Fire Risks in Railway Operations
for Transport Canada

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DISCLAIMER:

Executive Summary

In 2022 and 2023, Transport Canada contracted MxV Rail to study technologies and methods that can be used to identify and address fire risks in the rail industry. The objectives of this study were to determine the elements of railway operations that are susceptible to causing sparks and fires and understand technologies or policy changes that can reduce fire risks and build resiliency in the rail network. To ensure the inclusion of pertinent information, MxV Rail engineers conducted this study in four steps.

The first step was to understand the most common and most severe occurrences of fires in the rail industry. The information on these occurrences was found by examining both the Federal Railroad Administration (FRA) safety data and the Transport Canada safety data. An examination of Transport Canada safety data from a 10-year period showed the most common occurrences of fires were right-of-way fires, including grass fires and tie fires, followed by fires associated with the electrical and mechanical locomotive components of the. In contrast, the FRA safety data from a nine-year period showed the most common occurrences of fires were associated with the electrical and mechanical locomotive components. The release of hazardous material during a train derailment or collision increased the severity of the fires.

The second step was a literature review of the current published research into rail industry fire risks. Many published works on fire risk in the rail industry concentrate on the identification of fire risks and the potential mitigations of these risks. A quantitative risk assessment is used to measure fire risk comprehensively. Research topics include the 1) effect of fire on important rail infrastructure elements, 2) fire response simulations, and 3) case studies of rail fire events. A review of industry policies and regulations established in response to fire risks was also included in the literature review.

The third step was to conduct a survey of industry stakeholders and ask their views of the most common causes of fire and the precautions taken to minimize those risks. The survey questions ranged from fire risk identification to steps taken to prevent fires to technologies used or wanted to assist with fire prevention. When asked about their experiences, most stakeholders indicated the most common cause of fire in train operations was fires associated with brakes. When asked to rate the area of concern for fires in train operations, the highest rated area was locomotives, followed by brakes. When asked about their experience, stakeholders mentioned welding, grinding, and cutting as the most common cause of fire during maintenance activities and, coincidentally, as the highest rated area of concern.

The fourth step and final in this study was to assess technologies used to address fire risk in the rail industry. MxV Rail made an initial assessment of the technologies explored in the industry that were either mentioned in the literature review or the industry survey. The technologies (approaches and devices) used vary from advanced algorithms and simulation software to assess risk in various situations, to heat, fire, and smoke monitoring sensors and networks. Technology advancements in rail components are also used to prevent causes of fire.

Future work should concentrate on two different areas. The first area should be the efforts needed to reduce the most common occurrences of fires, i.e., on locomotives and on the right-of-way. This research would entail exploring fire detection sensors, such as air sampling smoke

detectors, optical smoke detectors, heat sensors, and multi-criteria detectors on locomotives, specifically deployed in exhaust systems or near motors. Targeted fire suppression systems, including foam and sprinklers, can also be deployed in key areas on the locomotive.

The second area of concentration should be fire monitoring and detection systems that can also be deployed to observe right-of-way areas and surrounding parts to detect fires started by or affecting rail traffic. These systems can include vision systems and unmanned aerial vehicles as well as technologies used to suppress fires along the right-of-way, such as handheld devices or from a maintenance-of-way vehicles. Foams and other sprays could also be used as a fire-prevention measure around vegetation or structures, such as timber bridges or tunnels.

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1.0   INTRODUCTION

Under the direction of Transport Canada, MxV Rail studied technologies and methods to identify and address fire risks in the rail industry. The objectives of this study were to 1) determine the elements of railway operations that are susceptible to causing sparks and fires, 2) understand existing technologies that the railroads have deployed, and 3) evaluate the feasibility of modifying and adapting other technologies that can potentially be applied to reduce fire risks and build resiliency in railway operations. Fires triggered by railway operations and exacerbated by extreme climate and environmental conditions can cause damage and distress to local communities and have negative effects on safe and reliable railway operations across North America, including serious disruptions in passenger and commodity transport. Therefore, it is important to understand fire risks in railway operations and ensure that the industry can identify, quantify, and mitigate fire risks.

This study was conducted in four steps. The first step was to understand the most common and most severe occurrences of fires in the rail industry. The information on these occurrences was found by examining both the Federal Railroad Administration (FRA) safety data (United States) and the Transport Canada safety data (Canada). The examination of Transport Canada safety data from a 10-year period showed the most common occurrences of fire were right-of-way fires, including grass fires and tie fires, followed by fires associated with the electrical and mechanical components of the locomotive. The FRA safety data from a nine-year period showed the most common occurrences of fires were associated with the electrical and mechanical components of the locomotive. The most severe occurrences of fires, measured monetarily in the data, were from the release of hazardous material during a train derailment or collision. Both of these government entities have different reporting conditions, so the safety data between the two countries should not be compared directly.

The second step was a literature review of the current published research into fire risks in the rail industry. Fire risk in the freight rail industry is an active area of research. Many published works concentrate on the identification of fire risks and potential mitigation methods for these risks. Most of the current research on fire risks in the rail industry used quantitative risk assessment to measure fire risks comprehensively. This measurement allows the fire risks to be compared and the greatest risks to be identified and reduced or removed. These methods are reviewed in this report. Other research topics include the effect of fire on important rail infrastructure elements, simulations of fire response, and case studies of rail fire events. This study also includes a review of railroad and government policies and regulations that were established in response to fire risks.

The third step was to conduct a survey of industry stakeholders, asking their views of the most common causes of fire and the precautions taken to minimize those risks. An industry survey was conducted by distributing a questionnaire to industry stakeholders, including railroad employees, contractors, and vendors. The questions ranged from the identification of fire risks to steps taken to prevent fires to technologies used or wanted to assist with fire prevention. When asked about their experience regarding the most common cause of fire in train operations, the most frequent response was fires associated with brakes. When asked to rate the area of concern for fires in train operations, the highest rated area was locomotives, followed by brakes. When

asked about their experience with the most common cause of fire during maintenance activities, the most frequent responses were welding, grinding, and cutting, which were also the highest rated area of concern.

Finally, the fourth step of this study was to assess technologies used to address fire risk in the rail industry. MxV Rail made an initial assessment of the technologies explored in the industry that were either mentioned in the literature review or the industry survey. The approaches and devices used vary from advanced algorithms and simulation software used to assess risk in various situations to heat, fire, and smoke monitoring sensors and networks. Preventative technology, including sprays for vegetation, insulation for structures, and improvements to tank cars, is also discussed. Researchers also reviewed fire suppression systems for rolling stock and right-of-way.

MxV Rail has performed a preliminary study of the technologies and methodologies used for fire risk assessment and mitigation in the freight rail industry. The safety data demonstrate where the fire risks existed in the industry historically. The industry survey shows that industry professionals are aware of these areas of fire risk and take active steps to address them. Research in the area of fire risks in the rail industry concentrates on the most severe causes of fire, namely derailments and hazardous material spills. Future work in these areas could focus on the technologies that will address the areas of highest risk and the areas where current research is lacking.

2.0   SAFETY DATA ANALYSIS

The first step of quantifying, assessing, and mitigating fire risk is to determine the causes and results of fires occurring in the rail industry. In North America, railroads are required to report safety incidents to the regulatory authority: Transport Canada in Canada and the Federal Railroad Administration (FRA) in the United States. Among the safety incidents reported are fires occurring during operation or on railroad property.

Railroads are required to report safety incidents to Transport Canada if the rolling stock and/or its contents cause or sustain a fire or explosion [1]. The FRA requires a Rail Equipment Accident/Incident Report for fires that cause damage over a certain dollar amount [2]. This amount has risen from $9,500 in 2012 to $11,200 in 2021 [3]. The different requirements can result in incidents of different causes and different severities being reported. Therefore, while common causes can be found, the safety data from Canada and the United States should be analyzed separately.

The data from Canada were obtained from the Transportation Safety Board of Canada [4]. For this report, the data was confined to the last 10 years of data, from 2012 to 2022. This data included 750 railway occurrences that have fire indicated. After a review of the narrative fields for each of these occurrences, some occurrences were removed for not involving a fire or as a duplicate report of another event, leaving 721 separate instances of fire. Figure 1 shows the number of incidents by year. The count of fire occurrences has increased since 2019.
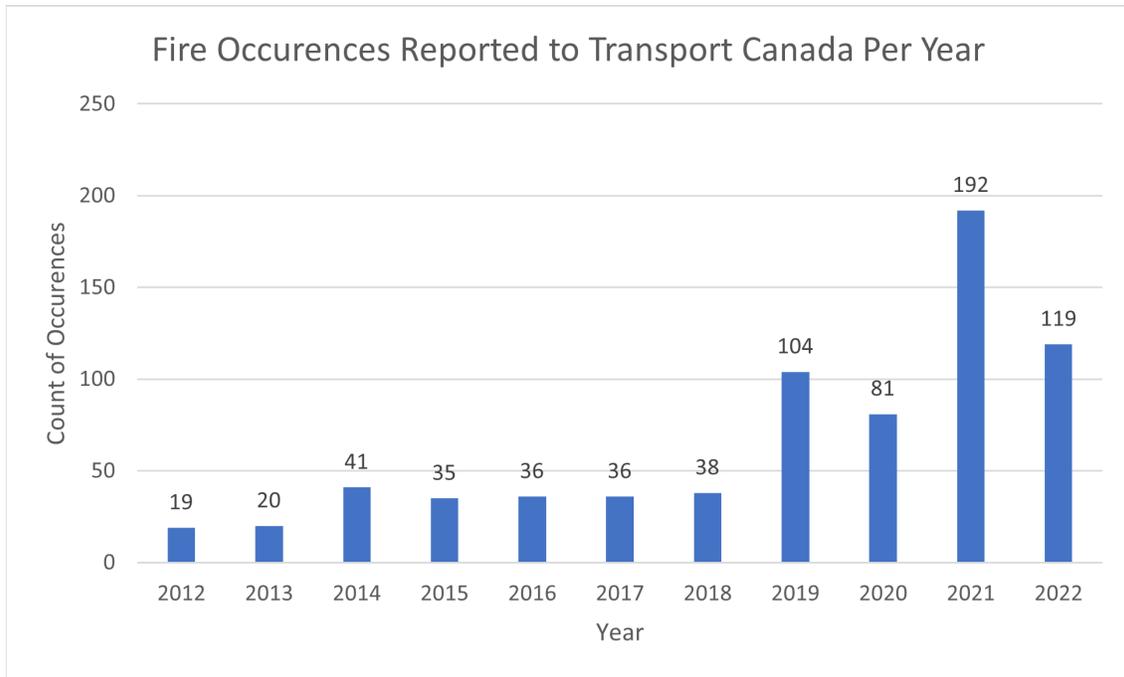
Figure 1. Fire Occurrences Reported to Transport Canada Per Year

The narratives of these incidents were investigated, and some regular causes or consequences of these fires were discovered, including 315 incidents listed as right-of-way or grass fires. While most of the right-of-way fires did not have a cause listed, 60 were attributed to rail grinder maintenance work; nine were related to sparks from a passing train; and one was attributed to welding work. Of the remaining incidents, 243 were related to the locomotive, either mechanical or electrical. Of the 243, 43 incidents were directly attributed to the traction motor, and another 14 were attributed to the exhaust stack. Another 74 incidents were from the rolling equipment, 45 of which were attributed to the cargo and 11 to mechanical failures. Figure 2 shows the counts reported for each of these different categories.
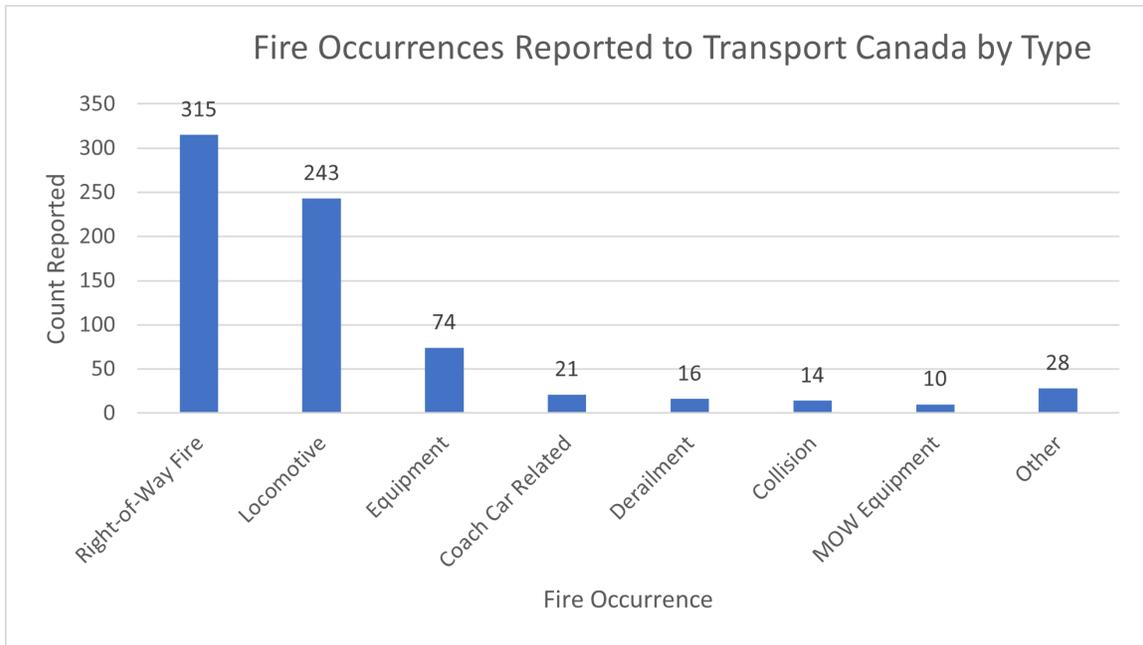
Figure 2. Fire Occurrences Reported to Transport Canada by Type for Entire Time Period

    The most common occurrence of fires was related to right-of-way fires that could be caused by train operations or maintenance activities. Figure 3 shows the count of fire occurrences by year, broken down by type. There was a large increase in reported right-of-way fires after 2018.
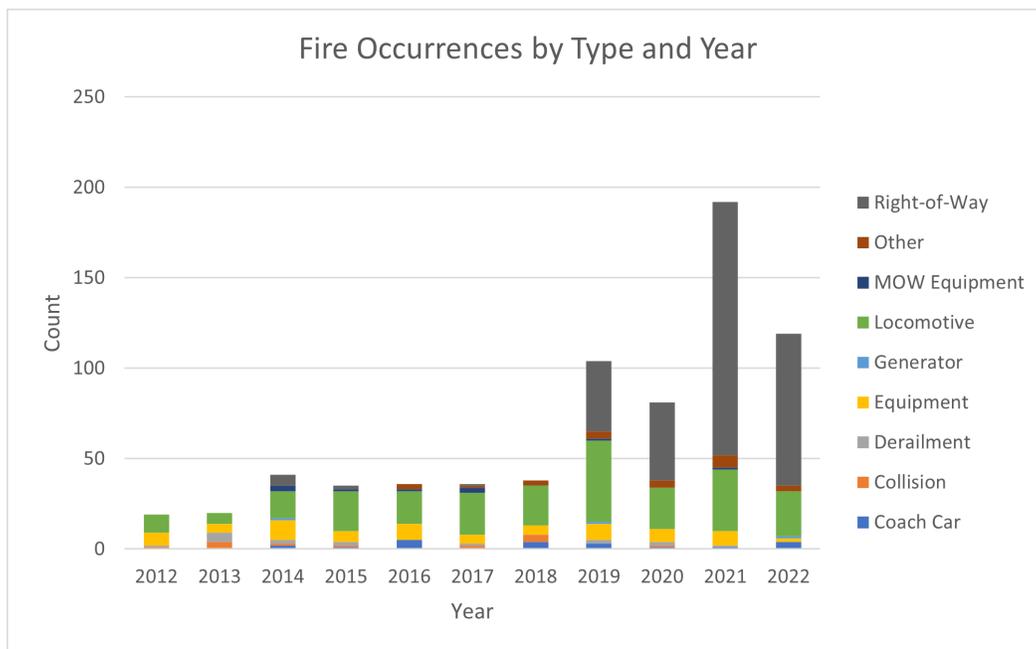
Figure 3. Fire Occurrences Reported to Transport Canada by Type and Year

The safety data do not offer a convenient method for quantifying the severity of the events in order to compare in similar units, such as monetary damages or injuries reported. The most severe event in the time period reviewed is the disaster of the Lac-Mégantec train derailment on July 6, 2013. During this event, an unattended oil train began rolling downhill toward Lac-Mégantec from its night stop location. While rolling, the train accelerated to 60 miles per hour (mph) and derailed at a curve in the downtown area. The oil tank cars ruptured and caught fire. The resulting explosion and fire resulted in 47 deaths and the destruction of 40 homes and businesses [5].

The data from the United States was obtained from the FRA's publicly available website [6]. For the purposes of this report, the data was confined to 2012 to 2021. This data included 548 reported separate instances of fire. Figure 3 shows the number of incidents by year.
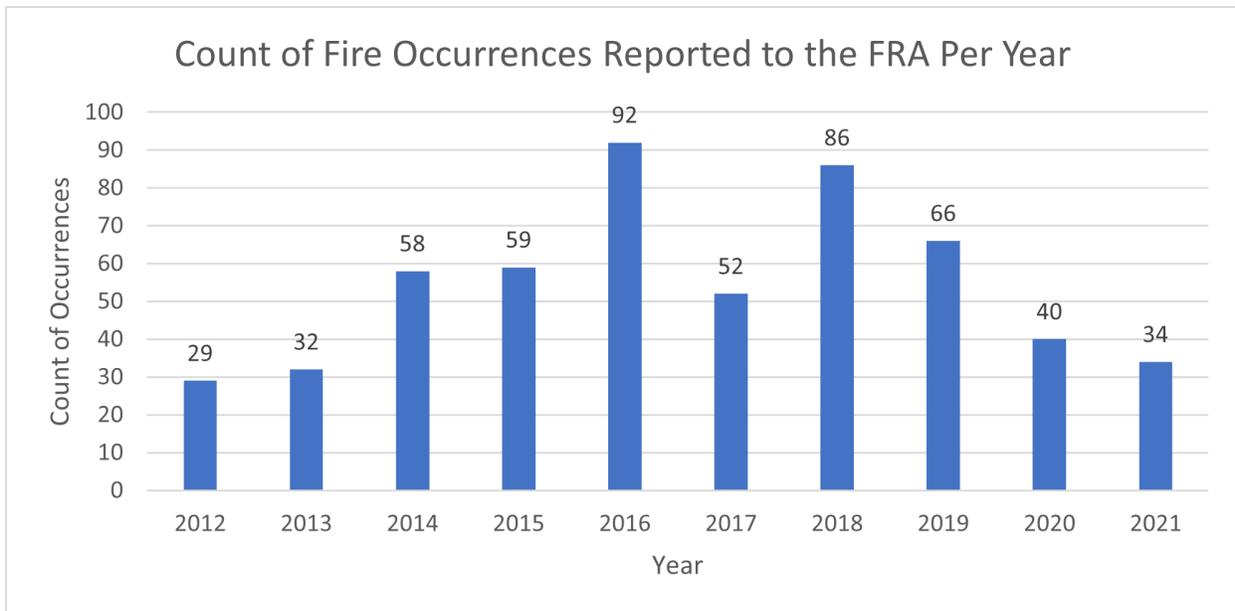
Figure 4. Count of Fire Occurrences Reported to the FRA Per Year

The FRA safety database allows users to choose a cause code for the occurrence. The counts of these cause codes are shown in Figure 5.
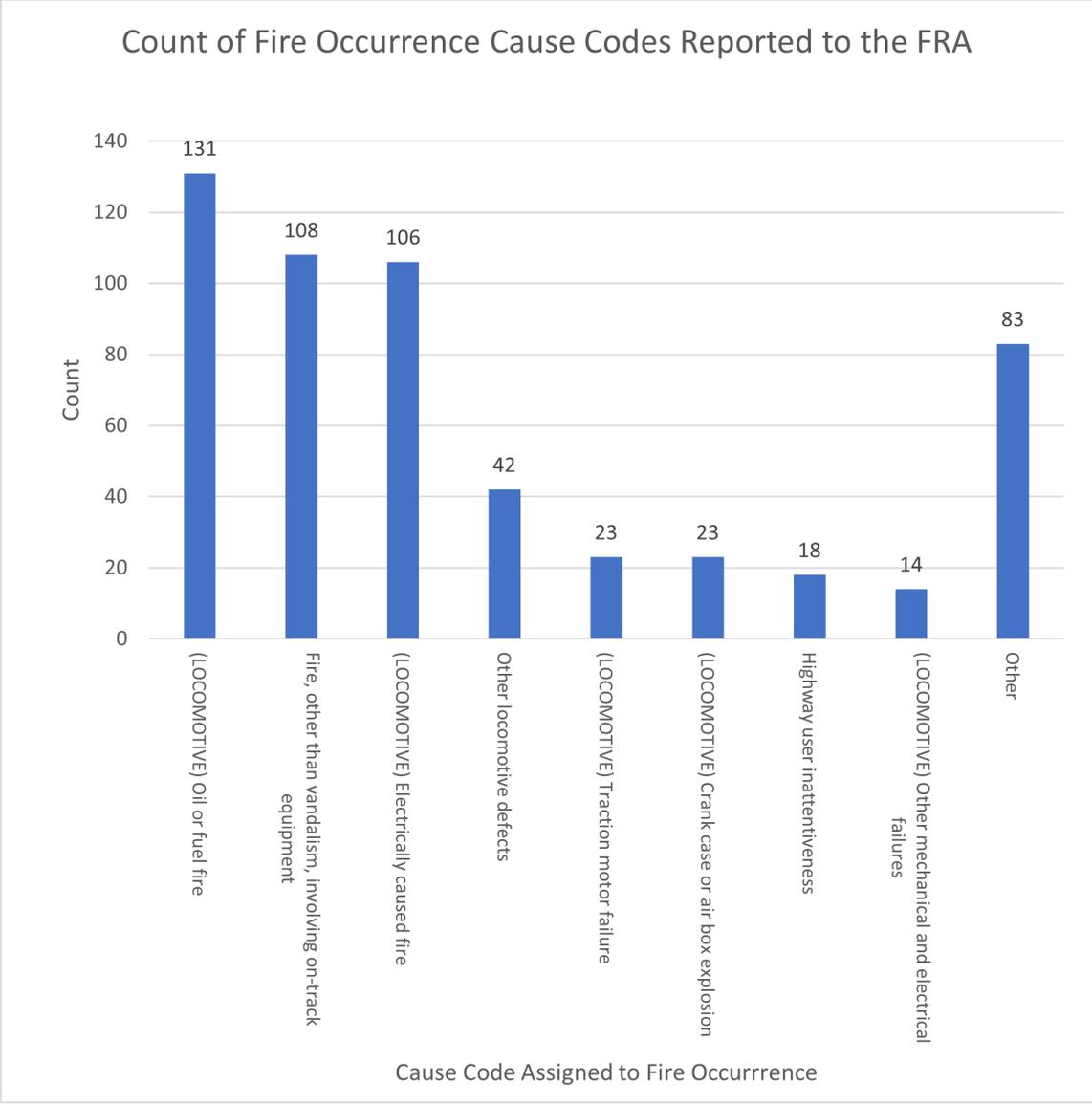
Figure 5. Count of Fire Occurrence by Cause Code for Entire Time Period

This study has grouped these categories into larger common groupings (Figure 5), e.g., all the electrical and mechanical causes related to the locomotives are grouped into the "Locomotive" category. The figure shows the largest category of fire occurrences is related to the locomotive. Some categories are listed with no clear cause, such as "Fire, other than vandalism, involving on-track equipment" and "Other miscellaneous causes." Reading through the narratives of these incidents has allowed the causes of these incidents to be discovered. The breakdown of the "Fire, other than vandalism, involving on-track equipment" causes is shown in Figure 7. Again, the most common occurrence is related to the locomotive. Figure 8 shows the fire occurrence count by year, broken down by type.
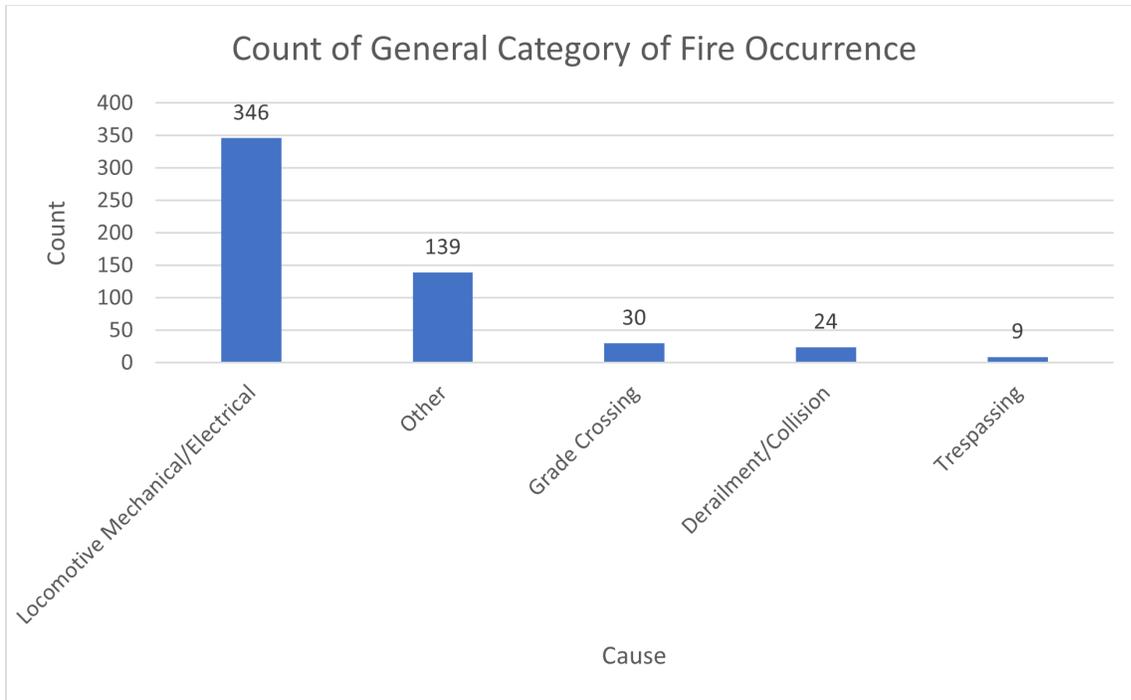
Figure 6. Count of General Category of Fire Occurrence for Entire Time Period
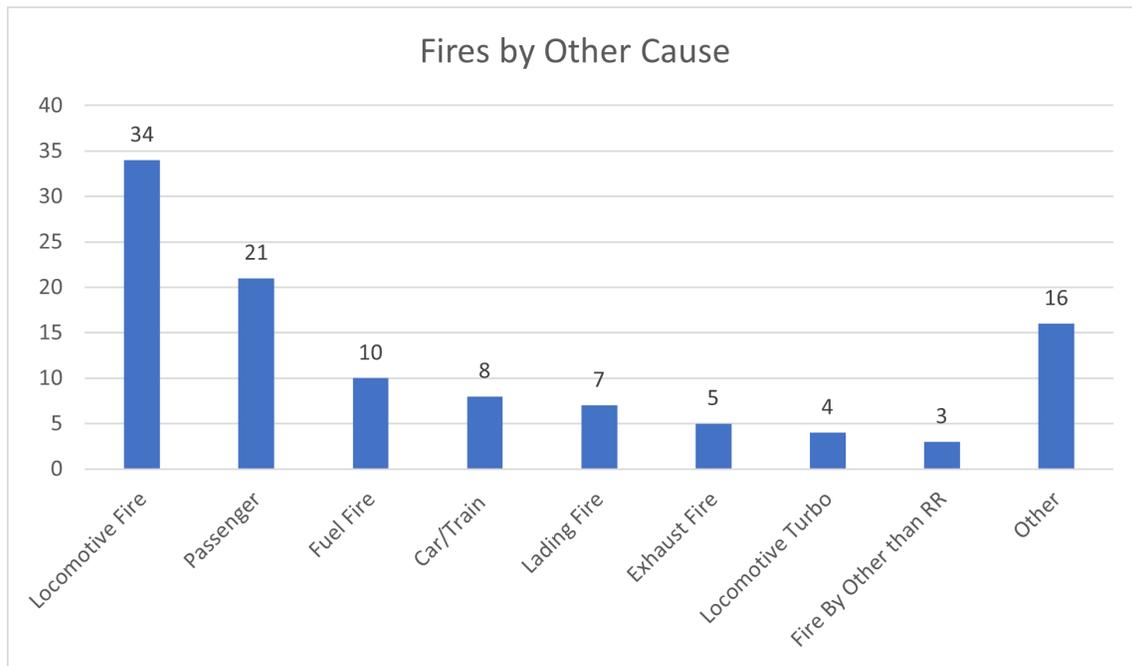
Figure 7. Fire Occurrence Count by Narrative "Fire, other than vandalism, involving on-track equipment"
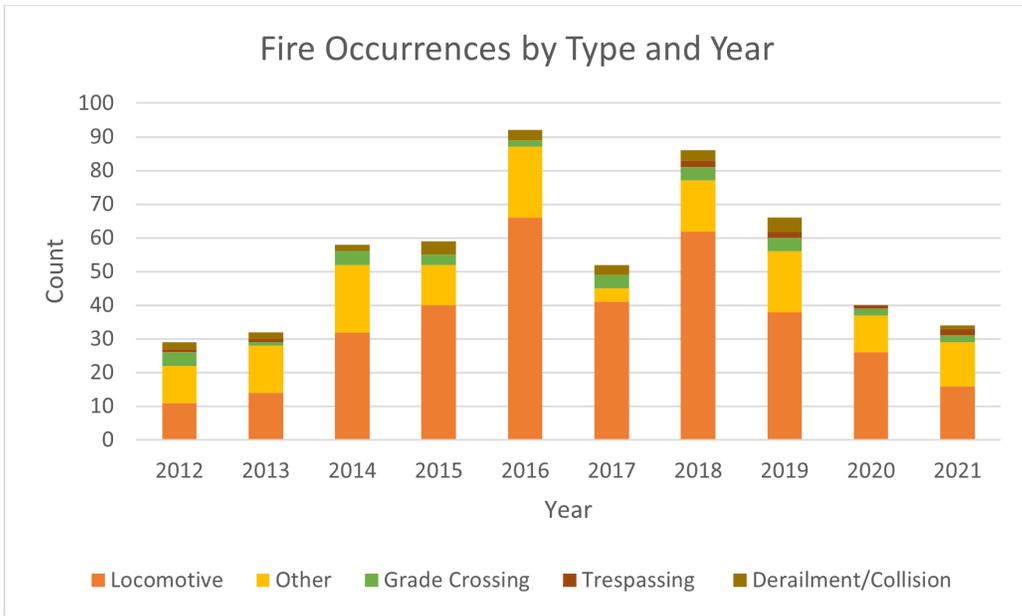
Figure 8. Fire Occurrence by Type and Year Reported to FRA

The FRA also requires an estimate of the monetary cost of the event. This allows a comparison of the severity of the events. The most severe causes of fire, in terms of monetary cost, are shown in Figure 9.
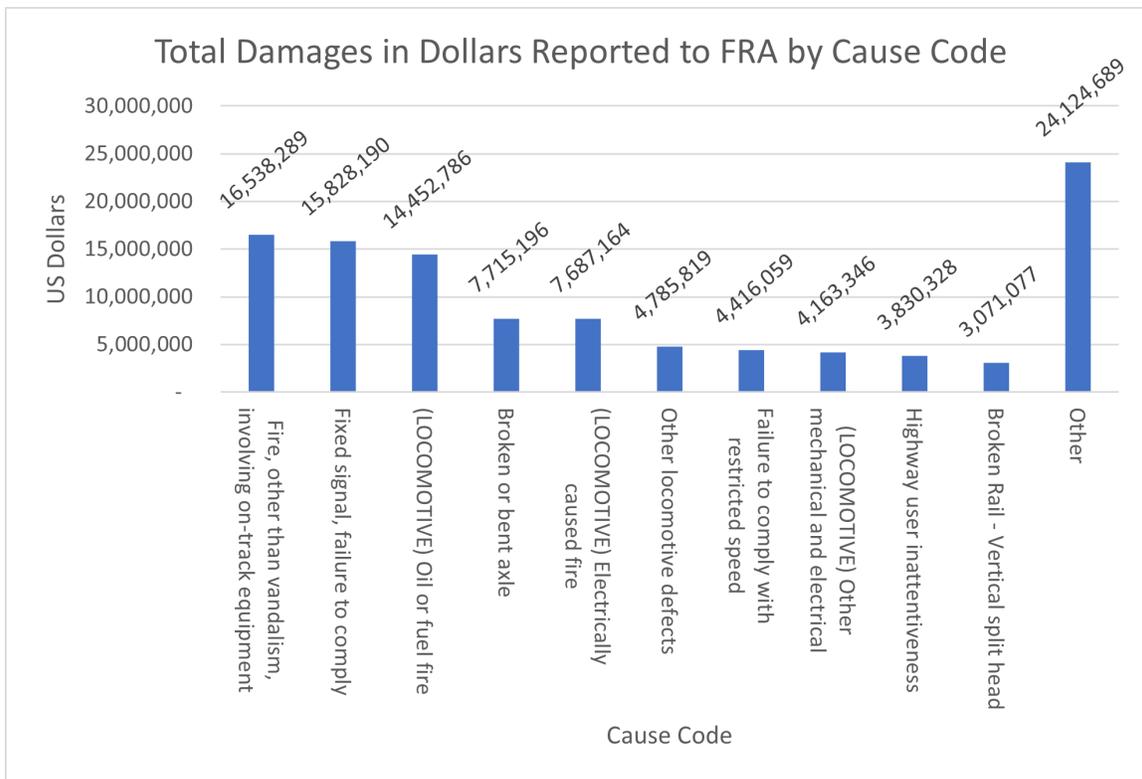
Figure 9. Total Damages in Dollars of Fire Occurrence for Entire Time Period

These events show the total cost of these occurrences. Some of these categories, such as "Fire, other than vandalism, involving on-track equipment" (broken down by count in Figure 7) and "(LOCOMOTIVE) Oil or fuel fire" also have the highest count of occurrences. Some of the other categories, such as "Fixed signal, failure to comply" and "Broken or bent axle" only have one or two occurrences in the last decade of data. In total, fire occurrences related to locomotive fires account for more than a third of the total damages reported. The high severity categories are either more common events with low average damages per occurrence or rare events with high damages per occurrence.

The top severe events from the FRA safety database are listed in Table 1. Severe events often involve flammable cargo, and the fire events are usually caused by derailment or collision. This list expresses the narratives of the most severe fire occurrences to provide for an understanding of the causes of these fires.

Table 1. List of Fire Occurrences with Highest Recorded Damages

Cause Code	Damage (U.S.D)	Summary of Narrative from the Most Severe Occurrence
Fixed signal (other than automatic block or interlocking signal), failure to comply.	$15,828,190.00	Collision during which eight locomotives and 13 railcars derailed. 13,500 gallons of diesel, 39,194 lbs of resin solution, and 441 lbs of flammable solids destroyed by fire.
Broken or bent axle between wheel seats	$7,670,196.00	13 cars derailed due to a broken axle. A second train struck the derailed cars and derailed two locomotives and 21 cars. 18 cars released 474,936 gallons of crude oil, which were consumed by fire
Failure to comply with restricted speed in connection with the restrictive indication of a block or interlocking signal.	$4,416,059.00	Train collided with stopped train. The locomotive unit caught fire due to diesel fuel. Tank car leaked and burned away entire load of crude oil.
Broken Rail - Vertical split head	$3,071,077.00	Derailed train resulted in crude oil fire.
Track damage caused by non-railroad interference with track structure	$2,813,217.00	Train derailed 27 cars and caught fire due to the track being washed out from flooding.
Failure to release hand brakes on car(s) (railroad employee)	$2,205,216.00	Truck derailed causing general pile-up. Propane tank car was found on fire. Hazardous material release of propane, and molten sulfur.
Broken Rail - Detail fracture from shelling or head check	$1,807,397.00	Derailment due to broken track. 49,748 gallons of denatured alcohol was released and consumed by fire.
Track alignment irregular (buckled/sunkink)	$1,400,085.00	Track buckle derailed 18 cars that started fires.

Cause Code	Damage (U.S.D)	Summary of Narrative from the Most Severe Occurrence
Other axle and journal bearing defects (CAR) (Provide detailed description in narrative)	$1,138,483.00	Car derailed and started on fire.

To summarize Table 1, the causes of these severe events are varied. The damage severity is caused by 1) the derailment of the equipment and 2) the cargo being exposed to fire. The derailment causes listed in the table can be summarized as follows:

- Failure to comply with signals or speed restrictions: 2 derailments.
- Broken rail: 1 derailment
- track alignment: 1 derailment
- broken axle: 1 derailment
- overheated bearing: 1 derailment
- Failure to release the hand brakes on the equipment: 1 derailment

In addition to reviewing the safety data of fire occurrences, researchers sent an industry survey to stakeholders. The survey asked the respondents to place a number of potential causes of fire in rail operations and maintenance activities in order of highest to least concern. The results of this question are summarized in Table 2. The survey is further explained in Section 4.0. The cause of highest concern in train operations is locomotive actions. The cause of highest concern in maintenance activities is rail grinding.

Table 2. Fire Cause of Highest Concern from Industry Survey

Rank	Cause of Highest Concern in Train Operations	Cause of Highest Concern in Maintenance Activities
1	Locomotives (tractive efforts, exhaust, soot accumulation, etc.)	Rail Grinding
2	Braking (sparks, overheating, etc.)	Sparking (welding, etc.)
3	Wheels, Axles and Bearings	Curve Patch Profiling
4	Operations (speed, curves, etc.)	Laying of Rail Crossties (creosote, tie storage)
5	Equipment Age	Track and Frog Replacement
6	Wayside Detector System Malfunction	Leftover Debris
7	Hazardous or Flammable Cargo	Timber Bridges and Tunnels

In summary, the most common occurrence of fire, as reported to the FRA, is related to the locomotive (electrical or mechanical). The most common occurrence of fire, as reported to Transport Canada, is right-of-way fires possibly caused by train or maintenance operations, followed by occurrences related to the locomotive. These findings agree with the opinions of industry members that locomotives are of the highest concern when considering fire causes in rail operations. In maintenance, industry members indicated rail grinding is the highest concern for fire cause. Researchers found that the number of occurrences attributed to rail grinding is

high compared to other causes reported to Transport Canada. Finally, the most severe causes based on the total cost of damage are again related to the locomotive due to the high number of occurrences. According to the FRA dataset, the events with the highest damage cost per incident are reported as derailments or collisions of trains carrying flammable material.

3.0   LITERATURE REVIEW

MxV Rail conducted a literature review of research published since 2015, examining fire risks in the rail industry. To conduct this literature review, the databases searched were Google Scholar, Semantic Scholar, Science.gov, and Bielefeld Academic Search Engine (BASE). The search terms were kept broad to incorporate as many papers as possible. The terms used were "Fire," "Risk," "Rail," and "Freight." Useful papers for the objectives of this research would address fire risk identification and mitigation in North American freight rail. However, other papers selected include 1) passenger rail risk identification and mitigation that are directly applicable to freight rail; 2) non-North American rail risk identification and mitigation that are directly applicable to North American freight rail; and 3) general freight rail risk identification and mitigation that specifically mentions fire as a category of risk. Using these conditions, researchers found 33 publications to review for this report.

This section will discuss three types of publications: 1) papers that pertain to safety risk identification methodology as it relates to fire in freight rail; 2) papers that focus on testing specific technologies and aspects of fire risks in freight rail, and 3) responses in policies and regulations from government and industry to fire risk. The goal is not to delve into the intricacies of each study, as the original publication serves that purpose, but to explore the directions and subjects of research. Appendix A includes a summary of the publications used for this literature review. Additional resources were found to clarify the government regulations mentioned below.

3.1   Risk Identification and Quantification

Papers that pertain to safety risk identification methodology show that fire risks can be compared to each other by examining their consequences and their probability of occurrence. This risk measurement method is called a quantitative risk assessment (QRA) [7, 8, 9, 10, 11, 12]. Using the measure of consequence of risk and the probability of its occurrence it is important when assigning a useful, practical metric [7]. The primary metric used in these publications is the probability of fatal harm [12]. For individuals, this metric describes the probability of severe injury when in the physical area of the risk. For society, this metric of risk is measured on an F-N curve, which describes the frequency (F) of an event resulting in a number (N) of fatalities. For risks described on an F-N curve in these papers, more frequent risks have a lower number of fatalities, and events with a high number of fatalities have a lower frequency of occurrence. On the F-N curve, there can be an indicated area of unacceptable and acceptable risk [7]. Using a comprehensive listing of all possible risks, quantified in the risk metric, allows for the possibility of identifying the risks that pose the greatest problem, either to the individual or to society, and making efforts to eliminate or reduce the risk of that activity. Some examples of risks that could be listed include derailment, shipment of hazardous material, or train collision.

The acceptable level of risk is a subjective decision made by the industry, regulatory authorities, and society as a whole. The limit of acceptable risk can be determined by 1)

historical risk criteria, 2) comparing the current risks to previous standards of those risks, 3) comparative risk criteria, 4) comparing the risks of one industry to those of another, or 5) expert judgement risk criteria (limits set by a group of experts in the area) [7]. Understanding the risks present can allow an industry to engage in effective accident prevention based on lessons learned from the past, managing still extant risks, and detecting dangers that have not yet occurred [8].

In risk analysis, the fire itself is considered the critical event. The causes leading to the fire can be enumerated, and the effects of the fire can be listed as well. Common techniques for systematically evaluating the causes and effects are fault tree analysis and effect tree analysis, respectively [9, 12, 13, 14, 15]. When used in combination, these two trees spread out before and after the critical event and are referred to as a bow-tie model [9]. The causes and effects of a fire can be found through historical data of the same or similar systems. A historical analysis of the causes and effects of fire risk in the rail industry is common, with one paper reviewing rail related fires for the last century [16]. Overall, railway-related fires have reduced in count significantly but still remain a risk. Another paper collected data by using a wireless sensor network to record the characteristics of cotton in railcars. The data was analyzed, and the highest risk factors were determined to be temperature and humidity in the car, allowing these factors to be mitigated [17]. Causes and effects can also be found by involving subject matter experts in the risk assessment process [12].

Once the causes and effects of a fire are understood, other efforts can be made in the risk model. These efforts can include understanding how the causes and effects are related, whether they have dependencies or create domino effects of consequences [10, 18]. Other approaches found in the literature include describing the geographical location of fire risks in the network to specify where risks exist [19, 20]. The paper concerning cotton in railcars mentioned above found risk factors with a k-means clustering algorithm and used a regression algorithm to evaluate the correlation between the factors [17].

The relationship between causes and effects during the fire occurrence is not deterministic. There are certain probabilities of events happening. At the same time, decisions are being made in response to a fire, creating possible events that may or may not occur. A Bayesian network [10, 21] defines the probabilities of consequences based on events that have occurred. A Bayesian network is a directed acyclic graph that connects events that occur with uncertainty. Because large railway systems consist of multiple actors during an emergency, these systems can be modeled as a Bayesian network.

Another approach taken to understand fire risk in the rail industry was the exploration of the psychological perception of decision makers for losses during emergency situations. A person's perception of a situation and whether certain emergency response plans offer loss reduction or even gains will direct the actions taken. Overall, people are more sensitive to loss than gain and will make decisions accordingly. Emergency plans should factor in decision-making tendencies [22].

Another method for risk reduction is route selection. The selection of routes may reduce handling and minimize costs. However, these decisions may also reduce the choice of routes for trains carrying hazardous materials, which could increase the risk load in certain areas and yards. One paper proposed that a mixed integer programming model used to determine the

optimal routes for hazardous material transportation should include the distribution of risk in the network [23]. This type of model will allow routes to be optimized for safety in addition to efficiency. One example of reducing risk is limiting the number of times hazardous cargo is switched in a yard.

While the reviewed papers proposed data-driven models and algorithms for risk assessment and mitigation, they used the following case studies to test their approaches.

- Four papers focused on hazardous or flammable material transportation [7, 10, 17, 23].
- Two papers focused specifically on derailments [12, 19].
- Two papers focused on vegetation fires started near rail operations [16, 20].
- Three papers focused on rail fires in tunnels and subways [9, 14, 15].

3.2   Effect of fire on structures and equipment

Research has also been conducted to understand the effect of fire on structures and equipment used in the rail industry. Understanding the response of these materials, devices, and structures to extreme heat and flame will help with risk assessment when engaging these elements in the rail industry.

Important structures such as bridges and tunnels were also explored. A simulation study was conducted to examine the structural damage of a cut-and-cover tunnel when exposed to fire—a low probability but high consequence event. One interesting finding stated freight trains carrying flammable material have a higher heat release rate than passenger or other types of freight cargo that would pose the highest risk to these structures [24].

High temperatures can reduce the mechanical material properties of bridges. It is important to reduce the vulnerability of bridges to fire. An analysis of bridge fire risks stated that bridges can be classified by their vulnerability. Material properties were modeled with finite element analysis (FEA), and the conclusion was that fire mitigation can be achieved in three ways: security, laws and regulation, and fire protection and insulation features [25].

It is important to detect that can interfere with train operations. One analysis explored using a machine learning algorithm to detect forest fires using video footage. Though not directly a rail application, the authors trained an algorithm to classify over 200 video samples to determine whether a fire was present or not. The final version had a 90 percent true positive rate on classifying the video clips.[26].

Fires can result from fuel tank punctures. A test was performed to understand the impact response on locomotive fuel tanks under dynamic loads. The purpose was to record data to aid in the understanding of the mechanical and material characteristics of the fuel tanks while punctured. This test attempted to characterize loading that may rupture a fuel tank, and it prescribed a second set of tests on a larger sample set to begin setting dynamic loading standards for locomotive fuel tanks [27].

Fire and rupture are also concerns regarding tank cars. One publication described testing performed on tank car pressure release devices, which protect the cars in fire situations by

venting the contents to limit the maximum pressure buildup. The test demonstrated the pressure release devices function adequately under high temperature conditions [28]. However, for some chemicals, there is a reason to transport them in a total containment condition that will not allow leaks out of the tank. To determine whether the DOT 111 tank car is capable of withstanding the fire and pressure without venting, another test was conducted to measure the response of the tank car materials [29].

In addition to tank cars, experiments have also explored the effect of fire and pressure on potential contents. One publication sought to understand the risk of transporting crude oil and whether the properties of crude oil warrant additional handling considerations. This publication also outlines the chemical properties of this substance compared to other substances transported by rail and states the Pipeline and Hazardous Materials Safety Administration (PHMSA) has been encouraged by the FRA and Association of American Railroads (AAR) to require 1) higher standards for tank cars transporting flammable liquids and 2) all existing cars to be retrofitted to this higher standard [30].

A simulation model was created to understand the fires of vapor clouds that can be released during a hazardous material spill. The results of the simulation were compared to the derailment of a rail tank car that was carrying liquefied petroleum gas. When compared to the observed fire consequences of the case study, the models developed produced conservative results and may be valid for fire risk safety assessments [31].

Additionally, two studies were published about the use of alternative fuels in rail transportation and the fire risks associated with them. The first study concentrated on hydrogen fuel. Hydrogen fuel for rail vehicles is different from other types of fuel and the fire risks need to be identified. Hydrogen fires can occur quickly and have high flame temperatures. These fires are also difficult to detect. However, they do not produce soot and radiate less heat. The study concluded that hydrogen fuel storage needs different considerations from diesel fuel [32]. The second study examined hydrogen, lithium batteries, and natural gas. While each of these fuels have advantages over traditional fuel sources, each one has a unique fire risk. The author proposes future study regarding the methods of deployment and the development of standards for the industry to accommodate the new risks [33].

3.3 Government and industry response to fire risk

In 2017, the National Transportation Safety Board (NTSB) released a report on a derailment of 33 railcars where three tank cars released of hazardous materials. The cause of the derailment was determined to be inappropriate train composition and use of hand brakes. In this report, the NTSB outlined the FRA's rule requiring Class I railroads and railroads with inadequate safety performance to submit a written railroad safety Risk Reduction Program (RRP) to the FRA for review and approval.

To comply with the minimum federal safety standards, railroads currently use engineering standards, rules, procedures, and training as risk mitigation strategies. The FRA's final rule on RRPs requires railroads to include a variety of new activities, including a risk-based hazard management program, a safety performance evaluation, safety outreach, a technology implementation plan, RRP employee and contractor training, railroad employee involvement,

and internal assessment of their RRP [34]. This rule was first proposed in 2015 and then finalized in 2020. The RRP is described as a comprehensive, system-oriented approach to safety that 1) determines an operation's level of risk by identifying and analyzing applicable hazards and 2) involves developing plans to mitigate, if not eliminate, that risk. The FRA also established the Close Call Reporting System (C3RS) to allow for the confidential reporting of close-call events, root-cause-analysis problem solving, and tracking changes [35].

In addition to this sweeping risk assessment response by the industry, there have been other regulations or policies implemented to address fire risk. Transport Canada developed guidelines for railroads to follow to create and implement an Interim Extreme Weather Fire Risk Mitigation plan during extreme weather conditions. This plan, also known as the Railway Extreme Heat and Fire Risk Mitigation Rules [36], requires railway companies to:

- Monitor fire risk levels
- Establish temperature thresholds for train speed restrictions and supplemental track inspection requirements
- Inspect and clean the entire locomotive exhaust system at regular intervals depending on the engine type
- Detect and report fires along right-of-way, including reporting by the public
- Manage vegetation and remove combustible materials from the right-of-way
- Mitigate fire hazards during maintenance activities
- Notify fire services when high-risk work must be conducted during high to extreme fire danger levels
- Respond to detected or reported fires, including immediate action to suppress the fire or communication to or deployment of appropriate emergency response [36]

In 2015, the FRA issued an Emergency Order (EO) that limited the maximum operating speed of trains transporting large quantities of flammable liquids to 40 mph in some urban areas to reduce the kinetic energy of the cars in the event of a derailment [37]. This speed restriction has now been included in the Code of Federal Regulations (CFR), but it does not apply to tank cars meeting the requirements of DOT Specifications 117, 117P, or 117R [38]. The PHSMA and FRA have published regulations in the CFR for 1) tank car designs, 2) speed restrictions of hazardous material transported by rail, and 3) train routing, and 4) sampling and classification of the tank car contents and notification requirements. [38, 39]

Current regulations require that all tank cars constructed after 2015 that carry high hazard flammable materials must meet the enhanced DOT Specification 117 or 117P design [38] and must be retrofitted. High-hazard flammable trains (HHFT) trains are limited to a maximum operating speed of 50 miles per hour and are required to have a two-way End-of-Train device or distributed power braking system. The railroad must provide a contact for first responders with regard to hazardous material routed through their territory [40]. The railroad must also perform a routing analysis that considers many safety and security factors [41].

The FRA also established additional requirements for both the attendance and securement of freight trains and vehicles outside of a yard or terminal, including additional securement requirements primarily for trains transporting poisonous or flammable materials. The rule requires all unattended locomotives outside of a yard be equipped with an exterior locking mechanism. Any train not able to be secured must be attended [39].

At the time this review, the CFR also allows the transportation of liquefied natural gas (LNG) by rail tank car. The regulations require LNG transported by rail only in DOT-113 tank cars that have an enhanced outer tank with a higher puncture resistance [42, 43]. These cars must meet operational, braking, and route analysis requirements [40, 41, 44]. Remote monitoring of the DOT 113 tank cars is also required [45].

In 2022, an FRA publication compared the U.S. fire safety regulations pertaining to the rail industry with industry standards in the European Union, Japan, and China [46]. The focus if this publication was to emphasize the differences in approaches to fire safety, and risk in general, to assist in decision making to improve fire safety in the United States.

The report discussed three standards in fire safety analysis in the United States produced by the National Fire Protection Association (NFPA), the American Society for Testing and Materials (ASTM) international, and the American Public Transportation Association (APTA). The general procedures outlined by all three are as follows: the determination of design requirements in a railcar, the assessment of vehicle fire performance, evaluation of specific fire scenarios, and the evaluation of suitability of design [46]. These four procedures provide an analysis of the vehicle in a comprehensive manner. This system emphasizes the autonomy of the railroads to complete the fire safety analysis, which allows more flexibility in design.

The U.S., Japan, and China all use two smoke-emission and flame/heat-spread tests to assess the fire performance of materials. The U.S. electrical fire safety standards have equivalent specifications to non-U.S. standards. In addition to setting performance standards for fire and heat spread and smoke accumulation, the report [46] suggests considering material toxicity and performance.

In the publications addressed in this report, three general approaches to fire risk were followed. The first approach is a quantitative risk assessment designed to review data collected from the rail industry and measure risk a comprehensive way. The publications that used a quantitative risk assessment then applied their methods to case studies. The second approach was to examine how rail industry materials, structures, and devices performed during a fire. The last publications addressed how the industry and government responded to this information in order to mitigate these risks and improve safety.

The vast majority of these publications concentrate on low probability, high consequence fire events. Eleven of the research papers discussed derailments, collisions, or hazardous material transportation. These areas were also the focus of regulatory actions. Five more papers discussed fires on bridges or in tunnels. One paper focused on fuel tank ruptures in locomotives, and two more discussed alternative fuels for locomotives. Two other papers discussed vegetation fires near railroad right-of-way. The published research mainly discusses those events that have a low number of occurrences in the safety data but have potential for high single-event damages.

The findings of the literature review can be summarized as follows:

- Three approaches to fire risk research
  - Quantitative risk assessment and data driven analysis
  - Examination of performance of materials, structures, and components during a fire
  - Industry and government regulation
- Publications reviewed concentrated on low probability, high consequence fire events, such as derailments, collisions or hazardous material spills
- Other than two papers that discuss right-of-way vegetation fires, the publications do not focus on the common causes of fire in the rail industry
- Technology discussed in the published research included data collection and data analysis methods, onboard cargo monitoring, and improvements to fuel tanks and tank cars
  - Additional technology is introduced through the industry survey in the next section
- Conclusions:
  - More research can be done on the most common fire risks in the rail industry, an area currently lacking in publications
  - More research should be done on the application of technology to mitigate fire risks in the rail industry, especially for common fire causes
  - Adoption of a standard risk consequence metric in rail safety data would allow for the most pressing fire risks to be identified for research

4.0   INDUSTRY SURVEY

Beyond what can be learned from published research, it is important to understand how the rail industry assesses and addresses fire risk during train and maintenance operations. MxV Rail developed a questionnaire of 10 short answer and ranking questions to send to industry stakeholders. This survey is included as Table 3. The survey was intended to be short enough to encourage respondents to finish and return, yet comprehensive enough to address all applicable areas of fire risk. The short answer questions were open ended and written to encourage diverse responses. The two ranking questions asked respondents to put the statements in order of importance. At the writing of this report, nine responses had been received. This is a small number of responses for the North American rail industry. However, these responses do include both interesting insight into fire risk in the rail industry and responses from employees of three Class I railroads.

Table 3. Industry Survey Questions and Responses

Question Number	Question	Responses
1	In your experience, what are the most common causes of fires during train operations?	Braking operation or malfunction (most common) Exhaust from the locomotive Sparks from the train Collisions
2	In your experience, what are the most common causes of fires during maintenance activities?	Grinding, welding, and cutting (most common) Vegetation Dry, windy conditions
3	What actions are taken for fire hazard detection and fire hazard mitigation, outside of what is mandatory/regulated?	Work tasks begin with a fire risk assessment (most common) Preparation of fire response materials, including available water Weather monitoring Removal of vegetation Installation of shields for sparks and flames Posting a fire watch
4	Beginning with 1, please rank your top concerns for causes of fires during train operations (1-Highest Concern, 2-Next Highest, etc.)	See Table 2
5	Beginning with 1, please rank the following categories in order of greatest concern for causes of fires during infrastructure maintenance activities (1-Highest Concern, 2-Next Highest, etc.)	See Table 2
6	What are common train operation precautions/risk reductions taken during fire seasons?	Braking precautions Spark arrestors on locomotive exhaust Ensuring fire extinguishers are on site Conducting pre-trip inspections Ensuring the proper locomotive horsepower is assigned to the load Adhering to speed restrictions and time of operations, as well as a review of the safety procedures
7	What are common maintenance precautions/risk reductions taken during fire season?	Post a fire watch during and after the work was completed (most common). Ensuring fire response materials were available to the work site, Controlling vegetation through removal or soaking Suspending work when the fire risk is too high. Conducting a review of safety procedures Conducting a fire risk assessment, Weather monitoring Installing spark shields
8	What challenges do you face in implementing fire prevention measures or technologies to monitor and reduce fire risk?	No challenges to implementing fire prevention (2 responses). Cost for implementing technologies (3 responses). Ensuring crews are not complacent and are following the fire plan in every task (2 responses)
9	Are you aware of any technology solutions used to monitor or reduce fire risks?	Heat, smoke, and flame detection sensors

Question Number	Question	Responses
		Fire suppression systems including foam sprinklers, both as a response and as a preventative measure for structures Networks for weather monitoring Risk assessments Fire alerts
10	Do you have any ideas for technologies that could be tested that may reduce fire risks in rail operations?	Heat, smoke, and flame detection sensors Fire suppression systems including foam sprinklers, both as a response and as a preventative measure for structures Networks for weather monitoring Risk assessments Fire alerts

The first question asked was "In your experience, what are the most common causes of fires during train operations?" The most common response was braking operation or malfunction. This was followed by exhaust from the locomotive and sparks from the train. There was one mention of collisions being a cause of fire in train operations.

The next question asked was "In your experience, what are the most common causes of fires during maintenance activities?" The most common response was grinding, welding, and cutting. Also mentioned were vegetation and dry, windy conditions.

The third question asked was "What actions are taken for fire hazard detection and fire hazard mitigation, outside of what is mandatory/regulated?" Most responses stated that work tasks begin with a fire risk assessment. The next most frequent response was the preparation of fire response materials, including available water. Other responses, in equal number, include weather monitoring, removal of vegetation, installation of shields for sparks and flames, and posting a fire watch.

The next two questions asked were "Beginning with 1, please rank your top concerns for causes of fires during train operations (1-Highest Concern, 2-Next Highest, etc.)" and "Beginning with 1, please rank the following categories in order of greatest concern for causes of fires during infrastructure maintenance activities (1-Highest Concern, 2-Next Highest, etc.)." The responses to these two questions were given in Table 2 above.

The next question asked was "What are common train operation precautions/risk reductions taken during fire seasons?" The response to this question showed the broad nature of the respondents. The responses included braking precautions, spark arrestors on locomotive exhaust, ensuring fire extinguishers are on site, conducting pre-trip inspections, ensuring the proper locomotive horsepower is assigned to the load, adhering to speed restrictions and time of operations, as well as a review of the safety procedures.

"What are common maintenance precautions/risk reductions taken during fire season?" was the next question asked. The most common answer was to post a fire watch during and after the work was completed. Other common answers were ensuring fire response materials were available to the work site, controlling vegetation through removal or soaking and suspending

work when the fire risk is too high. Other answers included conducting a review of safety procedures and a fire risk assessment, weather monitoring and installing spark shields.

The eighth question asked was "What challenges do you face in implementing fire prevention measures or technologies to monitor and reduce fire risk?" Two respondents stated there were no challenges to implementing fire prevention. Three others stated cost was a concern for implementing technologies. Two other answers stated that a challenge was ensuring crews are not complacent and follow the fire plan in every task.

The last two questions asked were "Are you aware of any technology solutions used to monitor or reduce fire risks?" and "Do you have any ideas for technologies that could be tested that may reduce fire risks in rail operations?" The respondents listed various technologies that they use or would like to see in the industry. These items are discussed in detail in the next section of this report and include heat, smoke, and flame detection sensors; fire suppression systems including foam sprinklers, both as a response and as a preventative measure for structures; networks for weather monitoring, risk assessment, and fire alerts.

The information gathered during the industry survey is consistent with the most frequent occurrences of fire. In particular, industry representatives are concerned about locomotive fires, as well as the possibility that sparks from trains and maintenance procedures, such as grinding and welding, could cause right-of-way fires. These concerns align with the historical data of fire occurrences in the safety data. The research and regulation focus has been on the most severe causes of fire, namely the derailment and release of flammable or hazardous material. Current research has also focused on the best method to assess risk and identify areas requiring attention.

It may be helpful to focus future research on the efforts to reduce the most common occurrence of fires: locomotives and right-of-way. This research would entail identifying processes and technologies to quickly detect, alert for, and respond to fires in the locomotive and on the rail right-of-way.

5.0 TECHNOLOGY REVIEW

This section presents technological solutions to assess, monitor, prevent, detect, and respond to fire risks in the rail industry. These solutions have been reviewed based on the literature review, industry survey results, and an assessment of fire risks in operations from the Transport Canada and FRA safety data, and they will be analyzed based on the following:

- Assumed time to deploy in the industry
- Assumed cost of deployment, and
- Area of impact will be expressed numerically

The analysis will also include a recommendation for the technologies that should be tested in an experiment designed to understand each technology's capabilities and limitations in revenue service.

1. Technologies associated with risk monitoring
2. Technologies pertaining to fire monitoring, detection, and response
3. A discussion of improvements to rail industry elements that may prevent fires.

All technologies are summarized and compared in Table 4.

5.1   Data Technologies

As discussed previously in the literature review, fire risk assessment is an important area of research in the rail industry. While not a traditional technological device, it is important to not overlook using the current developments in data collection, data analysis, modeling, and computer simulation to ensure a comprehensive and accurate fire risk assessment is made by the railroads.

5.1.1   Data Collection System

Data collection has increased in the rail industry and will continue to do so as sensors and data collection devices become ubiquitous and less expensive. The collection, storage, and use of data is essential to the measurement of many performance characteristics of the rail industry, and data gathering is the key first step to evaluating and responding to fire risks. At a minimum, railroads currently collect information on fire incidents as shown in some of the reviewed publications [4, 6]. Railroads also collect additional data from their detector networks, maintenance practices, and operations. Data collection can also be sophisticated and can include real-time data thereby allowing predictive responses to risks, as shown in the study of cotton cargo fires [17]. Data collection systems form the basis of risk assessment and response, and these systems can also be enhanced by technologies listed later in the section.

5.1.2   Data Analysis Algorithms

Advanced data analysis algorithms can transform the collected data into useful information about what fire risks exist where. This information presents an opportunity to reduce or remove these risks. These data analysis methods direct the limited resources of any industry to the highest risks. As detailed in the literature review, both a quantitative risk assessment and a fault and event tree analysis can identify the fire risks present in the rail industry [7, 8, 9, 10, 11, 12, 13, 14, 15]. The RRP promotes a comprehensive approach to identifying and addressing fire risk [35]. As indicated by the industry survey, assessing fire risk before engaging in tasks is a general practice in the rail industry. More specialized software can model accident scenarios, flame spread, [31], and material reactions to fire [24, 25] to better understand fire risks in specific scenarios.

5.2   Communication Technologies

The next types of technologies available or potentially available to the rail industry are in risk monitoring. Before beginning a trip, maintenance task, or any other rail-related activity it may be possible to determine the risks present.

5.2.1   Integrated Network for Risk Monitoring

The industry survey indicated the use of weather data systems is a regular occurrence when assessing fire risks. The survey also showed that there is a desire for a unified network to monitor fire risk causes, such as weather, and also receive fire alerts from monitoring technology. These types of technologies currently exist and could be quickly deployed to the rail industry to areas where they are not in use in the rail industry. Closely related to the need for a network for risk monitoring is the integration of the different data sources and storage into a single system. This integration will allow the fire risk data to be analyzed and presented in a single interface. Integrating multiple data feeds and monitoring systems into a single system could offer an advantage over using different systems, such as a weather app and local fire declarations, for each fire risk, which could lead to confusion and the inefficient use of information. However, large enterprise-wide software programs can be expensive to develop and maintain and may cause difficulty when adapting to changes in risks and data sources.

5.2.2   Mobile Application for Real-Time Information

Creating an integrated network for fire risks and alerts will benefit operators who are able to access the information. However, to increase the use of this important information, one of the suggestions from the industry survey was the development of a mobile application for the fire risk and alert system. Mobile applications can distribute information to anyone who may need to make decisions about work to be performed. These applications can connect operators to the risk assessments made using the analyzed data, as well as incorporate real time assessment factors, such as weather, wind, and fire alerts. This application could also be used to alert operators of detected fires or of responsibilities during a fire response.

Currently, many applications are available for monitoring weather and other risks. Railroads also employ mobile devices to allow operators to record inspection data and other activities. Remote access to these applications will increase over time. While these technologies would allow greater information sharing of fire risks, they would be limited by the availability and connectivity of mobile devices. They would also be limited by the training of decision makers to act on the available information.

5.3   Detection Technologies

5.3.1   Smoke, Heat, and Flame Detection Sensors

Fire monitoring and detection are crucial technologies for a quick response to fires both on rolling stock and along the right-of-way. These systems consist of sensors, such as air sampling smoke detectors, optical smoke detectors, heat sensors, and multi-criteria detectors on equipment or locomotives, and a signal system to relay alerts. The monitoring and detection systems can be coupled with fire suppression systems as discussed in the next subsection, and they can be deployed in exhaust systems, on the undercarriage, or in other areas in need of monitoring. There

are many vendors available for this technology and it could be deployed in freight locomotives in North America, if desired. The rail industry currently uses fire monitoring and detection technologies on passenger rail. There are many vendors available for these technologies, and it could be deployed in freight locomotives in North America, if desired.

In contrast to the deployment limitations on locomotives and passenger cars, a limitation of deploying these systems on rolling stock will be adequate power and communication. Most freight cars do not have power supplies or methods of communication with the locomotive or larger communication network. Deployment on freight equipment would require an investment in both an independent power supply and a communication method, as with all remote onboard sensors currently in development.

For equipment that may have multiple fire risk areas, such as a locomotive, many sensors and suppression units may need to be installed, and this could increase the cost and complexity of deployment. A final limitation of this technology is that it does not actually prevent fires but is intended to prevent more serious consequences of the fire. Therefore, wide adoption of this technology would not lessen incidents of fires, but it may reduce the severity of the fires that occur.

5.3.2 Onboard Mechanical Monitoring

Onboard asset health monitoring of bearings, wheels, axles, and brakes is available in the rail industry. Though not currently widely used in North American freight rail, due to power and communication restraints, these sensor systems are becoming more common. Many systems are undergoing industry testing, and some car owners currently employ these sensor systems to monitor cargo conditions. These systems allow for real-time monitoring of the performance of specific assets, such as brakes or bearings, and relate alerts when certain performance thresholds are met, much like wayside detector systems.

These systems carry the same power and communication issues mentioned in the fire monitoring systems because freight cars do not usually have power or communication systems. These monitors can be a self-contained sensor, power supply, and communication unit that can alert the locomotive in the case of crossing performance thresholds. The monitors can also be deployed in a car-wide system capable of local data processing. In theory, these systems could prevent severe train accidents, producing an alert that would allow defective equipment to be addressed before it fails.

5.3.3 Wayside Detectors

Wayside detectors are the most common freight equipment monitoring system in North America. These detectors can be deployed to monitor heat on equipment and locomotives, and specific wayside detectors can monitor certain aspects of the train, such as wheels, bearings, undercarriage, etc. New types of sensors that can monitor different areas of the train, monitor these areas with more accuracy, or monitor multiple areas of the train simultaneously are in development and could be used in the industry in a short period of time. Overall, these systems will allow a single installation to monitor multiple pieces of equipment. However, the limitation of these systems is that they can only monitor equipment that passes over them and only while the equipment is passing over them. Advancements in detector trending analysis allow for predictive maintenance scheduling, but components can still fail between detector passes.

5.3.4   Right-of-Way Detection Systems

Fire monitoring and detection systems can also be deployed to observe the right-of-way and surrounding areas to detect fires either started by or affecting rail traffic. These systems can include vision systems and unmanned aerial vehicles. Vision systems capable of detecting fires without human oversight is a new technology area with research currently being conducted [26]. Camera systems are currently available for forest fire detection and could be deployed to observe critical pieces of infrastructure, such as a bridge or tunnel. Observing large areas along the rail right-of-way would be a significant investment. Machine learning vision systems are in development, but they may require testing to ensure efficacy in the railroad environment.

Unmanned aerial vehicles (UAVs) are used in emergency response situations in the rail industry. The Security and Emergency Response Training Center (SERTC), which offers training programs in to handling rail-related accidents to emergency responders, conducts training in UAVs for these situations [47]. The UAV technology is still new, and the number of use cases for this technology is expanding in many industries. The rail industry could use UAV for routine train fire and right-of-way fire detection in the near future. Testing may be required to determine the efficacy of this system compared to other available technologies as UAVs may have limited flight time and usually require human supervision.

Both cameras and UAVs could be deployed in locations of highest fire risk. One concern when monitoring an isolated area would be how quickly responders could reach a detected fire. Without an adequate fire detection alert response plan, these systems may not reduce the severity of fire consequences.

5.4   Fire Suppression and Control Technologies

5.4.1   Fire Suppression Systems

Once a fire is detected, there are technologies that will allow a fast response to prevent more severe consequences. These technologies include targeted fire suppression systems, including foam and water sprinklers, that can be deployed in key areas, such as on a locomotive or in a passenger car. These systems can be fully automated to respond to a fire as soon as it is detected, thereby reducing the spread and preventing more severe consequences of a fire on a railcar. These systems are currently in use in passenger rail systems and could be quickly adapted to freight locomotives, where not already in place. The foam or sprinkler system would need to be deployed with a fire monitoring system, and multiple systems may need to be deployed to ensure coverage of high-risk areas on a single locomotive, such as exhaust area, engine compartment, and undercarriage. The main limitation of these systems is that the fire extinguishing substance (i.e., water, foam, etc.) would need to be carried on board, and a sufficient supply would need to be available to extinguish fires with different causes and in multiple locations. A recent study has shown that water-mist systems appear to be effective in passenger car fire scenarios, outside of major derailments and collisions [48].

Fire suppression systems, such as handheld devices or on a maintenance-of-way vehicle, can also be used to respond to grass or tie fires. These systems can take the form of more traditional fire extinguishers or hoses. The industry survey indicates that these systems are in extensive use in the rail industry and are often deployed in the area when operators are conducting rail

maintenance activities. Automated fire suppression systems could also be deployed to critical structures to quickly extinguish fires [48].

5.4.2   Vegetation Control

Foams, sprays, or wraps can also be used as a preventative measure for vegetation or structures, such as timber bridges or tunnels. The industry survey indicates that these suppression methods are widely used. The foam, spray, or wraps are placed over vegetation that is in proximity to rail maintenance work or a known flame source to prevent the vegetation from catching fire. These methods can eliminate one of the most common fire risks by preventing right-of-way fires caused by grinding, welding, or rail cutting.

Bridges or other structures could also have preventative insulation applied before fires to attempt to protect them from severe material degradation [25]. One limitation of a fire suppression system used for prevention is that the system will only be located where fires are expected and may not prevent fires that are difficult to predict.

5.4.3   Equipment and Component Safety

In addition to the quick detection of and response to fires, there are technological improvements that can prevent fires from starting in the first place. Some of these improvements include low sparking brake shoes to reduce spark risk. The AAR sets rules for brake shoes on interchanged equipment in North America [49]. Each shoe type listed in the rules has spark limitation requirements. An analysis of brake shoes that reduce sparks beyond this standard could be investigated for efficacy in reducing fire risk.

Another technological improvement is dynamic braking systems. These systems convert the mechanical energy of the train to electric energy and could be used to reduce brake usage and wheel wear. These systems are used often in North America. Researchers could use historical data and work with the railroads to determine the efficacy of these systems in fire risk reduction. It should be noted that there are fire incidents due to the dynamic braking grid becoming overloaded have been reported to the FRA.

As part of the dedication to equipment and component safety, the industry is continuing its efforts to improve tank cars, which can prevent leaks and punctures and prevent releasing flammable or hazardous materials. Some of these improvements were mentioned above in the literature review, and some are mandated by regulations. These improvements could reduce the severity of these rare but potentially serious derailment and collision accidents.

The major limitation of the changes to equipment and components is the slow roll out into revenue service. Typically, these changes are made as old parts or cars are replaced during maintenance activities. A complete changeover replacement of a non-essential component could take years.

5.5   Assessment of Technologies

These technologies are listed in Table 4, which includes 1) a description of the addressed fire risk area, 2) the assumed cost of the technology, 3) the assumed timeliness of deployment to the industry, if selected, 4) each technology's mode of operation (e.g., detection, prevention, or

response), and 5) the expected benefit of the technology, which relates the technology to the known areas of fire occurrence. The assumed cost and timeliness of application are estimates based on industry knowledge. Based on many factors, these estimates may be different from the cost of the actual deployment of the technology. For instance, a technology may be widely available in general, but the current iteration is not suitable for deployment in the railroad environment, and it may need a longer lead time to deploy in the industry.

To arrive at a quantitative assessment of the technologies that should be explored earliest in future testing, the following scores have been assigned to the three areas of measure:

- Cost: Ranging from minimal to high
  - A cost score of 1 would be assigned if the cost is assumed to be zero or minimal or if the railroad would already possess this technology.
  - A score of 5 would be assigned if the cost is assumed to be moderate, i.e., the purchase of a software program for an organization or the purchase of a few systems for targeted placement.
  - A score of 9 would be assigned if the cost is assumed to be high, such as purchasing devices for an entire fleet of cars, or for expansive areas of track.
  - To avoid all values settling at 5, only the values of 1, 3, 7 and 9 will be chosen, where 3 is between low and moderate cost, and 7 is between moderate and high cost.
- Timeliness: Scoring similar to cost
  - If the technology is available now or currently in use, the timeliness of application will receive a score of 1.
  - If it is assumed the technology would need lead time of a year or less to be ready for rail deployment, it will receive a score of 3.
  - If it assumed the technology will need between a year and five years, it will receive a score of 7.
  - If it is assumed that the technology would need extensive development or testing before deployment to the industry, possibly five years or more, it will receive a score of 9.
- Area of impact: based on one of the eight categories of fire risk from the FRA and Transport Canada safety data and industry survey. (Note: While these three data sets do not align exactly, an attempt is made to incorporate them into ranked categories.)
  1. Locomotive
  2. Right-of-way
  3. Rolling stock equipment
  4. Passenger cars
  5. Grade crossing collisions

6. Collisions
7. Derailments
8. Other

If a technology is applicable to multiple areas, all areas are listed, and a total impact score will be listed for each. To define the total impact of a technology, the assumed cost score, the assumed timeliness of application score, and the area of impact score will be multiplied together. The lower the score, the more likely the technology can be deployed quickly or cheaply and the more likely it will be to have a large impact on fire risk. The technologies with the best total impact score will be recommended for future study.

Table 4. Fire Safety Technology

Technology	Assumed Cost	Timeliness of application	Area of impact	Total Impact	Detection, Prevention, Response
Data collection system	3	1	1– 8	3– 24	Detection, Prevention, and Response
Data Analysis Algorithms – quantitative risk assessment, simulation, modelling	1	1	1– 8	1– 8	Detection and Prevention
Integrated Networks for weather monitoring, risk assessment, and fire alerts	7	3	1– 4, 8	21–84, 168	Prevention, Detection and Response
Mobile Applications for these software and sensor networks to enable real time risk assessment for work to be performed	7	7	2, 8	98, 392	Detection and Response
Heat, smoke, and flame detection sensors and alarm system – on board	7	1	1, 3, 4	7, 21, 28	Detection
Onboard mechanical monitoring of bearings, wheels, brakes, etc.	9	3	3, 7	81, 189	Detection
Wayside detection of heat or fire on locomotive or equipment – thermal cameras or other traditional sensors	7	3	3, 7	63, 147	Detection
Right-of-way detection systems or cameras facing critical infrastructure or scanning ground near the train to detect fires	9	3	2	54	Detection
UAVs to detect right-of-way or on train fires	7	3	2–4, 8	42–84, 168	Detection

Technology	Assumed Cost	Timeliness of application	Area of impact	Total Impact	Detection, Prevention, Response
Fire suppression systems, including foam and sprinklers – on board	7	1	1, 3, 4	7, 21, 28	Response
Vegetation Control (Sprays, wraps, etc.)	3	1	2	6	Prevention and Response
Low sparking type brake shoes	9	3	2, 3	54, 81	Prevention
Dynamic Braking System	9	1	2, 3	18, 27	Prevention
Tank car improvements	9	3	6, 7	162, 189	Prevention

The technologies with the best total impact scores are data collection and algorithms for risk assessment. Due to the RRP mentioned previously, these areas are assumed to be currently applied by the railroads. The next best total impact score for a technology is in the area of vegetation control. Sprays, foams, or wraps for vegetation to prevent fires or respond to fires are products that is in use in the industry. New products could be quickly adopted to the industry as they are developed by the vendors. These products could improve an area of high fire risk, with a lot of occurrences reported in the last decade.

The next best total impact scores for a technology are onboard fire detection and fire suppression systems for locomotives. These systems are available for rail service and are currently deployed widely in passenger rail applications. They can be deployed in multiple areas of the locomotive, such as the engine, exhaust stack, and cab, to quickly detect and suppress fires when they occur. These systems would also address one the most prevailing areas of fire risk both in number of occurrences and in total damages.

The next step in addressing fire risk in the rail industry is to delve into these technologies and develop a rigorous test plan to examine the capabilities and limitations of these products. Multiple systems from vendors will need to be obtained and an onsite or lab test could be conducted to determine the efficacy of the technologies.

6.0   RESEARCH NEEDS FOR THE INDUSTRY

Previous sections covered the safety data concerning fire occurrences in the rail industry, the published research on fire risks in freight rail, and the input from industry shareholders on fire risk assessment and response. These three aspects provide an extensive overview of the current state of fire risks in the North American freight rail industry.

In Canada, the most commonly reported occurrence of fire is right-of-way fires possibly caused by train or maintenance operations. The second most common occurrence is related to locomotives. The FRA reported the most common occurrence of fire as those being related to locomotives (electrical or mechanical). The most severe occurrences by cost of total damage are also related to locomotives. The high severity categories are either more common events with low average damages per occurrence or rare events with high damages per occurrence. According to the FRA dataset, the events with the highest damage cost per incident were reported as derailments or collisions of trains carrying flammable material.

The causes of the severe events are varied, and the severity of the damages is caused by the derailment of the equipment and the cargo being exposed to fire. The cause of two of the most severe derailments are indicated as failure to comply with signals or speed restrictions. Two others are indicated as having been caused by a broken rail and another by from track alignment. A broken axle and an overheated bearing are stated to be the cause of two other incidents. The final incident was indicated as being caused by a failure to release the hand brakes on the equipment. These varied causes make it difficult to address these events because 1) they are rare and 2) the causes range from human error to mechanical and material defects.

The information given in the literature review section showed that the majority of reviewed publications concentrated on low probability, high consequence fire events. Eleven of the research papers discussed derailments, collisions, or hazardous material transportation. The published research mainly uses case studies of or simulations for those events that have a potential for high single event damages but are rare in the safety fire data.

The opinions of the industry members who answered the survey indicated locomotives are of the highest concern for causing fires in rail operations. In maintenance, rail grinding is the highest concern of fire cause according to these industry members. In particular, the industry members are concerned about locomotive fires, as well as sparks from trains and maintenance, such as grinding and welding, causing right-of-way fires.

In the technology review section, the technologies associated with data collection and analysis would have the highest impact, based on the ease of execution in the industry and the areas of fire risk addressed. After these technologies, those products that deal with vegetation fire control would address fires occurring along the rail right-of-way. Technologies that monitor and suppress fires in locomotives would also be highly impactful. These technologies are of particular interest because they would impact an area of high fire occurrence in both count and severity, and they do not seem to be as widely used as the other technologies mentioned. Based on the number of fires that occur on locomotives, it would be beneficial to investigate this area further.

The published research very rarely addresses fires in locomotives either from electrical or mechanical causes. Beyond researching fire detection and suppression technology in this area, more research could be conducted to discover why these fires are caused in the first place.

7.0 CONCLUSION

MxV Rail has studied technologies and methods used to identify and address fire risks in the rail industry. The objectives of this study were 1) to determine the elements of railway operations that are susceptible to causing sparks and fires and 2) to understand technologies or policy changes to reduce fire risks and build resiliency in the rail network.

This study was conducted in four steps. The first step was to understand the most common and most severe occurrences of fires in the rail industry. This information was found by examining both the FRA safety reporting data and the Transport Canada safety data. An examination of Transport Canada safety data from a 10-year period indicated the most common occurrences of fire were right-of-way fires, including grass fires and tie fires, followed by fires associated with electrical and mechanical components of the locomotive. The FRA safety data

from a nine-year period showed the most common occurrences of fires were associated with electrical and mechanical components of the locomotive. The release of hazardous material during a train derailment or collision increased the severity of the fires.

The second step was a literature review of the current published research into fire risks in the rail industry. Many published works on fire risk in the rail industry concentrate on identifying fire risks and potential mitigations for these risks. A quantitative risk assessment is used to measure fire risk comprehensively. Research topics included the effect of fire on important rail infrastructure elements, simulations of fire response, and case studies of rail fire events. The review also covered industry policies and regulations that were established in response to fire risks.

The third step was to conduct a survey of industry stakeholders, asking their views of the most common causes of fire and the precautions taken to minimize those risks. An industry survey was sent to stakeholders. The questions ranged from the identification of fire risks to steps taken to prevent fires to technologies used or wanted to assist with fire prevention. When asked about their experiences with the most common cause of fire in train operations, the most frequent response was fires associated with brakes. When asked to rate the area of concern for fires in train operations, the highest rated area was locomotives, followed by brakes. When asked about their experience regarding the most common cause of fire during maintenance activities, the most frequent responses were welding, grinding, and cutting, which were also the highest rated areas of concern.

The fourth step was to review technologies used to address fire risks in the rail industry. A review of the industry survey, research literature, and reported fire occurrence data indicated the industry survey was consistent with the most frequent occurrences of fire. In particular, locomotive fires, as well as sparks from trains and maintenance, such as grinding and welding, causing right-of-way fires. These concerns align with the historical data of fire occurrences in the safety data. The research and industry regulation focus has been on the most severe causes of fire, namely the derailment and release of flammable or hazardous material. Current research has also focused on the best method to assess risk and identify areas requiring attention.

MxV Rail made an initial assessment of the technologies explored in the industry that were either mentioned in the literature review or the industry survey. The technologies (approaches and devices) used vary from advanced algorithms and simulation software to assess risk in various situations, to heat, fire, and smoke monitoring sensors and networks. Technology advancements in rail components are also used to prevent causes of fire. Future work should concentrate on the efforts to reduce the most common occurrence of fires—locomotives and right-of-way. This research would entail exploring fire detection sensors, such as air sampling smoke detectors, optical smoke detectors, heat sensors, and multi-criteria detectors on locomotives, specifically deployed in exhaust systems or near motors. These systems include targeted fire suppression systems, i.e., foam and sprinklers, that can be deployed in key areas on the locomotive.

The second area of concentration should be fire monitoring and detection systems that can also be deployed to observe right-of-way areas and surrounding parts to detect fires started by or affecting rail traffic. These systems can include vision systems and unmanned aerial vehicles as

well as technologies used to suppress fires along the right-of-way, such as handheld devices or from maintenance-of-way vehicles. Foams and other sprays could also be used as a fire-prevention measure around vegetation or structures, such as timber bridges or tunnels.

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APPENDIX A: PUBLICATION SUMMARY

Table A-1 gives a summary of the publications reviewed in this literature review.

Table A-1. Summary of Publications Reviewed

Research Area	References	Summary
Safety Risk Identification Methodology	Ehrhart, et al., 2020 [7]	Discusses risk acceptance criteria for the transportation of hazardous material in the U.S. [7]
	Szaciłło, et al., 2021 [8]	Assess the risk of freight trail transport in Poland based on accident data [8]
	Van Weyenberge, et al., 2016 [9]	Develops a risk assessment methodology to quantify safety risk in a rail tunnel fire [9]
	Zarei, et al., 2022 [10]	Develops a dynamic risk analysis model for analyzing domino effects in rail transport of hazardous material [10]
	Shubinskiy, 2022 [11]	Describes the safety and reliability system in the Russian railways [11]
	Leitner, 2017 [12]	Describes a railway system risk assessment model for Slovakian railways [12]
	Harrison and Daosheng, 2011 [13]	Provides a review of causes and consequences of potential accidents in the Great Britain rail industry [13]
	Yan, et al., 2016 [14]	Through analysis of historical subway fire data describes causes of the accidents [14]
	Lombardi, et al., 2015 [15]	Presents results of a quantitative risk analysis of a railway tunnel [15]
	Grunstra, 2014 [16]	Describes trends in railway fires between 1914 and 2011 [16]
	Hou, et al., 2016 [17]	Analyzed the main factors causing cotton fire in rail transport [17]
	Schöbel and Maly, 2012 [18]	Presents a matrix of dependencies among fault states in rail operations [18]
	Griffin, 2014 [19]	Developed a geospatial model of rail safety hazards across the Great Britain rail network [19]
	Nezval, et al., 2022 [20]	Analyzed the temporal and geographic patterns of vegetation fires near railway lines in the Czech Republic [20]
	Zhang, et al., 2018 [21]	This paper uses a Bayesian network to express the relationship between decision-making agents [21]
	Wang, et al., 2021 [22]	Considers the psychological behaviors of decision-makers in emergency response situations [22]
	Bornay, and Chauhan, 2021 [23]	Develops a mixed integer programming model for routing hazardous materials in freight rail [23]
Technologies and Aspects of Fire Risk	Elhami Khorasani, et al., 2018 [24]	Discusses the structural performance of a railway tunnel during fire [24]
	de Silva, Donatella, et al. 2023 [25]	Discusses fire risk mitigation in rail bridges [25]
	Sukuan Jin and Xiaobo Lu. 2019 [26]	Presents a vision-based machine learning algorithm for forest fire detection [26]

Technologies and Aspects of Fire Risk (continued)	Jacobsen, et al., 2013 [27]	Test results from a dynamic loading test of a locomotive fuel tank [27]
	Prabhakaran and Booth, 2022 [28]	Test results from the performance of a tank car pressure release device during fire [28]
	Prabhakaran, et al., 2018 [29]	Presents the performance of tank cars under total containment during fire [29]
	Andrews, 2014 [30]	Discusses the properties of crude oil in relation to rail transport [30]
	Tugnolia, Alessandro, et al. 2013 [31]	Describes flame model for a flash fire incident [31]
	Ehrhart, et al., 2021 [32]	Discusses issues of hydrogen fuel cells in the rail industry [32]
	Radziszewska-Wolinska, 2022 [33]	Presents fire risks from alternative fuels in the rail industry [33]
Policies and Regulations	National Transportation Safety Board, 2020 [34]	Railroad accident report from train derailment with hazardous materials release [34]
	Code of Federal Regulations, 2023 [35]	FRA's Risk Reduction Program [35]
	Transport Canada, 2022 [36]	Transport Canada's Extreme Heat and Fire Risk Mitigation Rules [36]
	Federal Railroad Administration, 2015 [37]	FRA order establishing a maximum speed for transport of flammable liquids by rail [37]
	Pipeline and Hazardous Materials Safety Administration, 2020 [42]	Order allowing Liquefied Natural Gas to be transported by rail [42]
	Stillman, 2022 [46]	A comparison of U.S. fire regulations with standards is Europe, Japan, and China [46]

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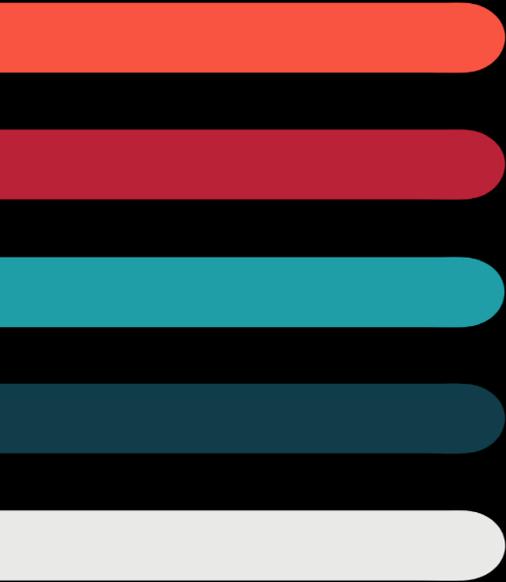
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