034	78	12.1%	1.59
Miscellaneous	12	1.3%	0.008	25	3.9%	2.08
Total	907	100.0%	0.629	647	100.0%	0.71

Table B-2: Mainline Freight Accident Frequency and Severity by Type of Accident, Sorted by Frequency

	Frequency	Percentage	Average Accident Rate	Total Cars Derailed	Percentage	Average Cars Derailed
Derailment	6,286	70.3%	0.795	57,350	92.5%	9.12
Grade Crossing	1,876	21.0%	0.237	1,323	2.1%	0.71
Collision	379	4.2%	0.048	2,600	4.2%	6.86
Obstruction	265	3.0%	0.034	387	0.6%	1.46
Miscellaneous	141	1.6%	0.018	329	0.5%	2.33
Total	8,947	100.0%	1.132	61,989	100.0%	6.93

Passenger Train Derailment and Collision Accident Cause Analysis

FRA train accident cause codes are hierarchically organized and categorized into major cause groups–track, equipment, human factors, signal, and miscellaneous. Each of these major cause groups has subgroups that include individual cause codes of related causes such as roadbed, track geometry, etc. within the track group, and similar subgroups within the other major cause groups.

In this Section, alternative FRA subgroups developed by Arthur D. Little (ADL) are used in which similar cause codes were grouped based on experts' opinions. Table B-3 shows the ADL's groupings of FRA accident cause codes.

ADL's groupings enable greater resolution for certain causes. For example, FRA combines broken rails, joint bars, and rail anchors in the same subgroup, whereas the ADL grouping distinguishes between broken rails and joint bar defects. Figure B-5 shows the frequency and severity graphs by the major accident cause categories, namely infrastructure related, human factors related, mechanical related, signal and communication related, and miscellaneous. The graph is also divided into four quadrants to enable easy comparison of the relative frequency and severity of different accident cause groups. The infrastructure-related cause category was identified as the most severe group, and the human factors-related cause category had higher frequency but lower severity. Both human factors-related and infrastructure-related accident cause categories consistently represented the most frequent or severe accident cause categories and therefore were analyzed in more detail.

Table B-3: ADL's Grouping for FRA Accident Cause Group Cause Codes

Cause Group	Description	CM/TM	FRA Cause Codes										
01T	Roadbed Defects	CM	T001	T099									
02T	Non-Traffic, Weather Causes	TM	T002	T401	T402	T403							
03T	Wide Gauge	CM	T110	T111	T112	T113							
04T	Track Geometry (excl. Wide Gauge)	CM	T101	T102	T103	T104	T105	T106	T107	T108	T199		
05T	Buckled Track	CM	T109										
06T	Rail Defects at Bolted Joint	CM	T201	T211									
07T	Joint Bar Defects	CM	T213	T214	T215	T216							
08T	Broken Rails or Welds	CM	T202	T203	T204	T207	T208	T210	T212	T218	T219	T220	T221
09T	Other Rail and Joint Defects	CM	T299										
10T	Turnout Defects - Switches	CM	T307	T308	T309	T310	T311	T312	T313	T314	T315	T319	
11T	Turnout Defects - Frogs	CM	T304	T316	T317	T318							
12T	Misc. Track and Structure Defects	CM	T205	T206	T217	T222	T301	T302	T303	T305	T306	T399	T499
			S001	S002	S003	S004	S005	S006	S007	S008	S009	S010	S011
01S	Signal Failures	TM	S012	S013	S099								
01E	Air Hose Defect (Car)	CM	E00C										
02E	Brake Rigging Defect (Car)	CM	E07C										
03E	Handbrake Defects (Car)	CM	E08C	E0HC									
04E	UDE (Car or Loco)	CM	E05C	E05L									
05E	Other Brake Defect (Car)	CM	E01C	E02C	E03C	E04C	E06C	E09C					
06E	Centerplate/Carbody Defects (Car)	CM	E20C	E21C	E22C	E23C	E24C	E25C	E26C	E27C	E29C		
07E	Coupler Defects (Car)	CM	E30C	E31C	E32C	E33C	E34C	E35C	E36C	E37C	E39C		
08E	Truck Structure Defects (Car)	CM	E44C	E45C									
09E	Sidebearing, Suspension Defects (Car)	CM	E40C	E41C	E42C	E43C	E47C	E48C					
10E	Bearing Failure (Car)	CM	E52C	E53C									
11E	Other Axle/Journal Defects (Car)	CM	E51C	E54C	E55C	E59C							
12E	Broken Wheels (Car)	CM	E60C	E61C	E62C	E63C	E6AC						
13E	Other Wheel Defects (Car)	CM	E64C	E65C	E66C	E67C	E68C	E69C					
14E	TOFC/COFC Defects	CM	E11C	E12C	E13C	E19C							
			E07L	E40L	E41L	E42L	E43L	E44L	E45L	E46L	E47L	E48L	E4TL
			E49L	E51L	E52L	E53L	E54L	E55L	E59L	E60L	E61L	E62L	E63L
15E	Loco Trucks/Bearings/Wheels	CM	E64L	E65L	E66L	E67L	E68L	E6AL	E69L	E70L	E77L		
16E	Loco Electrical and Fires	CM	E71L	E72L	E73L	E74L	E76L						
			E00L	E01L	E02L	E03L	E04L	E06L	E08L	E0HL	E09L	E20L	E21L
			E22L	E23L	E24L	E25L	E26L	E27L	E29L	E30L	E31L	E32L	E33L
17E	All Other Locomotive Defects	CM	E34L	E35L	E36L	E37L	E39L	E79L	E99L				
18E	All Other Car Defects	CM	E49C	E80C	E81C	E82C	E83C	E84C	E85C	E86C	E89C	E99C	
19E	Stiff Truck (Car)	CM	E46C										
20E	Track/Train Interaction (Hunting) (Car)	CM	E4TC										
21E	Current Collection Equipment (Loco)	CM	E75L										
			H510	H511	H512	H513	H514	H515	H516	H517	H518	H519	H520
01H	Brake Operation (Main Line)	TM	H521	H525	H526								
02H	Handbrake Operations	TM	H017	H018	H019	H020	H021	H022	H025	M504			
03H	Brake Operations (Other)	TM	H008	H099									
04H	Employee Physical Condition	TM	H101	H102	H103	H104	H199						
			H201	H202	H203	H204	H205	H206	H207	H208	H209	H215	H216
05H	Failure to Obey/Display Signals	TM	H217	H299									
06H	Radio Communications Error	TM	H210	H211	H212	H405							
			H301	H302	H303	H304	H305	H306	H307	H308	H309	H310	H311
07H	Switching Rules	TM	H312	H313	H314	H315	H399						
08H	Mainline Rules	TM	H401	H402	H403	H404	H406	H499					
			H501	H502	H503	H504	H505	H506	H507	H508	H509	H522	H523
09H	Train Handling (excl. Brakes)	TM	H524	H599									
10H	Train Speed	TM	H601	H602	H603	H604	H605	H606	H699				
11H	Use of Switches	TM	H701	H702	H703	H704	H705	H799					
12H	Misc. Human Factors	TM	H821	H822	H823	H824	H899	H991	H992	H993	H994	H995	H999
01M	Obstructions	TM	M101	M102	M103	M104	M105	M199	M402	M403	M404		
02M	Grade Crossing Collisions	TM	M301	M302	M303	M304	M305	M306	M307	M399			
03M	Lading Problems	CM	M201	M202	M203	M204	M205	M206	M207	M299	M409	M410	
04M	Track-Train Interaction	CM	M405										
05M	Other Miscellaneous	TM	M401	M406	M407	M408	M501	M502	M503	M505	M599		

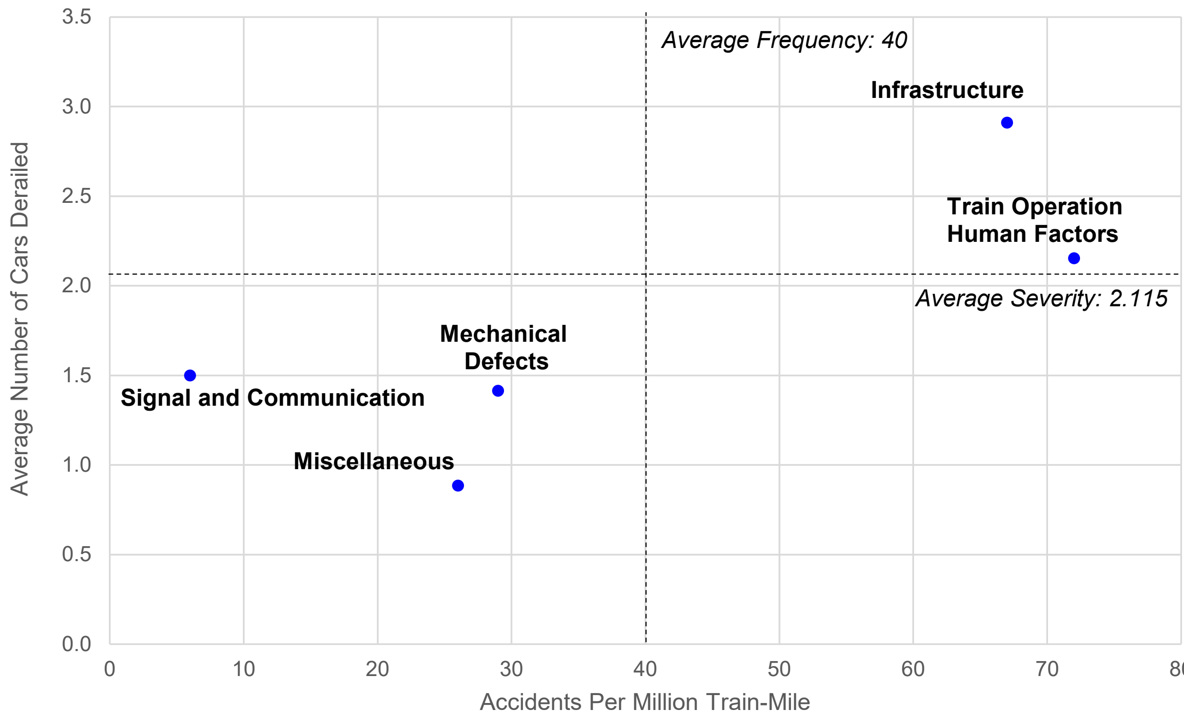


Figure B-5: Frequency and Severity Graph of Mainline Passenger Derailments and Collisions, 1999–2013, by Accident Cause Category, with Average Cars Derailed as Severity Indicator

In order to gain insights on what specific accident causes would result in high frequency or severity, accident cause categories were broken down into accident cause groups. Table B-3 shows the accident frequency and severity for individual accident cause groups. The accident cause groups are categorized into infrastructure related (T), human factors related (H), mechanical related (E), signal and communication related (S), and miscellaneous (M). The risk of each accident cause group is calculated by multiplying its accident rate by its severity. Overall, the top ten accident cause groups with the highest risk are:

- Failure to Obey/Display Signals (05H)
- Wide Gauge (03T)
- Train Speed (10H)
- Turnout Defects–Switches (10T)
- Broken Rails or Welds (08T)
- Use of Switches (11H)
- Joint Bar Defects (07T)
- Other Miscellaneous (05M)
- Misc. Track and Structure Defects (12T)
- Non-Traffic and Weather Causes (02T)

Most of the top ten accident cause groups are infrastructure related or human factors related. Table B-4 shows the top ten high-risk accident groups in infrastructure, human factor and mechanical category, respectively.

Table B-3: Passenger Train Derailment and Collision Frequency and Severity by Accident Cause Subgroup, Sorted by Risk

	Accident Cause Groups	Number of Accident	Accident Rate (per million train-mile	Number of Cars Derailed	Average Number of Cars Derailed Per Accident	Risk = Rate x Average Number of Cars Derailed
05H	Failure to Obey/Display Signals	22	0.0028	60	2.7273	0.0076
03T	Wide Gauge	17	0.0022	59	3.4706	0.0075
10H	Train Speed	14	0.0018	43	3.0714	0.0054
10T	Turnout Defects - Switches	21	0.0027	40	1.9048	0.0051
08T	Broken Rails or Welds	7	0.0009	36	5.1429	0.0046
11H	Use of Switches	15	0.0019	24	1.6000	0.0030
07T	Joint Bar Defects	3	0.0004	22	7.3333	0.0028
05M	Other Miscellaneous	11	0.0014	16	1.4545	0.0020
12T	Misc. Track and Structure Defects	8	0.0010	14	1.7500	0.0018
02T	Non-Traffic, Weather Causes	3	0.0004	13	4.3333	0.0016
07H	Switching Rules	7	0.0009	10	1.4286	0.0013
15E	Loco Trucks/Bearings/Wheels	6	0.0008	10	1.6667	0.0013
12H	Misc. Human Factors	5	0.0006	10	2.0000	0.0013
01S	Signal Failures	6	0.0008	9	1.5000	0.0011
08H	Mainline Rules	8	0.0010	8	1.0000	0.0010
18E	All Other Car Defects	4	0.0005	8	2.0000	0.0010
04T	Track Geometry (excl. Wide Gauge)	5	0.0006	6	1.2000	0.0008
13E	Other Wheel Defects (Car)	4	0.0005	6	1.5000	0.0008
17E	All Other Locomotive Defects	4	0.0005	5	1.2500	0.0006
04M	Track-Train Interaction	2	0.0003	5	2.5000	0.0006
11E	Other Axle/Journal Defects (Car)	3	0.0004	4	1.3333	0.0005
05T	Buckled Track	2	0.0003	4	2.0000	0.0005
16E	Loco Electrical and Fires	2	0.0003	4	2.0000	0.0005
14E	TOFC/COFC Defects	1	0.0001	4	4.0000	0.0005
03M	Lading Problems	3	0.0004	2	0.6667	0.0003
09T	Other Rail and Joint Defects	1	0.0001	1	1.0000	0.0001
06E	Centerplate/Carbody Defects (Car)	4	0.0005	0	0.0000	0.0000
02H	Handbrake Operations	1	0.0001	0	0.0000	0.0000
09E	Sidebearing, Suspension Defects (Car)	1	0.0001	0	0.0000	0.0000
01T	Roadbed Defects	0	0.0000	0	0.0000	0.0000
06T	Rail Defects at Bolted Joint	0	0.0000	0	0.0000	0.0000
11T	Turnout Defects - Frogs	0	0.0000	0	0.0000	0.0000
01H	Brake Operation (Main Line)	0	0.0000	0	0.0000	0.0000
03H	Brake Operations (Other)	0	0.0000	0	0.0000	0.0000
04H	Employee Physical Condition	0	0.0000	0	0.0000	0.0000
06H	Radio Communications Error	0	0.0000	0	0.0000	0.0000
09H	Train Handling (excl. Brakes)	0	0.0000	0	0.0000	0.0000
01E	Air Hose Defect (Car)	0	0.0000	0	0.0000	0.0000
02E	Brake Rigging Defect (Car)	0	0.0000	0	0.0000	0.0000
03E	Handbrake Defects (Car)	0	0.0000	0	0.0000	0.0000
04E	UDE (Car or Loco)	0	0.0000	0	0.0000	0.0000
05E	Other Brake Defect (Car)	0	0.0000	0	0.0000	0.0000
07E	Coupler Defects (Car)	0	0.0000	0	0.0000	0.0000
08E	Truck Structure Defects (Car)	0	0.0000	0	0.0000	0.0000
10E	Bearing Failure (Car)	0	0.0000	0	0.0000	0.0000
12E	Broken Wheels (Car)	0	0.0000	0	0.0000	0.0000
19E	Stiff Truck (Car)	0	0.0000	0	0.0000	0.0000
20E	Track/Train Interaction (Hunting) (Car)	0	0.0000	0	0.0000	0.0000
21E	Current Collection Equipment (Loco)	0	0.0000	0	0.0000	0.0000
	Total/Average	**190**	**0.0240**	**423**	**2.2263**	**0.0535**

Table B-4: Top Ten High-Risk Accident Causes of Mainline Passenger Train Accidents by Accident Cause Categories and Type of Accident, 1999–2013

	Accident Cause Groups	Number of Accident	Accident Rate (per million train-mile	Number of Cars Derailed	Average Number of Cars Derailed Per Accident	Risk = Rate x Average Number of Cars Derailed
Infrastructure Related						
03T	Wide Gauge	17	0.0118	59	3.4706	0.0075
10T	Turnout Defects - Switches	21	0.0146	40	1.9048	0.0051
08T	Broken Rails or Welds	7	0.0049	36	5.1429	0.0046
07T	Joint Bar Defects	3	0.0021	22	7.3333	0.0028
12T	Misc. Track and Structure Defects	8	0.0055	14	1.7500	0.0018
02T	Non-Traffic, Weather Causes	3	0.0021	13	4.3333	0.0016
04T	Track Geometry (excl. Wide Gauge)	5	0.0035	6	1.2000	0.0008
05T	Buckled Track	2	0.0014	4	2.0000	0.0005
09T	Other Rail and Joint Defects	1	0.0007	1	1.0000	0.0001
01T	Roadbed Defects	0	0.0000	0	0.0000	0.0000
Human Factor Related						
05H	Failure to Obey/Display Signals	22	0.0152	60	2.7273	0.0076
10H	Train Speed	14	0.0097	43	3.0714	0.0054
11H	Use of Switches	15	0.0104	24	1.6000	0.0030
07H	Switching Rules	7	0.0049	10	1.4286	0.0013
12H	Misc. Human Factors	5	0.0035	10	2.0000	0.0013
08H	Mainline Rules	8	0.0055	8	1.0000	0.0010
02H	Handbrake Operations	1	0.0007	0	0.0000	0.0000
01H	Brake Operation (Main Line)	0	0.0000	0	0.0000	0.0000
03H	Brake Operations (Other)	0	0.0000	0	0.0000	0.0000
04H	Employee Physical Condition	0	0.0000	0	0.0000	0.0000
Mechanical Related						
15E	Loco Trucks/Bearings/Wheels	6	0.0042	10	1.6667	0.0013
18E	All Other Car Defects	4	0.0028	8	2.0000	0.0010
13E	Other Wheel Defects (Car)	4	0.0028	6	1.5000	0.0008
17E	All Other Locomotive Defects	4	0.0028	5	1.2500	0.0006
11E	Other Axle/Journal Defects (Car)	3	0.0021	4	1.3333	0.0005
16E	Loco Electrical and Fires	2	0.0014	4	2.0000	0.0005
14E	TOFC/COFC Defects	1	0.0007	4	4.0000	0.0005
06E	Centerplate/Carbody Defects (Car)	4	0.0028	0	0.0000	0.0000
09E	Sidebearing, Suspension Defects (Car)	1	0.0007	0	0.0000	0.0000
01E	Air Hose Defect (Car)	0	0.0000	0	0.0000	0.0000

Freight Train Derailment and Collision Accident Cause Analysis

The accident causes of freight train derailments and collisions were analyzed in the same way as passenger train derailments and collisions. Figure B-6 shows the frequency and severity graphs by the major accident cause categories. The graph is also divided into four quadrants to enable easy comparison of the relative frequency and severity of different accident cause groups. The infrastructure-related cause category was identified as the most severe and frequent. The mechanical-related accident cause category had higher frequency but lower severity.

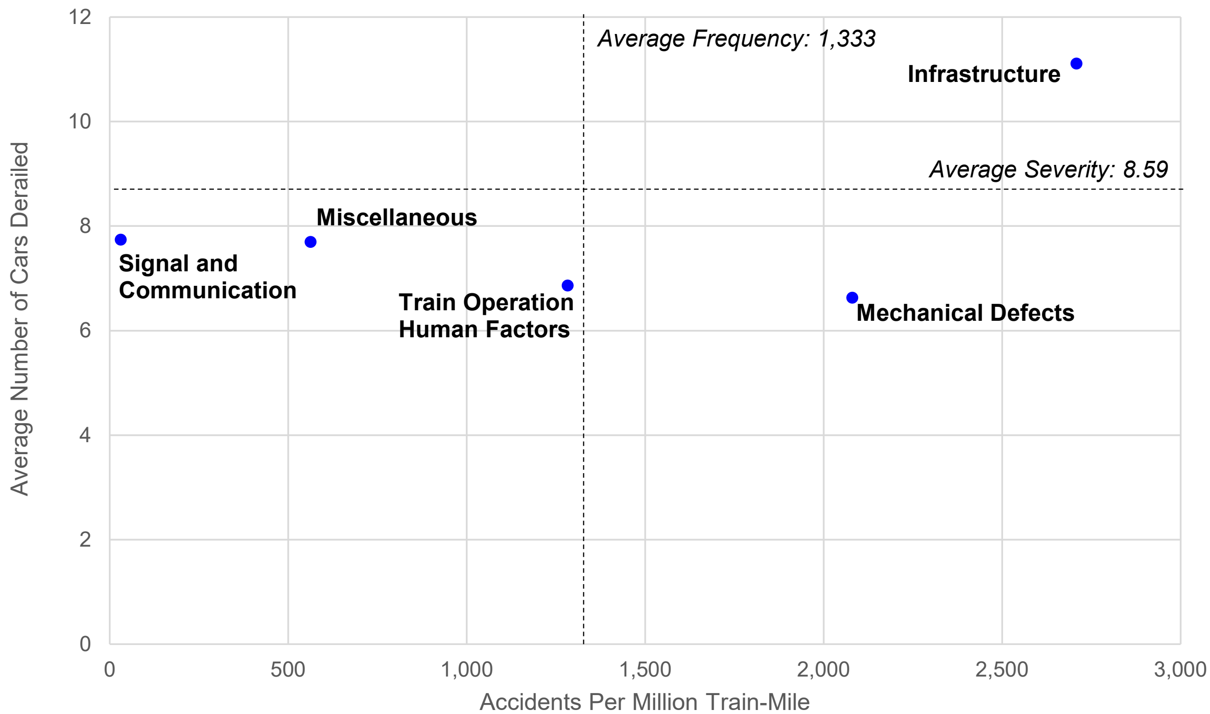


Figure B-6: Frequency and Severity Graph of Mainline Freight Derailments and Collisions, 1999–2013, by Accident Cause Category with Average Cars Derailed as Severity Indicator

Table B-5 shows the accident frequency and severity for individual accident cause groups. The accident cause groups are categorized into infrastructure related (T), human factor related (H), mechanical related (E), signal and communication related (S), and miscellaneous (M). The risk of each accident cause group is calculated by multiplying its accident rate by its severity. Overall, the top ten accident cause groups with the highest risk are:

- Broken Rails or Welds (08T)
- Buckled Track (05T)
- Track Geometry (excl. Wide Gauge) (04T)
- Wide Gauge (03T)
- Broken Wheels (Car) (12E)
- Bearing Failure (Car) (10E)
- Train Handling (excl. Brakes) (09H)
- Joint Bar Defects (07T)
- Track-Train Interaction (04M)
- Failure to Obey/Display Signals (05H)

Most of the top ten accident cause groups are infrastructure and some of them are mechanical related. Compared to passenger accident causes, more mechanical-related causes are of higher risk in freight train derailments and collisions. Table B-6 shows the top ten high-risk accident groups in infrastructure, human factors, and mechanical category, respectively.

Table B-5: Freight Train Derailment and Collision Frequency and Severity by Accident Cause Subgroup, Sorted by Risk

	Accident Cause Groups	Number of Accident	Accident Rate (per million train-mile	Number of Cars Derailed	Average Number of Cars Derailed Per Accident	Risk = Rate x Average Number of Cars Derailed
08T	Broken Rails or Welds	984	0.1245	12,756	12.9634	1.6138
05T	Buckled Track	238	0.0301	3,081	12.9454	0.3898
04T	Track Geometry (excl. Wide Gauge)	454	0.0574	2,977	6.5573	0.3766
03T	Wide Gauge	286	0.0362	2,691	9.4091	0.3404
	Mechanic Defects					
12E	Broken Wheels (Car)	312	0.0395	2,480	7.9487	0.3137
10E	Bearing Failure (Car)	384	0.0486	2,399	6.2474	0.3035
09H	Train Handling (excl. Brakes)	297	0.0376	2,170	7.3064	0.2745
07T	Joint Bar Defects	96	0.0121	1,723	17.9479	0.2180
04M	Track-Train Interaction	201	0.0254	1,643	8.1741	0.2079
05H	Failure to Obey/Display Signals	154	0.0195	1,543	10.0195	0.1952
09T	Other Rail and Joint Defects	74	0.0094	1,495	20.2027	0.1891
11E	Other Axle/Journal Defects (Car)	175	0.0221	1,471	8.4057	0.1861
05M	Other Miscellaneous	145	0.0183	1,466	10.1103	0.1855
09E	Sidebearing, Suspension Defects (Car)	178	0.0225	1,273	7.1517	0.1610
01H	Brake Operation (Main Line)	139	0.0176	1,247	8.9712	0.1578
06T	Rail Defects at Bolted Joint	68	0.0086	1,235	18.1618	0.1562
03M	Lading Problems	217	0.0275	1,225	5.6452	0.1550
10T	Turnout Defects - Switches	200	0.0253	1,191	5.9550	0.1507
01T	Roadbed Defects	112	0.0142	1,169	10.4375	0.1479
13E	Other Wheel Defects (Car)	193	0.0244	1,047	5.4249	0.1325
12T	Misc. Track and Structure Defects	113	0.0143	1,029	9.1062	0.1302
07E	Coupler Defects (Car)	176	0.0223	998	5.6705	0.1263
11H	Use of Switches	191	0.0242	936	4.9005	0.1184
10H	Train Speed	144	0.0182	915	6.3542	0.1158
06E	Centerplate/Carbody Defects (Car)	138	0.0175	637	4.6159	0.0806
12H	Misc. Human Factors	73	0.0092	595	8.1507	0.0753
19E	Stiff Truck (Car)	81	0.0102	567	7.0000	0.0717
20E	Track/Train Interaction (Hunting) (Car)	54	0.0068	520	9.6296	0.0658
02T	Non-Traffic, Weather Causes	60	0.0076	508	8.4667	0.0643
07H	Switching Rules	118	0.0149	471	3.9915	0.0596
08E	Truck Structure Defects (Car)	57	0.0072	418	7.3333	0.0529
18E	All Other Car Defects	72	0.0091	413	5.7361	0.0522
08H	Mainline Rules	61	0.0077	377	6.1803	0.0477
15E	Loco Trucks/Bearings/Wheels	64	0.0081	333	5.2031	0.0421
05E	Other Brake Defect (Car)	62	0.0078	327	5.2742	0.0414
02H	Handbrake Operations	70	0.0089	309	4.4143	0.0391
02E	Brake Rigging Defect (Car)	46	0.0058	259	5.6304	0.0328
01S	Signal Failures	31	0.0039	240	7.7419	0.0304
11T	Turnout Defects - Frogs	23	0.0029	239	10.3913	0.0302
17E	All Other Locomotive Defects	25	0.0032	232	9.2800	0.0294
01E	Air Hose Defect (Car)	23	0.0029	198	8.6087	0.0250
16E	Loco Electrical and Fires	25	0.0032	128	5.1200	0.0162
04H	Employee Physical Condition	8	0.0010	95	11.8750	0.0120
04E	UDE (Car or Loco)	10	0.0013	88	8.8000	0.0111
06H	Radio Communications Error	17	0.0022	76	4.4706	0.0096
03H	Brake Operations (Other)	11	0.0014	72	6.5455	0.0091
14E	TOFC/COFC Defects	3	0.0004	3	1.0000	0.0004
03E	Handbrake Defects (Car)	2	0.0003	3	1.5000	0.0004
21E	Current Collection Equipment (Loco)	0	0.0000	0	0.0000	0.0000
	Total/Average	**6,665**	**0.8432**	**57,268**	**8.5923**	**7.2450**

Table B-6: Top Ten High-Risk Accident Causes of Mainline Freight Train Accidents by Accident Cause Categories and Type of Accident, 1999–2013

Accident Cause Groups		Number of Accident	Accident Rate (per million train-mile	Number of Cars Derailed	Average Number of Cars Derailed Per Accident	Risk = Rate x Average Number of Cars Derailed
Infrastructure Related						
08T	Broken Rails or Welds	984	0.1245	12,756	12.9634	1.6138
05T	Buckled Track	238	0.0301	3,081	12.9454	0.3898
04T	Track Geometry (excl. Wide Gauge)	454	0.0574	2,977	6.5573	0.3766
03T	Wide Gauge	286	0.0362	2,691	9.4091	0.3404
07T	Joint Bar Defects	96	0.0121	1,723	17.9479	0.2180
09T	Other Rail and Joint Defects	74	0.0094	1,495	20.2027	0.1891
06T	Rail Defects at Bolted Joint	68	0.0086	1,235	18.1618	0.1562
10T	Turnout Defects - Switches	200	0.0253	1,191	5.9550	0.1507
01T	Roadbed Defects	112	0.0142	1,169	10.4375	0.1479
12T	Misc. Track and Structure Defects	113	0.0143	1,029	9.1062	0.1302
Human Factor Related						
09H	Train Handling (excl. Brakes)	297	0.0376	2,170	7.3064	0.2745
05H	Failure to Obey/Display Signals	154	0.0195	1,543	10.0195	0.1952
01H	Brake Operation (Main Line)	139	0.0176	1,247	8.9712	0.1578
11H	Use of Switches	191	0.0242	936	4.9005	0.1184
10H	Train Speed	144	0.0182	915	6.3542	0.1158
12H	Misc. Human Factors	73	0.0092	595	8.1507	0.0753
07H	Switching Rules	118	0.0149	471	3.9915	0.0596
08H	Mainline Rules	61	0.0077	377	6.1803	0.0477
02H	Handbrake Operations	70	0.0089	309	4.4143	0.0391
04H	Employee Physical Condition	8	0.0010	95	11.8750	0.0120
Mechanical Related						
12E	Broken Wheels (Car)	312	0.0395	2,480	7.9487	0.3137
10E	Bearing Failure (Car)	384	0.0486	2,399	6.2474	0.3035
11E	Other Axle/Journal Defects (Car)	175	0.0221	1,471	8.4057	0.1861
09E	Sidebearing, Suspension Defects (Car)	178	0.0225	1,273	7.1517	0.1610
13E	Other Wheel Defects (Car)	193	0.0244	1,047	5.4249	0.1325
07E	Coupler Defects (Car)	176	0.0223	998	5.6705	0.1263
06E	Centerplate/Carbody Defects (Car)	138	0.0175	637	4.6159	0.0806
19E	Stiff Truck (Car)	81	0.0102	567	7.0000	0.0717
20E	Track/Train Interaction (Hunting) (Car)	54	0.0068	520	9.6296	0.0658
08E	Truck Structure Defects (Car)	57	0.0072	418	7.3333	0.0529

Appendix C. Potential Risk Mitigation Strategies

Increase track center spacing: Adequate track center spacing keeps the HSR track and the conventional track far enough apart so that the likelihood of an intrusion from derailed equipment, shifted load, obstructions, and an intrusion of MOW staff and equipment is low. Abtahi (2013) conducted a study of intrusion protection for the California HSR system. In addition, some additional literature may provide information for track spacing selection (English, Highan, & Bagheri, 2007; Cockle, 2014). A more comprehensive risk assessment model, however, is required to determine adequate track spacing. Increasing track spacing is technically feasible, especially if considered during the initial planning of a new HSR line and if there is available space or ROW. Additional ROW to accommodate an alignment with multiple main tracks and sufficiently wide track centers may result in significantly higher costs, depending on the location and amount of ROW required.

Install intrusion detection system: An intrusion detection system detects the intrusion of derailed equipment or MOW equipment from an adjacent track. The system is able to set the signal controlling the track block to stop after an intrusion is detected in order to prevent trains from running into the intruded track block. The system also warns the engineer about the intrusion if the system is integrated with an onboard signaling and information display system on the train. Figure C-1 shows an example of the intrusion detection system–a fence with sensors is installed between the HSR track and the conventional track. The intrusion detection system is technically feasible for both existing and newly built shared operation settings. The total cost of such system depends on the length of the track segments where intrusion detection sensors are installed.

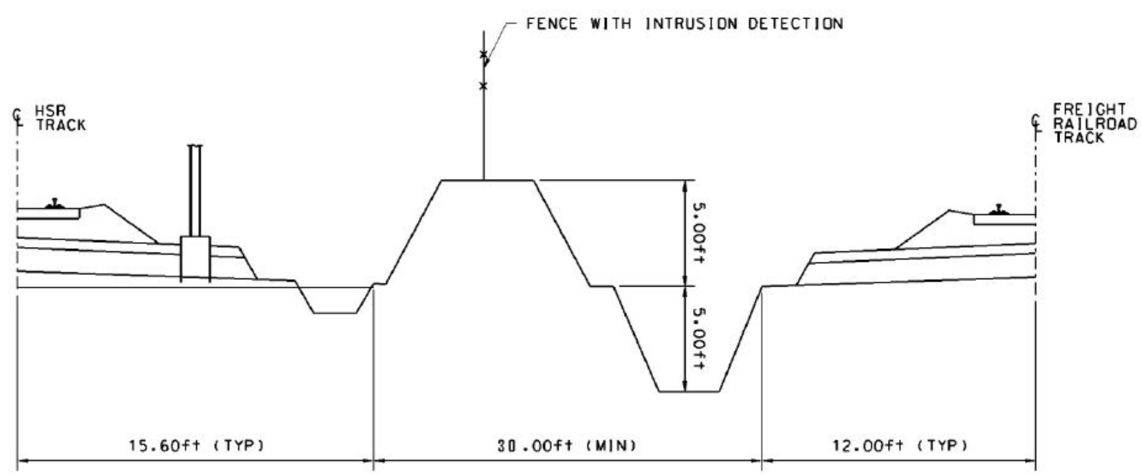


Figure C-1: Installation of the Intrusion Detection System (Abtahi, 2013)

Upgrade track class & increase maintenance standards: FRA track class has been used as a proxy for track quality and as a parameter for estimating derailment rate (Liu et al., 2011). Generally the higher the track class, the lower the derailment risk (Nayak, 1983; Anderson & Barkan, 2004; Liu et al., 2011). Upgrading track class refers to the improvement of track quality, more stringent maintenance standards, and more frequent track inspection frequency. This may reduce the train derailment rate and thus reduce the risk of intrusions and potential consequences. It can also mitigate the shifted load hazard because of better track geometry and thus less lateral or vertical acceleration. Upgrading track class is technically feasible for both existing and newly built shared operation settings. In the newly built shared operation settings, the existing conventional tracks can be upgraded to reduce derailment risk. Increasing inspection standards (including both frequency and quality) helps to reduce certain types of train derailments (e.g., broken rail derailments) (Liu et al., 2014). The effect of risk reduction by upgrading infrastructure can be weighed against the cost of upgrading infrastructure (Liu et al., 2010). Lovett et al. (2013) developed a model to evaluate rail maintenance planning, considering the benefit (reduced derailment risk) and cost (machine/labor cost and potential train delay). One institutional issue regarding upgrading the track class is that the adjacent railroad may not be in favor of upgrading the track class if not absolutely necessary (due to higher maintenance and inspection costs), particularly if the traffic level on the adjacent track is low. This will require buy-in from the adjacent railroads.

Install crash wall (between HSR track and conventional track): Crash walls are physical barriers that can be built between HSR tracks and conventional tracks to prevent the intrusion of derailed equipment. Typical crash wall types include earthwork barriers (Figure C-2), structural barriers (Figure C-3), and the combination of both. Another type of barrier is the pier protection barrier, which is built between the railroad and the pillar of an overpass bridge of a roadway or another railroad. Moyer et al. (1994) performed a comprehensive and detailed study on the intrusion barriers of HSR systems. The study discussed and analyzed barrier types and their functions, proper barrier offset distance, barrier design, barrier costs, hazard assessment, and hazards that may be prevented by installing barriers. The study suggested using structural barriers (e.g., a concrete crash wall) instead of earthwork barriers for HSR and adjacent conventional railroad systems. The typical height of the barrier is 10 feet. The study also suggested the distance from the train to barriers should be either less than 9 feet or greater than 40 feet to address the "zig-zag" effect. Abtahi (2013) suggested that both structural barriers and earthwork barriers could be used but each of them should be applied with different track spacing between HSR track and conventional railroad track. The suggested minimum track spacing for the implantation of earthwork barriers (76 feet) is larger than that of structural barriers (47 feet). As for pier protection, Abtahi (2013) suggested the minimum offset between a HSR track and the pier should be 25 feet based on AREMA recommendations. Otherwise, a crash wall or barrier should be built to protect the pier. Installing crash wall is technically feasible for both existing and newly built shared operation settings. The installation of a crash wall requires space between two tracks. In addition, the total cost is expected to be high, and it is a function of the type and length of the installation.

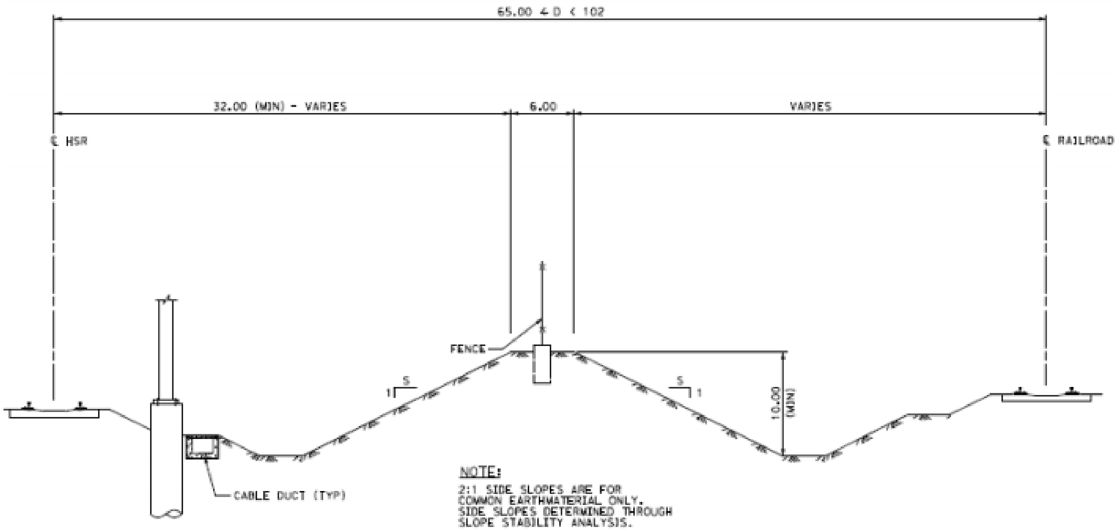


Figure C-2: Earthwork Barrier Protection (Abtahi, 2013)

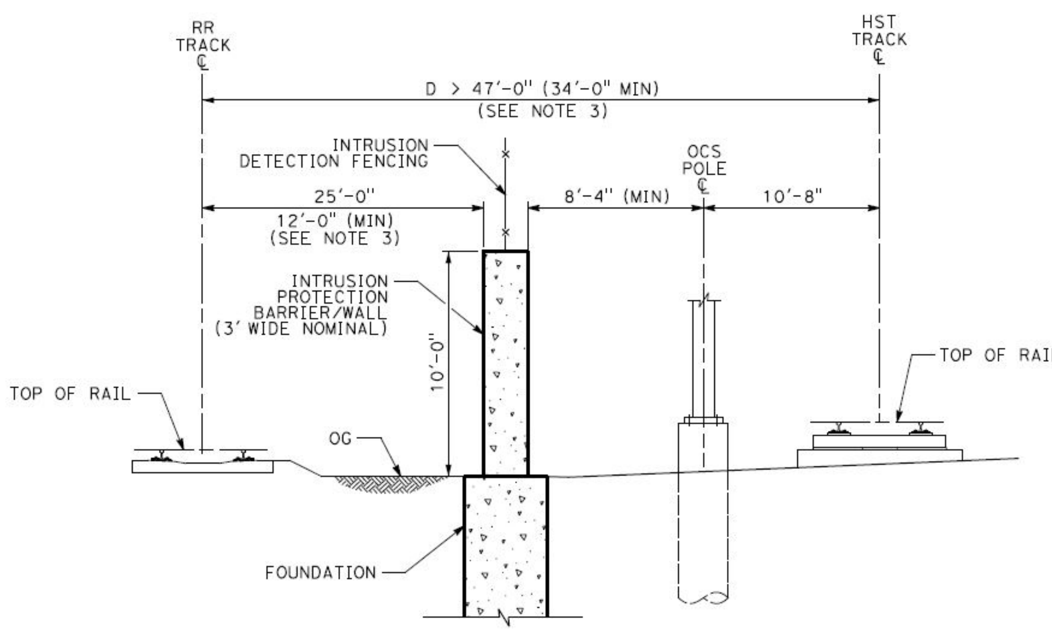


Figure C-3: Structural Barrier Protection (Abtahi, 2013)

Install train containment: Train containment is designed to prevent a HSR or conventional train from overturning or deviating away from its own track. Typical containment includes guard rails, parapets, and undercar guards. A guard rail is installed to contain the rolling stock and prevent it from intruding the adjacent track when it derails (Figure C-4). A parapet serves the same function; but instead of putting the containment inside the track, a parapet is installed along the track (Figure C-5). An undercar guard is a containment device installed under a rail car axle inside its wheels so that when derailment occurs, the containment would contact the gauge side of the rail and prevent the wheels from rolling away from the track (Figure C-6). Installing train containment has been a common practice in Europe (e.g., the Channel Tunnel Rail Link). Specific locations which have relative higher derailment risk are chosen to install containment, such as bridges, switches, and interlockings. Installing train containment is technically feasible for both existing and newly built shared operation settings. The containment can be installed on both HSR tracks and conventional tracks. The cost of containment depends on the type of containment and the length of containment.

Figure C-4: Guard Rail Protection (Abtahi, 2013)

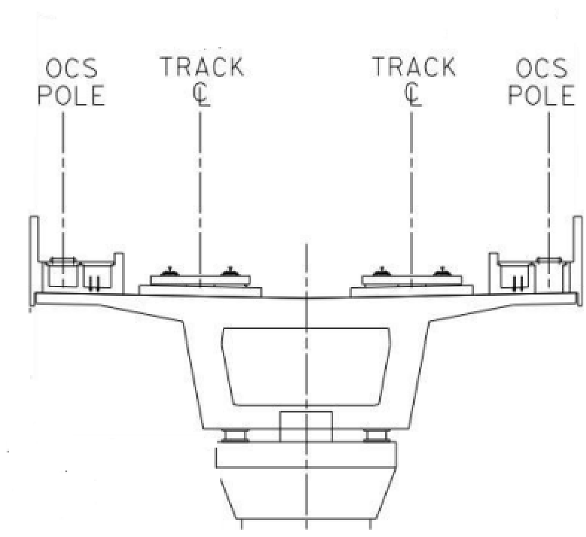


Figure C-5: Parapet protection (Abtahi, 2013)

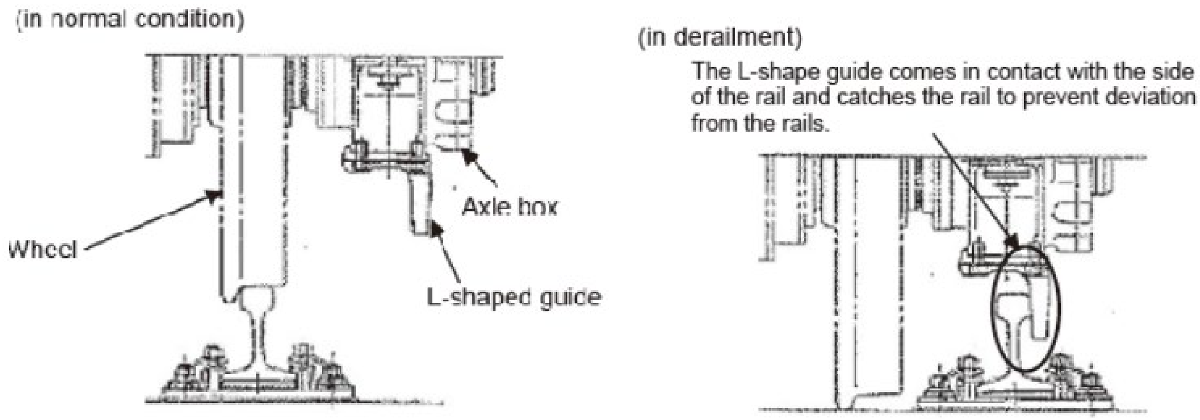


Figure C-6: Undercar Guard Protection (Abtahi, 2013)

Install shifted load detector: A shifted load detector is a wayside detector to detect any shifted load on passing trains. The cost of shifted load detector depends on the number of detectors installed along the railroad line. Negotiation will be required with the adjacent railroads to install the shifted load detector along their ROW.

Install enhanced grade-crossing protection/detection systems: Grade-crossing obstacle detection is defined by Glover (2009) as systems used in "identifying the presence of a vehicle or person on the crossing as the train approaches and communicating this to the train driver in time for him or her to stop before reaching it." Some grade-crossing protection includes four-quadrant gates, train approaching warning devices, long-arm gates, and traffic channelization devices. Figure C-7 shows an example of the combination of several grade-crossing protection/detection systems. Chadwick et al. (2014) conducted a comprehensive and extensive literature review on the challenges of grade crossings to shared HSR passenger and heavy-axle-load freight operations in the U.S. Some risk mitigation strategies are proposed and reviewed, including obstacle detection, traffic channelization, and grade-crossing warning devices. These can serve as the basis for future research directions.

Figure C-7: An Upgraded Grade Crossing with Four-Quadrant Gates, Train Approaching Warning Devices, and Traffic Channelization Devices (Bien-Aime, 2009)

Install obstruction detection systems (non-grade-crossing zone): Obstruction detection systems are defined by extending Glover's (2009) definition of an "obstacle detection" as "identifying the presence of a vehicle or person on the track as the train approaches and communicating this to the train driver in time for him or her to stop before reaching it."

Install inter-track barrier for workers' protection: An inter-track barrier is a continuous barrier of a permanent or semi-permanent nature that spans the entire work area with at least four feet in height and is of sufficient strength to prevent a roadway worker on conventional railroad track from fouling the adjacent HSR track (FRA, 2014), or vice-versa. With the protection of an intertrack barrier, a maintenance crew can continue working without ceasing the work for a passing train. This may reduce maintenance time and increase railroad efficiency. Installing an intertrack barrier is technically feasible for both existing and newly built shared operation settings. The cost of an intertrack barrier depends on the length of the barrier.

Increase situational awareness: Reinforced situational awareness is achieved by educating railroad employees to be more aware of the surrounding environment when working on the ground, especially near adjacent tracks.

Use enhanced tank car safety design: Improved tank car safety design reduces the conditional probability of the release of hazardous materials from a tank car if it derails by increasing tank car thickness or adding top fitting protection, jackets, additional head protection, and anti-climb couplers. There have been plenty of studies quantitatively addressing the effect of tank car safety design on the reduction of release risk. The results of these studies, combined with other risk mitigation strategies, can provide information on how to effectively mitigate the risk posed by transporting hazardous materials on tracks adjacent to a high-speed rail system.

Increase passenger cars' crashworthiness: Equipment strength is a key factor for reducing potential casualties on board passenger cars from a derailment and/or collision impact. Crashworthiness analyses have been conducted for higher-speed passenger trains (Tier I standard) (Carolan et al., 2011) to understand how reinforced equipment can withstand a larger collision impact and thus result in fewer casualties. Full-scale experiments have been conducted and results have been analyzed to provide levels of crashworthiness for future reference on regulations on the crashworthiness of higher-speed passenger equipment.

Implement temporal separation: Temporal separation refers to the spatial or time separation for the operations of HSR trains and conventional trains. For example, when practical, freight trains transporting hazardous materials could only operate at night so that they are separated from HSR trains, or hazardous traffic could be rerouted away from the tracks adjacent to HSR tracks. Temporal separation can completely eliminate certain hazards, such as hazardous materials transportation on adjacent tracks, but additional cost may incur due to more transportation cost for freight (due to rerouting) or inefficient use of line capacity (due to time separation). In addition, communication between HSR operators and conventional railroad agencies is required to reach an agreement on temporal separation. Generally, temporal separation is technically feasible on the corridors where there is only limited train traffic on the adjacent conventional tracks or HSR tracks.

Increase training on load securement: Load securement training educates railroad personnel on how to firmly secure a load so that the load will not be displaced by acceleration forces to prevent it from shifting or detaching from the freight car. Training should include either railroad employees who are in charge of loading and contractors or customers who load the cargo themselves before transportation by railroads.

References

Abtahi, A., (2013). Rolling Stock and Vehicle Intrusion Protection for High-Speed Rail and Adjacent Transportation Systems. Publication TM 2.1.7. New York: Parsons Brinckerhoff.

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

Bien-Aime, P. (2009). North Carolina "Sealed Corridor" Phase I, II, and III Assessment. Technical Report DOT/FRA/ORD-09/17. Washington, DC: U.S. Department of Transportation, Federal Railroad Administration.

Carolan, M., Jacobsen, K., Llana, P., Severson, K., Perlman, B., & Tyrell, D. (2011). Technical Criteria and Procedures for Evaluating the Crashworthiness and Occupant Protection Performance of Alternatively Designed Passenger Rail Equipment for Use in Tier I Service. Technical Report DOT/FRA/ORD-11/22. Washington, DC: U.S. Department of Transportation, Federal Railroad Administration.

Chadwick, S. G., Zhou, N., & Saat, M. R. (2014). Highway-rail grade crossing safety challenges for shared operations of high-speed passenger and heavy freight rail in the U.S. *Safety Science 68*, 128–137.

Cockle, J. (2014). Freight Railroads Adjacent to High-Speed Rail–Assessing the Risk. Proceedings of the *Joint Rail Conference*. Colorado Springs, CO.

English, G. W., Highan, G., & Bagheri, M. (2007). *Evaluation of Risk Associated with Stationary Dangerous Goods Railroad Cars*. Glenburnie, ON: TranSys Research, Ltd.

Federal Railroad Administration. (2014). Title 49 Code of Federal Regulations Part 214–Railroad Workplace Safety; Adjacent-Track On-Track Safety for Railroad Way Workers, Volume 79, No. 7. Washington, DC: U.S. Department of Transportation.

Glover, J. (2009). The Level Crossing Conundrum. *Rail Professional* (November), 30–31.

Liu, X., Saat & M. R., Barkan,C. P. L. (2010). Benefit-cost analysis of infrastructure improvement for derailment prevention. Joint Rail Conference, ASME. Urbana, IL.

Liu, X., Barkan, C. P. L., & Saat, M. R. (2011). Analysis of Derailments by Accident Cause: Evaluating Railroad Track Upgrades to Reduce Transportation Risk. *Transportation Research Record: Journal of the Transportation Research Board, 2261*, 178–185.

Liu, X., Lovett, A., Dick, C. T., Saat, M. R., & Barkan, C. P. L. (2014). Optimization of Rail Defect Inspection Frequency for the Improvement of Railway Transportation Safety and Efficiency. *Journal of Transportation Engineering, 140*(10).

Lovett, A. H., Barkan, C. P. L., & Dick, C.T. (2013). An Integrated Model for the Evaluation and Planning of Railroad Track Maintenance. Proceedings of the 2013 *Annual Conference, American Railway Engineering and Maintenance of Way Association*. Indianapolis, IN.

Moyer, P. D., James, R. W., & Bechara, C. H. (1994). Safety of High-Speed Guided Ground Transportation Systems: Intrusion Barrier Design Study. Technical Report: DOT/FRA/ORD-95/04. Washington, DC: U.S. Department of Transportation, Federal Railroad Administration.

Nayak, P. R., Rosenfield, D. B., & Hagopian, J. H. (1983). Event Probabilities and Impact Zones for Hazardous Materials Accidents on Railroads. Technical Report DOT/FRA/ORD-83/20. Washington, DC: U.S. Department of Transportation, Federal Railroad Administration.

Appendix D. Semi-Quantitative Risk Assessment of Adjacent Track Accidents on Shared-Use Rail Corridors

1. Introduction

1.1 Shared-Use Rail Corridor

A large number of developments of improved or expanded passenger rail service in the U.S. involves the use of existing railroad infrastructure or ROWs (Saat & Barkan, 2013). Shared or mixed-use rail corridors (SRC) refer to different types of passenger and/or freight train operations using common infrastructure in one way or another (Lin et al., 2013). Figure D-1 shows three types of SRCs: shared track, shared ROW and shared corridor, defined by the U.S. Department of Transportation, Federal Railroad Administration (FRA).

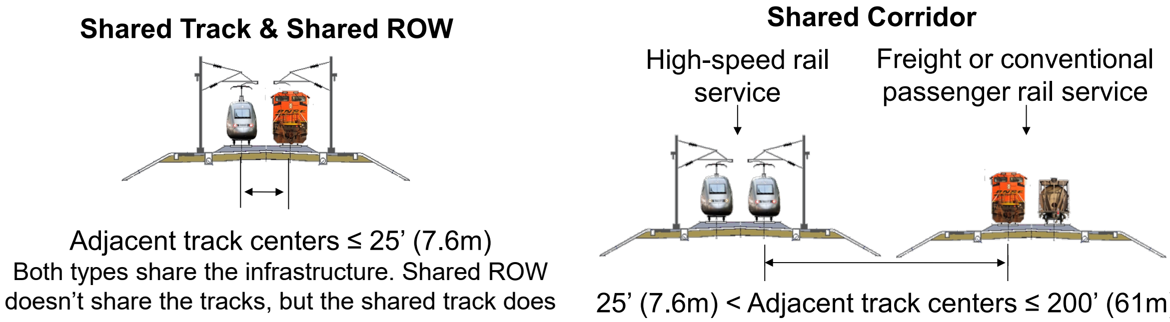


Figure D-1: Definition of SRC by FRA (Resor, 2003)

1.2 Adjacent Track Accident (ATA)

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

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

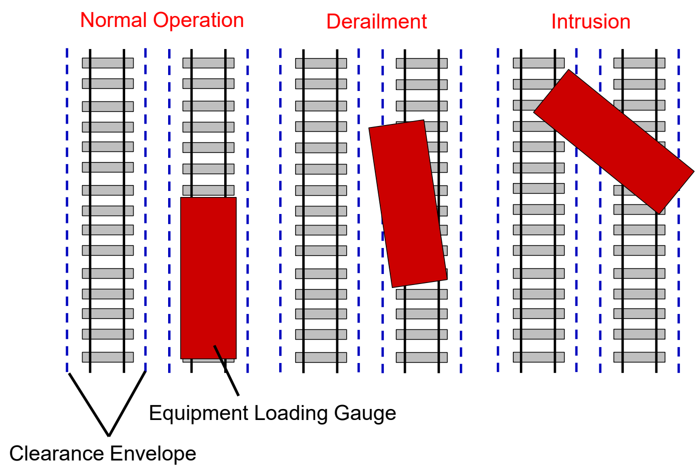


Figure D-2: A Typical Prequel for an ATA

1.3 Literature Review

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

1.4 Research Objectives

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

2. ATA Scenarios

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

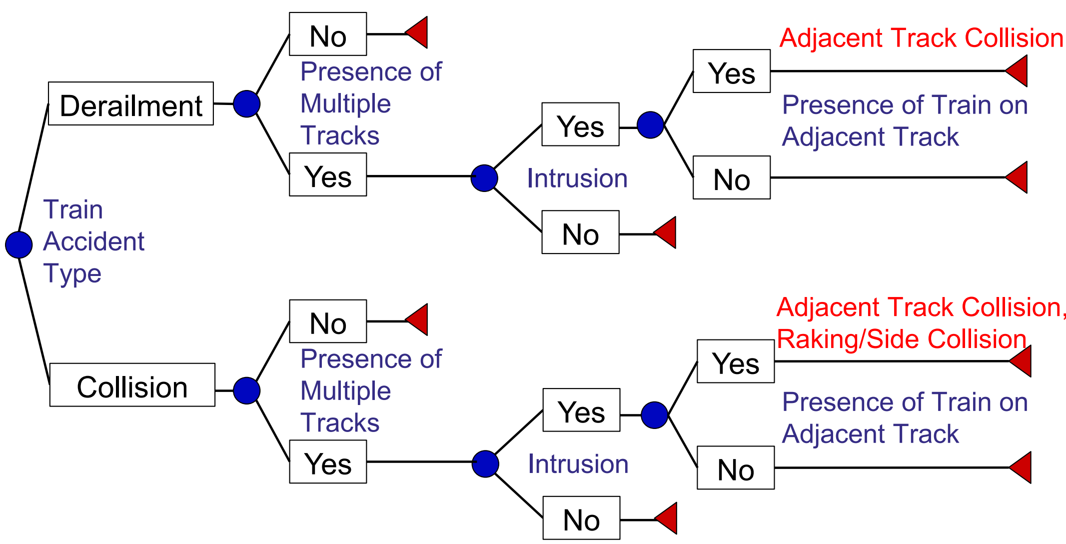


Figure D-3: Conceptual Framework for ATA

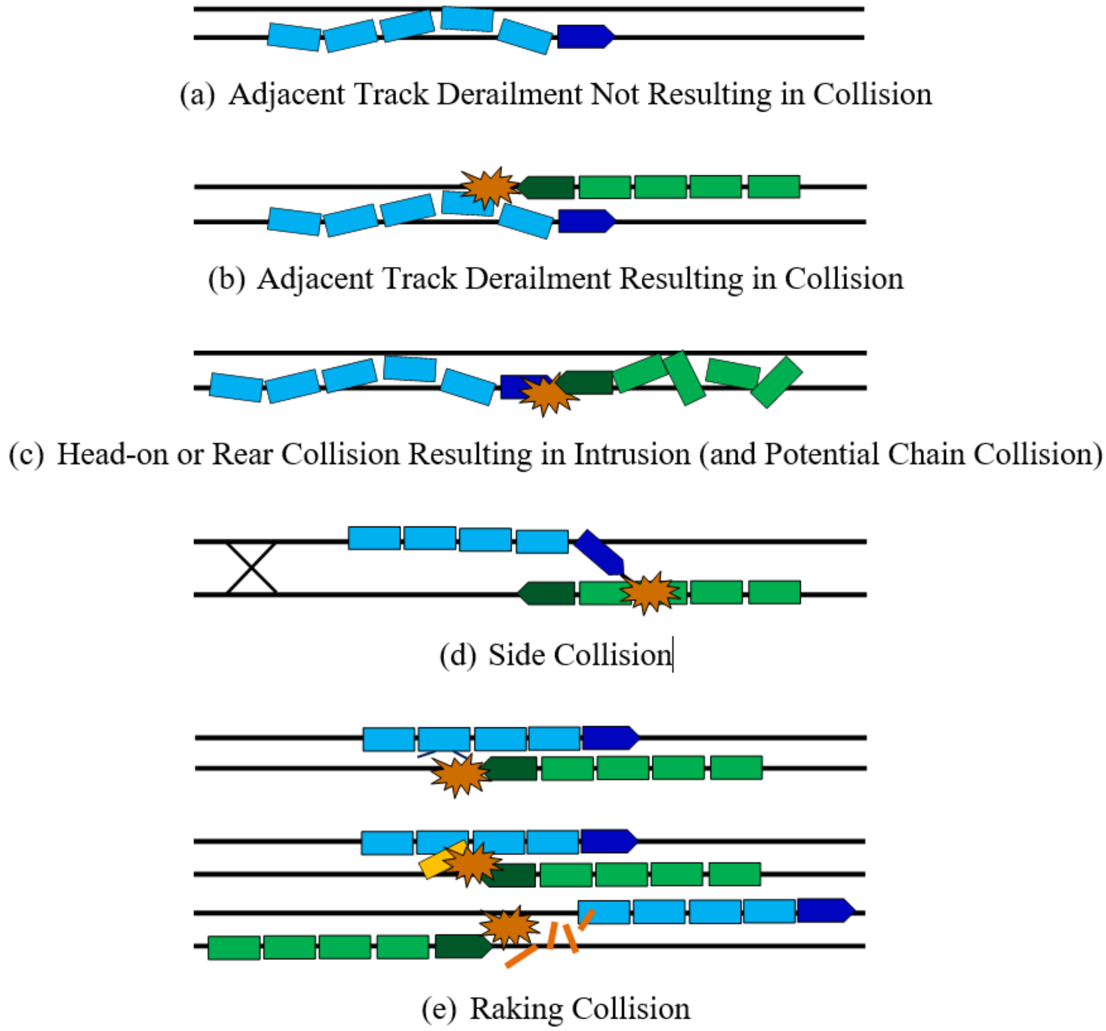


Figure D-4: Specific ATA Derailment and Collision Scenarios

3. Semi-Quantitative Risk Analysis

3.1 Risk Model

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

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

where:

R = The risk index for an ATA

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

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

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

C = The consequence of an ATA

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

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

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

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

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

Traffic Density
Traffic density on a freight line (or a freight and passenger mixed-traffic line), measured in annual million gross tonnage (MGT), may have an effect on the train derailment rate. The higher the traffic density, the lower the derailment rate. This may result from a more frequent maintenance and inspection rate and the installation of more wayside defect detection systems on heavy density traffic lines. Dedicated passenger lines usually have lower derailment rates due to higher track maintenance standards and inspection frequency. In addition, lighter passenger equipment generally causes less wear and damage to the track structure, reducing the potential

risk of accidents due to track structure defects. Thus, it was assumed that dedicated passenger lines have low derailment rates (Liu, 2013).

Type of Equipment

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

Defect Detectors and Track Inspections

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

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

Table D-1: Accident Factor Score Definitions

Accident Factor	Criteria	Accident Factor Score (AFS)
FRA Track Class	6 or above	1.0
	5	2.0
	4	4.0
	2, 3	8.0
	X, 1	16.0
Traffic Density	*Freight-Train only or Freight and Passenger Shared Lines:*	
	More than 60 MGT	1.0
	40 - 60 MGT	1.4
	20 - 40 MGT	2.0
	Less than 20 MGT	4.0
	Passenger-Train only Lines:	
	Dedicated Passenger Line	1.0
MOD	Signaled	1.0
	Non-Signaled	1.5
The highest score possible		**96.00**
The lowest score possible		**1.00**

Table D-2: Level of P(A)

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

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

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

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

The Distance between Track Centers

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

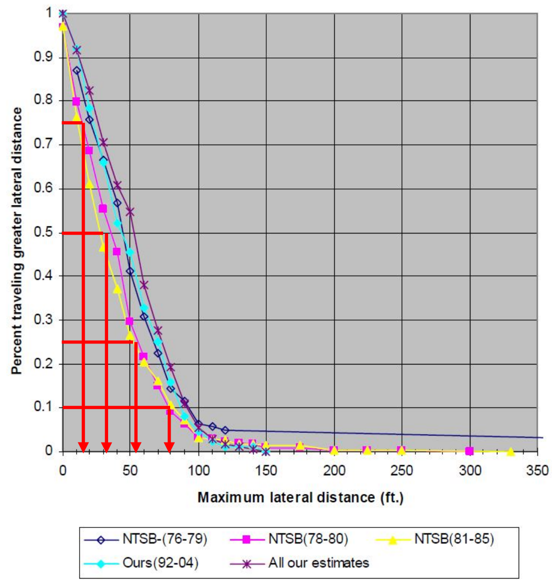


Figure D-5: Maximum Lateral Travel Distribution (*English et al., 2007*)

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

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

Track Alignment

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

Table D-4: Intrusion Factor Score Definitions for Track Alignment

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

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

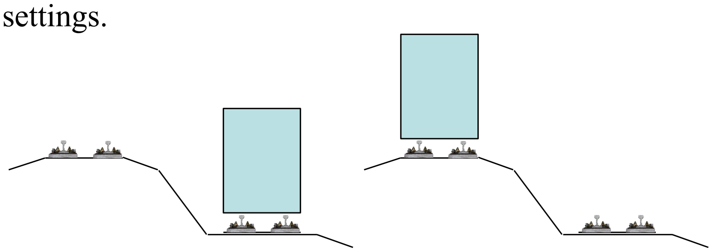


Figure D-6: Effect of Elevation Differential on CPI

Table D-5: Intrusion Factor Score Definitions for Elevation Differential

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

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

noise barrier, is located alongside with track. Densely constructed buildings along the track in an urban area can be considered a continuous structure.

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

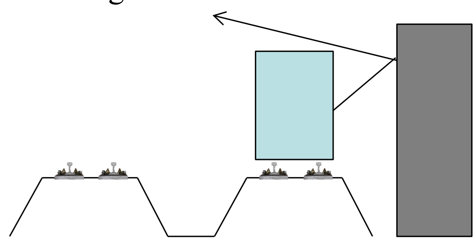


Figure D-7: Effect of Adjacent Structure on CPI

Table D-6: Intrusion Factor Score Definitions for Adjacent Structure

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

Containment

Containment is a structure located in between the adjacent tracks. The presence of containment can reduce the likelihood of intrusion by containing the derailed equipment, preventing it from intruding adjacent tracks. Containments can also reduce the consequences by absorbing the energy from derailed equipment (discussed in consequence subsection of this appendix). Three types of containment which are currently used in HSR systems in Europe and Asia are discussed: guard rails, parapets, and physical barriers (Hadden et al., 1992; Moyer et al., 1994; Ullman & Bing, 1995; Rulens, 2008).

Guard rails (or check rails) are frequently used in turnouts to prevent trains from derailment. Guard rails can also be used to contain rail equipment within the track clearance and prevent it from intruding adjacent tracks. Installing guard rails in a high-risk area is thus expected to reduce the CPI. Parapets have a similar function to guard rails but is installed on the sides of the track structure. Physical barriers, such as concrete walls, are installed between two tracks to absorb the impact of a train in a derailment and prevent the derailed equipment from intruding adjacent tracks (Figure D-8).

Table D-7 shows the IFS for different containment settings. Note that the types of containment discussed are conceptual and general. Site-specific evaluations would be necessary to decide the effectiveness of each approach.

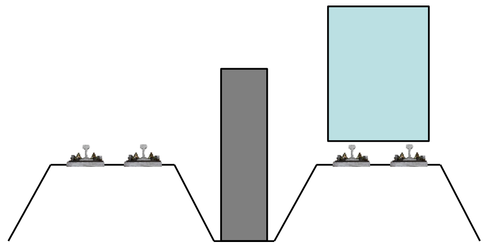


Figure D-8: Effect of Containment on CPI

Table D-7: Intrusion Factor Score Definitions for Containment

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

Train Speed

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

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

Table D-8: Intrusion Factor Score Definitions for Train Speed

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

Point of Derailment

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

Besides, compared with other intrusion factors, POD is a post-accident factor rather than a pre-accident factor. That is, it cannot be known which car in the train consist will derail before the derailment occurs. As such, it is difficult to pre-assign the IFS to this factor in the model.

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

Table D-9: Summary of All Intrusion Factor Score Definitions

Intrusion Factor	Criteria	Intrusion Factor Score (IFS)
Distance Between Track Centers, X, in feet (meters)	X > 80 (24.4)	1.0
	55 (16.7) < X ≤ 80 (24.4)	1.5
	30 (9.1) < X ≤ 55 (16.7)	2.0
	15 (4.5) < X ≤ 30 (9.1)	3.0
	X ≤ 15 (4.5)	5.0
Track Alignment	Tangent and level	1.0
	Tangent and on gradient	1.1
	Curved and level	1.5
	Curved and on gradient	1.7
Elevation Differential	Adjacent track is 10 ft. higher	0.7
	Adjacent track is level	1.0
	Adjacent track is 10 ft. lower	1.3
Adjacent Structure	No adjacent structure	1.0
	Single structure	1.1
	Discrete structure	1.2
	Continuous structure	1.3
Containment	All containments installed	0.5
	Physical barrier and guard rail or parapet installed	0.6
	Physical barrier installed only	0.7
	Parapet and guard rail installed	0.8
	Parapet or guard rail installed only	0.9

Intrusion Factor	Criteria	Intrusion Factor Score (IFS)
	No containment installed	1.0
Train Speed	Low (less than 40 mph)	1.0
	Medium (40 mph to 70 mph)	1.2
	High (more than 70 mph)	1.4
The highest score possible		**20.11**
The lowest score possible		**0.35**

Table D-10: Total IFS and Level of CPI Definitions

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

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

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

Factors affecting the conditional probability of train presence given an intrusion include intrusion detection and warning systems, traffic density, method of operation, train speed, and shunting problems. These factors are investigated in the following paragraphs.

Intrusion Detection and Warning System (IDW)

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

Traffic Density

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

Method of Operation

Different train control systems have different accuracy in identifying the locations of trains and communicating information. For example, a traditional track circuit system can only identify a train's location by "block" and does not provide the exact position of the train, whereas advanced train control systems can precisely locate the train. Representative systems include the European Rail Traffic Management System (ERTMS) in European countries and the Advanced Train Administration & Communications System (ATACS) in Japan. Positive Train Control (PTC) is the proposed advanced train control technology in the U.S. Also, advanced train control systems can communicate information more efficiently than traditional oral communication between dispatchers and engineers. IDW can also be integrated with advanced control systems so that intrusion warnings can be efficiently and instantly delivered to other trains in the same proximity (Hadden et al., 1992; Ullman & Bing, 1995).

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

Train Speed

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

Shunting

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

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

Table D-11: Train Presence Score Definitions

Train Presence Factors	Criteria	Train Presence Score (TPS)
IDW	Presence	1
	Absence	2
Traffic Density	*Freight or Freight and Passenger Shared Lines:*	
	Less than 20 MGT	1
	20 - 40 MGT	1.3
	40 - 60 MGT	1.6
	More than 60 MGT	2
	Passenger Lines:	
	Dedicated Passenger Line	2

Train Presence Factors	Criteria	Train Presence Score (TPS)
MOD	Advanced train control	1
	Typical train control system	2
	Dark territory	3
Average Train Speed	Low (less than 40 mph)	1
	Medium (40 mph to 70 mph)	2
	High (more than 70 mph)	3
The highest score possible		**36**
The lowest score possible		**1**

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

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

3.5 Consequences, C, and Consequence Factors

Consequences are the accident impacts from an ATA. The major concern are the severe consequences resulting from a collision between derailed equipment and trains on adjacent track. Previous research showed the average casualties for passenger train collisions is higher than the average casualties for passenger train derailments (Lin et al., 2013). Because ATAs may include both passenger and freight trains, the consequences of ATAs include multiple, possible types of impacts:

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

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

Equipment Strength

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

Train Speed

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

Containment

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

Product Being Transported (Freight Train)

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

Consequence level was defined as the evaluation of equipment strength, speed, presence of containment, and whether hazardous material was transported in the track section. Similar to the conditional probability of intrusion, the consequence factor score (CFS) was assigned to different situations in each consequence factor, as shown in Table D-13. The total CFS was calculated by multiplying the CFS from individual consequence factors together. The total CFS was then related to the level of consequences in Table D-14.

Table D-13: CFS for Consequence Factor Score Definitions

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

Table D-14: Level of Consequence Definitions

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

3.6 Overall Probability

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

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

Based on the values of P, a level of overall probability will be assigned. Table D-15 shows the relation between the value of P and the level of overall probability.

This level of overall probability will be multiplied by the consequence level to obtain the ATA risk index.

Table D-15: Overall Probability Level Definitions

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

3.7 Model Application

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

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

$R_{AB}+R_{BA}$

where

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

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

In R_{AB}, track A is called "initiating track" because the initial accident occurs at that track, and track B is called "intruded track" because it is the track being intruded.

If three tracks are close to each other, the ATA risk will be calculated for each combination of tracks. For instance, in Figure D-9b, there are three tracks adjacent to each other. The ATA risk for this segment is

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

Figure D-9c shows *n* tracks. The ATA risk for this segment is

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

where

$i < j \qquad\qquad \forall i$

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

$R_{AY}+R_{YA}$

where

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

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

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

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

where

$i < j \qquad \forall i$

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

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

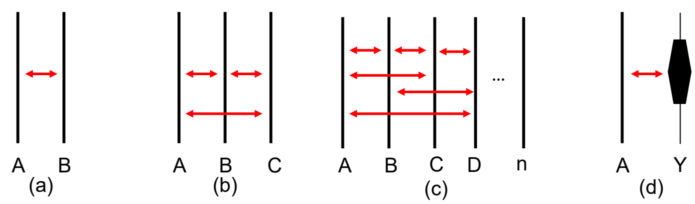


Figure D-9: Calculation of ATA Risk

4. Case Study

4.1 Hypothetical Shared-Use Rail Corridor Network

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

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

Various types of hazardous material are transported through Section 1 of the trunk line, including chlorine and crude oil. The trunk line contains all three shared-use settings and is thus suitable for this analysis. The trunk line was divided into three sections based on different shared-use settings. Route characteristics for each section is summarized in Figure D-11. Note that the table only shows the section characteristics, while some site-specific characteristics (for example, the relative elevation differential between two main tracks) were not listed in the table as they vary from site to site. These factors will be considered, however, in an example risk calculation in the next subsection.

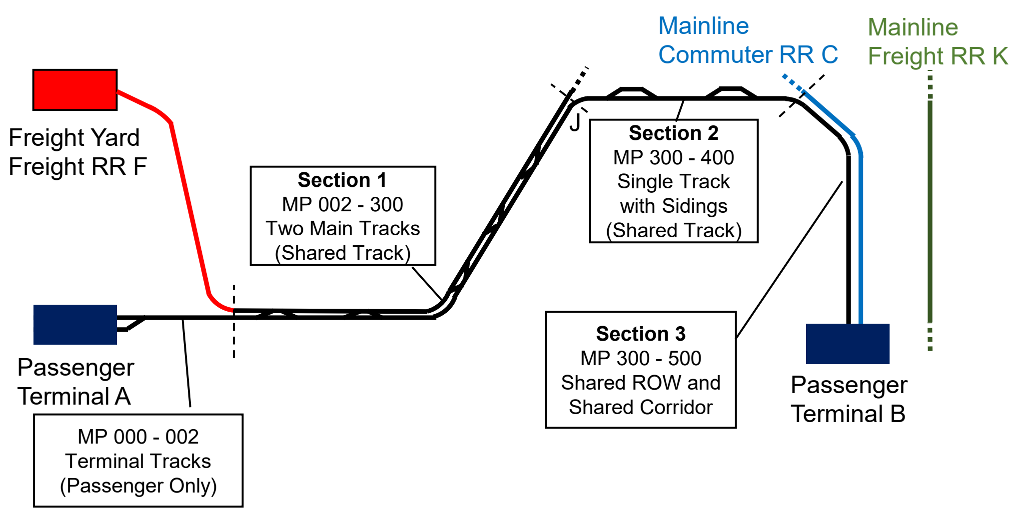


Figure D-10: Hypothetical Shared-Use Rail Corridor Network

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

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

[1] Centralized Traffic Control

[2] Positive Train Control

[3] Automatic Train Control

[4] Track Warrant Control

Note

1.The section MP 000 - 002 is not listed because it is not a shared-use section.

4.2 Risk Calculation and Comparison

In order to demonstrate the proposed risk analysis model, three sites from the hypothetical SRC network were chosen and the ATA risk of each site was evaluated and compared. The three sites were chosen from the three sections of the hypothetical network. Figure D-12 shows locations and risk calculations for each site. The ATA risk for a specific site considers the interactions of all railroad lines with regard to the line of interest (the trunk line). For example, Site 1 was chosen from Section 1 where two main tracks were shared by passenger trains and freight trains. The methodology of calculating the ATA risk discussed in Section 3.6 was applied for the three example segments.

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

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

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

Site 1: 20 (10+10)

Site 2: 12 (6+6)

Site 3: 9 (2+2+2+3)

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

The ATA risks calculated for every segment along the same route can be compared with each other. Figure D-13 shows the frequency diagram for the ATA risks of the trunk line. The whole route was divided into 880 segments and the ATA risk for each segment was calculated. The x-axis shows all values of ATA risk on the route and the y-axis shows how many segments have the specific value of ATA risk. The figure shows risk index 8 is the most frequent.

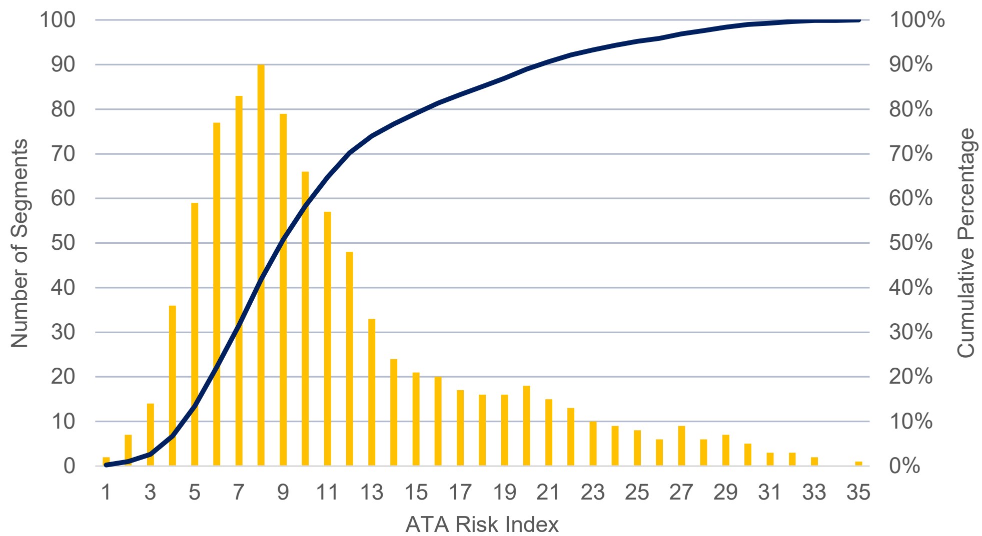


Figure D-11: Frequency of ATA Risk of the Trunk Line

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

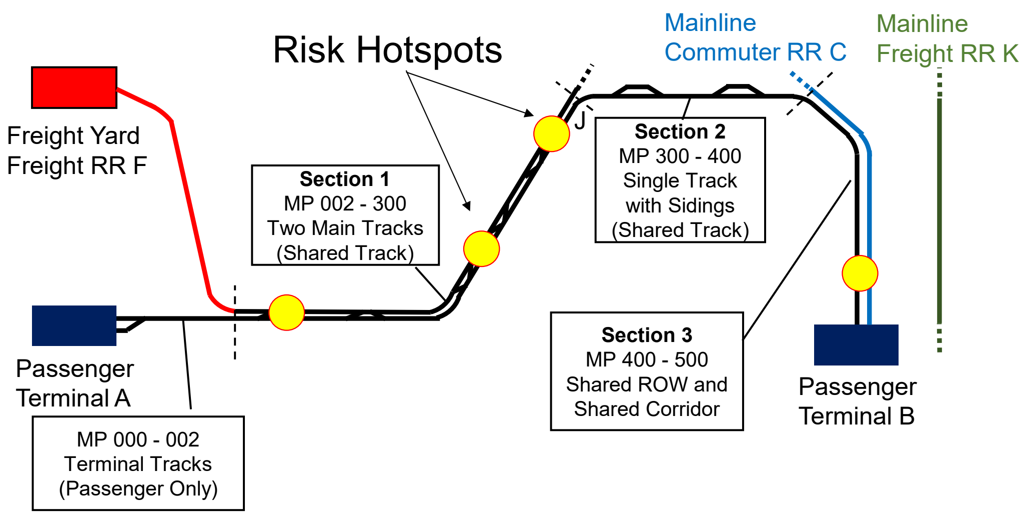


Figure D-12: Risk Hotspots of ATA Risk of the Trunk Line

5. Conclusion

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

References

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

Anderson, R. T. (2005). Quantitative Analysis of Factors Affecting Railroad Accident Probability and Severity (Master's thesis). University of Illinois at Urbana-Champaign, Urbana, IL.

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

Carolan, M., Jacobsen, K., Llana, P., Severson, K., Perlman, B., & Tyrell, D. (2011). Technical Criteria and Procedure for Evaluating the Crashworthiness and Occupant Protection Performance of Alternatively Designed Passenger Rail Equipment for Use in Tier I Service. Technical Report DOT/FRA/ORD-11/22. Washington, DC: U.S. Department of Transportation, Federal Railroad Administration.

Chadwick, S. G., Zhou, N., & Saat, M. R. (2014). Highway-rail grade crossing safety challenges for shared operations of high-speed passenger and heavy rail in the U.S. *Safety Science, 68*, 128–137.

Chisholm, G. (2002). Germany's Track-Sharing Experience: Mixed Use of Rail Corridors. *TCRP Research Results Digest, 47*. U.S. Department of Transportation, Washington, DC.

Cockle, J. (2014). Freight Railroads Adjacent to High-Speed Rail – Assessing the Risk. Proceedings of the *Joint Rail Conference*. Colorado Springs, CO.

Dick, C. T., Barkan, C. P. L., Chapman, E. R., & Stehly, M. P. (2003). Multivariate statistical model for predicting occurrence and location of broken rails. *Transportation Research Record–Journal of the Transportation Research Board, 1825,* 48 – 55.

Elvik, R. and Voll, N. G. (2014). Challenges of improving safety in very safe transport systems. *Safety Science, 63*, 115 – 123.

English, G. W., Highan, G. & Bagheri, M. (2007*). Evaluation of Risk Associated with Stationary Dangerous Goods Railroad Cars.* Glenburnie, ON: TranSys Research, Ltd.

Federal Railroad Administration (FRA). (2011). FRA Guide for Preparing Accident/Incident Reports, U.S. Department of Transportation, Washington, DC.

Federal Railroad Administration. (2011). FRA Track Safety Standards, U.S. Department of Transportation, Washington, DC.

Hadden, J., Lewalski, W., Kerr, D., & Ball, C. (1992). Safety of High-Speed Guided Ground Transportation Systems: Shared Right-of-Way Safety Issues. Technical Report DOT/FRA/ORD-92/13. Washington, DC: U.S. Department of Transportation, Federal Railroad Administration.

Hajibabai, H., Saat, M. R., Ouyang, Y., Barkan, C. P. L., Yang, Z., Bowling, K., Somani, K., Lauro, D., & Li, X. (2012). Wayside Defect Detector Data Mining to Predict Potential WILD

Train Stops. Presented at the Annual Conference and Exposition of the American Railway Engineering and Maintenance-of-Way Association. Chicago, IL.

Kawprasert, A. & Barkan, C. P. L. (2009). Communication and interpretation of results of route risk analysis of hazardous materials transportation by railroad. *Transportation Research Record–Journal of the Transportation Research Board, 2097*, 125–135.

Lin, C. Y., Saat, M. R., & Barkan, C. P. L. (2013). Causal Analysis of Passenger Train Accident on Shared-Use Rail Corridor. Proceedings of the *World Congress on Railway Research*, Sydney, Australia.

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

Liu, X. (2013). Optimal Strategies to Improve Railroad Train Safety and Reduce Hazardous Materials Transportation Risk. (Doctoral dissertation). University of Illinois at Urbana-Champaign, Urbana, IL.

Liu, X., Saat, M. R., Qin, X., & Barkan, C. P. L. (2013a). 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., Saat, M. R., & Barkan, C. P. L. (2013b). Integrated risk reduction framework to improve railway hazardous materials transportation safety. *Journal of Hazardous Materials, 260*, 131–140.

Liu, X., Saat, M. R., & Barkan, C. P. L. (2013c). Safety effectiveness of integrated risk reduction strategies for rail transport of hazardous materials. *Transportation Research Record–Journal of the Transportation Research Board, 2374,* 102 – 110.

Liu, X., Lovett, A., Barkan, C. P. L., Dick, C. T., & Saat, M. R. (2014). Optimization of rail defect inspection frequency for the improvement of railway transportation safety and efficiency. *Journal of Transportation Engineering, 140*(10).

Moyer, P. D., James, R. W., Bechara, C. H., & Chamberlain, K. L. (1994). Safety of High Speed Guided Ground Transportation Systems Intrusion Barrier Design Study. Technical Report DOT/FRA/ORD-95/04. Washington, DC: U.S. Department of Transportation, Federal Railroad Administration.

Nash, A., (2003). Best Practices in Shared-Use High-Speed Rail Systems. Publication ORNL-6973. Oak Ridge, TN: Oak Ridge National Laboratory.

Nayak, P. R., Rosenfield, D. B., & Hagopian, J. H. (1983). Event Probabilities and Impact Zones for Hazardous Materials Accidents on Railroads. Technical Report DOT/FRA/ORD-83/20. Washington, DC: U.S. Department of Transportation, Federal Railroad Administration.

Phraner, S. D., & Roberts, R. T. (1999). Joint Operation of Light Rail Transit or Diesel Multiple Unit Vehicles with Railroads. Transit Cooperative Research Program (TCRP) Report 52. Washington, DC: U.S. Department of Transportation, Federal Railroad Administration.

Phraner, S. D. (2001). Supplementing and Updating TCRP Report 52: Joint Operation of Light Rail Transit or Diesel Multiple Unit Vehicles with Railroads. *TCRP Research Results Digest, 42*. Washington, DC: U.S. Department of Transportation, Federal Railroad Administration.

Resor, R. R. (2003). Catalog of "Common Use" Rail Corridors. Technical Report DOT/FRA/ORD-03/16. Washington, DC: U.S. Department of Transportation, Federal Railroad Administration.

Rulens, D. (2008). Rolling Stock and Vehicle Intrusion Protection for High-Speed Rail and Adjacent Transportation Systems TM 2.1.7. New York: Parsons Brinckerhoff.

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

Ullman, K. B., & Bing, A. J. (1994). High Speed Passenger Trains in Freight Railroad Corridors: Operations and Safety Considerations. Technical Report DOT/FRA/ORD-95/05. Washington, DC: U.S. Department of Transportation, Federal Railroad Administration.

Van Dyk, B. J., Dersch, M. S., Edwards, J. R., Ruppert, Jr., C. R., & Barkan, C. P. L. (2013). Quantifying Shared Corridor Wheel Loading Variation Using Wheel Impact Load Detectors. *Proceedings of the* 2013 *ASME Joint Rail Conference,* Knoxville, TN.

Abbreviations and Acronyms

Abbreviation or Acronym	Name
AFS	Accident Factor Score
ATA	Adjacent Track Accident
ATACS	Advanced Train Administration & Communications System
AREMA	American Railway Engineering Maintenance-of-Way Association
ADL	Arthur D. Little
CTRL	Channel Tunnel Rail Link
CFS	Consequence Factor Score
CPI	Conditional Probability of Intrusion
EMI	Electromagnetic Interference
ERTMS	European Rail Traffic Management System
FTA	Fault-tree Analysis
FRA	Federal Railroad Administration
HrSR	Higher-speed Rail
HSR	High-Speed Rail
IDW	Intrusion Detection and Warning System
IFS	Intrusion Factor Score
MP	Milepost
MGT	Million Gross Tonnage
NTSB	National Transportation Safety Board
POD	Point of Derailment
PTC	Positive Train Control
PRA	Probabilistic Risk Assessment
PMBOK	Project Management Body of Knowledge Guide
RailTEC	Rail Transportation and Engineering Center
ROW	Right-of-way
SRC	Shared-use Rail Corridor
TPS	Train Presence Score
UI	University of Illinois at Urbana-Champaign