# Critical Analysis of Train Occurrences in Canada through Process Safety Techniques and Safety Risk Model Approach

by

Nafiseh Esmaeeli

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Department of Chemical and Materials Engineering
University of Alberta

## Abstract

Canada's national rail network is the third-largest in the world, playing a vital role in moving goods and people across the country. Rail transportation transfers $320 billion worth of goods and over 100 million passengers annually. Although railway activities are beneficial to Canada's economy, insufficient attention to safe transportation can have irreparable effects on the economy, human lives, and the environment. Recent rail accidents, like Lake Wabamun in 2005 and Lac-Mégantic in 2013, have shown that there is still room to increase the safety of rail transportation by improving the railway's safety management system (SMS). As a result, the first study of this thesis is part of these initiatives focusing on enhancing railway's SMS, particularly mitigating the likelihood of Dangerous Goods (DG) main-track train derailments, as these are associated with the potential for larger consequence magnitudes. The study applied detailed Root Cause Analysis (RCA), Event Tree Analysis (ETA), and Bow Tie Analysis (BTA) to identify the main causes and consequences of these types of accidents (2007-2017). Then, the relationship between these factors and gaps in SMS elements were identified and the frequency of each factor was investigated. The results showed that the main gaps are related to the process and equipment integrity, incident investigation, and company standards, codes, and regulations, respectively. Furthermore, some useful recommendations are presented to enhance the management of each SMS element and reduce the gaps.

The outcomes of the first paper demonstrated that among those SMS elements that showed the major gaps, there was a mutual cause-risk assessment. Weakness in implementing risk assessment makes it difficult to correctly define the objectives of SMS. To this end, the second study of this thesis focused on the risk assessment of the Canadian railway system by employing a useful model named Safety Risk Model (SRM). The study applied a customized Canadian SRM (C-SRM) to two groups of hazardous events, main-track derailments, and collisions with fatality and injury consequences calibrated for data between 2007- 2017. The model used Fault Tree Analysis (FTA) and Event Tree Analysis (ETA) to identify the collective risks of the hazardous event. Then, by applying those methods, the individual risks of the hazardous events were evaluated for three groups of people: passengers, employees, and members of the public (MOP). In the last step of the study, the developed C-SRM allowed to apply a risk reduction analysis to assess the effect of introducing a new control measure, Enhanced Train Control (ETC). ETC technologies are a combination of enhanced awareness and fail-safe systems with similar functionality to the US Positive Train Control (PTC) systems. ETC is aimed to prevent certain rail occurrences caused by human error. The results of the study showed that the collective risk of main-track derailments is higher than the main-track collision. Moreover, the risk to MOP and employees form the most significant proportion of the individual risk for main-track derailment and main-track collision, respectively. Finally, risk reduction analysis of the ETC revealed that this new control measure is useful in preventing certain rare but potentially high-consequences accidents. However, making a decision regarding the implementation of this system in the Canadian rail industry needs further investigation such as cost-benefit analysis.

## Preface

Chapter 2 of this thesis has been published as Esmaeeli N, Sattari F, Lefsrud L, Macciotta R. "Critical Analysis of Train Derailments in Canada through Process Safety Techniques and Insights into Enhanced Safety Management Systems", Journal of Transportation Research Record.

Chapter 3 of this thesis has been submitted for publishing as Esmaeeli N, Sattari F, Lefsrud L, Macciotta R. "Assessing the risks associated with the Canadian Railway System using a Safety Risk Model approach", Journal of Transportation Research Record.

I was responsible for the data collection, data analysis as well as manuscript composition. Dr. Lianne Lefsrud and Dr. Renato Macciotta were supervisors for this project and contributed to the study design and manuscript edits. Dr. Fereshteh Sattari was involved in study design, providing research direction, editing manuscripts, and assisting with publishing procedures.

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# 1. Introduction

## 1.1. Background

Canada's rail transportation network is a critical part of Canada's integrated supply chain which connects industries, consumers, and resource sectors to ports on the Atlantic and Pacific coasts. Operating more than 40,000 kilometers of track length across the country, Canadian railways play a prominent role in transferring goods and people across the country (1). This transportation activity resulted in moving $320 billion worth of goods and over 100 million passengers by rail each year (2,3).

The rail transportation system in Canada is adequately safe overall, when weighted against the benefits of it; as reflected by the social licence to operate. However, railway accidents still persist. The Lac-Mégantic accident, where 47 people lost their lives after a freight train derailment in 2013 (4) and the Lake Wabamun accident where a train derailment spilled 788,000 liters of product into the lake in 2005 (5) are two recent examples of severe rail occurrences. These rail events showed that there is still room for improvement in the safe transportation of passengers and goods by rail and the railway's Safety Management System (SMS) must be continually re-evaluated and improved. Investigating the literature showed that various researches have focused on evaluating one specific element of SMS, while a few studies analyzed the influence of the system as a whole on safety performance. To address this gap in the literature, the first study presented in this thesis focused on the assessment of the entire SMS elements (with a special focus on DG transportation) by applying Root Cause Analysis (RCA), Event Tree Analysis (ETA), and Bow Tie Analysis (BTA). Then, useful recommendations are provided to enhance SMS in the Canadian railway industry.

The findings of the first study revealed that among those SMS elements that showed the major gaps, there was a common cause: risk assessment. Risk assessment is a basis for the SMS and many of the flaws can be avoided if a thorough risk assessment is carried out, as this would properly identify the hazards and most effective and efficient mitigation strategies. Moreover, without a quantifiable risk assessment, defining the objectives of SMS would be difficult. Reviewing the literature showed that the SMS is usually formulated without a quantitative risk assessment as a support, because of its costs in terms of money and time (6). To this end, the second study presented in this thesis focused on railway risk assessment and quantification of risk by applying a useful model named Safety Risk Model (SRM). The SRM is using Fault Tree Analysis (FTA) and ETA to identify the current level of the risk in terms of injuries and fatalities. A review of the literature revealed that a comprehensive SRM that aggregates Canadian railway operations (Federally regulated) is not available. In order to address this gap and contribute to the continuous improvement of rail transportation safety, the second research evaluated the risks associated with the Canadian railway system by applying a Canadian customized SRM (C-SRM). Developing the C-SRM also provided an opportunity to implement a risk reduction analysis to estimate the effect of the introduction of a new control measure, Enhanced Train Control (ETC). ETC technologies were developed to increase awareness of the train operator in combination with fail-safe systems similar to the PTC system functionality implemented in the US (7).

## 1.2. Research objectives

Our research seeks to enhance rail transportation safety by:

- Finding the gaps in the railway's SMS based on the relationship between the causes and consequences of rail occurrences (with a special focus on DG main-track train derailments) and SMS elements
- Providing practical recommendations to improve the management of each SMS element and reduce the gaps
- Developing a customized Canadian SRM called C-SRM in order to quantify the risk (in terms of injuries and fatalities) and improve the risk assessment as a basis for the SMS
- Assessing the potential effects of developing ETC, a new control measurement, through a risk reduction analysis by using the employed C-SRM

## 1.3. Thesis outline

This thesis includes four chapters. Chapter 2 evaluates railway's SMS and presents useful recommendations for improving SMS in the Canadian railway industry. Chapter 3 investigates the risks associated with the Canadian railways by using a SRM approach. Chapter 4 summarizes the results of these studies.

## 1.4. References


1. Canada Gazette. Canada Gazette [Internet]. 2022. p. Part I, Volume 156, Number 6. Available from: https://www.gazette.gc.ca/rp-pr/p1/2022/2022-02-05/html/notice-avis-eng.html#nc2

2. Railway Association of Canada. Canada's Freight Railways: Moving the Economy [Internet]. 2020 [cited 2022 Jun 7]. Available from: https://www.railcan.ca/101/canadas-freight-railways-moving-the-economy/

3. Railway Association of Canada. Rail Trends 2020. 2020.

4. Transportation Safety Board of Canada (TSB). Railway Investigation Report R13D0054 [Internet]. 2014 [cited 2020 Jun 28]. Available from: https://www.tsb.gc.ca/eng/rapports-reports/rail/2013/R13D0054/R13D0054.html

5. Railway Investigation Report R05E0059 - Transportation Safety Board of Canada [Internet]. [cited 2022 Jul 4]. Available from: https://www.tsb.gc.ca/eng/rapports-reports/rail/2005/r05e0059/r05e0059.html

6. Demichela M, Piccinini N, Romano A. Risk analysis as a basis for safety management system. Journal of Loss Prevention in the Process Industries. 2004;17(3):179–85.

7. Canadian Rail Research Laboratory (CaRRL). Canadian Rail Research Laboratory Report on Enhanced Train Control. Transport Canada Report. 2018.

# 2. A critical analysis of train derailments in Canada through process safety techniques and insights into enhanced safety management systems

A version of this chapter was published as Esmaeeli N, Sattari F, Lefsrud L, Macciotta R. "Critical Analysis of Train Derailments in Canada through Process Safety Techniques and Insights into Enhanced Safety Management Systems", Journal of Transportation Research Record.

## 2.1. Introduction

Railways play a prominent role in Canada's integrated supply chain and help to ensure that the country stays competitive in global supply chains. Canadian railways open up world markets by operating more than 41,000 kilometers of track across the country. These railways connect industries, consumers, and resource sectors to ports on the Atlantic and Pacific coasts, which has resulted in transporting $310 billion worth of goods by rail each year (1). Rail transfers contribute to the transportation of various types of goods, including dangerous and non-dangerous goods. One essential transportation activity for most industries is rail transport of dangerous goods (DG). Rail transfer of fuels and chemicals increased by 42.5% between 2011 and 2017 (2). Furthermore, total annual oil production is expected to increase by an average of 3% until 2021 and reach 4.25 million barrels per day (b/d) by 2035 from 2.9 million b/d in 2018 (3). Railways provide the opportunity to deliver goods to locations that are inaccessible by other transportation modes such as pipeline and road. This feature makes the role of rail transportation more important than before, especially in accommodating the increase in traffic.

### 2.1.1. Dangerous goods transportation safety

The transportation system in Canada is relatively safe, as compared to other modes, even for the shipment of DG (4). Since promulgating the Canada Transportation Act in 1996, mainline accident rates have decreased considerably for federally regulated railways despite substantial growth in traffic (5). Transport Canada (TC) estimates that out of tens of millions of DG shipments every year, 99.997% of shipments arrive at their destination without any serious incidents (6). The decline in rail accident rates can result from the introduction of safety management systems (SMS), increased interaction between railway companies and regulators, and other new safety initiatives

(7) such as human factors analysis and classification system (HFACS). It is noted that although part of these initiatives is led by regulatory bodies (such as TC), many are initiated and led by industry. Nonetheless, railway accidents persist. The Lake Wabamun accident where a train derailment spilled 788,000 litres of product into the lake in 2005 (8) and the Lac-Mégantic accident where 47 people lost their lives after a freight train derailment in 2013 (9) are two recent examples of serious accidents that increased public sensitivity to transport of DGs by rail. These accidents show that there is still room for improvement in safe transportation of DG by rail and railway's SMS must be continually re-evaluated and improved.

### 2.1.2. Safety management systems

TC's experience and research show that complying with all regulated requirements does not guarantee that the organization's operations would not pose a risk to safety (10). As such, simply making more regulations to address specific occurrences does not necessarily improve transportation safety. According to Miller (4), comprehensive implementation of SMS is the primary tool for the transportation sector to responsibly, proactively, and systematically address risk within its operations. Edwards (11) defines SMS as a systematic and explicit approach which helps to manage risk and control losses. Roland et al. (12) expand on this by stating that system safety is the application of special technical and managerial skills to the systematic, forward-looking identification and control of hazards throughout the life cycle of a project, program, or activity.

The framework of SMS with its twelve elements was initially described in the Guidelines for Technical Management of Chemical Process Safety which was published in 1989, and developed as part of the chemical industry's responsible care initiative (13). The SMS framework includes process and equipment integrity, human factors, incident investigation, and more (Appendix B). Over time, the number of SMS elements has increased to 20 elements by adding new elements such as process safety culture (14). This study is part of a broader research project which has been already published, where a 12-element SMS framework was implemented (15). In order to align with that project and provide comparable results, a 12-element SMS framework was also chosen for the current study.

### 2.1.3. Literature review

Academic research has applied SMS to various transportation sectors, mostly focusing on one element of SMS. Havold (16) studied safety culture in the maritime transportation industry. The results of the study confirmed that measuring safety culture as a predictor of unsafe work behavior is an appropriate tool for accident prevention and safety improvement. Bielic et al. (17) examined how the characteristics and behaviors of leadership impact safety in maritime transportation. These elements have a positive effect on creating and maintaining a positive safety culture, and improve ship safety. Hsu et al. (18) focused on the aviation sector and examined the key components of airline SMS. They found that policies that convey the top managers' vision on safety to all staff is the most important SMS dimension. In the rail industry, one SMS element that has attracted researchers' attention is human factors (19–21). Kyriakidis et al. (22) proposed a data-based framework to identify the most significant human performance factor affecting the performance of railway operation. They analyzed 479 railway operational accidents and incidents from different countries such as Canada, United States (US), etc.  The results of the study revealed that safety culture and distraction are the prime contributors to accidents and incidents. Dindar et al. (23)

identified employees' physical conditions such as lack of sleep, insufficient efficiency and poor judgement due to alcohol or drugs, restriction of work or motion, and injury or illness as important factors in rail accidents.

Other researchers have examined SMS from a broader perspective. Read et al. (24) focused on improving railway SMS and identified three key insights. First, feedback mechanisms need improvement to better understand the effectiveness of control measures. Second, formal control at higher levels of the system need strengthening. Third, focusing on failures rather than normal performance provides additional insight on failure modes. Chen & Chen (25) focused on SMS in aviation, which showed that developing an SMS measurement scale to evaluate the performance of company's SMS can be done through a five-factor structure: documentation and commands, safety promotion and training, executive management commitment, emergency preparedness and response plan, and safety management policy.

To summarize, various studies have focused on analyzing one specific element of SMS, such as safety culture, human errors, etc. A few studies analyze the influence of the system as a whole on safety performance (26–28). To address this gap in literature, this study focuses on the assessment of the entire SMS on railway operations, specifically on the transportation of DG.

There are different risk analysis methods that can be used in this regard. Among them, bow tie analysis (BTA) has been employed in the current study because of the following advantages. Many studies have confirmed that this technique can present a direct and logical relationship between hazards, tasks, safety controls, risks, and the potential outcomes of accidents. As a result, BTA provides valuable information that can be used to prevent, control, and mitigate undesired events (29, 30). This method has also gained acceptance as a credible risk and safety management tool as it provides a graphical representation of accident scenarios, which is useful for comprehensive risk analysis and safety assessment (31). Also, BTA is easy to understand and does not need a high-level of expert knowledge (32). In order to develop the BTA, root cause analysis (RCA) and event tree analysis (ETA) have been employed in this study.

### 2.1.4. Research objectives

The main goal of this paper is to find gaps in the railways' SMS with a special focus on the DG main-track train derailments (from a list of class 1, 2, 3 out of six classes of occurrences) from 2007 to 2017, which resulted in the transportation safety board's (TSB) investigation of 40 accidents (Appendix A includes definitions of six classes of occurrences). This study will apply BTA on main-track derailments for petroleum crude oil trains to find the main causes and consequences of this type of accident. The reason for focusing on accidents pertaining to trains carrying petroleum crude oil is because these are among the highest consequence accidents. From this, we recommend preventive and mitigative measures to limit the consequences of similar accidents. Moreover, all 40 accidents are investigated in order to categorize their causes and consequences based on the BTA results. By investigating the frequency and the relationships between main causes and consequences of these accidents and the SMS elements, the gaps in the SMS elements are identified and ranked from most to least frequent. Finally, we aim to provide useful recommendations for enhancing SMS in the Canadian railway industry.

## 2.2. Methodology

### 2.2.1. Data sources and analysis methods

This study investigates the TSB main-track train derailment reports for class 1, 2, 3 occurrences (Appendix A) in transportation of DGs from 2007 to 2017. This research focuses on occurrences with significant consequences. As a result, Class 4 to 6 occurrences were not considered or assessed. At the time of this study, some occurrences in 2018 and 2019 were still under investigation, therefore the overall project included information until the last year of complete data.

A class 1 occurrence is a series of occurrences with similar characteristics that have formed a pattern of one or more significant safety risks over time. These safety risks have been previously identified in the investigations done by TSB (or similar organizations in other jurisdictions) or have emerged from statistical analysis. A class 2 occurrence attracts a high level of public interest across Canada or internationally because of its significant consequences. It affects many people, some of whom may be fatally or seriously injured, releases large amounts of DGs, and causes significant damage to property and/or the environment. A class 3 occurrence may have significant consequences resulting in a high level of public interest. The consequences may include multiple fatalities and/or serious injuries, or there may be a medium-sized release of DG. Also, there is moderate to significant damage to property and/or the environment (33).The class of occurrence is mentioned in the rail occurrence database system (RODS) – available at www.tsb.gc.ca.

TSB reports identify main-track derailments in the title. All 165 TSB reports (class 1, 2, 3 occurrences) between 2007 and 2017 were investigated to identify whether a DG tank car was involved in the derailment. It is noteworthy that the occurrences with the release of fuel from locomotive fuel tank were also considered as DG occurrences. There was a total of 40 DG main-track derailments (class 1, 2, 3 occurrences) in the study database, for this 10-year period. To identify the highest consequences occurrences, we selected DG occurrences involving DG release, fires, or explosions, resulting in a total of 14 accidents (Appendix A). Considering the class of each of the occurrences which represents the severity of their consequences, we identified petroleum crude oil as the DGs with the highest consequence when transported by rail (for main-track derailments investigated by the TSB).

Second, we started creating a bow tie (BT) for petroleum crude oil main track derailments. We included all of the petroleum crude oil investigations to determine the main causes, consequences, and prevention and mitigation measures for these accidents. Based on the results, we then drew a comprehensive BTA diagram to represent all accidents for petroleum crude oil. Throughout this second step, the relationship between main causes and consequences and gaps in railway SMS elements were identified through the development of RCA diagrams. Although regulated rail SMS have been tailored towards rail transport, in order to analyze the specifics of DG transportation, we adopted an SMS tailored to the production, storage, management and transportation of DG from the Canadian Society of Chemical Engineering (CSChE). Thus, the insights from our review are generalizable to any rail operator's specific SMS. The framework of SMS that was used in this study has twelve elements, which is described in detail in Appendix B. The Center for Chemical Process Safety (CCPS) moved from the twelve-element system to a risk-based approach in 2007. However, the CSChE's Process Safety Management Division (PSMD) retained the original, more easily implementable CCPS for use in Canada, where SMS is not regulated and, thus, relies on voluntary adoption by site operators (34).

Next, we categorized the causes and consequences of all the study dataset based on BTA results. By investigating the frequency of each category, the main causes and consequences were ranked. Based on the identified relationship between SMS elements and causes and consequences, the gaps in the SMS elements were identified and then ranked from most to least frequent. Figure 2-1 summarizes our methodology.

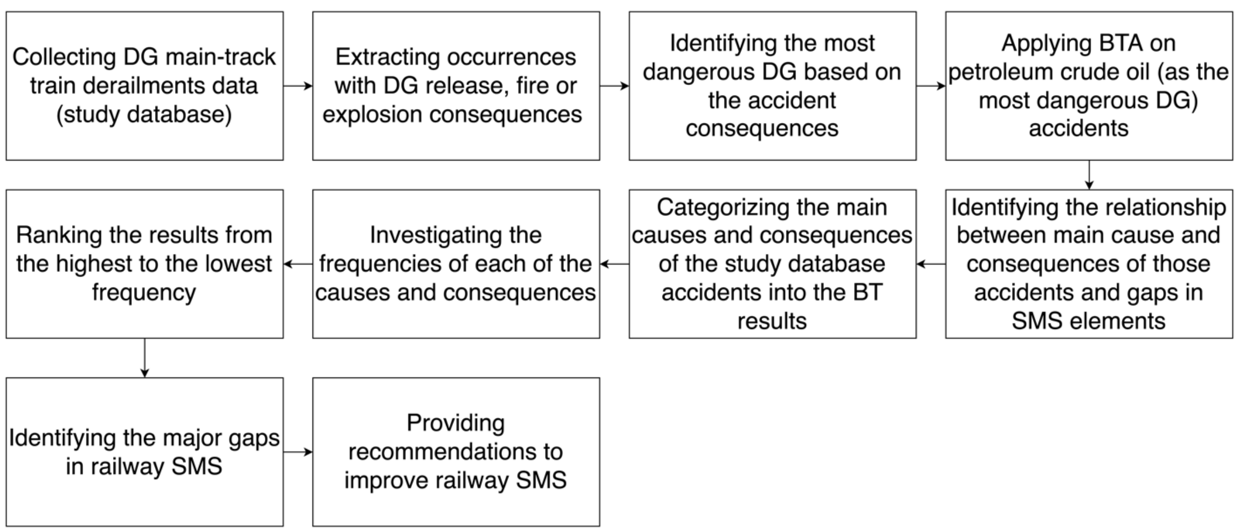


**Figure 2-1.** Methodology flowchart

## 2.2.2. Root cause analysis (RCA)

RCA is a retrospective technique which reviews the sequence of events that lead to any given endpoint (35). Applying this technique identifies the factors that allows failure modes. It also examines whether the same or related factors are present in other parts of the system. Determining the root causes of an incident identifies preventative measures such as modifying the design, manufacturing process, or operating procedures (36). For this study, we used RCA instead of fault tree analysis (FTA) to understand the sequence of causes that led to the incidents.

### 2.2.3. Event tree analysis (ETA)

ETA is a forward-looking, bottom up, logical modeling technique which starts with a loss of containment event (top event) and analyzes all possible outcomes resulting in a range of consequences (37). ETA is developed qualitatively; however, the likelihood of different consequences can be quantified by determining the frequency (by using historical data) or probability (by using experimental failure mode data) for each possible pathway. This technique can be applied before an incident happens to quantify the range of possible outcomes or after an incident to investigate the functional failures of the system. This technique is typically used in transportation and nuclear power plants (38,39).

### 2.2.4. Bow tie analysis (BTA)

BTA is a fairly new method for safety assessment and risk analysis of a system to illustrate the relationships among various factors — hazards, causes, and consequences — and identify measures to prevent the likelihood of occurrence of undesired events and/or mitigating the consequences of failures within an industrial system (31, 40). This technique is a combination of FTA and ETA, which are connected through the top (loss of containment) event. Loss of containment is the top event for the backward looking FTA or RCA, whilst it is the initiating event for the forward looking ETA (41). BTA's advantages are its simplicity, versatility, and pictorial display, which make it easily understandable and applicable areas across industries (42). For instance, oil and gas (43, 44), chemical (45), healthcare (42, 46), marine (47), and transportation industries (48, 49) have benefited from the use of BTA.

### 2.3. Results

After investigating all the 165 rail occurrences (class 1, 2, 3 occurrences) between 2007 and 2017 that have TSB reports, we identified 40 DG main-track train derailments that had occurred while transporting DG. It is noteworthy that rail accidents and incidents together are called rail occurrences (Appendix A). All 40 DG main-track train derailments (class 1, 2, 3 occurrences) which represent our study database were in the category of accidents.

To identify the occurrences with the highest consequences, we selected accidents caused by DG release, fire or explosion, leaving us with 14 accidents in the first step. Out of the 14 accidents, ten had a DG release and also resulted in a fire or explosion. Further investigations of these 10 accidents revealed that three of them were in class 2, while the rest of them were in class 3. There were no class 1 occurrences among these 10 accidents.

All of the three main-track train derailments in class 2 happened while transporting petroleum crude oil. As class 2 occurrences have more severe outcomes compared to class 3 occurrences, we concluded that accidents involving transportation of petroleum crude oil have the highest consequences when compared to other DG rail occurrences investigated by TSB. We applied RCA on TSB's main-track derailments reports for the trains transporting petroleum crude oil (Figures 2-2_2-8) to understand the sequence of events resulting in the train derailments and the main causes of these accidents. Accident R13T0060 is a class 3 petroleum crude oil occurrence. Although the consequence level is different than class 2, the processes leading to the occurrence when transporting petroleum crude oil still provide valuable information to identify the main causes of petroleum crude oil accidents. Collectively, based on the RCA results, the main causes of these derailments consist of the following:

- Weaknesses in different aspects of risk assessment (e.g., gaps in railway risk assessment when making a change to its operations, weakness in TC risk-based approach for identifying targeted regulatory inspection).
- Rail defects (e.g., rail end batter (REB), vertical split head (VSH) defects, and vertical split rim (VSR) crack).
- Gaps in regulations (e.g., using new technologies for inspection is not required by regulation, absence of regulatory requirement for wheel impact load detector (WILD) threshold)
- Gaps in railway guidelines and instructions (e.g., weakness in railway track inspection guidelines for joint inspection and rail grinding).
- Weaknesses in training (e.g., insufficient mentoring and support for assistant track supervisor (ATS) during the on-the-job portion of the training, working as fully qualified ATS while the employee was newly hired, not reinforcing training by practical training).
- Weaknesses in railway standards (e.g., weakness in railway standard for REB monitoring).
- Weaknesses in audit (e.g., gaps in internal audit, not formally assessing safety culture, ineffective audit programs and follow-up, insufficient oversight, inadequate inspection).
- Infrequently performed tasks by employees (e.g., track foreman with no locomotive engineer (LE) operation background assessed fire engine post-accident).

- Human error (e.g., track supervisor (TSPVR) occupied with another task and did not check the rail repair process, no physical measurement was taken by snow patrol foreman (SPF) in rail end mismatch situation).
- Cold weather condition (e.g., reducing material fracture toughness and ductility in low temperature which causing rail breaks, wheel breaks).

After identifying these causes, the research team verified that the relationship between causes and gaps in SMS elements were shown in the following RCA figures along with a summary of the accident reports. Following is an example of an accident report:

**Report R13T0060:** On 03 April 2013, a Canadian Pacific Railway (CP) freight train was proceeding eastward on the Heron Bay Subdivision when it experienced an undesired emergency brake application near White River, Ontario. Twenty-two cars derailed, seven of which were DG tank cars loaded with petroleum crude oil. A number of cars rolled down an embarkment and two of the DGs tank cars released approximately 101,700 litres of product. There were no injuries.

The derailment occurred due to the R1 wheel of the 34th car failure. The R1 wheel fractured as a result of a VSR. When the vertical split rim crack reached a critical size, the rim could no longer support normal service loads and the wheel failure occurred. The other factor that affected wheel failure was that the wheel with high impact was not removed from the service in a timely manner. Although recorded wheel impact was condemnable under association of American railroads (AAR) Rule 41, the WILD guidelines of CP permitted the R1 wheel to remain in service. The reason was railway guideline regarding WILD did not provide adequate guidance for dealing with wheel impacts that are condemnable under AAR Rule 41. In the absence of regulatory threshold and oversight for WILD technology, company guidelines for WILD thresholds may not be sufficiently robust and increase the risk that wheels with elevated impact remain in the service.

After the train derailment, a large amount of product was released from tank car top and bottom fittings. Those fittings arrangements met design criteria; however, they were not adequately protected and resulted in the release of petroleum crude oil (50).

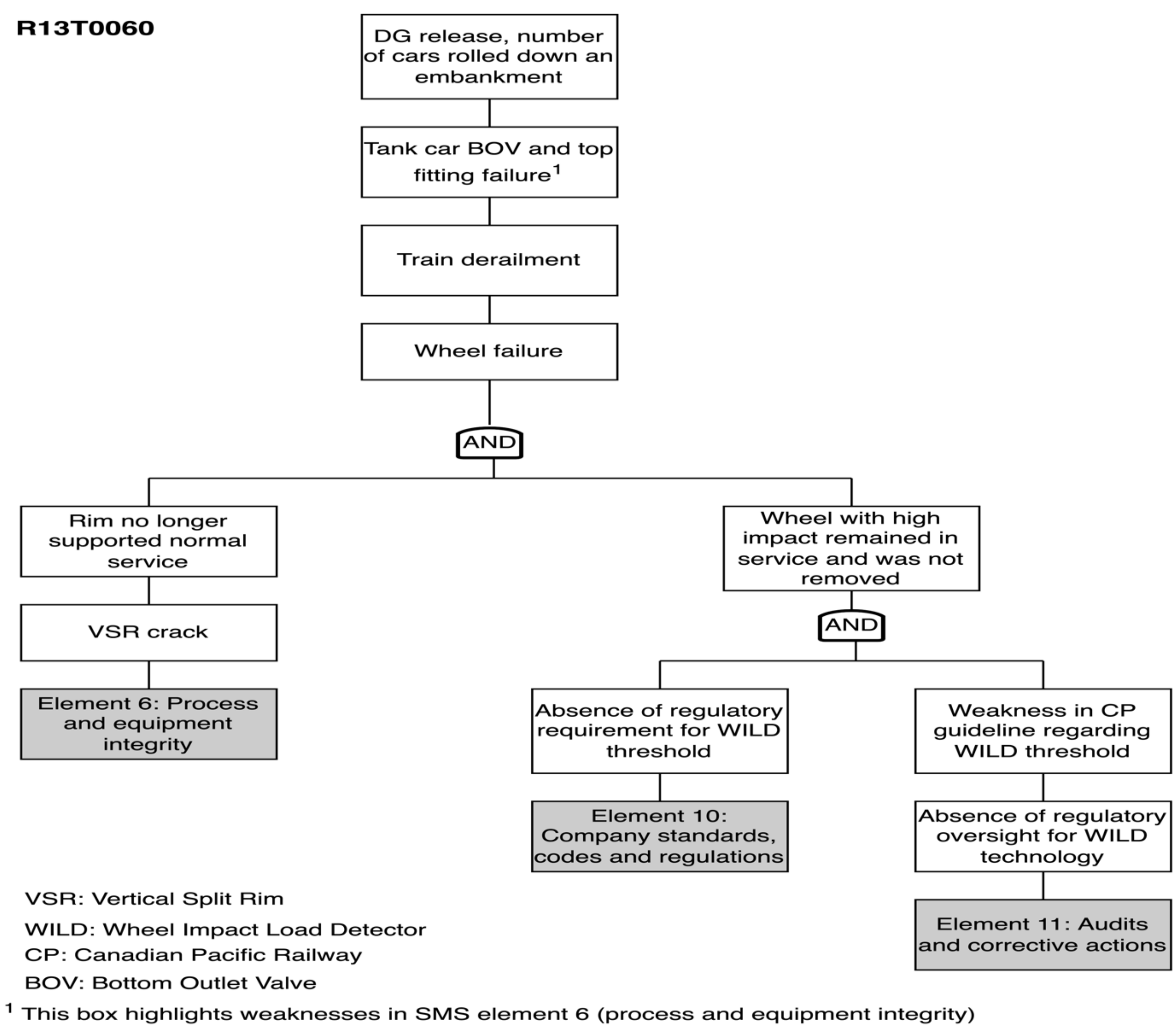


**Figure 2-2.** RCA for accident R13T0060

This accident highlights that some weaknesses in SMS elements, such as process and equipment integrity, company standards codes and regulations, and audits and corrective actions, had increased the potential for a train derailment.

**Report R13D0054:** On 06 July 2013, eastward a Montreal, Maine & Atlantic railway (MMA) freight train which was parked unattended for the night at Nantes, Quebec, started to roll. The train travelled approximately 7.2 miles, reaching a speed of 65 mph when it approached the centre of the town of Lac-Mégantic, Quebec. Sixty-three tank cars carrying petroleum crude oil and two box cars derailed. About six million litres of petroleum crude oil spilled. Unfortunately, there were fires and explosions, which destroyed 40 buildings, 53 vehicles, and the railway tracks. Forty-seven people were fatally injured. There was also environmental contamination of the downtown area and of the adjacent river and lake.

There were several factors contributing to the train derailment. They are presented in detail in Figures 2-3 and 2-4. On the evening before the accident, the LE parked the train on a grade on the main track. The LE performed a hand brake effectiveness test to check if the number of hand brakes were enough to secure the train alone, but he did not implement the test properly. Although the LE released the automatic brakes, the locomotive independent brakes had not been released during the test. As a result, the train was held in place by a combination of hand brakes and independent brakes instead of being held by the hand brakes alone. Furthermore, there were no additional physical safety defences in place in order to prevent uncontrolled movement of the train.

Prior to the time of derailment, the LE noticed that the lead locomotive engine was producing excessive amounts of black and white smoke. It was caused by the failure of a non-standard engine repair which had been done eight months prior to the accident. The LE discussed the situation with the rail traffic controller (RTC) and they decided to deal with the situation in the morning. Later that night, the locomotive engine caught fire, and firefighters were sent to the location. When firefighters shut down the locomotive engine to extinguish the engine fire, no other locomotive was started. As a result, the compressor no longer supplied air to the air brake system and the effectiveness of the air brakes was reduced. The combination of air brakes and hand brakes could no longer hold the train. The train rolled down the hill and accelerated, reaching a speed of 65mph. Since there was excessive rail wear on some of the rails in the Lac-Mégantic area, it could not bear the excessive stress of a high-speed train. As a result, the train derailed in the curve at the Mégantic West turnout.

The TSB investigation shows that some of the abovementioned issues were caused by MMA's weak safety culture, for example, MMA management's tolerance of non-standard repairs like what had been done for the locomotive engine. Another instance was the systemic practice of leaving unattended trains on a descending grade without sufficient defences in place to prevent an uncontrolled movement of the train.

Following the train derailment, a large amount of petroleum crude oil was released into the environment. One of the major sources of product loss was from damaged tank heads and shells. In addition, almost every derailed tank car exhibited at least one damaged stub sill or coupler. Protection of tank car fittings were also not sufficient, which led to the release of product from damaged top fittings and bottom out valves (BOV). Another source of product loss was from breaches caused by thermal tears. In the absence of thicker steel, jackets, thermal protection on tank cars, and adequate pressure-relief capacity increase the chance of thermal tear.

A large fireball and pool fire started after the train derailment. The large quantities of spilled petroleum crude oil, the rapid rate of product release, as well as the product's high volatility and low viscosity were major factors resulting in the large post-derailment fire (50).

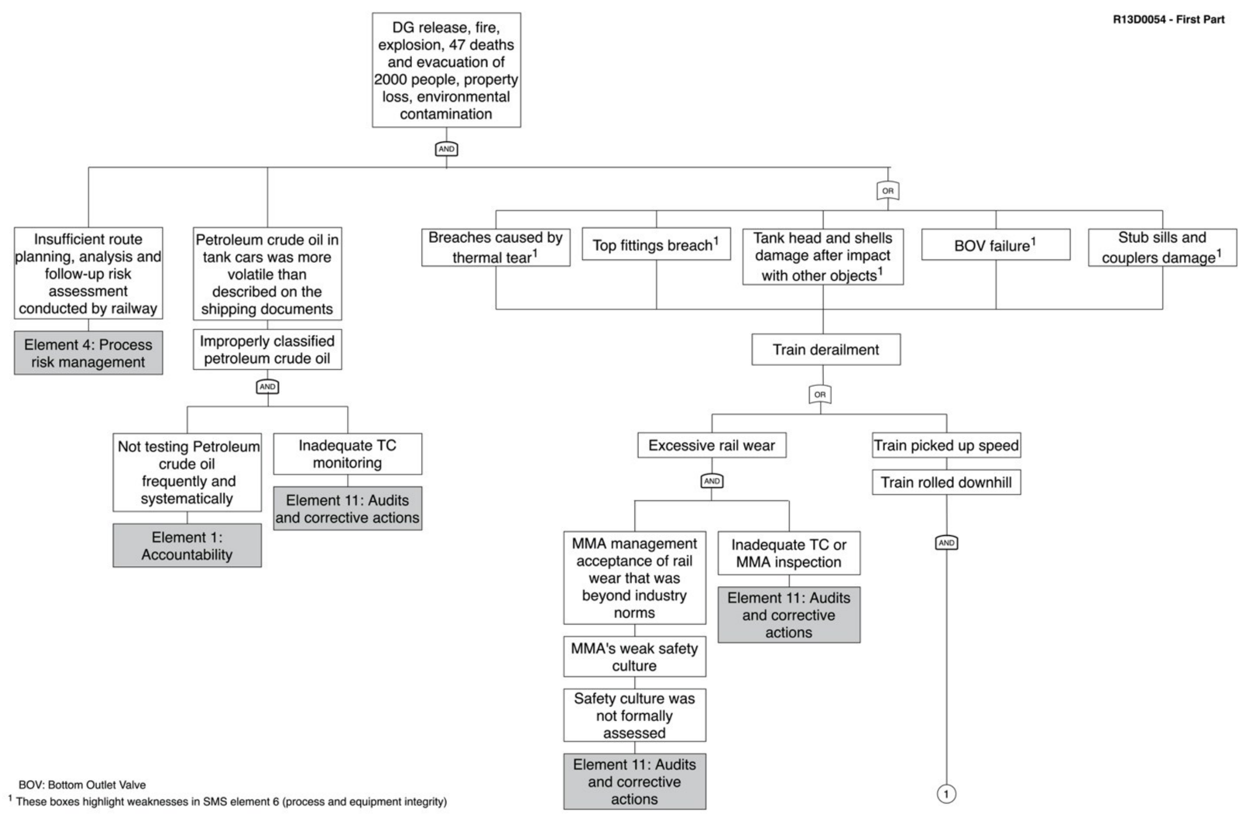


**Figure 2-3.** RCA for accident R13D0054 - First part

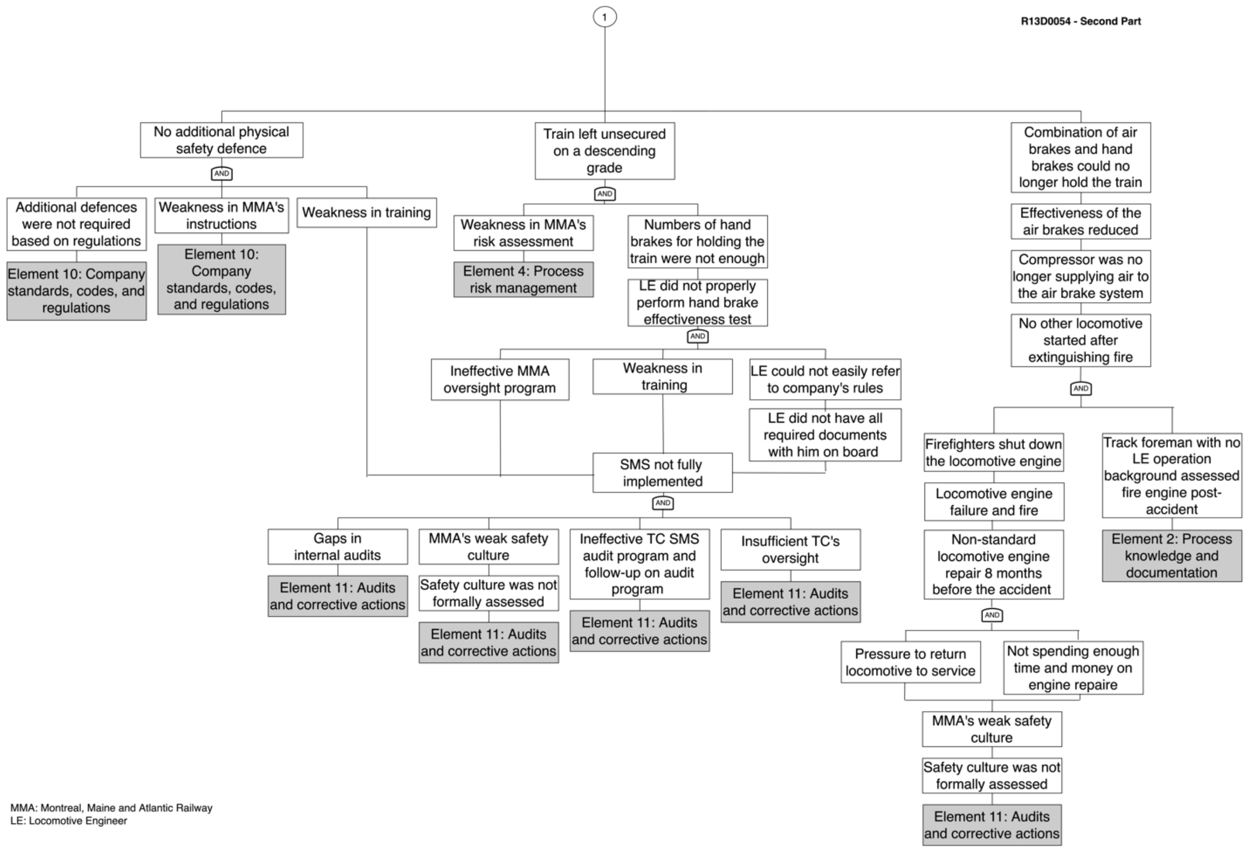


**Figure 2-4.** RCA for accident R13D0054 - Second part

The Lac-Mégantic accident again confirmed that in addition to weaknesses in the three elements that played a role in accident R13T0060, there are some other gaps in SMS elements like process risk management, process knowledge, and documentation. Moreover, human errors such as errors made by the locomotive engineer during the hand brake test, reveal that human factors can significantly impact rail accidents.

**Report R15H0013:** On 14 February 2015, a Canadian National Railway Company (CN) crude oil unit train was proceeding eastward on CN's Ruel Subdivision when it experienced a train-initiated emergency brake application at Gladwick, near Gogama, Ontario. Twenty-nine tank cars derailed. Nineteen of the tank cars were breached, and about 1.7 million litres of petroleum crude oil were released to either the atmosphere or the earth's surface. The released product ignited, and the fire lasted for five days. About 900 feet of mainline track was destroyed, but there was no evacuation or injury.

The train derailment happened when the insulated rail joint in the south rail failed beneath the head-end of the train. The failure of the insulated joint bars was caused by different factors. Low temperature at the time of the accidents reduced joint bar material fracture toughness and ductility and made it more susceptible to brittle failure. In addition, there were fatigue cracks which led to the REB condition in the joint bar. REB is indicative of a degrading joint support and can ultimately lead to the rail or joint failure. These factors, combined with repeated wheel impact, resulted in increased stress to track infrastructure. Another contributor to the joint failure was insufficient track maintenance while traffic tonnage was increased. This could lead to more rapidly degrading track structure and increase the risk of track infrastructure failures.

The mentioned fatigue cracks were presented in the joint bar some time before the train derailment; however, they remained undetected until the rail failure occurred. The ATS who was responsible for the joint inspection did not have sufficient experience and training for performing his job. Furthermore, there were weaknesses in CN's standard for REB monitoring. As a result, the inspection process was not performed properly by the ATS. Moreover, the use of new technologies for track inspection was not required based on existing regulations. Consequently, the chance of not identifying the rail deficiencies was much higher. These factors, as well as insufficient TC inspection, resulted in the fatigue cracks that were not detected until the rail failure occurred.

The accident occurred when the train was traveling at 38 mph. The speed of the train increased the severity of the derailment and its outcomes. As a result of damage to the tank cars (including shell breach and BOV failure), petroleum crude oil was released to the environment and caused contaminations and fire (50).

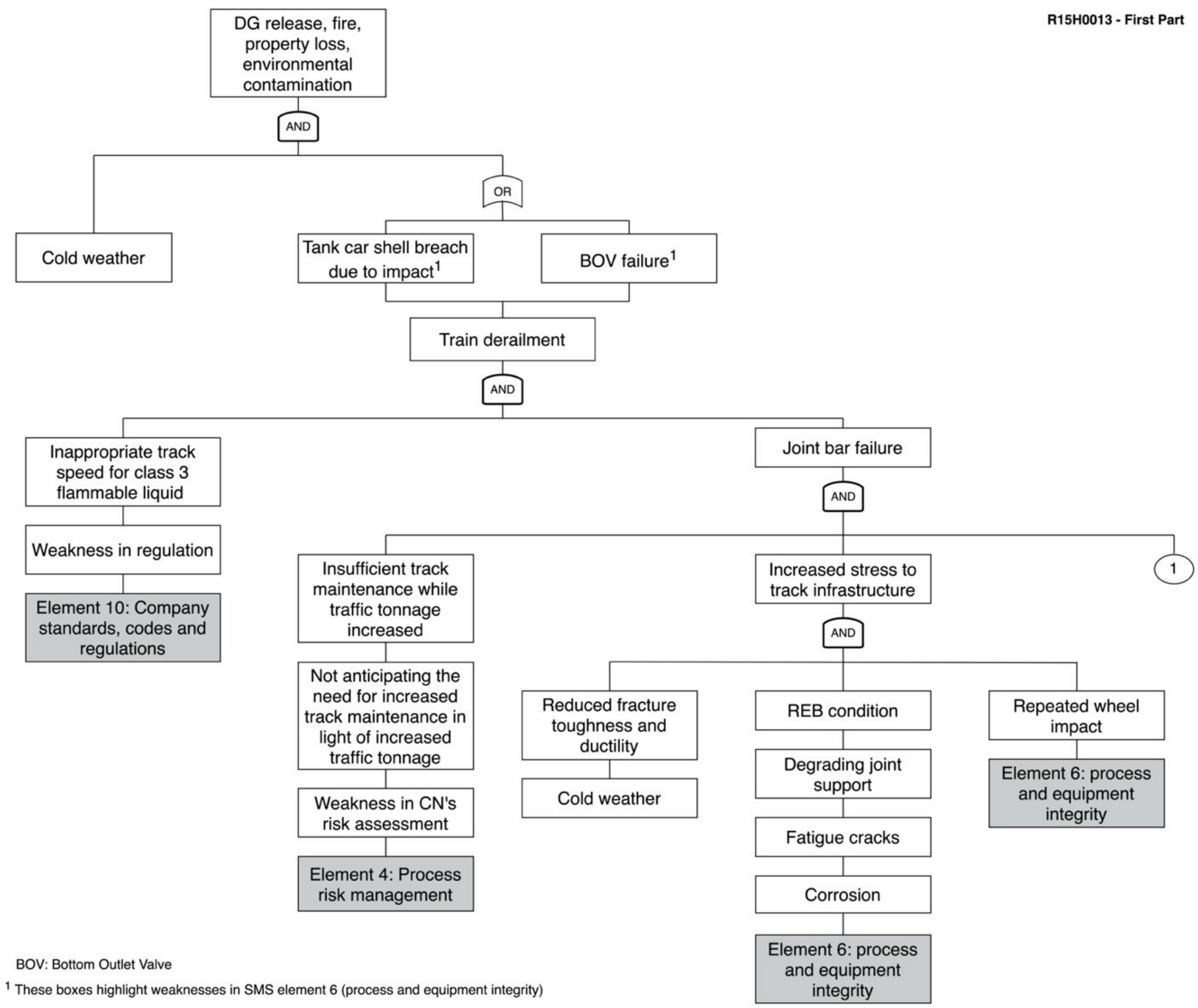


**Figure 2-5.** RCA for accident R15H0013 - First part

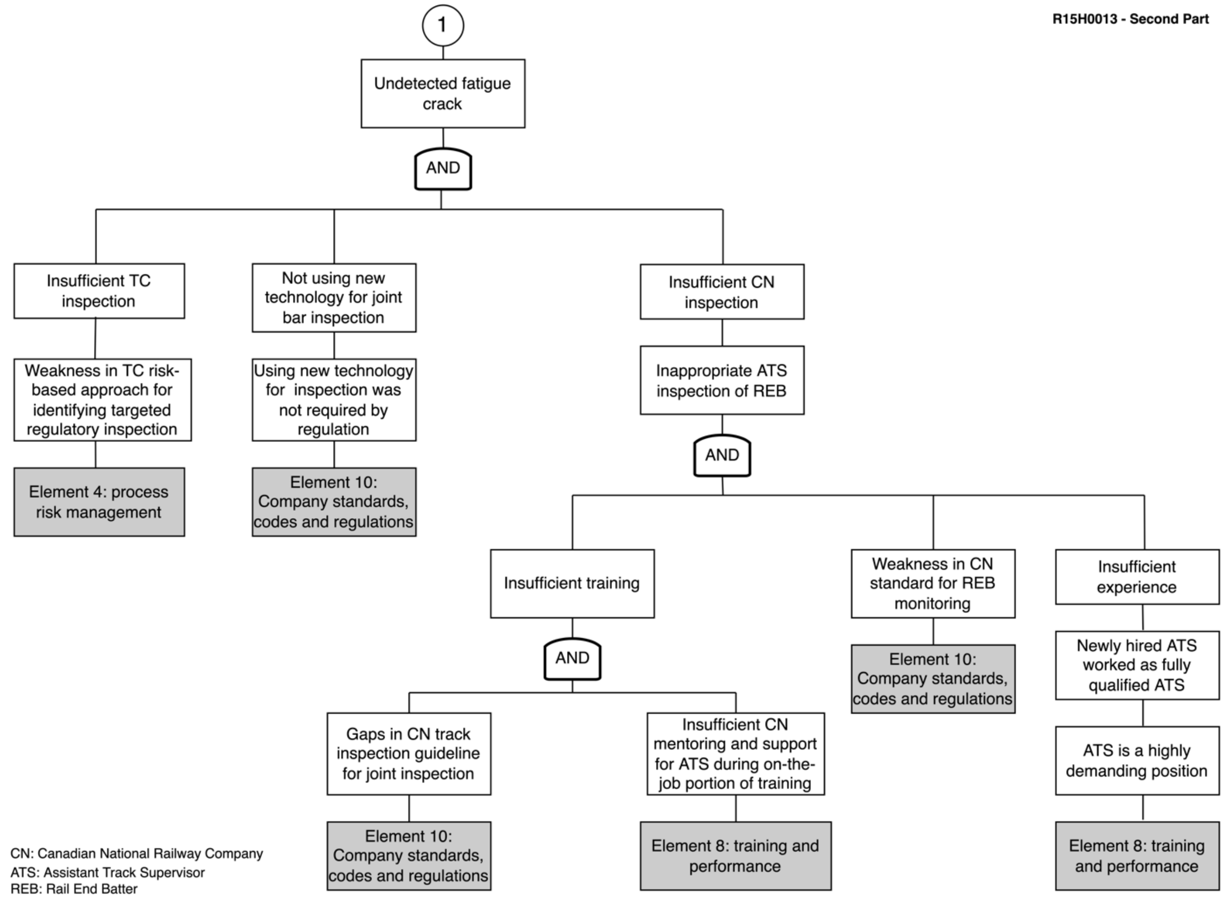


**Figure 2-6.** RCA for accident R15H0013 - Second part

Accident R15H0013 revealed that in addition to the previously mentioned gaps in SMS elements, weakness in the training and performance element can also influence rail accidents.

**Report R15H0021:** On 07 March 2015, a CN crude oil unit train was proceeding eastward on CN's Ruel Subdivision when it experienced a train-initiated emergency brake application near Gogama, Ontario. Thirty-nine tank cars were derailed. As a result, about 2.6 million litres of petroleum crude oil were released to atmosphere, water, or earth's surface. The released product ignited and caused explosions. However, neither evacuation nor injuries were reported.

The derailment happened when the south rail failed catastrophically beneath the train. TSB investigations show that VSH defects had been present in the east parent rail but were not identified during the SPF inspection because a dye penetrant test was not performed. Moreover, plug rail repair was not implemented properly by the SPF. After the repair, the plug rail was higher than the parent rail; however, no physical measurements were taken. In addition, no specific guidance was provided to CN engineering employees relating to the length of grinding. Therefore, the SPF visually assessed the mismatched situation which resulted in an inaccurate estimation of the difference between plug rail and parent rail. As a result, the applied rail grinding was insufficient. On the day of the repair, the TSPVR, who was responsible for checking the repairment result, became occupied responding to another derailment and did not check the plug rail repair. On the other hand, the VSH defect was either not present or too small to be detected during the last ultrasonic test conducted on the rail. Finally, all of these issues led to train derailment while proceeding the track.

The accident occurred at 43 mph which was lower than the authorized track speed of 50 mph. However, the speed of the train increased the severity of the derailment. After the derailment, a large quantity of product released into the environment because of the tank car damages (stub sill damage, shell breach, BOV failure and others) (50).

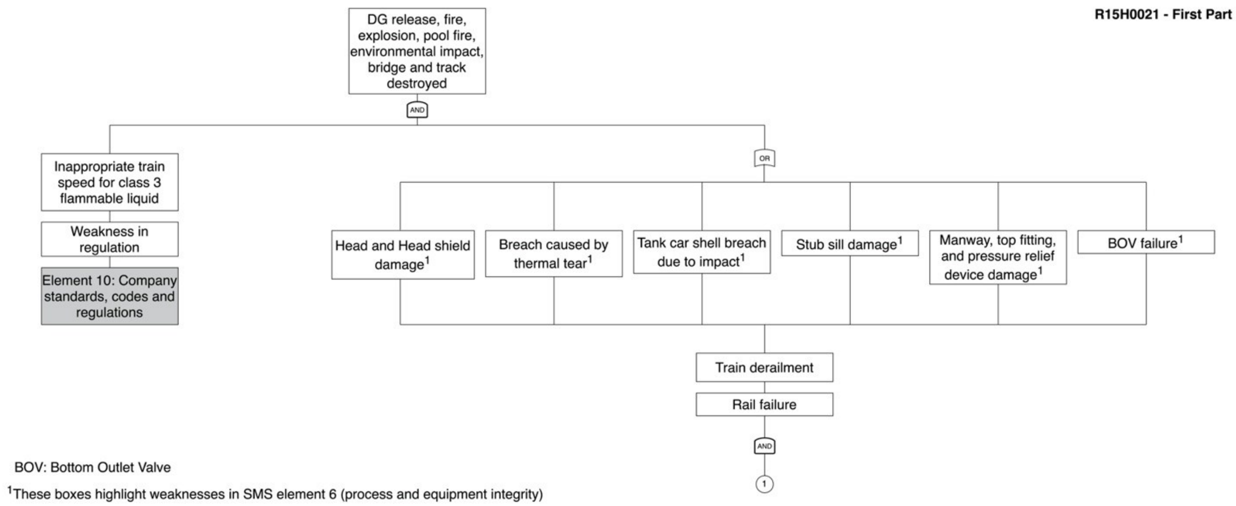


**Figure 2-7.** RCA for accident R15H0021 - First part

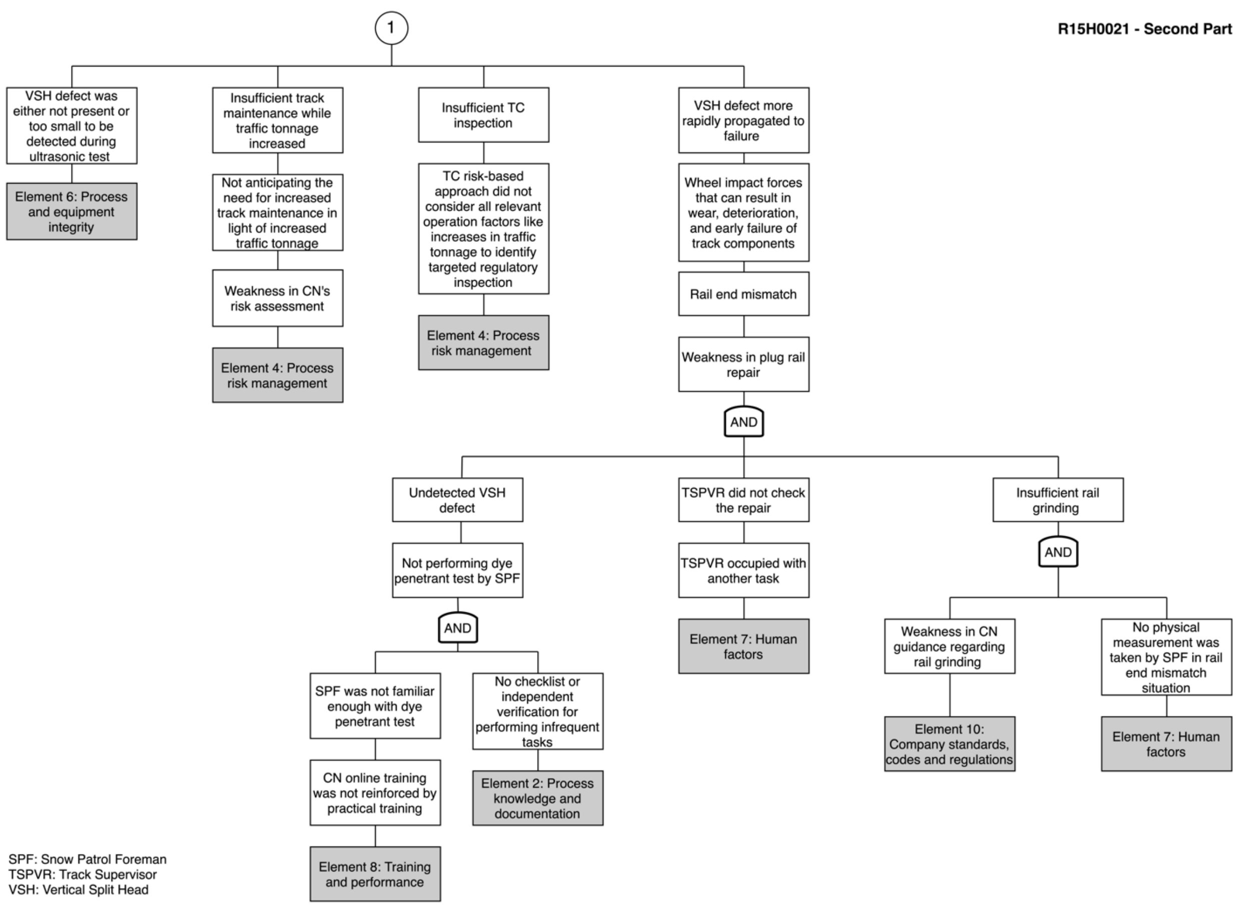


**Figure 2-8.** RCA for accident R15H0021 - Second part

This train derailment again revealed that human factors impact rail accidents significantly. Human factors are identified as one of the leading causes in occurrences in rail transportation in Canada (51). Furthermore, over the years, many of railway accidents around the world have happened because of human factor-related problems in the design and operation of railway systems (52–54).

In the next step, in order to apply ETA, the consequences of main-track derailment for petroleum crude oil train were extracted from their TSB reports. These included tank car damage, breach or rupture, DG release, explosion, fire, pool fire, property damage (track, building, etc.), environmental contamination, evacuation, and injury or death. Iranitalab et al. (55) pointed out that in case of accidents leading to release, rail transportation of large quantities of petroleum crude oil potentially exposes people living in the vicinity of railways to the ill effects of hazardous materials. An ETA was constructed based on the above-mentioned consequences. Through evaluation of the detailed reports for the 40 DG main-track train derailments (class 1, 2, 3 occurrences), the relative frequency of each consequence was calculated (Figure 2-9). For example, 23 of 40 accidents had tank car damage and the rest of the accidents had no tank car damage. As a result, within our study database, the frequency of an accident with tank car damage is 0.57 while the frequency of an accident with no tank car damage is 0.43. Among 23 accidents which had tank car damage, 17 accidents had DG release and six had no DG release. So, the frequency of an accident with tank car damage and DG release is 0.74. Also, the frequency of an accident with tank car damage and no DG release is 0.26. The relative frequency of each consequence was calculated similarly. Finally, the relative frequencies provide an approximation to the actual probabilities for each ETA branch (Frequentist approach). It is acknowledged that past performance is not necessarily an indicator of future performance; however, these statistics are considered relevant given that rail operations have not seen significant changes during the period of analysis. It is noteworthy that there is no sequence between DG release, explosion, fire, pool fire, property damage, environmental contamination, evacuation, and injury or death, meaning that they can occur simultaneously.

Table 2-1 shows how the rate of DG main-track train derailment (class 1, 2, 3 occurrences) in the ETA was calculated. The second column of the table indicates originated DG carloads for each year. These were extracted from the railway association of Canada (RAC) annual report on the performance of Canada's railway industry (2, 56). The third column of the table represents the number of DG main-track derailments (class 1, 2, 3 occurrences) investigated and reported by the TSB each year. The accident rate was derived from the division of the third column by the second column, and multiplied by 1000 to represent the accident rate per 1000 DG carloads.

**Table 2-1.** DG main-track train derailment (class 1, 2, 3 occurrences) rate calculation

| Year | Originated DG carloads | Number of DG main-track derailment (class 1, 2, 3 occurrences) reported by TSB | Accident rate (accidents per 1000 DG carloads) |
|---|---|---|---|
| 2007 | 426,789 | 6 | 0.014 |
| 2008 | 422,764 | 2 | 0.005 |
| 2009 | 379,650 | 6 | 0.016 |
| 2010 | 400,318 | 7 | 0.017 |
| 2011 | 425,124 | 2 | 0.005 |
| 2012 | 428,660 | 1 | 0.002 |
| 2013 | 493,360 | 4 | 0.008 |
| 2014 | 576,226 | 6 | 0.010 |
| 2015 | 491,802 | 4 | 0.008 |

| | | | |
|---|---|---|---|
| 2016 | 436,053 | 1 | 0.002 |
| 2017 | 504,620 | 1 | 0.002 |
| | **Total originated DG carloads (2007-2017)** | **Total number of DG main-track derailment (class 1, 2, 3 occurrences) reported by TSB (2007-2017)** | **Average accident rate (accidents per 1000 DG carloads) (2007-2017)** |
| | 4,985,366 | 40 | 0.008 |

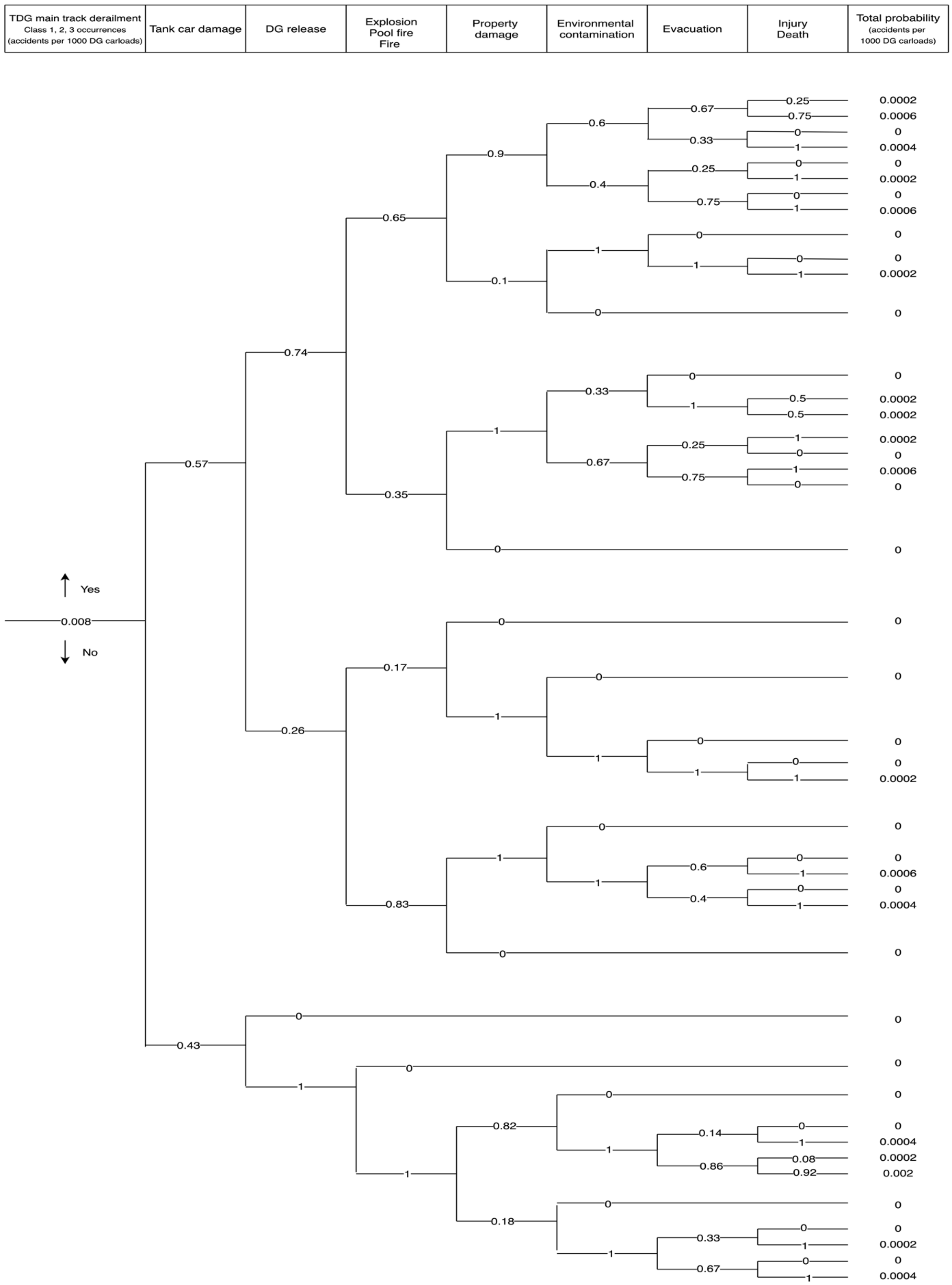


**Figure 2-9.** ETA for 40 DG main-track train derailments

The ETA results show that among those scenarios leading to death or injury, the most likely scenario had a probability of 0.0006 accidents per 1000 DG carloads. This probability pertains to DG main-track train derailment with tank car damage, DG release, and property damages. Surprisingly, there was no explosion, fire, pool fire, environmental contamination, and evacuation in this scenario. The other scenarios that caused fatality or injury were less frequent compared to the former. All of them had a similar probability of 0.0002 accidents per 1000 DG carloads.

Also, ETA results reveal that there were DG main-track derailments which had none of the outcomes showed in the ETA. This means that these derailments had no tank car damage, DG release, explosion, fire, pool fire, property damage, environmental contamination, evacuation, injury, or death consequences. The probability of this branch was 0.0004 accidents per 1000 DG carloads.

Overall, the highest total probability was 0.002 accidents per 1000 DG carloads which was related to DG main-track train derailment with no tank car damage, DG release and fire, pool fire and explosion, environmental contamination, evacuation, and injury or death. The only negative consequence of this branch of derailment was related to property damages such as building, vehicle, and railway track destruction.

The probabilities derived from these analyses follow a frequentist approach. These are associated with significant uncertainty given the limited database available, and the fact that operations evolve with time (e.g. implementation of new train handling procedures, novel technologies, changes in elements at risk, etc.). However, these probabilities provide an important quantitative description of the relative likelihoods of the different consequence scenarios that can be used for ground probability estimations of risk assessments associated with the transportation of DG by rail in Canada.

Finally, by using RCA and ETA results, a BTA diagram illustrates the relationships between the causes and consequences from a loss of containment event and proposes some useful practical mitigation and prevention measures (Figure 2-10).

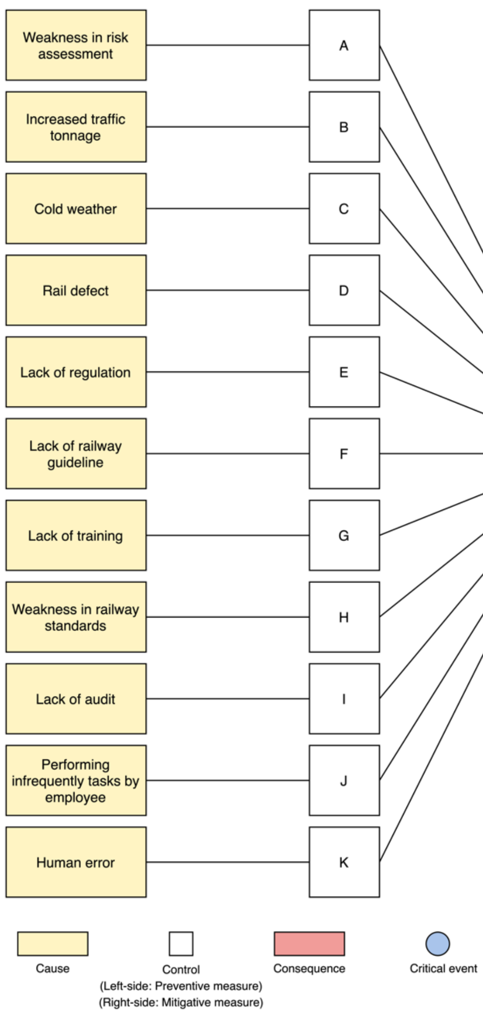


**Figure 2-10.** BTA diagram based on 40 DG main-track train derailments

Table 2-2 presents several preventative strategies. Implementing these strategies can help to prevent a train derailment from reoccurring. Some of the preventive measures in the table have been inspired by TSB reports.

**Table 2-2.** Preventive measures.

| Cause | Symbol | Preventive measure |
|---|---|---|
| Weakness in risk assessment | A | • Conducting route planning<br>• Documenting risk assessments<br>• Identifying risks and implementing mitigation measures and subsequent monitoring to assess their effectiveness |
| Increased traffic tonnage | B | • Risk assessment when making significant operational changes on the network<br>• Employees must be kept abreast when changes occur in rules<br>• Increased track maintenance demands resulting from increased traffic tonnage |
| Cold weather | C | • Developing an extreme cold weather inspection policy<br>• Establishing a cold weather temporary speed restriction |
| Rail defect | D | • Immediate remedial action<br>• Performing inspection by railway and TC<br>• Using new technologies for inspection<br>• Railway's risk assessment<br>• Place a slow order on the track<br>• Increased track maintenance demands resulting from increased traffic tonnage<br>• Increasing the investment for maintenance activities |
| Weaknesses in regulation | E | • Rules promote the use of proven new technologies for inspection<br>• Defining regulatory requirements for proven technologies (e.g. performance based on tool's metrics) |
| Weaknesses in guidelines | F | • Modifying railway track inspection guideline for joint inspection<br>• Improving railway guidance regarding rail grinding |
| Weaknesses in training | G | • Adequate mentoring and support during training<br>• Having practical training alongside the online training<br>• Assessing crew's ability with appropriate tests<br>• Providing clear rules and instructions to employees |
| Weakness in railway standards | H | • Improving and modifying railway standards regarding REB monitoring<br>• Providing adequate guidance for dealing with wheel impacts |
| Weaknesses in audits | I | • Auditing railway's SMS by TC in sufficient depth and frequency<br>• Follow-up to verify that the corrective action plans had been implemented<br>• Verifying rules and instructions are being followed<br>• Monitoring of regional audits (external) |
| Performing infrequent tasks by employee | J | • Employees must have access to the necessary reference materials<br>• Having checklist or independent verification for performing infrequently tasks |

| | | |
|---|---|---|
| | | • Adequate training<br>• Assessing crew's ability with appropriate tests |
| Human error | K | • Providing sufficient training<br>• Observing employees unannounced<br>• Proactive safety culture<br>• Formally assess or document safety culture within regulatory inspections or audits<br>• Effective railway's employees oversight program |

Table 2-3 proposes some strategies to mitigate the consequences of a train derailment once it has occurred. Some of the mitigative measures in the table have been inspired by TSB reports.

**Table 2-3.** Mitigative measures

| Consequence | Symbol | Mitigative measure |
|---|---|---|
| Tank car damage | L | • Reducing track speed for Class 3 flammable liquids. Requires adequate study on speed-consequence relationships<br>• Thicker steel<br>• Not attaching tank car stub sills directly to the tank shell<br>• Design improvements to BOV's handle<br>• Full-height head shields<br>• Providing top discontinuity protection for tank car top fitting<br>• Jackets and thermal protection on tank cars combined with adequate pressure-relief |
| Property damage | M | • Periodic assessments of the safety risks along the selected route<br>• Route planning and analysis<br>• Shipper develop an adequate regulator-approved Emergency Response Assistance Plan (ERAP) |
| DG release | N | • Using tank cars that are sufficiently robust and more impact resistant |
| Fire, pool fire and explosion | O | • Using tank-car thermal protection |
| Deaths and injuries | P | • Periodic assessments of the safety risks along the selected route<br>• Route planning and analysis<br>• Accurate sign-in/sign-out records<br>• Implementing site control measures<br>• Constructing road access for emergency response in remote locations if it is possible<br>• Shipper develop an adequate regulator-approved ERAP<br>• Accurate information on safety data sheets (SDS) for communicating the dangers of the product |
| Evacuation | Q | • Periodic assessments of the safety risks along the selected route<br>• Route planning and analysis<br>• Shipper develop an adequate regulator-approved ERAP |
| Environmental contamination | R | • River and lake shoreline surface restoration<br>• Planting program to return the lost vegetation species |

| | | |
|---|---|---|
| | | • Mobile wastewater treatment units<br>• Removing containment soil from derailment site |

Applying BTA resulted in verifying the relationship between main causes as well as gaps in railway SMS elements. Table 2-4 demonstrates how these factors are related to each other. It is noteworthy that in order to better categorize the main causes for all 40 DG main-track train derailments, we chose some general expressions which are already explained in the beginning the result section.

**Table 2-4.** Relationship between causes and gaps in SMS elements

| Causes | Gaps in SMS element |
|---|---|
| Weakness in risk assessment | Element 4: Process risk management |
| Rail defect | Element 6: Process and equipment integrity |
| Weaknesses in the regulation | Element 10: Company standards, codes, and regulations |
| Weaknesses in guidelines | Element 10: Company standards, codes, and regulations |
| Weakness in training | Element 8: training and performance |
| Weakness in railway standards | Element 10: Company standards, codes, and regulations |
| | Element 6: Process and equipment integrity |
| Weakness in audits | Element 11: Audits and corrective actions |
| Performing infrequently tasks by employee | Element 2: Process knowledge and documentation |
| Human error | Element 7: Human factors |
| Cold weather | - |

The consequences of a train derailment also revealed that there are some gaps in the railway SMS. Table 2-5 presents the relationship between those consequences and gaps in railway SMS elements.

**Table 2-5.** Relationship between consequences and gaps in SMS elements

| Consequence | Gaps in SMS element |
|---|---|
| Tank car or fuel tank damage | Element 6: Process and equipment integrity |
| DG release | Element 6: Process and equipment integrity |
| Fire, pool fire and explosion | Element 6: Process and equipment integrity |
| Deaths and injuries | Element 9: Incident investigation |
| Evacuation | Element 9: Incident investigation |
| Property damage | Element 9: Incident investigation |
| Environmental contamination | Element 9: Incident investigation |

Moreover, to have a better and complete understanding of accidents, causes, and consequences, we expanded the results to include the entire database of 40 DG main-track train derailments. The frequency in each category was identified in order to prioritize causes and consequences from most frequent to least. As shown in the Tables 2-4 and 2-5, each cause and consequence demonstrate weakness in at least one SMS element. By finding the frequencies of causes and consequences, the frequency of SMS element weaknesses was calculated as well. For example, by investigating the causes of 40 DG main-track train derailments, it was identified that there were 25 causes related to the rail defects. As shown in Table 2-4, rail defects demonstrate a gap in the process and equipment integrity element of SMS. Further investigation of the 40 accident reports revealed that there were four causes related to the weakness in railway standard. Weakness in railway standard can demonstrate weakness in two different SMS elements which are company standards, codes, and regulations or process and equipment integrity (Table 2-4). The accident reports confirmed that two of the four causes were related to the gap in process and equipment integrity element of SMS. As a result, the frequency of gaps in the process and equipment integrity element of the SMS were 27 (25+2=27) based on the accident causes.

Furthermore, accident reports demonstrate that there were 23 instances of tank car or fuel tank damage, 17 DG releases and 12 fire, pool fire, and explosion outcomes. All of these consequences show gaps in the process and equipment integrity element of SMS (Table 2-5). As a result, the frequency of gaps in the process and equipment integrity element of the SMS were 52 (23+17+12=52) based on the accident consequences. Therefore, the frequency of the gaps in the process and equipment integrity element of the SMS were 79 (27+52=79) in total. The frequency of other causes, consequences and gaps in the SMS elements were calculated in the same way. Table 2-6 represents those frequencies.

**Table 2-6.** Causes, Consequences, and SMS elements' rankings

| **Ranking** | **Cause** | **Frequency** |
|---|---|---|
| 1 | Rail defect (or failure) | 25 |
| 1 | Weakness in the audit | 25 |
| 2 | Weaknesses in guidelines | 15 |
| 3 | Weakness in risk assessment | 13 |
| 4 | Weaknesses in regulation | 11 |
| 5 | Human errors | 10 |
| 6 | Weakness in training | 7 |
| 7 | Cold weather | 4 |
| 7 | Weakness in railway standards | 4 |
| 8 | Performing infrequently task by employee | 3 |
| **Ranking** | **SMS element (based on causes)** | **Frequency** |
| 1 | Element 10: Company standards, codes, and regulations | 28 |
| 2 | Element 6: Process and equipment integrity | 27 |
| 3 | Element 11: Audits and corrective actions | 25 |
| 4 | Element 4: Process risk management | 13 |
| 5 | Element 7: Human factors | 10 |
| 6 | Element 8: training and performance | 7 |

| | | |
|---|---|---|
| 7 | Element 2: Process knowledge and documentation | 3 |
| **Ranking** | **Consequence** | **Frequency** |
| 1 | Property damage | 35 |
| 2 | Tank car or fuel tank damage | 23 |
| 3 | DG release | 17 |
| 4 | Fire, pool fire and explosion | 12 |
| 4 | Evacuation | 12 |
| 5 | Environmental contamination | 9 |
| 6 | Deaths and injuries | 7 |
| **Ranking** | **SMS element (based on consequences)** | **Frequency** |
| 1 | Element 9: Incident investigation | 63 |
| 2 | Element 6: Process and Equipment integrity | 52 |
| **Ranking** | **SMS element ranking (totally)** | **Frequency** |
| 1 | Element 6: Process and equipment integrity | 79 |
| 2 | Element 9: Incident investigation | 63 |
| 3 | Element 10: Company standards, codes, and regulations | 28 |
| 4 | Element 11: Audits and corrective actions | 25 |
| 5 | Element 4: Process risk management | 13 |
| 6 | Element 7: Human factors | 10 |
| 7 | Element 8: Training and performance | 7 |
| 8 | Element 2: Process knowledge and documentation | 3 |

As shown in table 2-6, the most common causes of DG main-track train derailment were rail defects or failures and weakness in audits. The next most common cause would be weaknesses in guidelines and in risk assessments. Furthermore, the three most common consequences of these accidents were property damage, tank car or fuel tank damage, and DG release. Prioritizing the weaknesses in SMS elements confirmed that process and equipment integrity is the first SMS element that needs to be improved. Incident investigation and company standards, codes, and regulations are the next SMS elements that need enhancement.

## 2.4. Discussion

Rail transportation is a safety-critical system (57) which experiences catastrophic incidents like train derailments. Our examination of investigated derailments shows that there are weaknesses in railway SMS.

Our aim was to find and address these deficiencies by applying BTA specifically on the DG main-track train derailments. We ranked the SMS elements to be enhanced: 1) process and equipment integrity; 2) incident investigation; 3) company standards, codes, and regulations; 4) audits and corrective actions; 5) process risk management; 6) human factors; 7) training and performance; and 8) process knowledge and documentation, respectively. Next, we present some practical recommendations to improve these SMS elements, some of which are inspired by TSB reports.

Process and equipment integrity is the first and foremost SMS element that requires enhancement. In the US, which has similar rail operating characteristics as Canada, the primary cause of train derailment on main track is also track and equipment failure (20). One of the main things that require more attention is reducing or preventing rail defects and failures from occurring. Although ultrasonic tests are commonly used for rail inspection and are useful in rail defect detection, defects are still difficult to detect due to technical limitations and varying features of defects (type, size, and location) (58). As a consequence, other novel technologies and approaches are also being used to identify rail defects more effectively. Lanza di scalea et al. (59) worked with the Federal Railway Authority (FRA) on ultrasonic detectors combined with laser sensors to better identify transverse defects under horizontal shelling. Xiong et al. (60) proposed a three-dimensional laser profiling system (3D-LPS) to attain rail surface defects information in complex environments. Zhang et al. (61) studied acoustic emission (AE) methods to detect track cracks at high-speed. In addition, performing more frequent inspections will help to better identify rail deficiencies before track failure. Scheduling rail inspections depend on factors such as limited track availability due to the train traffic and routine maintenance (62). Because of these challenges, some researchers have focused on finding enhancements to rail inspection. Jeong et al. (62) developed a Monte Carlo risk assessment model to examine the relationship between different operational factors like inspection frequency and rail failures. Liu et al. (63) worked on optimizing rail inspection frequency to maximize safety and efficiency. Their study showed that optimal rail inspection frequency varies with traffic density, rail age, and inspection technology reliability. Since rail deficiencies grow faster in colder weather, it is recommended that rail tests be conducted more frequently during colder months of the year (62). After identifying rail defects, delay in remediations can accelerate rail defect progress. Yet, for smaller, subcritical defects, the cost of immediate action outweighs the risks of failure (64). Another important factor that influences rail defect frequency and growth is increased traffic tonnage. By increasing the traffic tonnage, track maintenance activity needs to be done more frequently, and sufficient time and money should be dedicated to rail maintenance. In some cases, placing a slow order on a defect track is also useful (report R15H0021).

Another aspect of the process and equipment integrity is the design of tank cars carrying DGs. Based on the TSB reports, parts of Canadian rail transportation tank cars carrying flammable liquids like petroleum crude oil are still Class 111 tank cars (e.g., report R15H0013, report R13T0060). Yet, DG release and damage to the persons, property, and the environment are still high in accidents that involve Class 111 tank cars (report R07Q0001). This report emphasizes the importance of replacing TC/DOT 111 tank cars with the TC-117 tank cars, which are more puncture resistant and equipped with a thermal protection system. The design of the bottom outlet valve has also changed to address previous failure modes (65). In research done by Liu et al. (66) in the US, it is shown that in addition to enhancing tank car safety design, decreasing train speed and changing tank car placement are also useful to reducing the number of tank cars releasing per derailment.

Some measures improve incident investigation, for example, enhanced communication. Providing accurate DG information on safety data sheet (SDS) and product quantities is vital especially when a train is transporting DG. It helps crews and emergency responders to provide appropriate control measures for those trains (report R13D0054). It is the responsibility of the shipper to develop a regulator-approved emergency response assistance plan (ERAP) which provides required resources to assist local responders (report R13D0054). Additionally, route planning and periodic risk assessment of DG routes are necessary in identifying the emergency response capability along the route, including site access in remote areas (report R15H0013).

Another important factor in incident investigation involves the reliability of the reports. In some cases, the crews are under a lot of stress after an incident and cannot assess the situation in a comprehensive and objective manner. Recognizing the significance of the need for objectivity, if another qualified person is sent to the incident site as soon as possible, this individual could provide 'cold eyes' to assess the incident. Finally, the incident investigation report would document all the contributing factors and evidence. Yet, investigators may not have received standardized and comprehensive training in accident investigations. Providing a checklist of SMS and Human Factors elements would help those completing the report to identify contributing factors. These reports must be comprehensive and complete if we are to rely on them to identify gaps and enhance mitigation and control measures.

Our research also identified gaps in company standards, codes, and regulations. Following a railway incident, it is necessary to discover the root causes of the failures to assess whether a weakness in the company standards, codes, and regulations contributed to an increased likelihood of the accident. Furthermore, company standards, codes, and regulations must be comprehensive and consistent. Any inconsistency between them can lead to serious incidents like what happened in accident R13T0060. Although the recorded wheel impact was condemnable under AAR Rule 41, the WILD guidelines of CP permitted the wheel to remain in service until it failed later and caused the train derailment. In order to prevent workers' errors related to the company standards, codes, and regulations, they should be clear and understandable in a manner such that all workers can interpret them and respond in the same manner. If workers have questions, additional references and support must be available. Unaddressed inconsistencies, ambiguities, and complexities can become embedded in workplace training and workers' training competencies for future tasks. Therefore, standards, codes, and regulations should be continually enhanced as essential information is refined.

Our findings also suggest that audits and corrective actions require enhancement. Auditing should assure compliance with both records keeping and the adequacy of the SMS to the particular operations (67). SMS audits are complementary to the inspection process by identifying the causes of underlying unsafe conditions to mitigate and prevent similar conditions in the future. An effective SMS audit is performed with sufficient depth and frequency. For verified deficiencies in railway's SMS, implementation of corrective actions with follow-ups ensure that corrective actions are applied effectively so that railways are capable of managing and mitigating the risks. One of the most useful measures to improve audits and corrective actions is performing internal audits (report R13D0054) to help railways to identify and address persistent gaps in their SMS before a regulator identifies them in its audit program.

For process risk management, the transportation and catastrophic release of DGs in populated or environmentally sensitive areas results in the highest consequences. Macciotta et al. (68) present a useful hazard ranking tool for rail transport of DGs in Canada. Route planning and periodic risk assessments also play a vital role in preventing and mitigating the risk associated with such events. Route planning verifies factors that affect the probability and consequences associated with the transportation of DGs like operations, traffic, infrastructure, population density, and environmental conditions. Ideally, the route with lowest overall risk should be chosen. However, routing is difficult in countries like Canada with little route redundancy. If prevention and mitigation measures need to be applied on a route, periodic risk assessment and auditing (especially after significant operational changes) ensure that the risks associated with transporting DGs remain at an acceptable level. Furthermore, it is necessary to document risk assessments and audits to reduces missing data and errors.

Human factors continue to contribute to rail incidents. Errors that frequently cause accidents and incidents need to be identified (69). Several approaches have been developed to document incidents of this type. The computer-aided system for human error analysis and reduction (CAS-HEAR) helps analysts to find multiple levels of errors and their causal relationship (70). HFACS is one popular approach for analyzing human errors more specifically. Li et al. (71) proposed a hybrid method based on HFACS and Systems–Theoretical Accident Modelling and Processes (STAMP) to identify and analyze the role of human errors in railway accidents. Zhan et al. (72) developed another hybrid method based on the HFACS-Railway Accidents (HFACS-RAs) framework to identify and assess how human and organizational factors contributed in railway occurrences.

Following the identification of human errors, appropriate prevention and/or mitigation strategies can be developed and implemented (73). Conducting regular team meetings strengthens teamwork (72). Sufficient training for employees equips them with the resources they need to perform their jobs. Online training is beneficial in improving the knowledge of the employees; however, practical training should also be provided for the trainees alongside the online training to help them learn how to apply knowledge and skills in practice (report R15H0021). One of the situations that can cause human error is doing non-routine tasks; checklists ensure that every step has been completed. Sufficient mentoring and support for the trainees helps them to identify their weaknesses and to address them, especially for non-routine tasks (74). Supervisors also need training to ensure that they can provide appropriate guidance for workers (72). After starting the job, regular assessment of competence for both workers and supervisors can ensure that individuals are capable of properly applying their knowledge in practice. Unannounced observations of workers on the job and effective oversight ensures that workers follow standard operating procedures and do their job properly. Regular tracking of employee assessments by specific supervisors and corrective actions (including work suspensions) are also preventive measures that can be used (72). Another potential measure to prevent and mitigate human errors is enhanced systems for train control that alerts crews if they do not respond appropriately to a signal or other restriction and may stop trains or reduce their speeds (report R07E0129). Z. Zhang et al. (75) shows that, in the US, positive train control (PTC) is an advanced rail safety technology. The US railway industry is spending time and resources to complete the implementation of PTC in its system.

Lastly, process knowledge and documentation have prominent roles as SMS elements, and have already been discussed in each section (e.g., incident investigation, process risk management, human factors). Essential reference materials must be documented, regularly updated, and easily accessible for all employees in required situations. Organizing the company's rules, supplements, and general operating instructions in multiple documents/platforms makes version control, interpretability, and accessibility extremely difficult (report R13D0054). When employees need to work with new equipment, any special rules, regulations, training, and competency assessments must be established in advance (72). Standardization through process documentation is essential for organizations to ensure consistency in operation. Ungan (76) suggests documenting how the best performers complete their tasks – a process which the company can then standardize.

In sum, our research leverages process safety management tools which we use to suggest methods for railway operators, contractors, suppliers, and regulators to identify leading indicators, prevention measures, and mitigation measures for DG main-track train derailments. The aim of leading indicators is to identify the potential for an incident and then to prevent it (77). For example, some rail defects are more likely to cause rail failure and derailment than others (report R14W0256). Inconsistencies between company standard operating procedures, codes, and regulations are another indicator of potential errors. By reassessing these documents, gaps in companies' SMS can be identified and mitigated.

## 2.5. Conclusion

Railways play a prominent role in Canada's economy by transporting goods to destinations that are not easily accessible by road or pipeline. While railways are one of the safest modes of transportation for DGs, the persistence of derailments demonstrates room for improvement. Enhancing railways' SMS is seen as the path forward towards improved safety.

By applying RCA, ETA, and BTA on petroleum crude oil main-track train derailments, we identified the causes and consequences of these accidents. Additionally, by connecting the relationships between these factors and SMS elements, the associated gaps in SMS elements were identified. Then, we expanded the results to include the entire database of 40 DG main-track train derailments (class 1, 2, 3 occurrences). The frequency in each category was identified in order to prioritize causes and consequences and gaps in SMS elements. The results of our study revealed that the top main causes of DG main-track train derailments include rail defects/failures, weaknesses in audits, and weaknesses in guidelines. The top three SMS elements that need enhancement comprises of process and equipment integrity, incident investigation, and company standards, codes, and regulations. Enhancing railways' SMS will improve safe transportation of DGs and reduce potential negative impacts on people's lives, the environment, and the global economy.

Limitations of the study are related to the probabilities derived from the ETA. Since we were restricted to the study database of 40 DG main-track train derailment (class 1, 2, 3 occurrences), there is a certain measure of variability and uncertainty. This is common when developing statistical estimates following a frequentist approach for events with low frequencies. For future studies, researchers may address this limitation by considering other types and classes of rail occurrences to increase sample size. The limitation of this is associated with increasing the number of variables when aggregating incidents from other jurisdictions or different operational characteristics. Other options include the use of subjective measurements of uncertainty associated with the probabilities in the event trees, such as defining fuzzy probabilities.

## 2.6. References


1. Railways 101 | RAC [Internet]. [cited 2020 Apr 18]. Available from: https://www.railcan.ca/railways-101/
2. Railway Association of Canada. Rail Trends. 2018.
3. Crude Oil Forecast | Canadian Association of Petroleum Producers [Internet]. [cited 2020 Apr 18]. Available from: https://www.capp.ca/resources/crude-oil-forecast/
4. Miller L. Review of the Canadian transportation safety regime: Transportation of dangerous goods and safety report of the Standing Committee on Transport , Infrastructure and Communities. 2015.
5. Canada Transportation Act Review Panel. Vision and balance : report of the Canada Transportation Act Review Panel. 2001. 88 p.
6. Parliament of Canada - House of Commons. Standing Committee on Transport, Infrastructure and Communities. 41st Parliam 2st Sess. 2013;(27 November).
7. Railway Safety Management System Regulations. Canada Gazette. 2014 Jul 5;Part I, Vol. 148, No. 27.
8. Railway Investigation Report R05E0059 - Transportation Safety Board of Canada [Internet]. [cited 2020 Jun 29]. Available from: https://www.tsb.gc.ca/eng/rapports-reports/rail/2005/r05e0059/r05e0059.html
9. Railway Investigation Report R13D0054 - Transportation Safety Board of Canada [Internet]. [cited 2020 Jun 29]. Available from: https://www.tsb.gc.ca/eng/rapports-reports/rail/2013/R13D0054/R13D0054.html
10. Parliament of Canada - House of Commons. Standing Committee on Transport, Infrastructure and Communities. 41st Parliam 2st Sess. 2013;(25 November).
11. Edwards CJ. Developing of safety case with an aircraft operator. In: IBC Conference on Aviation Safety Management, London, 20–21 May. 1999.
12. E. Roland H, Moriarty B. System Safety Engineering and Management. John Wileys & Sons Inc.; 1990.
13. CCPS. Guidelines for process safety documentation. American Institute of Chemical

Engineers; 1995.

14. A. Crowl D, F. Louvar J. Chemical process safety. 4th ed. Prentice Hall; 2019.
15. Ebrahimi H, Sattari F, Lefsrud L, Macciotta R. Analysis of train derailments and collisions to identify leading causes of loss incidents in rail transport of dangerous goods in Canada. J Loss Prev Process Ind. 2021;72(May):104517.
16. Håvold JI. Safety culture and safety management aboard tankers. Reliab Eng Syst Saf. 2010;95(5):511–9.
17. Bielic T, Predovan D, ēulin J. The Role of the Master in Improving Safety Culture Onboard Ships. TransNav, Int J Mar Navig Saf Sea Transp. 2017;11(1):121–4.
18. Hsu YL, Li WC, Chen KW. Structuring critical success factors of airline safety management system using a hybrid model. Transp Res Part E Logist Transp Rev. 2010;46(2):222–35.
19. Kyriakidis M, Pak KT, Majumdar A. Railway accidents caused by human error: Historic analysis of UK railways, 1945 to 2012. Transp Res Rec. 2015;2476:126–36.
20. Liu X, Saat MR, Barkan CPL. Analysis of causes of major train derailment and their effect on accident rates. Transp Res Rec. 2012;(2289):154–63.
21. Rudin-Brown CM, George MFS, Stuart JJ. Human factors issues of accidents at passively controlled rural level crossings. Transp Res Rec. 2014;2458:96–103.
22. Kyriakidis M, Majumdar A, Ochieng WY. Data based framework to identify the most significant performance shaping factors in railway operations. Saf Sci. 2015;78:60–76.
23. Dindar S, Kaewunruen S, An M. Bayesian network-based human error reliability assessment of derailments. Reliab Eng Syst Saf. 2020;197(November 2019):106825.
24. Read GJM, Naweed A, Salmon PM. Complexity on the rails: A systems-based approach to understanding safety management in rail transport. Reliab Eng Syst Saf. 2019;188(September 2018):352–65.
25. Chen CF, Chen SC. Scale development of safety management system evaluation for the airline industry. Accid Anal Prev. 2012;47:177–81.
26. Basso B, Carpegna C, Dibitonto C, Gaido G, Robotto A, Zonato C. Reviewing the safety management system by incident investigation and performance indicators. J Loss Prev Process Ind. 2004;17(3):225–31.
27. Hale AR, Heming BHJ, Carthey J, Kirwan B. Modelling of safety management systems. Saf Sci. 1997;26(1–2):121–40.
28. Hurst N. From research to practical tools - developing assessment tools for safety management and safety culture. J Loss Prev Process Ind. 1997;10(1):63–6.
29. De Dianous V, Fiévez C. ARAMIS project: A more explicit demonstration of risk control through the use of bow-tie diagrams and the evaluation of safety barrier performance. J Hazard Mater. 2006;130(3 SPEC. ISS.):220–33.
30. Hughes P, Shipp D, Figueres-Esteban M, van Gulijk C. From free-text to structured safety management: Introduction of a semi-automated classification method of railway hazard reports to elements on a bow-tie diagram. Saf Sci. 2018;110(June 2017):11–9.

31. Ferdous R, Khan F, Sadiq R, Amyotte P, Veitch B. Analyzing system safety and risks under uncertainty using a bow-tie diagram: An innovative approach. Process Saf Environ Prot. 2013;91(1–2):1–18.

32. Zhang C, Wei Y, Li Z, Zhao Y. Hazard-Based Design of the Bow-Tie Method to Prevent and Mitigate Mine Accidents. J Fail Anal Prev. 2018;18(1):29–40.

33. Policy on Occurrence Classification - Transportation Safety Board of Canada [Internet]. [cited 2020 Jun 29]. Available from: https://www.tsb.gc.ca/eng/lois-acts/evenements-occurrences.html

34. Canadian Society for Chemical Engineering. PSM, Process Safety Management Guide, 4th Ed. 2012.

35. Vollmer CM, Sanchez N, Gondek S, McAuliffe J, Kent TS, Christein JD, et al. A Root-Cause Analysis of Mortality Following Major Pancreatectomy. J Gastrointest Surg. 2012;16(1):89–103.

36. Todinov MT. Generic Approaches To Reducing the Likelihood of Critical Failures. Risk-Based Reliab Anal Generic Princ Risk Reduct. 2007;181–92.

37. Barry T. Risk-informed, performance-based industrial fire protection: an alternative to prescriptive codes. Tennessee Val Publ. 2002;

38. Crawley F, Tyler B. Hazard identification method. Inst of Chemical Engineers (IChemE): London, UK.; 2003.

39. Rubin O, Dahlberg R. A Dictionary of Disaster Management. Oxford University Press: Oxford, UK.; 2017.

40. Ferdous R, Khan F, Sadiq R, Amyotte P, Veitch B. Handling and updating uncertain information in bow-tie analysis. J Loss Prev Process Ind. 2012;25(1):8–19.

41. Vileiniskis M, Remenyte-Prescott R. Quantitative risk prognostics framework based on Petri Net and Bow-Tie models. Reliab Eng Syst Saf. 2017;165:62–73.

42. Culwick MD, Merry AF, Clarke DM, Taraporewalla KJ, Gibbs NM. Bow-tie diagrams for risk management in anaesthesia. Anaesth Intensive Care. 2016;44(6):712–8.

43. de Ruijter A, Guldenmund F. The bowtie method: A review. Saf Sci. 2015;88:211–8.

44. Shahriar A, Sadiq R, Tesfamariam S. Risk analysis for oil & gas pipelines: A sustainability assessment approach using fuzzy based bow-tie analysis. J Loss Prev Process Ind. 2012;25(3):505–23.

45. Papazoglou IA, Bellamy LJ, Hale AR, Aneziris ON, Ale BJM, Post JG, et al. I-Risk: Development of an integrated technical and management risk methodology for chemical installations. J Loss Prev Process Ind. 2003;16(6):575–91.

46. Abdi Z, Ravaghi H, Abbasi M, Delgoshaei B, Esfandiari S. Application of Bow-tie methodology to improve patient safety. Int J Health Care Qual Assur. 2016;29(4):425–40.

47. Cormier R, Elliott M, Rice J. Putting on a bow-tie to sort out who does what and why in the complex arena of marine policy and management. Sci Total Environ. 2019;648:293–305.

48. Delmotte F. A sociotechnical framework for the integration of human and organizational

factors in project management and risk analysis. Ind Syst Eng. 2003;

49. Van Scyoc K, Hughes G. Rail ruminations for process safety improvement. J Loss Prev Process Ind. 2009;22(6):689–94.

50. Rail transportation safety investigations and reports - Transportation Safety Board of Canada [Internet]. [cited 2020 Apr 16]. Available from: https://www.tsb.gc.ca/eng/rapports-reports/rail/index.html

51. Sattari F, Macciotta R, Lefsrud L. Process Safety Approach to Identify Opportunities for Enhancing Rail Transport Safety in Canada. Transp Res Rec. 2020;2675(1):49–66.

52. Reinach, S., Viale A. Application of a Human Error Framework to Conduct Train Accident/Incident Investigations. Accid Anal Prev. 2006;38:396_406.

53. Report No. DOT/FRA/RRS-22. Fed Railr Adm Guid Prep Accid Reports,. 2003;

54. Whittingham RB. The Blame Machine: Why Human Error Causes Accidents. Elsevier Butterworth-Heinemann, Oxford, UK. 2004;

55. Iranitalab A, Khattak A, Thompson E. Statistical modeling of types and consequences of rail-based crude oil release incidents in the United States. Reliab Eng Syst Saf. 2019;185(November 2018):232–9.

56. Railway Association of Canada. Rail trends. 2017.

57. Wilson JR, Farrington-Darby T, Cox G, Bye R, Hockey GRJ. The railway as a socio-technical system: Human factors at the heart of successful rail engineering. Proc Inst Mech Eng Part F J Rail Rapid Transit. 2007;221(1):101–15.

58. Orringer O. Control of Rail Integrity by Self-Adaptive Scheduling of Rail Tests. Dot/Fra/Ord-90/05. 1990.

59. Lanza di scalea F, Rizzo P, Coccia S, Bartoli I, Fateh M. Laser-air-coupled hybrid noncontact system for defect detection in rail tracks: Status of FRA prototype development at University of California-San Diego. Transp Res Rec. 2006;

60. Xiong Z, Li Q, Mao Q, Zou Q. A 3D laser profiling system for rail surface defect detection. Sensors (Switzerland). 2017;17(8):1–19.

61. Zhang X, Feng N, Wang Y, Shen Y. Acoustic emission detection of rail defect based on wavelet transform and Shannon entropy. J Sound Vib. 2015;339:419–32.

62. Jeong DY, Gordon JE. Evaluation of rail test frequencies using risk analysis. Proc ASME/IEEE Jt Rail Conf 2009, JRC2009. 2009;23–30.

63. Liu X, Lovett A, Dick T, Rapik Saat M, Barkan CPL. Optimization of ultrasonic rail-defect inspection for improving railway transportation safety and efficiency. J Transp Eng. 2014;140(10):1–10.

64. Orringer O, Tang YH, Jeong DY, Perlman AB. Risk/Benefit Assessment of Delayed Action Concept for Rail Inspection. Dot/Fra/Ord-99/03. 1999.

65. Shaun S, Stéphane G. Transportation of Dangerous Goods NEWSLETTER 2016_Vol.36 No 1. 2016;

66. Liu X, Saat MR, Barkan CPL. Probability analysis of multiple-tank-car release incidents in

railway hazardous materials transportation. J Hazard Mater. 2014;276:442–51.

67. Lefsrud L, Macciotta R, Nkoro A. Performance-based regulations for safety management systems in the canadian railway industry: An analytical discussion. Can J Civ Eng. 2020;47(3):248–56.

68. Macciotta R, Robitaille S, Hendry M, Martin CD. Hazard ranking for railway transport of dangerous goods in Canada. Case Stud Transp Policy. 2018;6(1):43–50.

69. Baysari MT, McIntosh AS, Wilson JR. Understanding the human factors contribution to railway accidents and incidents in Australia. Accid Anal Prev. 2008;40(5):1750–7.

70. Kim DS, Baek DH, Yoon WC. Development and evaluation of a computer-aided system for analyzing human error in railway operations. Reliab Eng Syst Saf. 2010;95(2):87–98.

71. Li C, Tang T, Chatzimichailidou MM, Jun GT, Waterson P. A hybrid human and organisational analysis method for railway accidents based on STAMP-HFACS and human information processing. Appl Ergon. 2019;79(February):122–42.

72. Zhan Q, Zheng W, Zhao B. A hybrid human and organizational analysis method for railway accidents based on HFACS-Railway Accidents (HFACS-RAs). Saf Sci. 2017;91:232–50.

73. De Felice F, Petrillo A. Methodological approach for performing human reliability and error analysis in railway transportation system. Int J Eng Technol. 2011;3(5):341–53.

74. Read GJM, Lenné MG, Moss SA. Associations between task, training and social environmental factors and error types involved in rail incidents and accidents. Accid Anal Prev. 2012;48:416–22.

75. Zhang Z, Liu X, Holt K. Positive Train Control (PTC) for railway safety in the United States: Policy developments and critical issues. Util Policy. 2018;51(June 2017):33–40.

76. Ungan MC. Standardization through process documentation. Bus Process Manag J. 2006;12(2):135–48.

77. Leveson N. A systems approach to risk management through leading safety indicators. Reliab Eng Syst Saf. 2014;

## 2.7. Amendment to the chapter 2

1. Route planning is not applicable for large section of Canada because of little route redundancy in this country.

2. The main causes of the accidents refer to the basic causes of the accidents (sub-standard conditions and practices).

3. The “insufficient/inadequate mentoring and support”, “insufficient/inadequate oversight”, “insufficient/inadequate track maintenance”, “insufficient/inadequate TC inspection” expressions should be replaced by “weakness in mentoring and support”, “weakness in oversight”, “weakness in track maintenance”, and “weakness in TC inspection” phrases. We are not aware of how TSB reports define “sufficient/insufficient” and “adequate/inadequate” phrases for each expression, and their feasibility needs further investigations.

4. The inputs of the RCA were TSB reports to identify the basic causes of the accidents, and the sequence of the event leading to the DG main-track derailments. The output of the analysis was identifying the relationship between the causes of the accidents and gaps in the SMS elements. The inputs of the ETA were TSB reports to verify the consequences of the DG main-track derailments and their relative frequency. The outputs of the ETA were calculating the actual probabilities for each ETA branch (Frequentist approach). The input of the BTA was the causes and consequences of the DG main-track derailments (from the RCA and ETA). The output of the BTA was illustrating the relationship between the causes and consequences by defining the critical event which was DG main-track derailments. BTA is also helpful to demonstrate the preventive measurements, strategies that can help to prevent a train derailment from reoccurring, and mitigative measurements, strategies to mitigate the consequences of derailment. It is important that how critical event is defined in the BTA because it would impact the causes, consequences, and

preventive and mitigative strategies. For example, if we change the critical event from DG main-track derailments to the DG release, the DG main-track derailments would be a cause of DG release. Also, preventive and mitigative measurements would be impacted accordingly.

5. Future research can focus on the areas that were not investigated in the TSB reports such as safety culture, near misses, and under-reporting injuries.

Safety culture has gained a high level of attention in research and industry fields due to its latent implications on safety performance (1). Kyriakidis et al. (2) identified safety culture as one of the most significant contributors to the operators' performance. Uttal (3) defined safety culture as "shared values and beliefs that interact with an organization's structures and control systems to produce behavioral norms". Turner et al. (4), further defined it as "the set of beliefs, norms, attitudes, roles, and social and technical practices that are concerned with minimizing the exposure of employees, managers, customers, and members of the public to conditions considered dangerous or injurious". Analysis, comparison, and reviewing the literature show that there are 13 elements in safety culture including safety environment, safety commitment, safety training, safety leadership, risk management, safety encouragement and punishment, contractor management, safety communication, worker participation, etc (5).

Various studies have focused on developing a reliable tool to assess the safety culture and its impact on safety performance. For example, a standardized written survey instrument can be used to gain a broader understanding of the safety culture (6). Bailey and Petersen (7) concluded that the effectiveness of safety efforts can be measured with surveys of employee perceptions. A perception survey can effectively identify the strengths and weaknesses of elements of a safety system, and major discrepancies in perception of program elements between hourly rated employees and levels of management. Moreover, it is helpful to identify enhancement in and deterioration of safety system elements if administered periodically. Ostrom et al. (6) insisted that a properly developed survey is a valuable tool to compare against a company's accident-illness record. In addition, the data provided in the form of survey results can be used in the safety meetings covering the real safety concerns that employees have. A survey provides the opportunity for the organization to compare the results from a certain department or company with another in a standardized, structured manner. It helps to target efforts in light of limited safety budgets. Ostrom et al. (6) study provided examples of safety culture survey questions for various areas of assessment such as safety awareness, teamwork, pride and commitment, excellence, honesty, communication, leadership, supervision, etc. Wang et al. (8) extensively investigated the safety culture of the Taiwan railway industry by implementing a survey approach.

Another tool to evaluate the safety culture is conducting interviews with employees and management. It helps to a have better understanding of what lay behind the survey's responses. Farrington-Darby et al. (9) used an interview approach to assess the safety culture of a specific organization working in rail maintenance. Through careful and traceable identification of perceptions of the staff, from track workers to senior management, the primary factors that affect the track worker's safety behavior and organization's safety culture were determined.

Some other approaches were also investigated in the literature to assess the safety culture. Cooper (10) explained that safety culture is a result of interactions between people (psychological), jobs (behavioral), and the organization (situational). Attitudes and perceptions can be assessed through safety climate questionnaires. Actual safety-related behaviors can be evaluated by checklists developed as part of behavioral safety initiatives. Situational features can be assessed through SMS audits/inspections, peer reviews, and observations. Strauch (11) suggested that rather than attempting to evaluate the safety culture directly, assessing company actions and decisions directly after an accident would help to make inferences about the safety culture at the time of the accident. The study proposes a method to directly assess the nature of organizational errors in an accident and identify the logic that can link these errors to accident causation.

Considering the above-mentioned tools, future studies can further investigate the literature and identify an appropriate approach to assess the Canadian railway safety culture, its impact on rail occurrences, and identify its role in the railway's SMS.

Another factor that was not investigated in the TSB reports was related to the near misses. Although organizations learn from obvious failures, it is harder for them to learn from near misses, events that could have escalated into an accident and chance played a role in averting failure (12,13). Near misses provide the opportunity to correct mistakes before they become catastrophes. The full learning value of near misses will be realized only when they are evaluated as a failure rather than a success, and examined to show not only system resilience, but also system vulnerability (12). The main mechanism used to capture data about near misses is reporting system (14). Jones et al. (15) mentioned that the rate of near miss reports is a valuable numerical indicator of the industry's safety awareness. Cambraia et al. (13) suggested that in order to collect complementary data about near misses, multiple sources of evidence should be used. For example, having daily meetings with the employees and asking them about the occurrence of near misses on the previous day, and monthly interviews with groups of employees. In addition to the reporting systems, some novel approaches are implemented to detect near misses. Banerjee et al. (16) propose a multi-sensor approach and novel algorithms to identify, classify and remotely monitor the Employees-on-Duty (EoDs) in the railway industry. Zaman et al. (17) developed a framework for utilizing artificial intelligence (AI) technologies for automatically analyzing railroad video data (in the US) to detect all the near miss events associated with unsafe trespassing of grade crossing and extract useful information for understanding human behavioral characteristics.

Despite the importance of near misses, there is little knowledge about their characteristics, and it is not yet a commonly accepted fact that investigating near misses should be an integral part of the SMS in industrial facilities (13,15). Future studies can evaluate the role of near misses in rail occurrences and identify how they can play role in enhancing the safety of rail transportation in the context of railway SMS.

Under-reporting injuries were another factor that was not investigated in the TSB reports. The problem of under-reporting is widely acknowledged as a significant issue across industries. It refers particularly to occurrences that do not involve equipment failure or damage (18) but relate to the failure to report quite serious occupational injuries (19,20). Workers explained various reasons for not reporting their injuries, including fear of reprisal, lack of management responsibility after previous reports, a belief that pain is a usual consequence of work activity or aging, and fear of losing their job. Incentive programs are also another cause of the under reporting. Safety incentive programs usually encourage managers and workers for decreasing workplace injury rates, and thus may unintentionally prevent proper reporting. Due to under-reporting, employee surveys and symptom reports are useful to provide important and timely information regarding risks than recordable injury logs (21). Staes et al. (22) mentioned that keeping data confidential is an important factor for the workers who report, and public transportation agencies that collect, analyze, and maintain safety data in support of SMS. Protections granted to workers will ensure greater reporting and, in turn, safer public transportation agencies. The study also proposed using an external party to manage the employee safety report (ESR) system. It increases the likelihood of reporting safety events and decreases the likelihood of associated punitive consequences. However, there was concern related to the costs of instituting the program through a third party.

The proper implementation of safety measurements depends upon the accurate recording of cases of injuries. Future studies can investigate the under-reporting injuries in Canadian railways, their causes, and their relationship with the railway's SMS.

Moreover, future studies can focus on providing comprehensive investigation reports for rail occurrences in Canada by considering the role of the above-mentioned factors (safety culture, near misses, and under-reporting injuries) in rail occurrences along with TSB reports and RODS database information. It would be useful to provide more detailed information about the areas that need improvement to enhance railway safety.

## 2.8. References (amendment to the chapter 2)


1. Wang L, Sun R. A new safety culture measurement tool and its application. Int J Saf Secur Eng. 2014;4(1):77–86.
2. Kyriakidis M, Majumdar A, Grote G, Ochieng WY. Development and assessment of taxonomy for performance-shaping factors for railway operations. Transp Res Rec. 2012;(2289):145–53.
3. Uttal B. The corporate culture vultures. Fortune Mag. 1983;
4. Turner BA, Pidgeon N, Blockley D, Toft B. Safety culture: its importance in future risk management. Position Pap Second World Bank Work Saf Control Risk Manag. 1989;
5. He A, Xu S, Fu G. Study on the basic problems of safety culture. Procedia Eng. 2012;43:245–9.
6. Ostrom L, Wilhelmsen C, Kaplan B. Assessing Safety Culture. Tech Prog. 1977;34–2:163–72.
7. C. W. Bailey, D. Petersen. Using Perception Surveys to Assess Safety System Effectiveness. Prof Saf. 34:22–6.
8. Wang CH, Liu YJ. Omnidirectional safety culture analysis and discussion for railway industry. Saf Sci. 2012;50(5):1196–204.
9. Farrington-Darby T, Pickup L, Wilson JR. Safety culture in railway maintenance. Saf Sci. 2005;43(1):39–60.
10. Cooper MD. Towards a model of safety culture. Saf Sci. 2000;36(2):111–36.
11. Strauch B. Can we examine safety culture in accident investigations, or should we? Saf Sci. 2015;77:102–11.
12. Dillon RL, Tinsley CH. How near-misses influence decision making under risk: A missed opportunity for learning. Manage Sci. 2008;54(8):1425–40.
13. Cambraia FB, Saurin TA, Formoso CT. Identification, analysis and dissemination of information on near misses: A case study in the construction industry. Saf Sci. 2010;48(1):91–9.
14. Schaaf V der, Tjerk W, Moraal J, Hale AR. Near miss reporting in the chemical process industry. Tech Univ Eindhoven, Proefschr. 1992;
15. Jones S, Kirchsteiger C, Bjerke W. The importance of near miss reporting to further improve safety performance. J Loss Prev Process Ind. 1999;12(1):59–67.
16. Banerjee S, Santos J, Hempel M, Ghasemzadeh P, Sharif H. A novel method of near-miss event detection with software defined radar in improving railyard safety. Safety. 2019;5(3).
17. Zaman A, Liu X, Zhang Z. Video Analytics for Railroad Safety Research: An Artificial Intelligence Approach. Transp Res Rec. 2018;2672(10):269–77.
18. Trommelen M. Causes of, and backgrounds to human error in accidents at the nylon-plant. Intern report, Leiden Univ. 1991;

19. Powell PI, Hale M, Martin J, Simon M. 2000 Accidents: A Shop Floor Study of their cases. Rep no 21 (London Natl Inst Ind Psychol. 1971;

20. Senneck CR. Over three-day absences and safety. Appl Ergowomics. 1975;147–53.

21. Pransky G, Snyder T, Dembe A, Himmelstein J. Under-reporting of work-related disorders in the workplace: A case study and review of the literature. Ergonomics. 1999;42(1):171–82.

22. Staes L, Godfrey J. Characteristics of non-punitive employee safety reporting systems for public transportation as abridged from tcrp report 218. Transp Res Rec. 2021;2675(6):254–64.

# 3. Assessing the risks associated with the Canadian Railway System using a Safety Risk Model approach

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## 3.1. Introduction

Canada's national rail transportation system is the third-largest in the world, operating more than 40,000 kilometers of track length across the country (1). The rail network connects industries, consumers, and resource sectors to ports on the Atlantic and Pacific coasts, which has resulted in transporting $320 billion worth of goods by rail each year (2). Furthermore, each year, over 100 million passengers travel on Canada's railways (3).

Severe freight and passenger train occurrences are rare events. However, when they happen, they have the potential to cause injuries and fatalities, along with environmental and property losses (1). The Lac-Mégantic accident, where 47 people lost their lives after a freight train derailment in 2013 (4) and the Burlington accident, where a passenger train derailment resulted in three fatalities and 45 people injured to various degrees in 2012 (5) are two examples of recent railway accidents showing the potential consequences of these kind of events. These rail accidents demonstrate the dangerous nature of the railway industry and emphasize the need for increased awareness and continuous enhancement and updating of risk assessments in order to control existing residual risks.

Understanding risk is essential for the safe management of any business, particularly those sectors called 'high-hazard' such as oil and gas extraction, mining, airlines, and railways (6). Applying an appropriate risk assessment tool will help to identify the current level of risk and develop a plan to mitigate those risks. Various risk assessment techniques are currently used in the railway industry (7–9). One of the popular models among those comprehensive and quantitative approaches is Safety Risk Model (SRM). This model was developed in the UK for the first time to improve railway safety in an impartial and scientifically supportable manner. The SRM is developed in the form of a cause and consequence analysis using Fault Tree Analysis (FTA) and Event Tree Analysis (ETA). The model is focused on hazardous events which have the potential to lead directly to death or injury. Risk in the context of SRM is defined as the estimate of the potential for harm to passengers, staff, and members of the public (MOP) from the operation and maintenance of the railway. The results of SRM represent the level of the residual risk. In other words, it shows the level of risk with the assumption that all current control measures are established with their current degree of effectiveness (6).

SRM has been widely used in the UK (6,9) and the US (10).In the UK, the outcome of SRM is used to produce a regularly updated 'Risk Profile Bulletin', which is used by UK railway in the production of their statutory Safety Cases. The model is also helpful in testing the impact of proposed new controls on risk levels (6). In the US, the Federal Railroad Administration (FRA) has developed the SRM as a means for quantitative risk-ranking to facilitate project selection. The results of the SRM assist the FRA to focus its R&D effort on the topics that cause the highest level of harm in railroad industry. It is beneficial in making strategic project investments for maximum safety benefit. Employing SRM also allows for future assessment of risk reduction resulting from implementation of the mitigation strategies (10).

Close collaborations between US and Canadian railways (1) motivated this research to investigate the application of the SRM in the Canadian rail network. Reviewing the literature revealed that a comprehensive SRM that aggregates Canadian railway operations (federally regulated) is not available. As a result, in order to address this gap and contribute towards the continuous improvement of rail transportation safety, this research will focus on risk assessment of railway accidents by applying a customized Canadian SRM (C-SRM).

The techniques used in the SRM are applicable to other railroad industries; however, the FTA and ETA need to be amended for the particular configuration of that railway. C-SRM is a national-wide risk assessment model which reflects the characteristics of Canadian railway operations. The main difference between SRM and C-SRM is that SRM considers different subdivisions for individual rail occurrence types. For example, collision was divided into different groups such as a collision between two passenger trains (other than on platform), a collision between a passenger train and a non-passenger train, and so on. In this study, due to the limited database, all of the subdivisions related to one accident type (collision, derailment) were considered into one group and no further subdivisions were investigated.

Developing C-SRM also provides an opportunity to apply risk reduction analysis to determine the effect of the introduction of a new control measure, Enhanced Train Control (ETC). ETC technologies developed to increase awareness of the train operator in combination with fail-safe systems similar to the PTC system functionality implemented in the US (11).

Applying Positive Train Control (PTC) on certain Class 1 railroad main lines in the US causes railway operators in Canada to raise several major concerns regarding their experience with PTC implementation. For example, expensiveness, complexity, and significant effort requirement to apply it (11).

A research done by Canada's Advisory Council on Railway Safety in 2016 recommended that the development of a targeted, risk-based, corridor-specific train control approach is the best option for the deployment of this technology in Canada. This suggestion has been the “working assumption” for implementing ETC in Canada. ETC technologies help to prevent certain rail accidents caused by human error and as a result, improve safety for passenger and freight trains. These technologies act as a driver assist mechanism by alerting the train crew to danger and, at their highest functionality, applying train brakes to slow or stop a train to prevent a collision or derailment. The recent Notice of Intent published in the Canada Gazette on February 5, 2022, revealed that Transport Canada (TC) intends to implement ETC in Canada to make Canada’s rail transportation system even safer (1). The current study is also aimed to assess the impact of ETC implementation on rail transport risk. Therefore, risk is calculated in terms of collective risk (the average number of equivalent fatalities per year), and individual risk (the annual probability of equivalent fatality/year for a particular passenger or staff group using the railway). Then, the risk reduction analysis of ETC implementation is applied.

## 3.2. Methods

This study is focused on investigating the Transportation Safety Board of Canada (TSB) and Rail Occurrence Database System (RODS) databases for main-track train derailment and collision, class 1-5 occurrences (Appendix A – Definitions of classes of occurrences). The assessment is performed on the 1,085 reported main-track derailments and collisions in the eleven-year period between January 1, 2007, and December 31, 2017. This time frame was chosen due to available databases for part of the study analysis (FTA analysis). For those accidents that were not reported by RODS, TSB reports were used to collect the required information.

It is noteworthy to mention that trespassing and crossing accidents were not included in this research. These accidents are responsible for major fatalities and injuries every year. In 2020, 96.6% of fatalities and 81.6% of serious injuries in rail industry were resulted by trespassing and crossing occurrences (12). However, due to nature of these events which is mainly related to the self-harm or reckless behavior of a third party, the estimation of number of people exposed to such events was accompanied with difficulties and uncertainty (13) and out of the scope of this study.

SRM is a form of cause and consequence analysis using FTA and ETA to represent each of the hazardous events. A hazardous event is taken to mean an event that has the potential to lead directly to fatalities or injuries. This event can be considered as a knot between FTA and ETA. The focus of this study is on two groups of hazardous events: main-track derailments and main-track collisions with death and serious or minor injury outcomes. The RODS-injury database was used to see if a main-track derailment or collision could be taken into account as a hazardous event.

In order to apply FTA, Arthur D. Little Inc. (ADL) cause-classification was used. ADL divided similar accident causes into 51 unique groups. These groups were also separated into five main categories including mechanical, human, signal, track, and miscellaneous causes (14,15). The frequency of these cause groups for main-track derailments and collisions was obtained from RODS database (13). Then, the probability of a hazardous event was calculated per train miles that the train traveled.

Then, ETA was implemented. After a hazardous event, there are several processes such as DG release, fire, and explosion that lead to the fatality, serious or minor injuries. The critical factors influencing the final outcome of each hazardous event and their probability was identified by investigating the RODS database. Finally, by the combination of the FTA and ETA, risk of the hazardous event was calculated.

In the first step of the study, collective risk of the hazardous events was evaluated. The collective risk was calculated based on the following equation (6):

$$CR = F \times C.$$

Where F is the frequency (average frequency at which the hazardous event occurs) in the number of events per year; C is Consequences (the average consequences if a hazardous event occurs) in the number of equivalent fatalities per event; and CR is the collective risk which is the average number of the equivalent fatality per year.

As the next step, the individual risk of hazardous events was calculated for three groups of people including passengers, staff, and MOP. Individual risk is the total annual risk to passengers, staff, and MOP using the railway (6,16). It has a similar formula to the collective risk, but the risk is evaluated in the average number of passengers/staff/MOP equivalent fatality per year.

It might be worth mentioning that in order to distinguish the difference in severity implied by injuries and fatalities, different weights were assigned to the fatality, major and minor injury. In an effort to do that, ten major injuries and 200 minor injuries are both equal to one equivalent fatality (16).

During the third phase of the study, a risk reduction analysis was performed by using the applied C-SRM. The purpose of this step was to assess the impact of ETC implementation on rail transport risk. ETC system functionality falls into two categories: Driver Advisory Systems and Automatic Train Protection Systems. In the Driver Advisory System, various information and alerts are provided for the train crew to enhance their situational awareness. In this category, train crews are still responsible for rule compliance. Hence, this system may reduce the probability of human error but not eliminate it. The Automatic Train Protection System has the Driver Advisory System's capabilities. In addition, in a situation when safety risk is imminent, it provides automatic ("fail-safe") enforcement by applying the train brakes to prevent derailments (1). In this study, in order to assess the most benefit of ETC implementation, its functionality was considered in the Automatic Train Protection System category. This functionality provides an opportunity to eliminate human errors that play role in train accidents. As a result, a hundred percent effectiveness was considered for two accident causes, main-track authority and speed, which are preventable by ETC implementation at the Automatic Train Protection System level. Then, the risk of the hazardous event was assessed in both terms of collective risk and individual risk. The Figure 2-1 Depicts the research method of this study. At this time, the details of ETC capabilities are not know. Therefore, any prevention of other accident causes, such as trains travelling on misaligned switches, were not considered. However, the consideration of movements that exceed limits of authority and over speeding is judged to provide an adequate illustration of the preventability that can be achieved through ETC implementation.

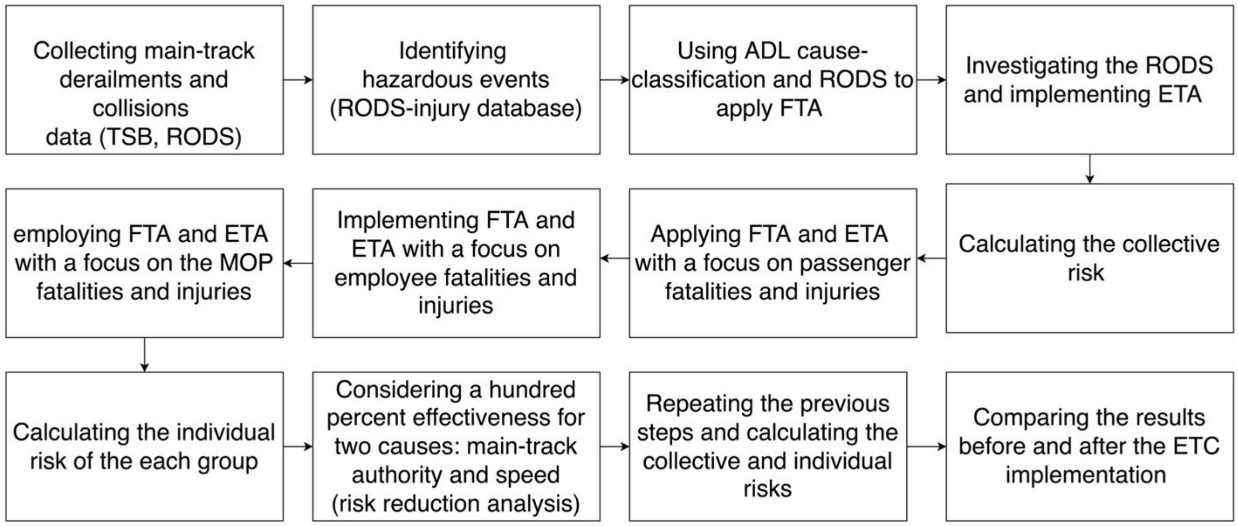


**Figure 3-11.** Research methodology for this study

## 3.3. Results

### 3.3.1. Collective risk

Investigating RODS database revealed that 1,026 main-track derailments class 1-5 occurrences have occurred between 2007 to 2017. Evaluating RODS-injury database showed that 14 freight and passenger train derailments resulted into fatality and injury. Figure 3-2 represents the distribution of the fatalities, serious and minor injuries based on the year of occurrence.

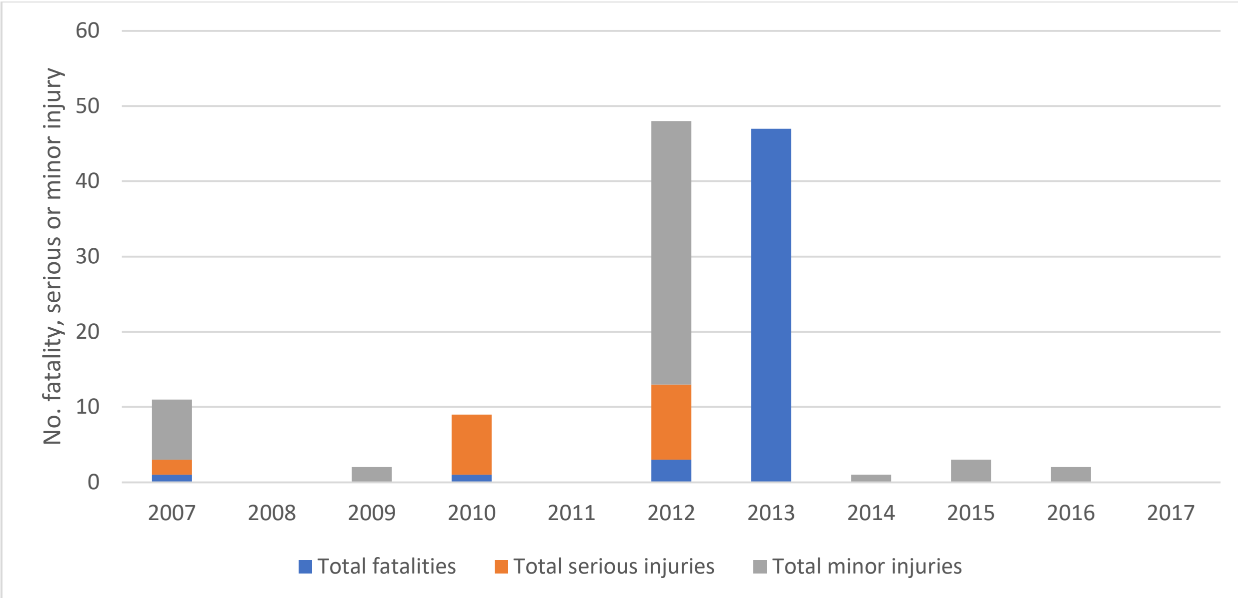


**Figure 3-12.** Number of fatalities /serious injuries /minor injuries per year for main-track derailments

Since the data evaluation was limited to the main-track derailments, the number of fatalities and serious or minor injuries has been zero for some of the years. A peak in 2013 fatalities was related to the Lac-Mégantic disaster with 47 casualties (4). Moreover, the spike in 2012 corresponded to the Burlington passenger train derailment which caused three fatalities, ten serious and 35 minor injuries (5) .Despite the fluctuation in the recorded data, no fatality and serious injury from 2014 to 2017 revealed an improvement in decreasing the number of occurrences with the potential for fatality and serious injuries.

In order to identify the collective risk of the main-track derailments, FTA was applied. The main groups and subgroups of causes reported for main-track derailments are shown in Figure 3-3. The FTA also consists of data relating to the failure annual probability of each cause. Intending to eliminate the variability associated with train traffic fluctuation, the FTA was normalized per train mile. As shown in Figure 3-3, cause groups are led by track, roadbed, and structures, followed by mechanical and electrical failure. At the subgroup level, rail brakes, track geometry, and train handling show the highest probabilities respectively. Based on the failure annual probability of the causes, the annual probability of a main-track derailment leading to fatality and injury was calculated per train miles that the train traveled. It is noteworthy to point out that the total distance traveled by Canada's freight and passenger trains on the main track between 2007 to 2017 was 858.8 million train-miles (17).

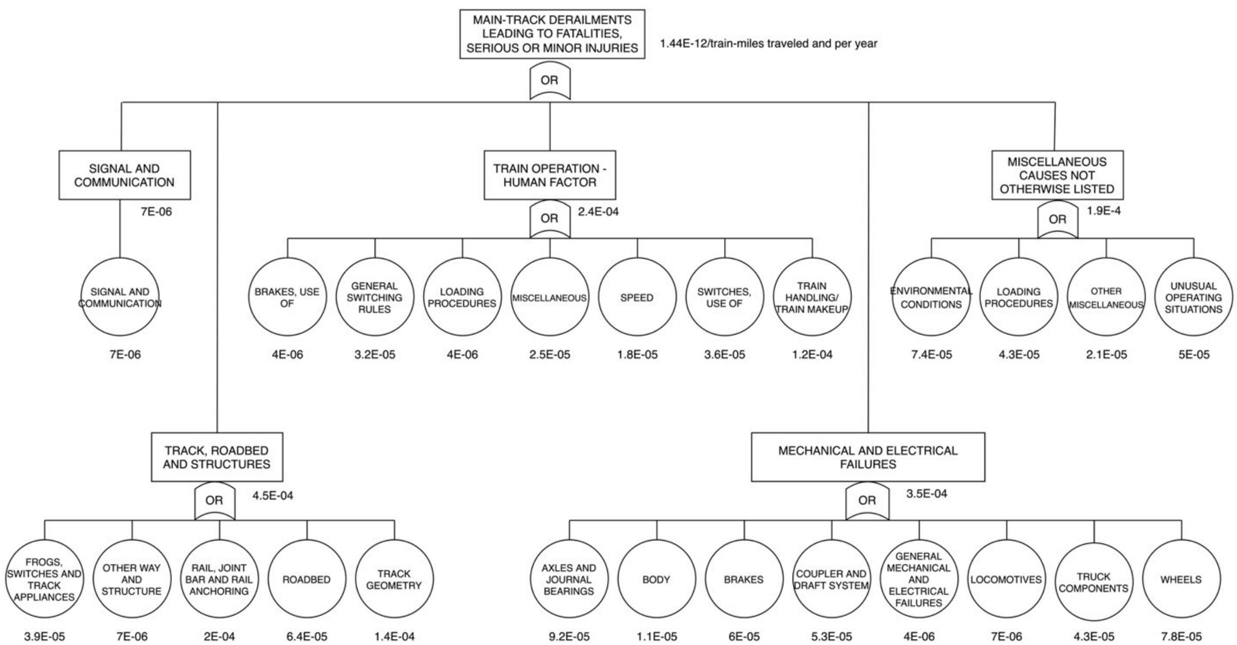


**Figure 3-13.** FTA for main-track train derailments leading to fatalities and injuries

Followed by FTA, an ETA was applied. Evaluating the RODS showed that a main-track train derailment might lead to a collision, Dangerous Good (DG) release, fire, explosion, and evacuation. ETA includes the probability of each consequence. The results of the ETA are presented in terms of frequency of occurrence (number of events/year) and the risk (number of equivalent fatalities per year). The accident scenario leading to all of the mentioned outcomes was associated with the highest level of risk to life which was $4.07 \times 10^{-3}$ equivalent fatalities per year. The ETA outcomes and collective risk of main-track derailments causing fatality and injury are shown in Figure 3-4. The little difference in some of the numbers is caused by rounding up or down the numbers during the calculation process.

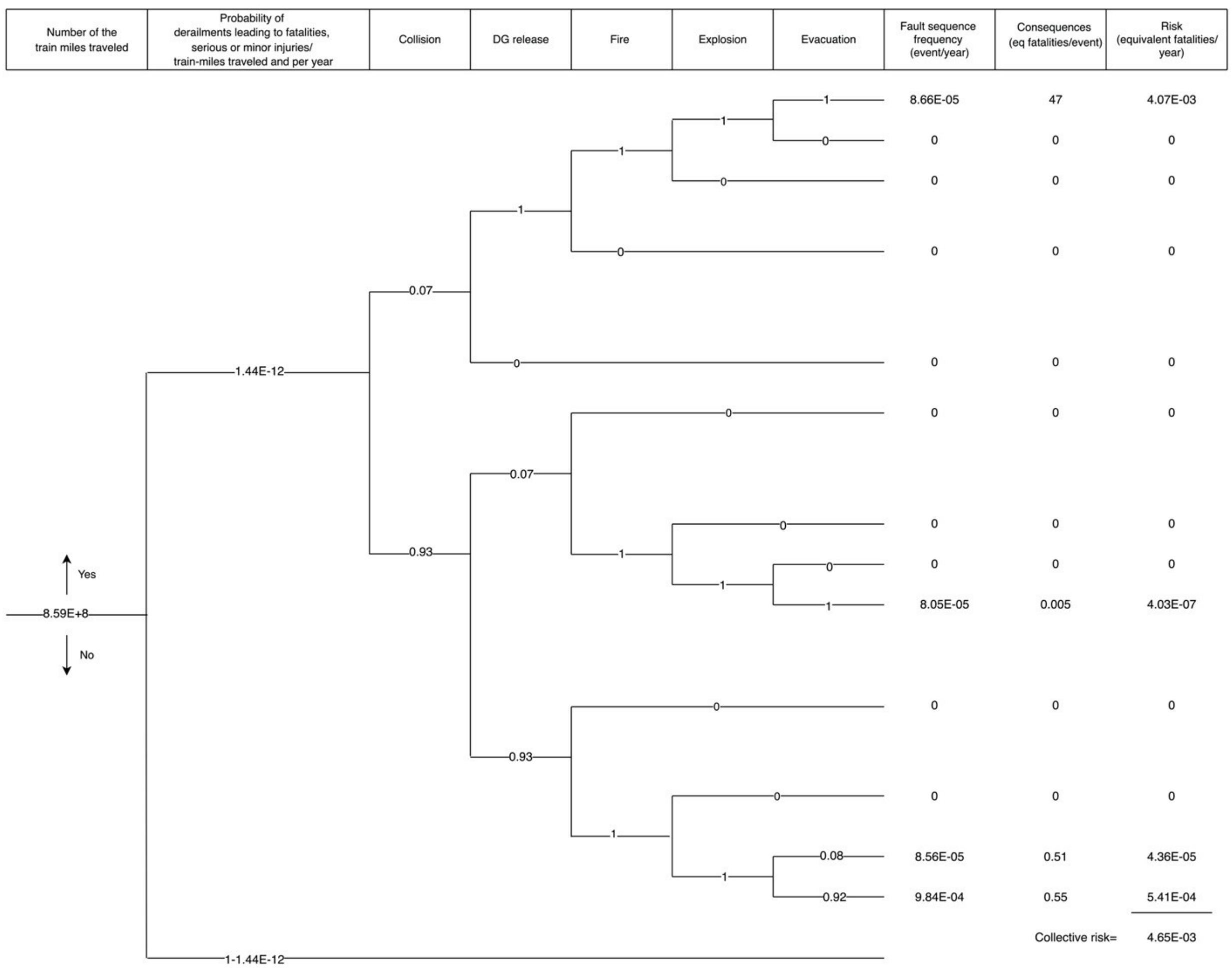


**Figure 3-14.** ETA for main-track train derailments leading to fatalities and injuries

The next stage of the study was to evaluate the collective risk of the main-track train collisions. The assessment of the RODS database showed that 59 main-track collisions (class 1-5 occurrences) have occurred between 2007 to 2017. Based on the RODS-injury database, six of the freight and passenger train collisions had fatality or injury consequences. The distribution of the fatalities, serious and minor injuries based on the year of occurrence are presented in Figure 3-5.

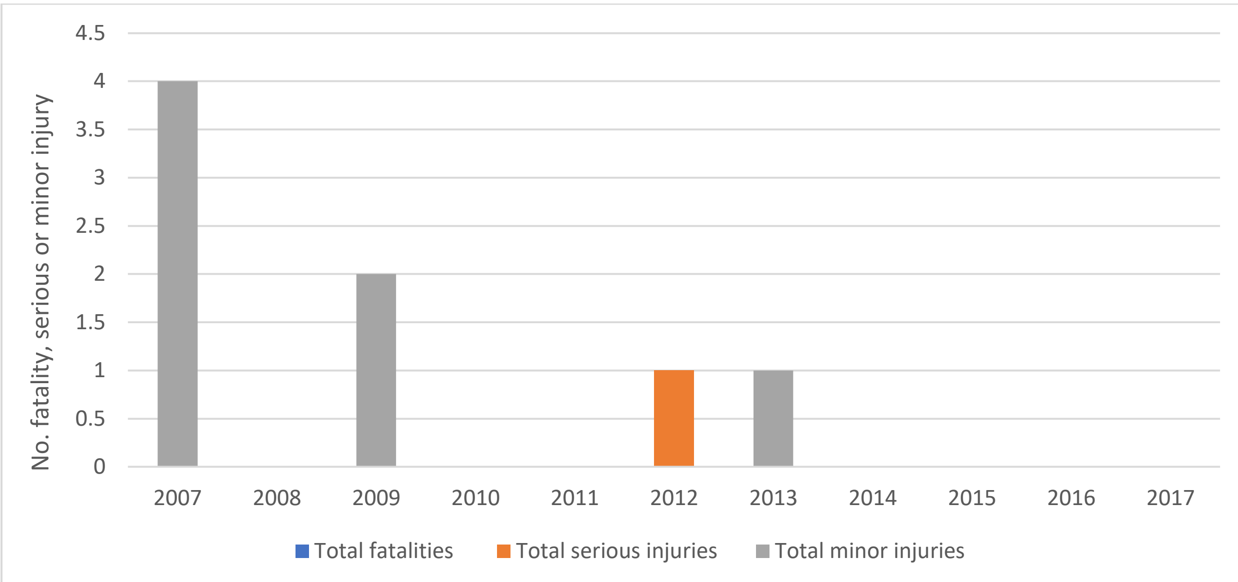


**Figure 3-15.** Number of fatalities /serious injuries /minor injuries per year for main-track train collisions

Restricting the data assessment into the main-track collisions, the number of fatalities and serious or minor injuries has been zero for some of the years. Main-track collision accidents had mainly resulted in minor injuries compared to fatality and serious injury consequences. Since 2014, there were no occurrences with fatality, serious, and minor injury outcomes which indicates an enhancement in reducing the number of occurrences.

A diagrammatic representation of the FTA for main-track collision is presented in Figure 3-6. The results provided by FTA illustrate that train operation - human factors group is the leading cause group of these kind of accidents. This cause group also includes all the subgroups with the highest probability: speed, violations of authority, train handling/makeup, and the use of brakes. Similar to previous stage, in the end step of the FTA, the annual probability of a main-track collisions with fatality and injury consequences was calculated per train miles that the train traveled.

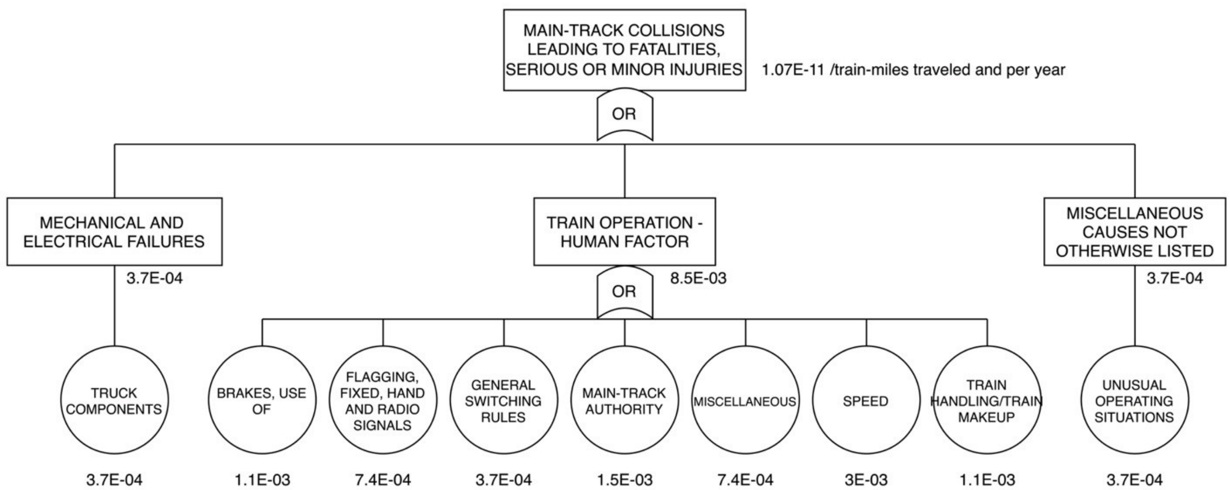


**Figure 3-16.** FTA for main-track train collisions leading to fatalities and injuries

According to RODS database, a main-track train collision might result into a derailment, DG release, fire, explosion, and evacuation. Figure 3-7 presents the probability of each consequence, frequency of occurrence (number of events/year) and the risk (number of equivalent fatalities per year) for each accident scenario. As shown in Figure 3-7, the highest level of risk to life was $2.16 \times 10^{-4}$ equivalent fatalities per year which was related to the main-track collision followed by derailment with no DG release, fire, explosion, and evacuation outcomes. Finally, the risk of different accident scenarios led to identifying the collective risk of main-track collisions causing fatality and injury.

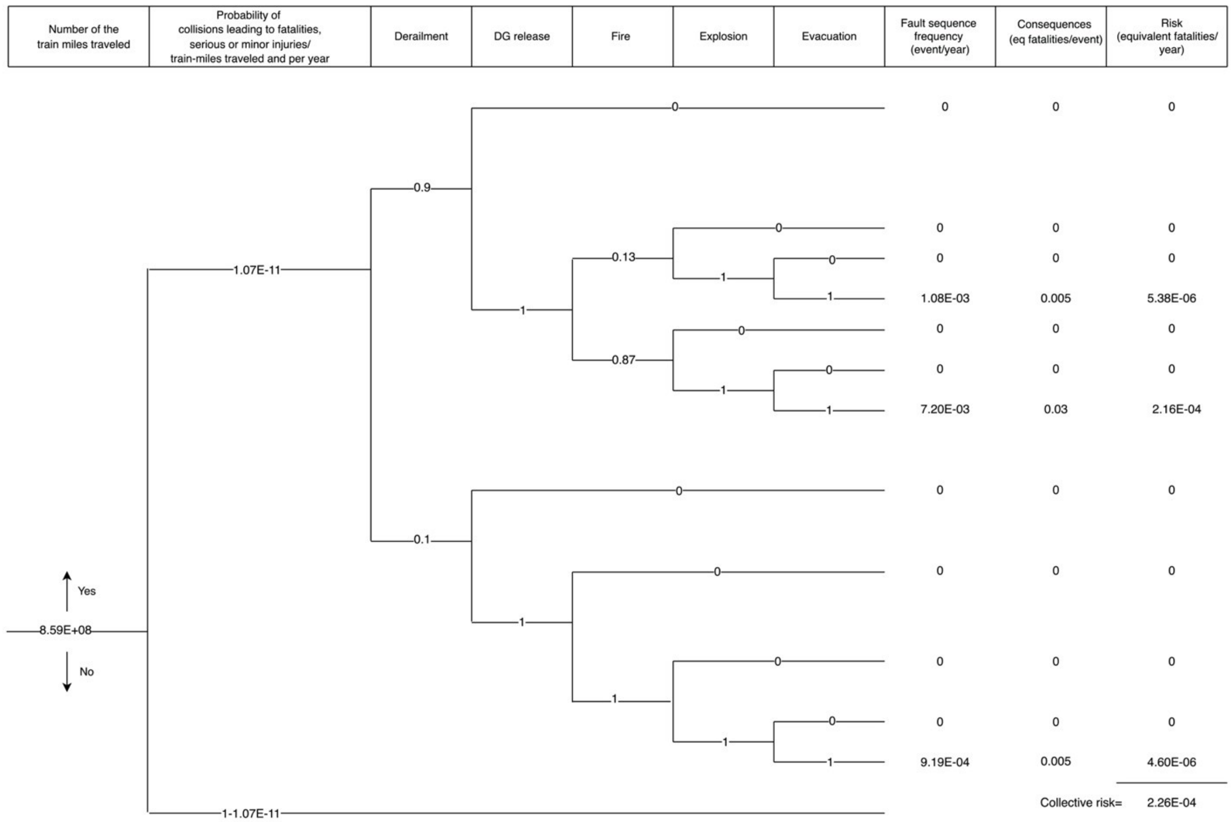


**Figure 3-17.** ETA for for main-track train collisions leading to fatalities and injuries

Evaluating the RODS database revealed that 1,026 main-track derailments, and 59 main-track collisions (class 1-5 occurrences) have occurred between 2007 to 2017. Table 3-1 shows the collective risk, the average number of equivalent fatalities per year, by accident category. The total collective risk of main-track derailments and collisions is also presented.

**Table 3-7.** Collective risk by accident category

| Accident category | Collective risk |
|---|---|
| Risk of main-track derailments (equivalent fatality/ year) | 4.771 |
| Risk of main-track collisions (equivalent fatality/ year) | 0.013 |
| Total risk of main-track derailments and collisions (equivalent fatality/ year) | 4.784 |

### 3.3.2. Individual risk

Individual risk is the probability of fatality per year for a particular group of people using railways, which means passenger, workforce, and MOP (6,16). Identifying the individual risk of two hazardous events, main-track derailments and collision, FTA and ETA were applied. The FTA was similar to the evaluating the collective risk stage. The ETA also kept its structure with the difference that the number of fatalities and injuries considered for ETA was related to the group of people for which its individual risk was supposed to be calculated. For example, in an effort to evaluate the risk of main-track derailments for passengers, the number of passengers who died or were injured as a result of such an accident was counted toward applying the ETA. The ETAs for individual risk assessment are provided in Appendix C. Considering the total 1,026 main-track derailments, and 59 main-track collisions (class 1-5 occurrences), Table 3-2 presents the results of this phase.

**Table 3-8.** Individual risk by accident category

| | Risk for Passengers (equivalent Fatality/year | Risk for Employees (equivalent Fatality/year) | Risk for MOP (equivalent Fatality/year) |
|---|---|---|---|
| Main-track derailments | 0.064 | 0.365 | 4.258 |
| Main-track collisions | 0 | 0.013 | 0 |
| Total risk of main-track derailments and collisions | 0.064 | 0.378 | 4.258 |

### 3.3.3. ETC implementation

Applying C-SRM provided an opportunity to evaluate the effects of implementing ETC in Canadian railways. Two accident causes, main-track authority, and speed are preventable by applying ETC on the rail network. Considering a hundred percent effectiveness for those causes, collective and individual risks of the main-track derailments and collisions were reassessed. The FTAs and ETAs after applying the ETC are presented in Appendix D. Table 3-3 shows the results of the risk assessment before and after the ETC development.

**Table 3-9.** Risk reduction assessment of ETC implementation

| | Risk (equivalent Fatality/year) | Risk for passengers (equivalent Fatality/year) | Risk for employees (equivalent Fatality/year) | Risk for MOP (equivalent Fatality/year) |
|---|---|---|---|---|
| Main-track derailment | 4.771 | 0.064 | 0.365 | 4.258 |
| Main-track derailment (ETC applied) | 4.678 (1.95% decreased) | 0.063 | 0.357 | 4.165 |
| Main-track collision | 0.013 | 0 | 0.013 | 0 |
| Main-track collision (ETC applied) | 0.007 (46.15% decreased) | 0 | 0.007 | 0 |

## 3.4. Discussion

In high-hazard industries like railways, developing a good Safety Management System (SMS) along with sound engineering and competent staff can decrease the probability of hazard occurrence to a very low level. It is beneficial in improving the overall safety performance of these industries in comparison with less-controlled human activity such as road transportation (6).

In order to implement a good SMS, it is essential to consider the risk assessment as a basis for the SMS. Demichela et al. (18) mentioned that the SMS is often formulated without a quantitative risk assessment as a support, because of its cost in terms of money and time. Moreover, sometimes the required data is not available to conduct a quantitative analysis. Without a quantifiable risk assessment, defining the objective of SMS would be difficult (18). Therefore, it is necessary that railway engineers, managers, and safety analysts implement a risk assessment method for their SMS and define the safety standards (19). Having a good understanding of the risk provides an opportunity to allocate the limited available resources in the most effective way to enhance the safety.

This research presented a Canadian customized risk assessment model (C-SRM) to improve the understanding of the risk. The model is based on the quantification of the risk resulting from hazardous events that have the potential to lead to fatalities, serious and minor injuries.

The results derived from C-SRM will enable the rail industry to understand the current level of the residual risks, prioritize areas for safety improvements and planning for developing additional control measures that would decrease the risk. Moreover, it allows as low as reasonably practicable (ALARP) assessments and cost benefit analyses to be undertaken to assist decision-making process for applying proposed changes and modifications. SRM is also useful to identify and prioritize issues for the audit. It provides a basis for evaluating the risk for a particular line of rout or for a particular train company (6). Furthermore, this model enables sensitivity analyses to be carried out to evaluate the risk reduction from the introduction of new control measures (16).

Applying C-SRM was useful to evaluate the collective risk, the average number of equivalent fatalities per year, for two groups of hazardous events: the main-track derailments and collisions.

The outcomes of the FTA revealed that the annual probability of a main-track collision leading to casualties and injuries per train mile is higher than that probability for the main-track derailment. In other words, when a train collision occurs, it is more likely there will be injuries than if a derailment occurs. However, applying ETA and identifying the collective risks of these two hazardous events demonstrated that the risk of the main-track derailments is greater than the risk of main-track collisions in terms of fatality and injury. Risk is affected by both frequency and consequence. Higher risk of main-track derailments could be related to both the factors. Considering the frequency, the proportion of main-track derailment accidents in 2020 was 7% while only 1% of rail occurrences were related to the main-track collisions (12). In terms of consequences, as shown in Figures 3-2 and 3-5, the main-track derailments resulted in fatalities, serious, and minor injuries. In contrast, the main-track collisions mainly caused minor injuries with a few serious injuries. There were no fatality outcomes for this accident within the study timeframe. Since the weight of fatality and serious injury is higher than the weight of the minor injury in calculating the equivalent fatality, it had a significant impact on increasing the consequences of the main-track derailments and eventually increasing the risk of this hazardous event.

It might be worth mentioning the results of SRM for European countries which their SRM's results was publicly available. However, it should be noted that the operational characteristics of European railways are different from North American railways and the results are not comparable. The risk of main-track derailments and collisions for the same period of time (2007-2017) are 3.69 and 0.68 for Slovakian railways (16). In an effort to investigate the UK railways, the Hazardous Event Train accident (HET) category of UK SRM which includes collision and derailment accidents were considered. The risk of the HET is 7.8 equivalent fatalities per year in the period 1999 to September 2013 (20). It is noteworthy that HET category of UK's SRM includes some other types of accidents (e.g. passenger train collision with road vehicle on level crossings, non-passenger train collision with road vehicle on level crossings) in addition to the derailments and collisions. Moreover, UK SRM considers both reportable and non-reportable injuries in its assessment. In C-SRM, due to limited available resources only reportable injuries were included.

It might also be worth mentioning that the results of ETA (Figures 3-4 and 3-7) for both kinds of accidents demonstrated the important role of evacuation on the risk of these occurrences. Fatalities and injuries were mainly observed in those branches where there was no evacuation after the accident. This shows that mitigation strategies related to the evacuation and emergency response plans still need further assessment and improvement. Evacuating more than 200,000 people after the Mississauga train derailment in 1979 in Mississauga, Ontario, Canada is a successful example of evacuation that saved people with no fatalities after the accident. Fordham (21) investigated some of the reasons for the success of this evacuation.

The collective risks of the hazardous events provided an overall view of the safety performance. However, it is also worth assessing this performance in relation to employees, passengers, and MOP. Developing C-SRM was helpful to identify the individual risks of the main-track derailments and collisions. The risk under this approach is the annual estimation of the potential harm to the employees, passengers, and MOP from the operation of the railways. Table 3-2 shows that the risk for the MOP forms the greatest proportion of the individual risk of derailment accidents. Main-track derailment is one of the most serious types of rail occurrences in terms of the potential risk to the public and financial damages, especially when it occurred in populated areas (12). The Lac-Mégantic accident with 47 fatalities (4) is an example of these rail events which played an important role in increasing the individual risk of train derailments for MOP in this study. These low-frequency high-consequences rail occurrences cause an elevated level of risk. In the UK, approximately 63 percent of the overall risk from passenger train derailment was related to low-frequency high-consequences events (6). Sattari et al. (13) further investigated the low-frequency high-consequences rail occurrences by evaluating their societal risk. The potential for this type of occurrence shows that there is still an opportunity for optimizing resource allocation for risk control and mitigation strategies in this regard.

In terms of the main-track collisions, the highest individual risk was related to the employees. As show in the Figure 3-6, human error is the leading cause of the main-track collision accidents. As a result, there might be a potential relationship between this factor and high risk to the employees. A study done by Kyriakidis et al. (22) identified distraction/loss of concentration, safety culture, proper communication between employees, workload, training, and stress as the most significant contributors to the operators' performance in rail industry. Esmaeeli et al. (23) discussed some of the appropriate strategies that can be implemented to reduce the employees' errors. For instance, conducting regular team meetings to strengthen the teamwork (24), providing practical training alongside the online training (25), and regular assessment of employee's competencies to ensure that individuals are capable of properly applying their knowledge in practice. However, confirming the correlation between human errors and risk for the employees needs further investigations and is beyond the scope of this study.

It is noteworthy that no risk for the passengers and MOP might result from a limited database that consists of main-track collisions leading to fatality and injuries (six occurrences). Furthermore, most of the collision accidents within the study database were freight with no passengers.

Considering the risk of Canadian railways in terms of fatalities and injuries, applying new control measurements can reduce the risk and even achieve the ultimate goal of zero fatality. Japan's 'Shinkansen' high-speed train system's performance is an impressive example in this regard with zero passenger fatalities in train collisions and derailments for more than 35 years (6).

Employing C-SRM gave an opportunity to assess the effects of developing a new control measure, ETC, through a risk reduction analysis. ETC systems are fail-safe technologies developed to be similar to the PTC system functionality implemented in the US (11,26).

PTC is a well-known control measure that has been mandated by Rail Safety Improvement Act of 2008 (RSIA) for development on certain Class 1 railroads main lines in the US to improve rail transportation safety. In December of 2020, FRA announced that PTC technology is implemented on all required freight and passenger railroad route miles (10). While the railway industry supports this measure, railway operators in Canada have raised several major concerns regarding their experience with PTC implementation in the US such as expensiveness, complexity, and significant effort requirement to apply it (11).

According to the Canada's Advisory Council research on Railway Safety in 2016, developing a targeted, risk-based, corridor-specific train control approach is the best option for deployment of this technology in Canada. This recommendation has been the “working assumption” for developing ETC in Canada. ETC systems are intended to prevent certain rail occurrences caused by human error. The technologies provide a wide range of innovative safety solutions to support the train crew. It could be ranged from assisting in recognizing and following the signals to automatically applying the train brakes to prevent a collision or derailment (1). The core functional objective of ETC system in Canada is to prevent train-to-train collisions, over speed derailments, train entering a foreman's work authority, and train occupying improperly aligned switches (11).

The current approach of controlling train movements in Canada is “rule-based”. Occupancy control system rules is applied on low density corridors, with verbal clearances and other instructions issued to train crews. Higher density corridors follow centralized traffic control, with wayside signals indicating speed limits and clearances. In both cases, it is the responsibility of the crews to comply with the rules. Currently, there is no regulatory requirement in order to install technologies on board locomotives to protect against excessive speed operation or not following a wayside signal indication. The reliance is solely placed on train crews. As a result, there have been occasions that unintended rule violent due to a loss of situational awareness resulted in derailments or collisions. It is this potential for human error that ETC technologies are aimed to address it (1).

Implementing ETC technologies on Canadian rail network is a priority for TC which is reflected in the recent Notice of Intent published in the Canada Gazette on February 5, 2022. It revealed that TC intends to establish ETC system on Canadian railways to add an important layer of safety to its already safe rail transportation system and enhance passenger and freight train safety (1).

In this study, in order to assess the impact of ETC on rail transport risk, a hundred percent effectiveness was considered for two accident causes, main-track authority and speed. As mentioned in the methods section, this level of effectiveness is achievable by ETC implementation at the Automatic Train Protection System level. The results of risk reduction analysis (Table 3-3) showed that developing ETC system resulted to reducing 1.95% and 46.15% of the risk of main-track derailments and collision, respectively. It is evident that the proportion of the risk reduction for collision accidents was much greater than that for derailment accidents. The reason for this can be related to the underlying cause of these accidents. The FTA of main-track collisions (Figure 3-6) demonstrate that human error is the primary cause of these accidents. It also shows speed and main-track authority are the most probable cause of main-track collisions in the subcategory level. However, the FTA for main-track derailments (Figure 3-3) reveals that human error was third-ranked cause of these accident. Moreover, there was no main-track authority subcategory in its FTA and the probability of the speed sub category was also very low. Hence, as ETC systems are intended to be effective on human errors (speed and main-track authority), its implementation was much more effective in reducing the risk of main-track collisions compared to the main-track derailments.

The result of risk reduction analysis of this study is in line with the result of the Canadian Rail Research Laboratory (CaRRL) report to the TC. CaRRL (11) analysis also showed that a much greater proportion (on percentage basis) of main-track collisions are preventable compared to the main-track derailments by implementing ETC. The outcomes of their study revealed that between 20.4% and 30.5% of main-track collisions and 1.1% to 2.4% of main-track derailments could have been prevented with an ETC system.

Although the ETC technologies were more effective in decreasing the risk of main-track collision, their impact on reducing the risk of main-track derailments is not negligible. Main-track derailments and collisions leading to fatality and injury are rare events with potentially high consequences. Decreasing the risk of these events even by a couple of percentages would significantly improve the safety of passenger and freight trains. This is the reason which makes the ETC system a useful control measure to prevent certain rare, but potentially high-consequences accidents. However, decision-making about the implementation of this technology on Canadian railways needs further investigation such as cost-benefit analysis.

## 3.5. Conclusion and future work

### 3.5.1. Conclusion

This study contains the results of the risk assessment of the Canadian railways by developing a customized Canadian SRM called C-SRM. The risk in this context is defined in relation to rail occurrences leading to fatalities and injuries. The research is focused on two groups of hazardous events: main-track derailments and collision accidents. The outcomes of the employed model will increase the industry's knowledge of the risk and allow the identification of areas of railway operation that need further risk controls. It also enables sensitivity analyses to be carried out to determine the risk reduction from the introduction of new control measures.

In order to implement C-SRM, FTA and ETA were applied to the hazardous events. The outcomes of the study revealed when a train collision occurs, it is more likely there will be injuries than if a derailment happens. However, the risk of the main-track derailments was greater. Evaluating the individual risk of hazardous events showed that the highest individual risk of the main-track derailment was related to the MOP. Low-frequency high-consequence rail events like the Lac-Mégantic accident played a prominent role in elevating the risk for this group of people. Moreover, the risk for employees was the highest individual risk of main-track collision. There might be a potential relationship between human error which was the most frequent cause of the collision accident and this level of risk for employees. However, it needs further investigation which was beyond the scope of this study. Considering the risk of Canadian operations in terms of fatalities and injuries, there are still opportunities for enhancing safety and decreasing the risk. For example, improving emergency response plans, applying control measurements to mitigate low-frequency high-consequences accidents, etc.

The last step of the study was the risk reduction assessment of developing ETC systems on Canadian railways. The result of the analysis showed that ETC technologies are useful control measurements in preventing certain rare, but potentially high-consequences accidents. However, decision-making about the development of this system on Canadian railways needs further assessment such as cost-benefit analysis.

### 3.5.2 Limitation of the study

The limitation of the research is related to the scope of the study which was focused on main-track derailments and collisions. Considering other types of hazardous events and increasing the level of the details in order to categorize them would enhance the accuracy of the risk assessment. Furthermore, due to limited available resources, only reportable injuries were included in the analysis. Considering non-reportable injuries would definitely change the risk profiles and improve the level of accuracy.

### 3.5.3. Future work

The C-SRM presented in this study provides a national-wide risk and does not show how the risk is distributed across the network. Future updates to the model will include means to assess the risk for a particular line of route. Rail Safety and Standards Board (RSSB) is an example in this regard that has developed Geospatial models (GeoSRM) of rail safety hazards in Great Britain (GB) (27,28). Macciotta et al. (29) discussed some of the complexities of risk assessment for a particular corridor in Canada.

In order to assess the risk for a particular line, localized FTA and ETA are needed. This would greatly increase the number of calculations required for the C-SRM and therefore new and more efficient ways of calculating will be needed (30). Two different methods would be suggested. 1) Converting the FTA and ETA into a Bayesian Network (BN) and undertaking calculations using algorithms in the SamIam software package (31). 2). Using traditional FTA and ETA calculations coded in the R software package (32).

## 3.6. References

1. Canada Gazette. Canada Gazette [Internet]. 2022. p. Part I, Volume 156, Number 6. Available from: https://www.gazette.gc.ca/rp-pr/p1/2022/2022-02-05/html/notice-avis-eng.html#nc2

2. Railway Association of Canada. Canada’s Freight Railways: Moving the Economy [Internet]. 2020 [cited 2022 Jun 7]. Available from: https://www.railcan.ca/101/canadas-freight-railways-moving-the-economy/

3. Railway Association of Canada. Rail Trends 2020. 2020.

4. Transportation Safety Board of Canada (TSB). Railway Investigation Report R13D0054 [Internet]. 2014 [cited 2020 Jun 28]. Available from: https://www.tsb.gc.ca/eng/rapports-reports/rail/2013/R13D0054/R13D0054.html

5. Transportation Safety Board of Canada (TSB). Railway Investigation Report R12T0038 [Internet]. 2013. Available from: https://www.tsb.gc.ca/eng/rapports-reports/rail/2012/r12t0038/r12t0038.html

6. Muttram RI. Railway safety's safety risk model. Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit. 2002;216(2):71–9.

7. Kawprasert A, Barkan CPL. Communication and Interpretation of Results of Route Risk Analyses of Hazardous Materials Transportation by Railroad. Transportation Research Record: Journal of the Transportation Research Board. 2009;(2097):125–35.

8. Liu X, Barkan CPL, Saat MR. Analysis of Derailments by Accident Cause: Evaluating Railroad Track Upgrades to Reduce Transportation Risk. Transportation Research Record: Journal of the Transportation Research Board. 2011;(2261):178–85.

9. Ellis J. Research on risk models at the European level Final Report. 2015.

10. Federal Railroad Administration (FRA). Rail moving America forward. In: 2021 TRB Annual Conference [Internet]. FRA OFFICE OF RESEARCH, DEVELOPMENT, and TECHNOLOGY; 2021. Available from: https://railroads.dot.gov/sites/fra.dot.gov/files/2020-12/2021_RDT_CurrentProjects_complete_pdfa.pdf

11. Canadian Rail Research Laboratory (CaRRL). Canadian Rail Research Laboratory Report on Enhanced Train Control. Transport Canada Report. 2018.

12. Transportation Safety Board of Canada (TSB). Rail transportation occurrences in 2020 [Internet]. 2021. Available from: https://www.tsb.gc.ca/eng/stats/rail/2020/sser-ssro-2020.html#3.0

13. Sattari F, Macciotta R, Lefsrud L. Process Safety Approach to Identify Opportunities for Enhancing Rail Transport Safety in Canada. Transportation Research Record. 2020;2675(1):49–66.

14. Schafer DH, Barkan CPL. Relationship between train length and accident causes and rates. Transportation Research Record. 2008;750(2043):73–82.

15. D. Little A. Risk Assessment for the Transportation of Hazardous Materials by Rail. Supplementary Report: Railroad Accident Rate and Risk Reduction Option Effectiveness Analysis and Data (2nd Revision). 1996.

16. Leitner B. A General Model for Railway Systems Risk Assessment with the Use of Railway Accident Scenarios Analysis. Procedia Engineering. 2017;187:150–9.

17. Transportation Safety Board of Canada (TSB). Statistical Summary - Railway Occurrences 2017 [Internet]. 2018 [cited 2022 Jun 9]. Available from: https://www.tsb.gc.ca/eng/stats/rail/2017/sser-ssro-2017.html

18. Demichela M, Piccinini N, Romano A. Risk analysis as a basis for safety management system. Journal of Loss Prevention in the Process Industries. 2004;17(3):179–85.

19. An M, Chen Y, Baker CJ. A fuzzy reasoning and fuzzy-analytical hierarchy process based approach to the process of railway risk information: A railway risk management system. Information Sciences. 2011;181(18):3946–66.

20. Rail Safety and Standards Board. Safety Risk Model: Risk Profile Bulletin, version 8.1 [Internet]. 2014. Available from: https://studylib.net/doc/11430882/safety-risk-model--risk-profile-bulletin--version-8.1

21. Fordham RF. Mississauga Train Derailment. Vol. 044, Loss Prevention Bulletin. 1981. p. 15–32.

22. Kyriakidis M, Majumdar A, Grote G, Ochieng WY. Development and assessment of taxonomy for performance-shaping factors for railway operations. Transportation Research Record. 2012;(2289):145–53.

23. Esmaeeli N, Sattari F, Lefsrud L, Macciotta R. Critical Analysis of Train Derailments in Canada through Process Safety Techniques and Insights into Enhanced Safety Management Systems. Transportation Research Record: Journal of the Transportation Research Board. 2022;2676(4):603–25.

24. Zhan Q, Zheng W, Zhao B. A hybrid human and organizational analysis method for railway accidents based on HFACS-Railway Accidents (HFACS-RAs). Safety Science. 2017;91:232–50.

25. Transportation Safety Board of Canada (TSB). Rail transportation safety investigation R15H0021 [Internet]. 2017 [cited 2022 Jun 17]. Available from: https://www.tsb.gc.ca/eng/enquetes-investigations/rail/2015/r15h0021/r15h0021.html

26. Working Group. Train Control Working Group Final Report Presented to : The Advisory Council. 2016.

27. Griffin DJK. Geospatial modelling of rail safety hazards. Safety and Reliability: Methodology and Applications - Proceedings of the European Safety and Reliability Conference, ESREL 2014. 2015;1639–47.

28. Sadler J, Griffin D, Gilchrist A, Austin J, Kit O, Heavisides J. GeoSRM - Online geospatial safety risk model for the GB rail network. IET Intelligent Transport Systems. 2016;10(1):17–24.

29. Macciotta R, Robitaille S, Hendry M, Martin CD. Hazard ranking for railway transport of dangerous goods in Canada. Case Studies on Transport Policy [Internet]. 2018;6(1):43–50. Available from: https://doi.org/10.1016/j.cstp.2017.11.006

30. Gilchrist A, Harrison C. Developing a new Safety Risk Model (SRM) methodology for the GB rail industry. Safety and Reliability. 2021;40(1):28–47.

31. Automated Reasoning Group. SamIam: Sensitivity analysis modeling inference and more [Internet]. University of California. 2004. Available from: http://reasoning.cs.ucla.edu/samiam/

32. R Core Team. R: A language and environment for statistical computing [Internet]. R Foundation for Statistical Computing. 2014. Available from: http://www.r-project.org/

# 4. Conclusions and future work

## 4.1. Conclusions

Railways play a significant role in Canada's economy, transporting goods and offering people transportation services across the country. Rail transportation system can be considered adequately safe overall, when weighted against the benefits of it; as reflected by the social licence to operate. However, the persistence of the rail occurrences shows that there are still opportunities to further enhance its safety. In an effort to evaluate the railway's SMS, the results of the first study revealed that the top three SMS elements that need improvement include process and equipment integrity, incident investigation, and company standards, codes, and regulations. Useful recommendations were also proposed to enhance the management of each element and reduce the gap. For example, employing new and novel technologies and approaches in order to identify rail defects, and placing a slow order on a defect track are beneficial in improving the process and equipment integrity element of SMS. Moreover, providing accurate information on SDS and also information outlining the amount of product released is vital for communicating the dangers of the product and useful in enhancing the incident investigation element of the SMS.

Risk assessment is a basis for the SMS and helps to define the SMS objectives. Applying an appropriate risk assessment model is helpful to identify the current level of risk, prioritize areas for safety improvements, and develop a plan to mitigate those risks. A useful and customized Canadian risk assessment model named C-SRM was presented in the second study to identify the risk of Canadian railways in terms of injuries and fatalities. The outcomes of the study showed that the collective risk of the main-track derailments was higher than the main-track collisions. Furthermore, evaluating the individual risks of these rail events revealed that the highest risks were related to the MOP and employees for main-track derailments and main-track collisions, respectively. Finally, applying risk reduction analysis for the ETC development demonstrated that these technologies are beneficial in preventing certain rare, but potentially high-consequences accidents. Although the ETC technologies had a greater impact on decreasing the risk of main-track collision, their effect on reducing the risk of main-track derailments is not negligible. Main-track derailments and collisions with fatalities and injury outcomes are rare occurrences with potentially high consequences and reducing their risks even by a couple of percentages would significantly enhance the safety of passenger and freight trains. However, decision-making regarding the implementation of this system in the Canadian rail industry needs further investigation such as cost-benefit analysis.

## 4.2. Future work

In order to assess the SMS in the first paper, a framework of SMS with twelve elements was implemented. This study was part of a broader research project which has been already published, where a 12-element SMS framework was used (1). In order to align with that project and provide comparable results, the mentioned SMS framework was also chosen for this study. However, over time, the number of SMS elements has increased to 20 elements by adding new elements such as process safety culture (2). Future studies can consider the new framework of SMS and investigate the railway's SMS which can provide further details on the areas requiring improvement. Moreover, this study was focused on DG main-track derailments (class 1, 2, and 3 occurrences), following the initial statement of the problem. Including other types and classes of rail occurrences would allow extrapolation to overall railway transportation (e.g. other commodities and passengers) and enhance the level of accuracy of the investigation.

In the second study, applying C-SRM provided a national-wide risk estimate, however this overall analysis did not show how the risk was distributed across the network. Future updates to the model can include means to evaluate the risk for a particular line of route. In order to do that, localized FTA and ETA are needed which would greatly increase the number of calculations required for the C-SRM. Two different methods would be suggested to increase the efficiency of the calculations. 1) Converting the FTA and ETA into a Bayesian Network (BN) and undertaking calculations using algorithms in the SamIam software package (3). 2). Using traditional FTA and ETA calculations coded in the R software package (4).

## 4.3. References


1. Ebrahimi H, Sattari F, Lefsrud L, Macciotta R. Analysis of train derailments and collisions to identify leading causes of loss incidents in rail transport of dangerous goods in Canada. Journal of Loss Prevention in the Process Industries. 2021;72(May):104517.

2. A. Crowl D, F. Louvar J. Chemical process safety. 4th ed. Prentice Hall; 2019.

3. Automated Reasoning Group. SamIam: Sensitivity analysis modeling inference and more [Internet]. University of California. 2004. Available from: http://reasoning.cs.ucla.edu/samiam/

4. R Core Team. R: A language and environment for statistical computing [Internet]. R Foundation for Statistical Computing. 2014. Available from: http://www.r-project.org/

## Works Cited


1. Railways 101 | RAC [Internet]. [cited 2020 Apr 18]. Available from: https://www.railcan.ca/railways-101/

2. Railway Association of Canada. Rail Trends. 2018.

3. Crude Oil Forecast | Canadian Association of Petroleum Producers [Internet]. [cited 2020 Apr 18]. Available from: https://www.capp.ca/resources/crude-oil-forecast/

4. Miller L. REVIEW OF THE CANADIAN TRANSPORTATION SAFETY REGIME : TRANSPORTATION OF DANGEROUS GOODS AND SAFETY Report of the Standing Committee on Transport , Infrastructure and Communities. 2015.

5. Canada Transportation Act Review Panel. Vision and balance : report of the Canada Transportation Act Review Panel. 2001. 88 p.

6. Parliament of Canada - House of Commons. Standing Committee on Transport, Infrastructure and Communities. 41st PARLIAMENT, 2st SESSION. 2013;(27 November).

7. Railway Safety Management System Regulations. Canada Gazette. 2014 Jul 5;Part I, Vol. 148, No. 27.

8. Railway Investigation Report R05E0059 - Transportation Safety Board of Canada [Internet]. [cited 2020 Jun 29]. Available from: https://www.tsb.gc.ca/eng/rapports-reports/rail/2005/r05e0059/r05e0059.html

9. Transportation Safety Board of Canada (TSB). Railway Investigation Report R13D0054 [Internet]. 2014 [cited 2020 Jun 28]. Available from: https://www.tsb.gc.ca/eng/rapports-reports/rail/2013/R13D0054/R13D0054.html

10. Parliament of Canada - House of Commons. Standing Committee on Transport, Infrastructure and Communities. 41st PARLIAMENT, 2st SESSION. 2013;(25 November).

11. Edwards CJ. Developing of safety case with an aircraft operator. In: IBC Conference on Aviation Safety Management, London, 20–21 May. 1999.

12. E. Roland H, Moriarty B. System Safety Engineering and Management. John Wileys & Sons Inc.; 1990.

13. CCPS. Guidelines for process safety documentation. American Institute of Chemical Engineers; 1995.

14. A. Crowl D, F. Louvar J. Chemical process safety. 4th ed. Prentice Hall; 2019.

15. Ebrahimi H, Sattari F, Lefsrud L, Macciotta R. Analysis of train derailments and collisions to identify leading causes of loss incidents in rail transport of dangerous goods in Canada. Journal of Loss Prevention in the Process Industries. 2021;72(May):104517.

16. Håvold JI. Safety culture and safety management aboard tankers. Reliability Engineering and System Safety. 2010;95(5):511–9.

17. Bielic T, Predovan D, ēulin J. The Role of the Master in Improving Safety Culture Onboard Ships. TransNav, the International Journal on Marine Navigation and Safety of Sea Transportation. 2017;11(1):121–4.

18. Hsu YL, Li WC, Chen KW. Structuring critical success factors of airline safety management system using a hybrid model. Transportation Research Part E: Logistics and Transportation Review. 2010;46(2):222–35.

19. Kyriakidis M, Pak KT, Majumdar A. Railway accidents caused by human error: Historic analysis of UK railways, 1945 to 2012. Transportation Research Record. 2015;2476:126–36.

20. Liu X, Saat MR, Barkan CPL. Analysis of causes of major train derailment and their effect on accident rates. Transportation Research Record. 2012;(2289):154–63.

21. Rudin-Brown CM, George MFS, Stuart JJ. Human factors issues of accidents at passively controlled rural level crossings. Transportation Research Record. 2014;2458:96–103.

22. Kyriakidis M, Majumdar A, Ochieng WY. Data based framework to identify the most significant performance shaping factors in railway operations. Safety Science. 2015;78:60–76.

23. Dindar S, Kaewunruen S, An M. Bayesian network-based human error reliability assessment of derailments. Reliability Engineering and System Safety. 2020;197(November 2019):106825.

24. Read GJM, Naweed A, Salmon PM. Complexity on the rails: A systems-based approach to understanding safety management in rail transport. Reliability Engineering and System Safety. 2019;188(September 2018):352–65.

25. Chen CF, Chen SC. Scale development of safety management system evaluation for the airline industry. Accident Analysis and Prevention. 2012;47:177–81.

26. Basso B, Carpegna C, Dibitonto C, Gaido G, Robotto A, Zonato C. Reviewing the safety management system by incident investigation and performance indicators. Journal of Loss Prevention in the Process Industries. 2004;17(3):225–31.

27. Hale AR, Heming BHJ, Carthey J, Kirwan B. Modelling of safety management systems. Safety Science. 1997;26(1–2):121–40.

28. Hurst N. From research to practical tools - developing assessment tools for safety management and safety culture. Journal of Loss Prevention in the Process Industries. 1997;10(1):63–6.

29. De Dianous V, Fiévez C. ARAMIS project: A more explicit demonstration of risk control through the use of bow-tie diagrams and the evaluation of safety barrier performance. Journal of Hazardous Materials. 2006;130(3 SPEC. ISS.):220–33.

30. Hughes P, Shipp D, Figueres-Esteban M, van Gulijk C. From free-text to structured safety management: Introduction of a semi-automated classification method of railway hazard reports to elements on a bow-tie diagram. Safety Science. 2018;110(June 2017):11–9.

31. Ferdous R, Khan F, Sadiq R, Amyotte P, Veitch B. Analyzing system safety and risks under uncertainty using a bow-tie diagram: An innovative approach. Process Safety and Environmental Protection. 2013;91(1–2):1–18.

32. Zhang C, Wei Y, Li Z, Zhao Y. Hazard-Based Design of the Bow-Tie Method to Prevent and Mitigate Mine Accidents. Journal of Failure Analysis and Prevention. 2018;18(1):29–40.

33. Policy on Occurrence Classification - Transportation Safety Board of Canada [Internet]. [cited 2020 Jun 29]. Available from: https://www.tsb.gc.ca/eng/lois-acts/evenements-occurrences.html

34. Canadian Society for Chemical Engineering. PSM, Process Safety Management Guide, 4th Ed. 2012.

35. Vollmer CM, Sanchez N, Gondek S, McAuliffe J, Kent TS, Christein JD, et al. A Root-Cause Analysis of Mortality Following Major Pancreatectomy. Journal of Gastrointestinal Surgery. 2012;16(1):89–103.

36. Todinov MT. Generic Approaches To Reducing the Likelihood of Critical Failures. Risk-Based Reliability Analysis and Generic Principles for Risk Reduction. 2007;181–92.

37. Barry T. Risk-informed, performance-based industrial fire protection: an alternative to prescriptive codes. Tennessee Valley Publishing. 2002;

38. Crawley F, Tyler B. Hazard identification method. Inst of Chemical Engineers (IChemE): London, UK.; 2003.

39. Rubin O, Dahlberg R. A Dictionary of Disaster Management. Oxford University Press: Oxford, UK.; 2017.

40. Ferdous R, Khan F, Sadiq R, Amyotte P, Veitch B. Handling and updating uncertain information in bow-tie analysis. Journal of Loss Prevention in the Process Industries. 2012;25(1):8–19.

41. Vileiniskis M, Remenyte-Prescott R. Quantitative risk prognostics framework based on Petri Net and Bow-Tie models. Reliability Engineering and System Safety. 2017;165:62–73.

42. Culwick MD, Merry AF, Clarke DM, Taraporewalla KJ, Gibbs NM. Bow-tie diagrams for risk management in anaesthesia. Anaesthesia and Intensive Care. 2016;44(6):712–8.

43. de Ruijter A, Guldenmund F. The bowtie method: A review. Safety Science. 2015;88:211–8.

44. Shahriar A, Sadiq R, Tesfamariam S. Risk analysis for oil & gas pipelines: A sustainability assessment approach using fuzzy based bow-tie analysis. Journal of Loss Prevention in the Process Industries. 2012;25(3):505–23.

45. Papazoglou IA, Bellamy LJ, Hale AR, Aneziris ON, Ale BJM, Post JG, et al. I-Risk: Development of an integrated technical and management risk methodology for chemical installations. Journal of Loss Prevention in the Process Industries. 2003;16(6):575–91.

46. Abdi Z, Ravaghi H, Abbasi M, Delgoshaei B, Esfandiari S. Application of Bow-tie methodology to improve patient safety. International Journal of Health Care Quality Assurance. 2016;29(4):425–40.

47. Cormier R, Elliott M, Rice J. Putting on a bow-tie to sort out who does what and why in the complex arena of marine policy and management. Science of the Total Environment. 2019;648:293–305.

48. Delmotte F. A sociotechnical framework for the integration of human and organizational factors in project management and risk analysis. Industrial and Systems Engineering. 2003;

49. Van Scyoc K, Hughes G. Rail ruminations for process safety improvement. Journal of Loss Prevention in the Process Industries. 2009;22(6):689–94.

50. Rail transportation safety investigations and reports - Transportation Safety Board of Canada [Internet]. [cited 2020 Apr 16]. Available from: https://www.tsb.gc.ca/eng/rapports-reports/rail/index.html

51. Sattari F, Macciotta R, Lefsrud L. Process Safety Approach to Identify Opportunities for Enhancing Rail Transport Safety in Canada. Transportation Research Record. 2020;2675(1):49–66.

52. Reinach, S., Viale A. Application of a Human Error Framework to Conduct Train Accident/Incident Investigations. Accident Analysis and Prevention. 2006;38:396_406.

53. Report No. DOT/FRA/RRS-22. Federal Railroad Administration (FRA) Guide for Preparing Accident/Incident Reports,. 2003;

54. Whittingham RB. The Blame Machine: Why Human Error Causes Accidents. Elsevier Butterworth-Heinemann, Oxford, UK. 2004;

55. Iranitalab A, Khattak A, Thompson E. Statistical modeling of types and consequences of rail-based crude oil release incidents in the United States. Reliability Engineering and System Safety. 2019;185(November 2018):232–9.

56. Railway Association of Canada. Rail trends. 2017.

57. Wilson JR, Farrington-Darby T, Cox G, Bye R, Hockey GRJ. The railway as a socio-technical system: Human factors at the heart of successful rail engineering. Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit. 2007;221(1):101–15.

58. Liu X, Saat MR, Barkan CPL. Analysis of causes of major train derailment and their effect on accident rates. Transportation Research Record. 2012;(2289):154–63.

59. Orringer O. Control of Rail Integrity by Self-Adaptive Scheduling of Rail Tests. Dot/Fra/Ord-90/05. 1990.

60. Lanza di scalea F, Rizzo P, Coccia S, Bartoli I, Fateh M. Laser-air-coupled hybrid noncontact system for defect detection in rail tracks: Status of FRA prototype development at University of California-San Diego. Transportation Research Record. 2006;

61. Xiong Z, Li Q, Mao Q, Zou Q. A 3D laser profiling system for rail surface defect detection. Sensors (Switzerland). 2017;17(8):1–19.

62. Zhang X, Feng N, Wang Y, Shen Y. Acoustic emission detection of rail defect based on wavelet transform and Shannon entropy. Journal of Sound and Vibration. 2015;339:419–32.

63. Jeong DY, Gordon JE. Evaluation of rail test frequencies using risk analysis. Proceedings of the ASME/IEEE Joint Rail Conference 2009, JRC2009. 2009;23–30.

64. Liu X, Lovett A, Dick T, Rapik Saat M, Barkan CPL. Optimization of ultrasonic rail-defect inspection for improving railway transportation safety and efficiency. Journal of Transportation Engineering. 2014;140(10):1–10.

65. Orringer O, Tang YH, Jeong DY, Perlman AB. Risk/Benefit Assessment of Delayed Action Concept for Rail Inspection. Dot/Fra/Ord-99/03. 1999.

66. Shaun S, Stéphane G. Transportation of Dangerous Goods NEWSLETTER 2016_Vol.36 No 1. 2016;

67. Liu X, Saat MR, Barkan CPL. Probability analysis of multiple-tank-car release incidents in railway hazardous materials transportation. Journal of Hazardous Materials. 2014;276:442–51.

68. Lefsrud L, Macciotta R, Nkoro A. Performance-based regulations for safety management systems in the canadian railway industry: An analytical discussion. Canadian Journal of Civil Engineering. 2020;47(3):248–56.

69. Macciotta R, Robitaille S, Hendry M, Martin CD. Hazard ranking for railway transport of dangerous goods in Canada. Case Studies on Transport Policy [Internet]. 2018;6(1):43–50. Available from: https://doi.org/10.1016/j.cstp.2017.11.006

70. Baysari MT, McIntosh AS, Wilson JR. Understanding the human factors contribution to railway accidents and incidents in Australia. Accident Analysis and Prevention. 2008;40(5):1750–7.

71. Kim DS, Baek DH, Yoon WC. Development and evaluation of a computer-aided system for analyzing human error in railway operations. Reliability Engineering and System Safety. 2010;95(2):87–98.

72. Li C, Tang T, Chatzimichailidou MM, Jun GT, Waterson P. A hybrid human and organisational analysis method for railway accidents based on STAMP-HFACS and human information processing. Applied Ergonomics. 2019;79(February):122–42.

73. Zhan Q, Zheng W, Zhao B. A hybrid human and organizational analysis method for railway accidents based on HFACS-Railway Accidents (HFACS-RAs). Safety Science. 2017;91:232–50.

74. De Felice F, Petrillo A. Methodological approach for performing human reliability and error analysis in railway transportation system. International Journal of Engineering and Technology. 2011;3(5):341–53.

75. Read GJM, Lenné MG, Moss SA. Associations between task, training and social environmental factors and error types involved in rail incidents and accidents. Accident Analysis and Prevention. 2012;48:416–22.

76. Zhang Z, Liu X, Holt K. Positive Train Control (PTC) for railway safety in the United States: Policy developments and critical issues. Utilities Policy. 2018;51(June 2017):33–40.

77. Ungan MC. Standardization through process documentation. Business Process Management Journal. 2006;12(2):135–48.

78. Leveson N. A systems approach to risk management through leading safety indicators. Reliability Engineering and System Safety. 2014;

79. Canada Gazette. Canada Gazette [Internet]. 2022. p. Part I, Volume 156, Number 6. Available from: https://www.gazette.gc.ca/rp-pr/p1/2022/2022-02-05/html/notice-avis-eng.html#nc2

80. Railway Association of Canada. Canada's Freight Railways: Moving the Economy [Internet]. 2020 [cited 2022 Jun 7]. Available from: https://www.railcan.ca/101/canadas-freight-railways-moving-the-economy/

81. Railway Association of Canada. Rail Trends 2020. 2020.

82. Transportation Safety Board of Canada (TSB). Railway Investigation Report R12T0038 [Internet]. 2013. Available from: https://www.tsb.gc.ca/eng/rapports-reports/rail/2012/r12t0038/r12t0038.html

83. Muttram RI. Railway safety's safety risk model. Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit. 2002;216(2):71–9.

84. Kawprasert A, Barkan CPL. Communication and Interpretation of Results of Route Risk Analyses of Hazardous Materials Transportation by Railroad. Transportation Research Record: Journal of the Transportation Research Board. 2009;(2097):125–35.

85. Liu X, Barkan CPL, Saat MR. Analysis of Derailments by Accident Cause: Evaluating Railroad Track Upgrades to Reduce Transportation Risk. Transportation Research Record: Journal of the Transportation Research Board. 2011;(2261):178–85.

86. Ellis J. Research on risk models at the European level Final Report. 2015.

87. Federal Railroad Administration (FRA). Rail moving America forward. In: 2021 TRB Annual Conference [Internet]. FRA OFFICE OF RESEARCH, DEVELOPMENT, and TECHNOLOGY; 2021. Available from: https://railroads.dot.gov/sites/fra.dot.gov/files/2020-12/2021_RDT_CurrentProjects_complete_pdfa.pdf

88. Canadian Rail Research Laboratory (CaRRL). Canadian Rail Research Laboratory Report on Enhanced Train Control. Transport Canada Report. 2018.

89. Transportation Safety Board of Canada (TSB). Rail transportation occurrences in 2020 [Internet]. 2021. Available from: https://www.tsb.gc.ca/eng/stats/rail/2020/sser-ssro-2020.html#3.0

90. Sattari F, Macciotta R, Lefsrud L. Process Safety Approach to Identify Opportunities for Enhancing Rail Transport Safety in Canada. Transportation Research Record. 2020;2675(1):49–66.

91. Schafer DH, Barkan CPL. Relationship between train length and accident causes and rates. Transportation Research Record. 2008;750(2043):73–82.

92. D. Little A. Risk Assessment for the Transportation of Hazardous Materials by Rail. Supplementary Report: Railroad Accident Rate and Risk Reduction Option Effectiveness Analysis and Data (2nd Revision). 1996.

93. Leitner B. A General Model for Railway Systems Risk Assessment with the Use of Railway Accident Scenarios Analysis. Procedia Engineering. 2017;187:150–9.

94. Transportation Safety Board of Canada (TSB). Statistical Summary - Railway Occurrences 2017 [Internet]. 2018 [cited 2022 Jun 9]. Available from: https://www.tsb.gc.ca/eng/stats/rail/2017/sser-ssro-2017.html

95. Demichela M, Piccinini N, Romano A. Risk analysis as a basis for safety management system. Journal of Loss Prevention in the Process Industries. 2004;17(3):179–85.

96. An M, Chen Y, Baker CJ. A fuzzy reasoning and fuzzy-analytical hierarchy process based approach to the process of railway risk information: A railway risk management system. Information Sciences. 2011;181(18):3946–66.

97. Rail Safety and Standards Board. Safety Risk Model: Risk Profile Bulletin, version 8.1 [Internet]. 2014. Available from: https://studylib.net/doc/11430882/safety-risk-model--risk-profile-bulletin--version-8.1

98. Fordham RF. Mississauga Train Derailment. Vol. 044, Loss Prevention Bulletin. 1981. p. 15–32.

99. Kyriakidis M, Majumdar A, Grote G, Ochieng WY. Development and assessment of taxonomy for performance-shaping factors for railway operations. Transportation Research Record. 2012;(2289):145–53.

100. Esmaeeli N, Sattari F, Lefsrud L, Macciotta R. Critical Analysis of Train Derailments in Canada through Process Safety Techniques and Insights into Enhanced Safety Management Systems. Transportation Research Record: Journal of the Transportation Research Board. 2022;2676(4):603–25.

101. Zhan Q, Zheng W, Zhao B. A hybrid human and organizational analysis method for railway accidents based on HFACS-Railway Accidents (HFACS-RAs). Safety Science. 2017;91:232–50.

102. Transportation Safety Board of Canada (TSB). Rail transportation safety investigation R15H0021 [Internet]. 2017 [cited 2022 Jun 17]. Available from: https://www.tsb.gc.ca/eng/enquetes-investigations/rail/2015/r15h0021/r15h0021.html

103. Working Group. Train Control Working Group Final Report Presented to : The Advisory Council. 2016.

104. Griffin DJK. Geospatial modelling of rail safety hazards. Safety and Reliability: Methodology and Applications - Proceedings of the European Safety and Reliability Conference, ESREL 2014. 2015;1639–47.

105. Sadler J, Griffin D, Gilchrist A, Austin J, Kit O, Heavisides J. GeoSRM - Online geospatial safety risk model for the GB rail network. IET Intelligent Transport Systems. 2016;10(1):17–24.

106. Gilchrist A, Harrison C. Developing a new Safety Risk Model (SRM) methodology for the GB rail industry. Safety and Reliability. 2021;40(1):28–47.

107. Automated Reasoning Group. SamIam: Sensitivity analysis modeling inference and more [Internet]. University of California. 2004. Available from: http://reasoning.cs.ucla.edu/samiam/

108. R Core Team. R: A language and environment for statistical computing [Internet]. R Foundation for Statistical Computing. 2014. Available from: http://www.r-project.org/

109. Wang L, Sun R. A new safety culture measurement tool and its application. Int J Saf Secur Eng. 2014;4(1):77–86.

110. Kyriakidis M, Majumdar A, Grote G, Ochieng WY. Development and assessment of taxonomy for performance-shaping factors for railway operations. Transp Res Rec. 2012;(2289):145–53.

111. Uttal B. The corporate culture vultures. Fortune Mag. 1983;

112. Turner BA, Pidgeon N, Blockley D, Toft B. Safety culture: its importance in future risk

management. Position Pap Second World Bank Work Saf Control Risk Manag. 1989;

113. He A, Xu S, Fu G. Study on the basic problems of safety culture. Procedia Eng. 2012;43:245–9.

114. Ostrom L, Wilhelmsen C, Kaplan B. Assessing Safety Culture. Tech Prog. 1977;34–2:163–72.

115. C. W. Bailey, D. Petersen. Using Perception Surveys to Assess Safety System Effectiveness. Prof Saf. 34:22–6.

116. Wang CH, Liu YJ. Omnidirectional safety culture analysis and discussion for railway industry. Saf Sci. 2012;50(5):1196–204.

117. Farrington-Darby T, Pickup L, Wilson JR. Safety culture in railway maintenance. Saf Sci. 2005;43(1):39–60.

118. Cooper MD. Towards a model of safety culture. Saf Sci. 2000;36(2):111–36.

119. Strauch B. Can we examine safety culture in accident investigations, or should we? Saf Sci. 2015;77:102–11.

120. Dillon RL, Tinsley CH. How near-misses influence decision making under risk: A missed opportunity for learning. Manage Sci. 2008;54(8):1425–40.

121. Cambraia FB, Saurin TA, Formoso CT. Identification, analysis and dissemination of information on near misses: A case study in the construction industry. Saf Sci. 2010;48(1):91–9.

122. Schaaf V der, Tjerk W, Moraal J, Hale AR. Near miss reporting in the chemical process industry. Tech Univ Eindhoven, Proefschr. 1992;

123. Jones S, Kirchsteiger C, Bjerke W. The importance of near miss reporting to further improve safety performance. J Loss Prev Process Ind. 1999;12(1):59–67.

124. Banerjee S, Santos J, Hempel M, Ghasemzadeh P, Sharif H. A novel method of near-miss event detection with software defined radar in improving railyard safety. Safety. 2019;5(3).

125. Zaman A, Liu X, Zhang Z. Video Analytics for Railroad Safety Research: An Artificial Intelligence Approach. Transp Res Rec. 2018;2672(10):269–77.

126. Trommelen M. Causes of, and backgrounds to human error in accidents at the nylon-plant. Intern report, Leiden Univ. 1991;

127. Powell PI, Hale M, Martin J, Simon M. 2000 Accidents: A Shop Floor Study of their cases. Rep no 21 (London Natl Inst Ind Psychol. 1971;

128. Senneck CR. Over three-day absences and safety. Appl Ergowomics. 1975;147–53.

129. Pransky G, Snyder T, Dembe A, Himmelstein J. Under-reporting of work-related disorders in the workplace: A case study and review of the literature. Ergonomics. 1999;42(1):171–82.

130. Staes L, Godfrey J. Characteristics of non-punitive employee safety reporting systems for public transportation as abridged from tcrp report 218. Transp Res Rec. 2021;2675(6):254–64.

## Appendix A – Definitions of occurrence, accident, and incident terms and classes of occurrences

**Occurrence:** TSB uses the term 'occurrence' to include reportable accidents and incidents, as defined by the *TSB Regulations* Section 5(1). This includes: a) fatalities or serious injuries; b) rolling stock collisions or derailments, fire or explosion, or damage to the rolling stock or railway that effects safety; c) a risk of collision between rolling stock; d) unprotected main track or subdivision track switch left in an unsafe position; e) a railway signal that displays a less restrictive indication; f) rolling stock or trackwork in contravention of the Rules; g) rolling stock passing a stop signal; h) unplanned or uncontrolled movement of rolling stock; i) incapacitated crew members; j) accidental release of DG. As mentioned in the TSB website, there are six classes of occurrences:

**Class 1 occurrence:** A class 1 occurrence is a series of occurrences with similar characteristics that have formed a pattern of one or more significant safety risks over time. These safety risks have been previously identified in the investigations done by TSB (or similar organizations in other jurisdictions) or emerged from statistical analysis.

**Class 2 occurrence:** A class 2 occurrence attracts a high level of public interest across Canada or internationally because of its significant consequences. It affects many people, some of whom may be fatally or seriously injured, releasing large amount of DG and significant damage to property and/or the environment.

**Class 3 occurrence:** A class 3 occurrence may have significant consequences which resulted in attracting a high level of public interest. Those consequences may include multiple fatalities and/or serious injuries, or there may be a medium-sized release of DG. Also, there is moderate to significant damage to property and/or the environment.

**Class 4 occurrence:** A class 4 occurrence may have some important consequences such as small release of DG, moderate to minor damage to property and/or the environment. It may cause fatalities or serious injuries. The occurrence attracts immediate region or province/territory public interest.

**Class 5 occurrence:** A class 5 occurrence may involve fatalities and/or serious injuries and little or no release of DG. The damage to property or the environment is minimal. The occurrence attracts limited public interest outside of the immediate region.

**Class 6 occurrence:** A class 6 occurrence is a transportation occurrence that happens outside of Canada. The TSB is notified about these occurrences in accordance with international conventions and/or memoranda of understanding, and an investigation may or may not be done by a foreign investigation body.

**Accident:** TSB policy on occurrence classification section A7. defines ‘accident’ as an occurrence caused directly by the operation of rolling stock. This includes: a) fatalities or serious injuries; b) rolling stock collisions or derailments, fire or explosion, or damage to the rolling stock or railway that effects safety; c) accidental release of DG or an emission of radiation resulting from damage to the containment system.

**Incident:** TSB policy on occurrence classification section A8. defines 'incident' as an occurrence resulting directly from the operation of rolling stock. This include: a) rolling stock minor collision and/or minor derailment; b) a risk of collision between rolling stock; c) unprotected main track or subdivision track switch left in an unsafe position; d) a railway signal that displays a less restrictive indication; e) rolling stock or trackwork in contravention of the rules; f) rolling stock passing a stop signal; g) unplanned or uncontrolled movement of rolling stock; h) incapacitated crew members; i) accidental release of DG or an emission of radiation resulting from damage to the containment system.

## Appendix B – Elements and components of SMS used in this study (CSChE, 2012)

**1. Accountability: Objectives and Goals**

Continuity of operation

Continuity of system

Continuity of organization

Quality process

Control of exceptions

Alternative methods

Management accessibility

Communications

Company expectation

**2. Process knowledge and documentation**

Chemical and occupational health hazards

Process definition/design criteria

Process and equipment design

Protective system

Normal and upset conditions

Process risk management decisions

Company memory

**3. Capital project review and design procedures**

Appropriation request procedures

Hazard review

Sitting

Process design and review procedures

Plot plan

Project management procedures and control

**4. Process risk management**

Hazard identification

Risk analysis of the operation

Reduction of risk

Residual risk management

Encouraging client and supplier companies to adopt similar risk management practices

Process management during emergencies

Selection of businesses with acceptable risk

**5. Management of change**

Change of process technology

Change of facility

Organizational changes

Variance procedures

Permanent changes

Temporary changes

**6. Process and equipment integrity**

Reliability engineering

Material of construction

Preventive maintenance

Maintenance procedures

Alarm and instrument management

Process hardware, system inspection, and testing

Fabrication and inspection procedures

Installation procedures

**7. Human factors**

Operator-process/equipment interface

Administrative control versus engineering control

Human error assessment

**8. Training and performance**

Definition of skill and knowledge

Instructor program

Records management

Ongoing performance and refresher training

Design of operating and maintenance procedures

Initial qualification assessment

Selection and development of a training program

Measuring performance and effectiveness

**9. Incident investigation**

Major incidents

Communication

Incident recording, reporting, analysis

Third party participation

Follow-up and resolution

Near miss reporting

**10. Company standard, codes, regulation**

Internal standard

External codes/ regulations

**11. Audits**

SMS system audits

Process safety audits

Corrective actions

Compliance reviews

Internal/external auditors

**12. Enhancement of process safety knowledge**

Quality control program and process safety

Professional and trade association program

Technical association program

Research development, documentation and implementation

Improved predictive system

Process safety resource centre and reference library

# Appendix C – Individual risks of main-track derailments and collisions

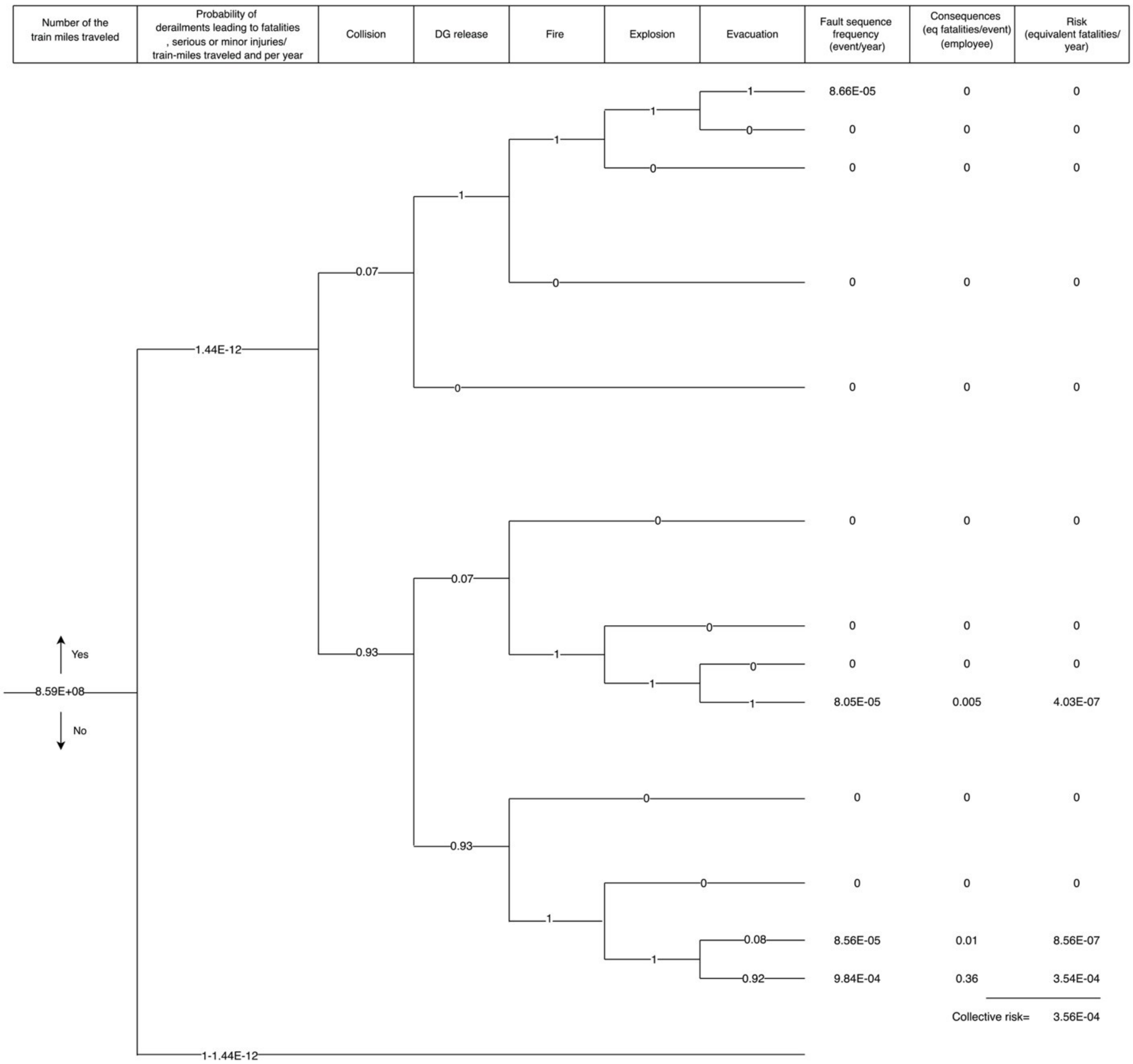


**Figure C-18.** Main-track derailments leading to fatalities and injuries risk for the employees

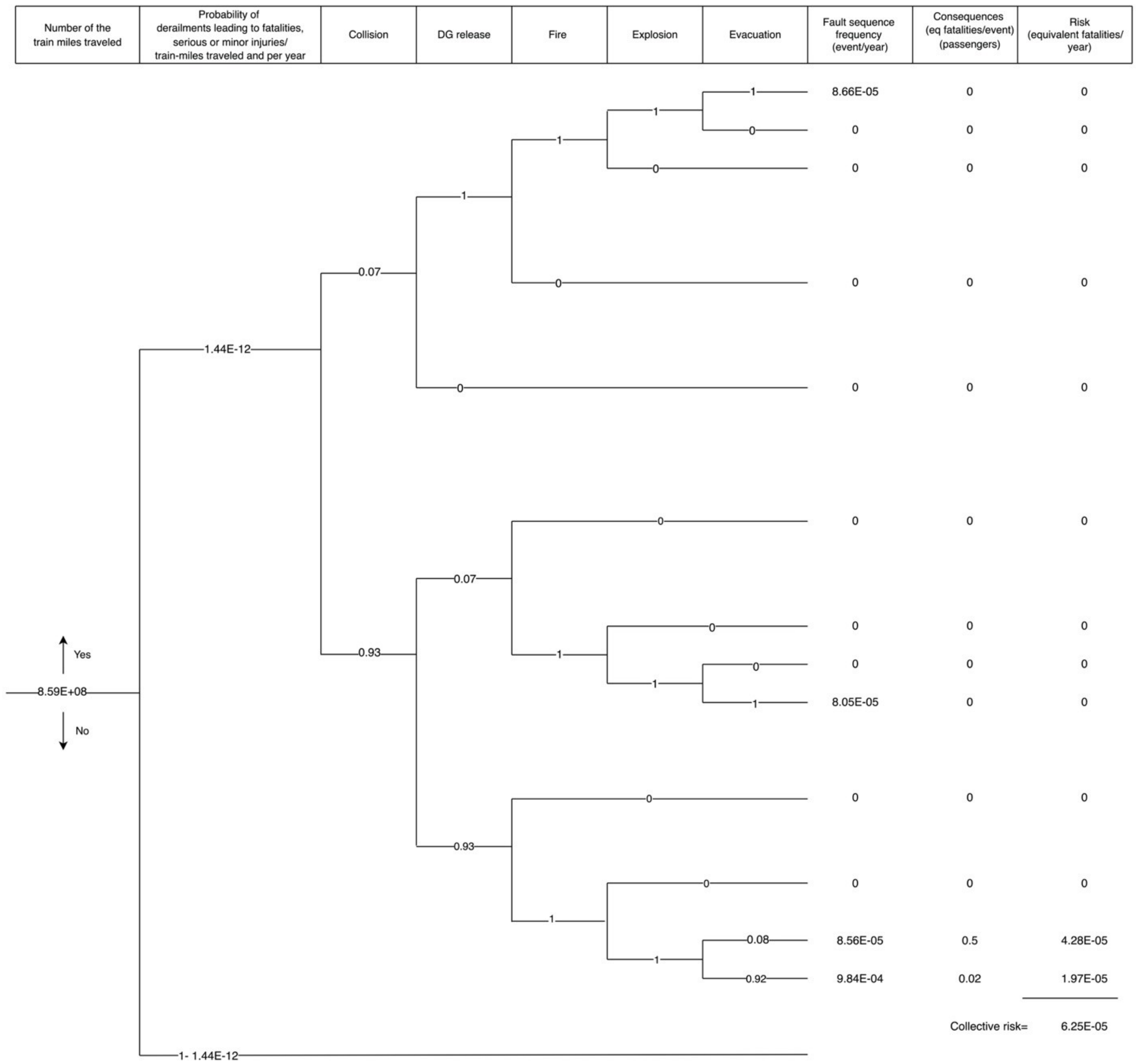


**Figure C-19.** Main-track derailments leading to fatalities and injuries risk for the passengers

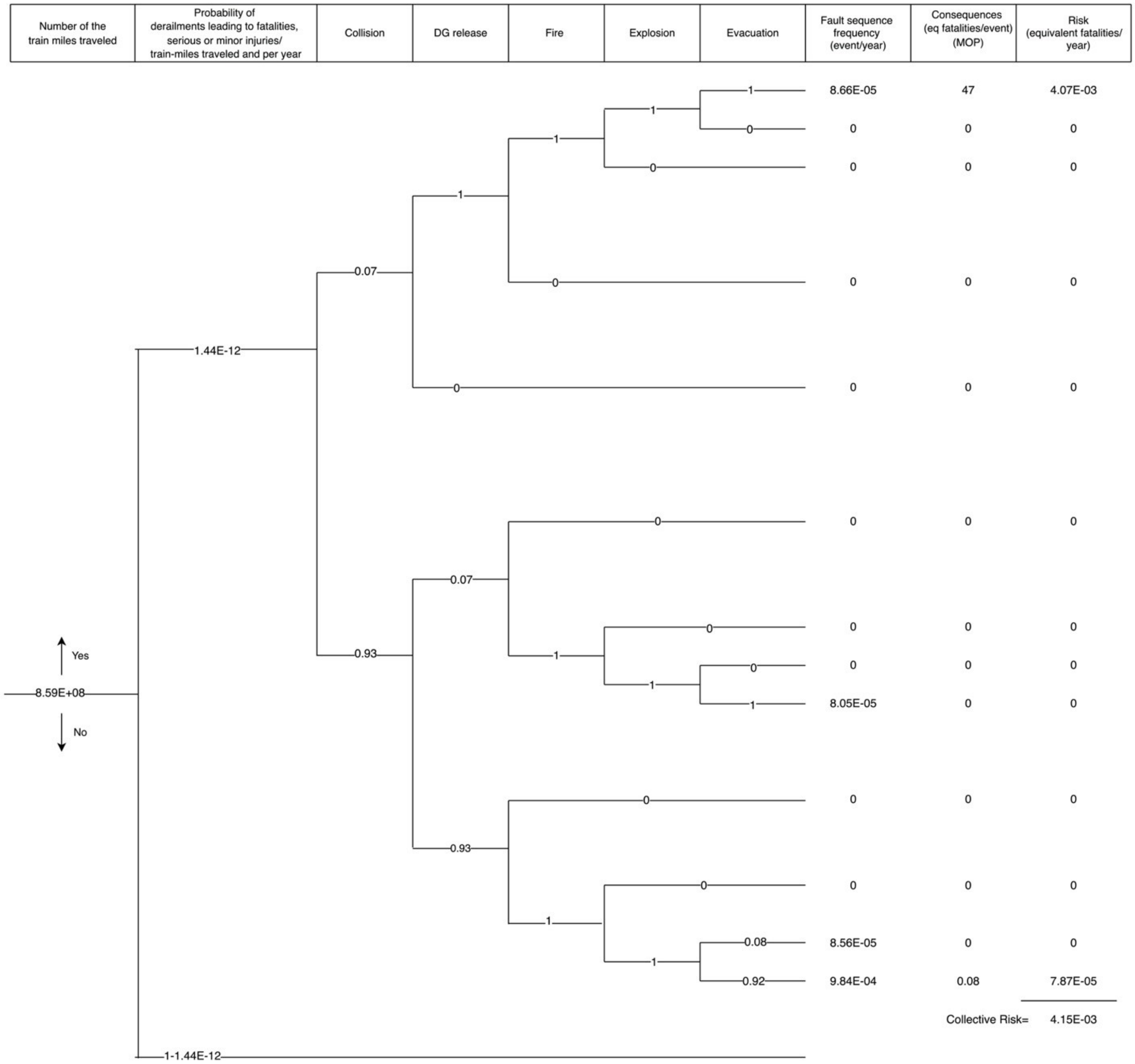


**Figure C-20.** Main-track derailments leading to fatalities and injuries risk for the MOP

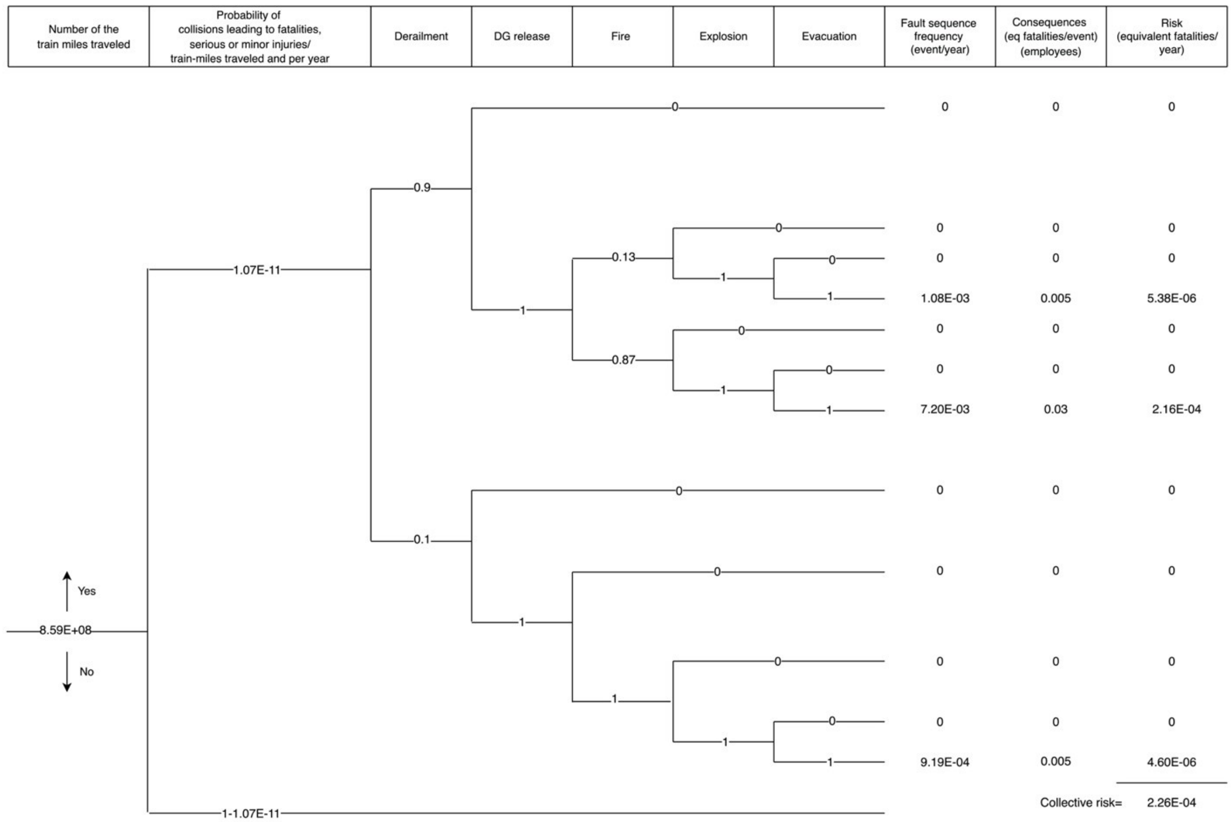


**Figure C-21.** Main-track collisions leading to fatalities and injuries risk for the employees

# Appendix D – Risk reduction assessment of the ETC implementation

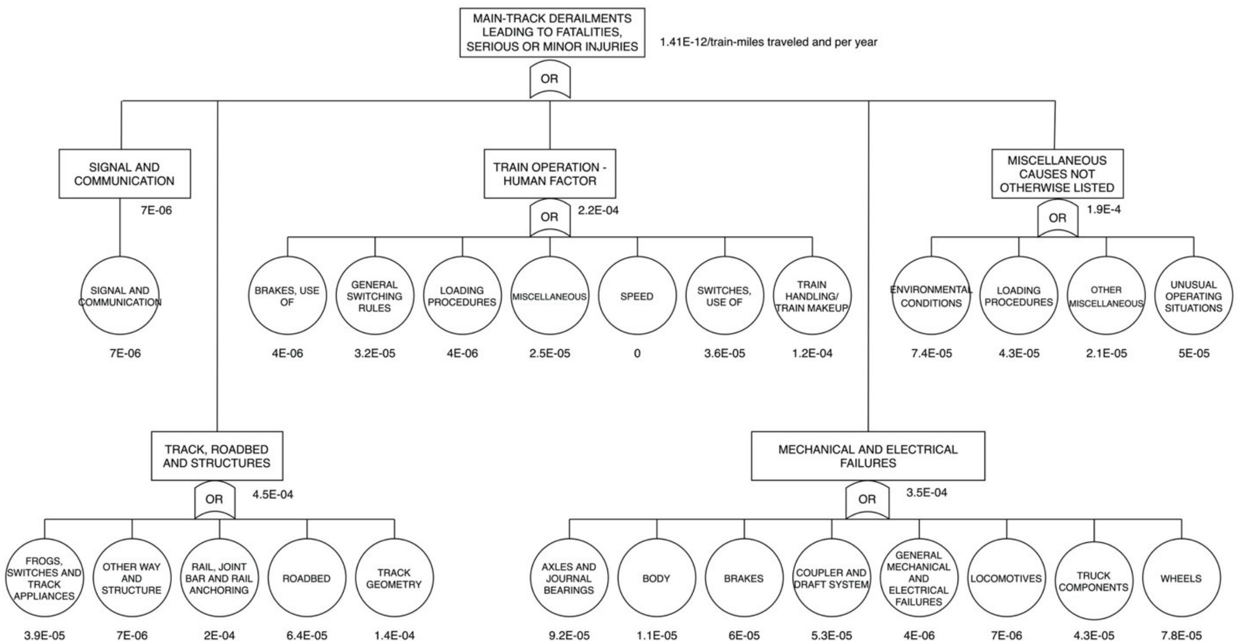


**Figure D-22.** FTA for main-track derailments leading to fatalities and injuries after ETC implementation

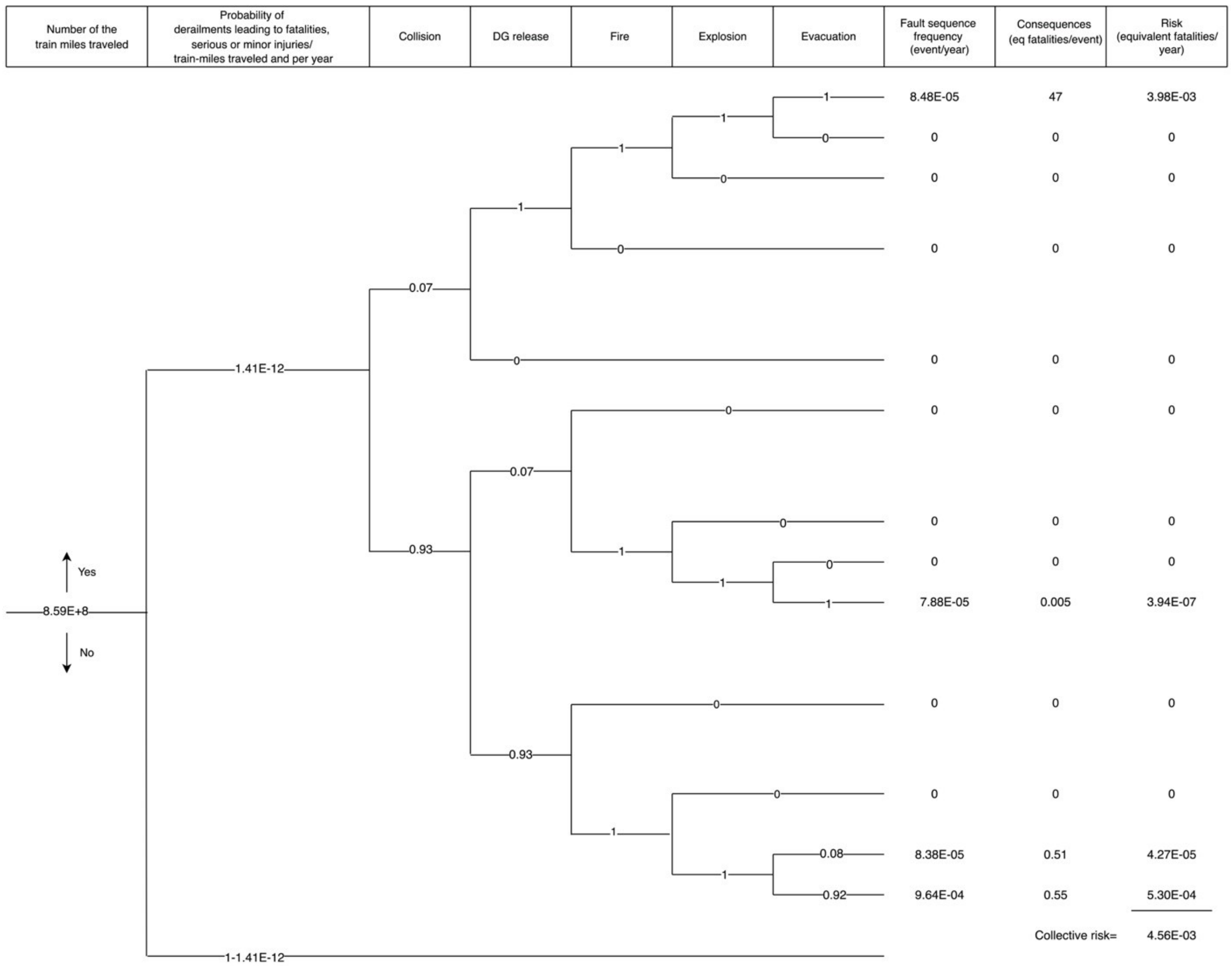


**Figure D-23.** ETA for main-track derailments leading to fatalities and injuries after ETC implementation

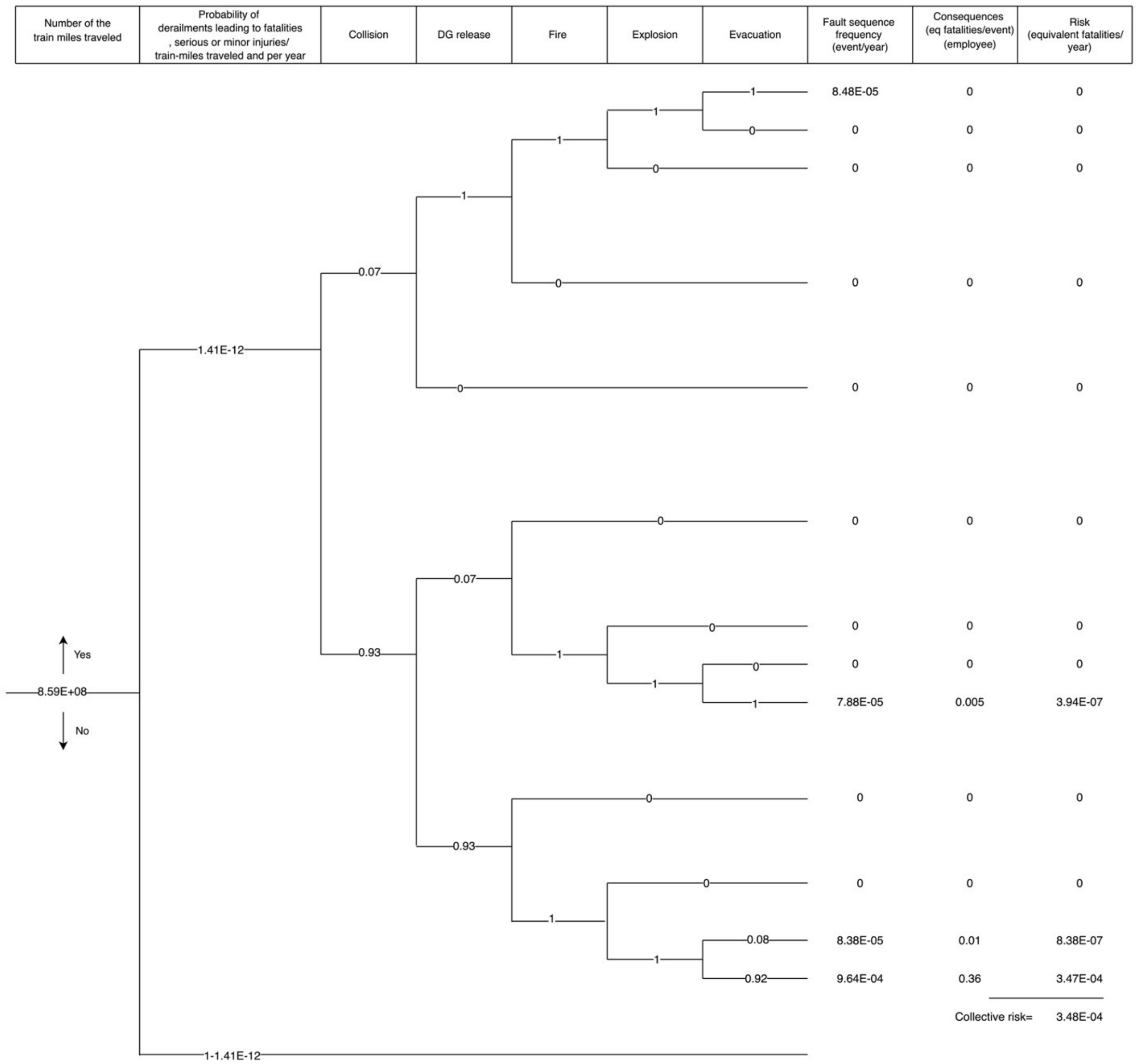


**Figure D-24.** Main-track derailments leading to fatalities and injuries risk for the employees after ETC implementation

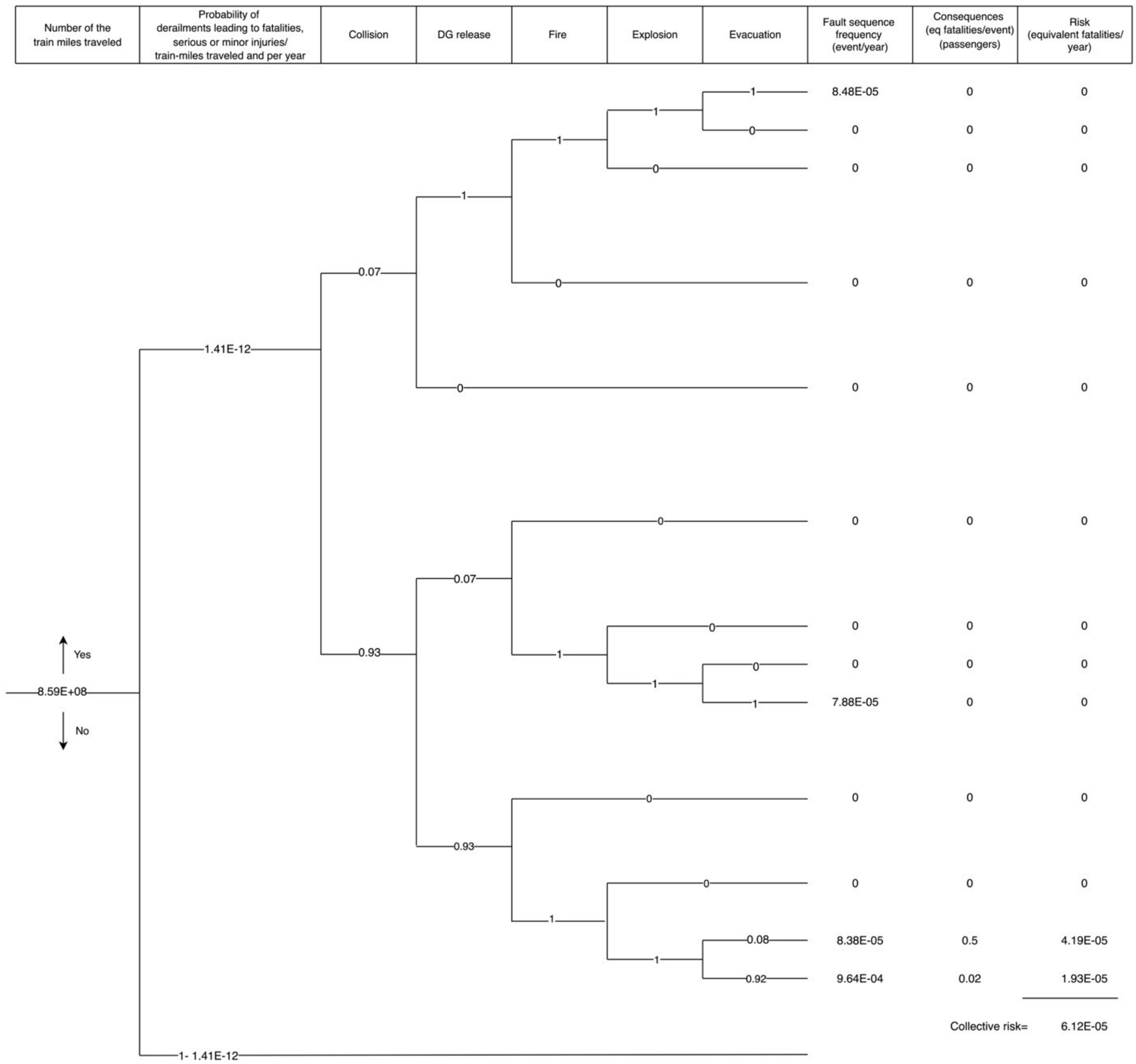


**Figure D-25.** Main-track derailments leading to fatalities and injuries risk for the passengers after ETC implementation

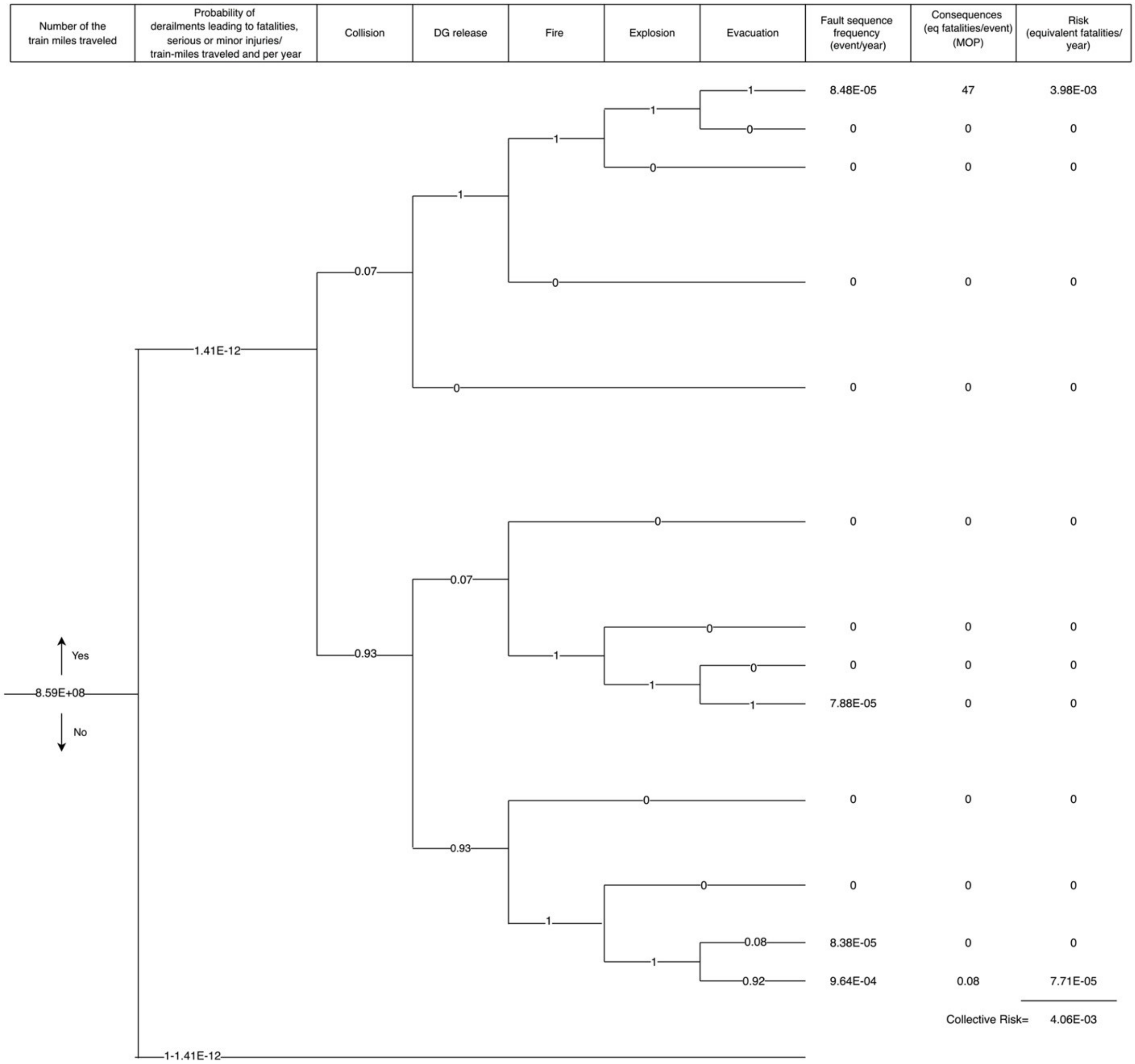


**Figure D-26.** Main-track derailments leading to fatalities and injuries risk for the MOP after ETC implementation

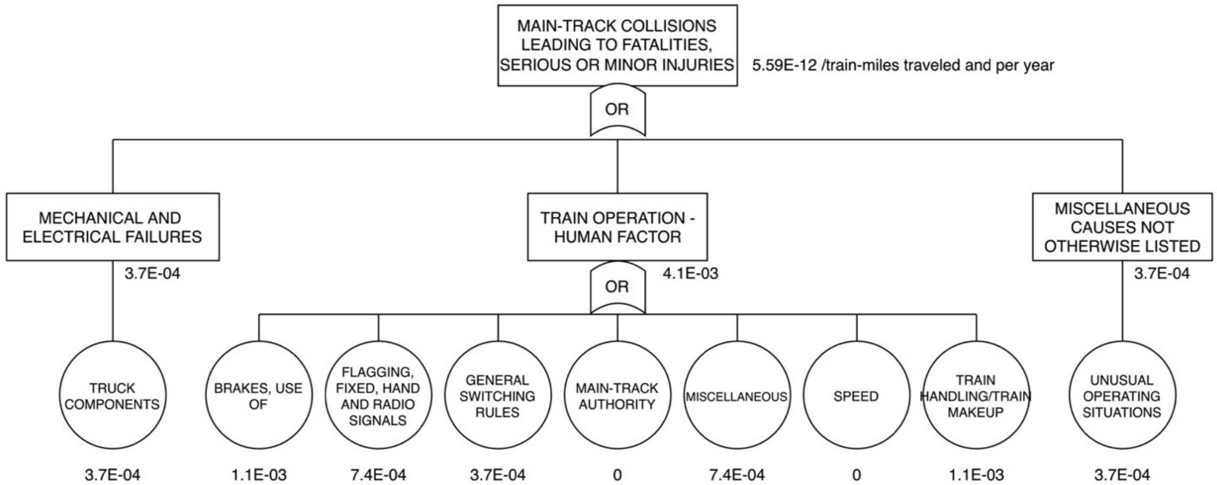


**Figure D-27.** FTA for main-track collisions leading to fatalities and injuries after ETC implementation

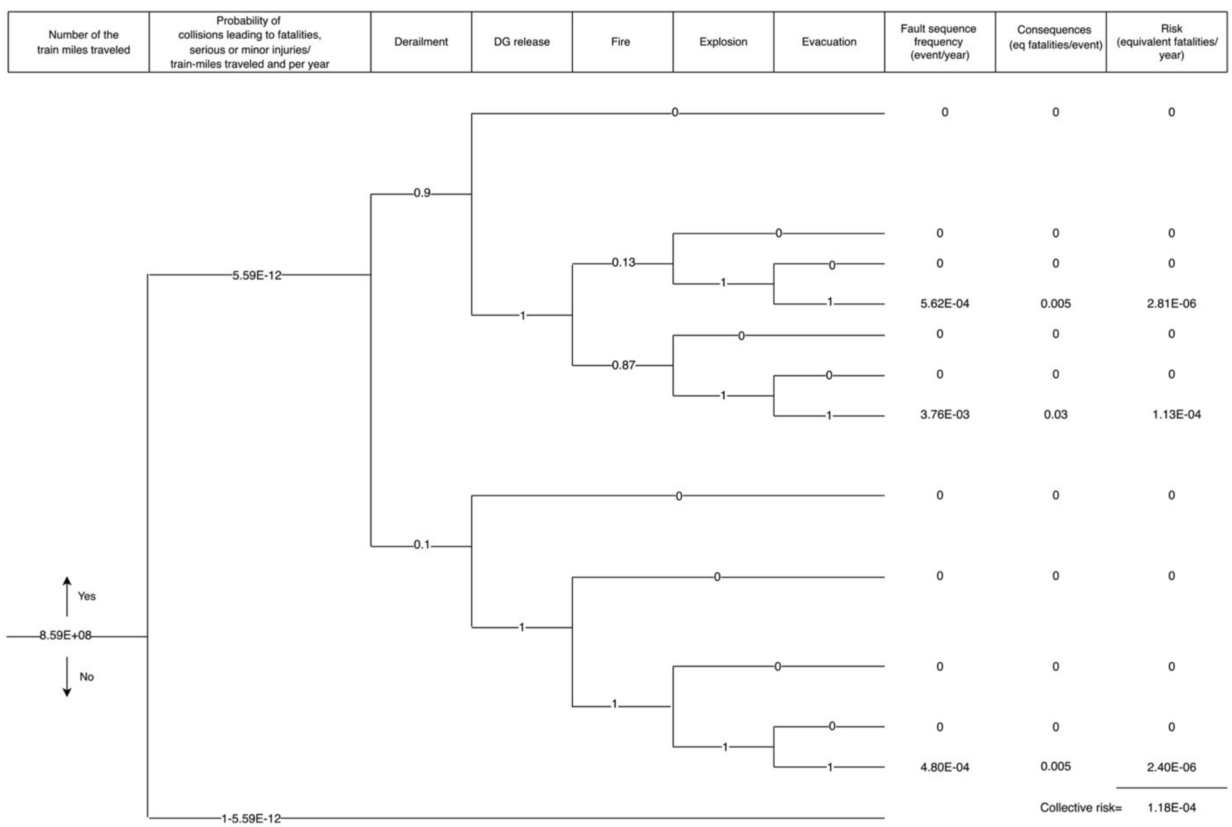


**Figure D-28.** ETA for main-track collisions leading to fatalities and injuries after ETC implementation

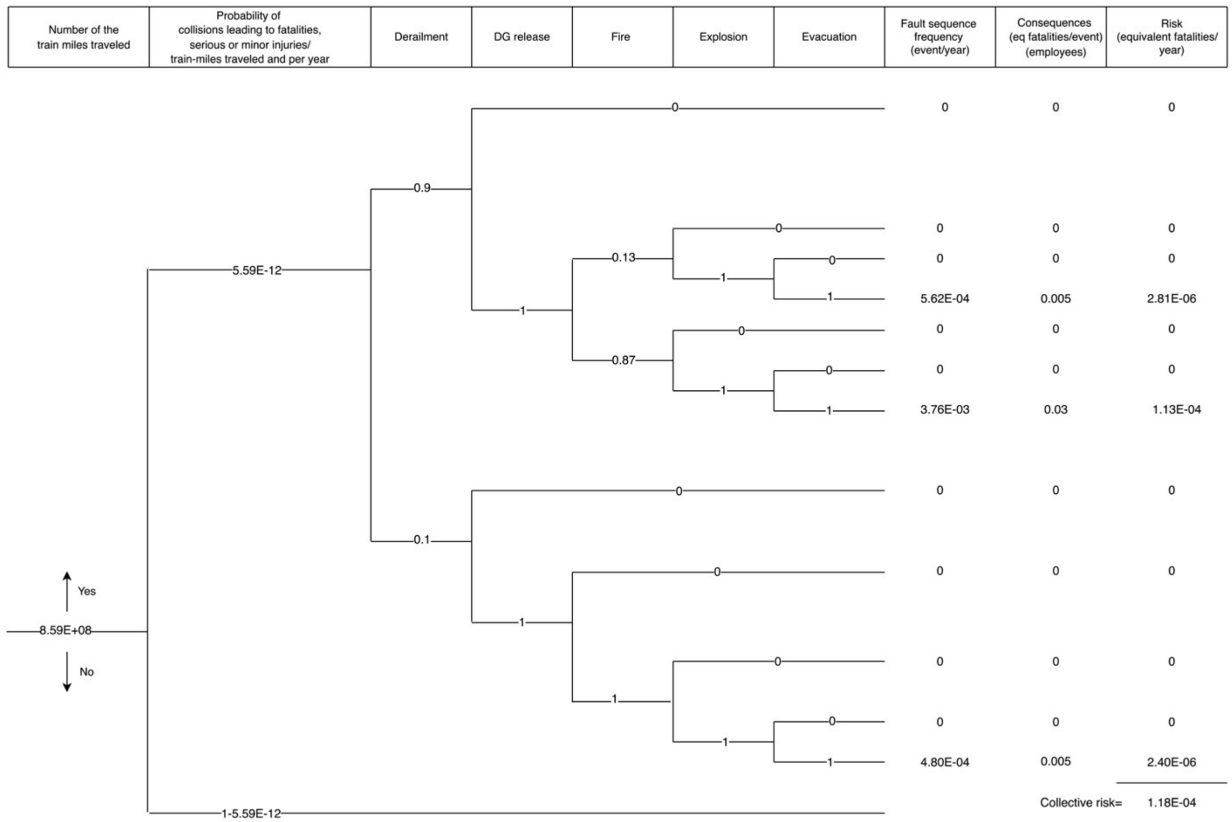


**Figure D-29.** Main-track collisions leading to fatalities and injuries risk for the employees after ETC implementation