Bow Tie Analysis of the Lac-Mégantic Rail Disaster

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Abstract

Oil transportation by rail is one of the most important, yet dangerous means of transportation. The analysis of transportation incidents is important to determine the faults in the system and the root causes in order to prevent these incidents from recurring. Bow tie analysis is one of the methods used to understand the events, consequences, barriers and mitigative controls of incidents, such as the Lac-Mégantic Rail catastrophe. This disastrous incident occurred on July 6, 2013, and it destroyed 50 vehicles, 40 buildings, the railway tracks at the west end of the Mégantic Yard and tragically caused the death of 47 people. There was damage to the environment, 2000 people were forced to evacuate, almost all 63 tank cars were destroyed and most of downtown Lac-Mégantic was ruined. By studying relevant case reports, a bow tie diagram was created analyzing the root causes of this incident. We believe that human factors, organizational safety culture, and engineering-related factors were key contributors to the incident. The sequence of events was used to determine underlying causes, possible preventative measures, and mitigative controls. The analysis of the root causes and sequence of events is important for determining the causes of the incident, understanding the underlying issues in the safety management system, and ensuring this type of catastrophe cannot happen in the future.

Introduction

Many hazardous materials (HAZMAT) are transported by railway in Canada. HAZMAT include but are not limited to the following: explosive materials, flammable materials, and toxic substances. They are necessary for maintaining quality of life in society, as they provide fuel for vehicles and homes and facilitate manufacturing and industrial processes. The transportation of

HAZMAT is dangerous due to the severe consequences of HAZMAT release in railway and road incidents, including fire, explosion, and environmental contamination [1].

In 2020, the top 5 hazardous materials transported by CN rail were: liquified petroleum gas (29.0%); petroleum crude oil (12.0%); diesel fuel (11.8%); sulphuric acid (4.8%), and gasoline (3.8%) [2]. Since many industrial and manufacturing activities increasingly rely on HAZMAT, performing risk analyses is of utmost importance to control or mitigate the potential severe consequences of railway incidents during HAZMAT transportation.

In this paper we will briefly describe three of the more common tools, namely (i) root cause analysis (RCA); (ii) event tree analysis; and (iii) bow-tie analysis. Specifically, we will apply a bow tie analysis to the case of the Lac-Mégantic rail disaster in Quebec in 2013.

Risk analysis tools have been developed over recent years to help identify risks and prevent incidents that pose a danger to humans, the environment, and animals related to the manufacturing, transportation and use of HAZMAT. Many industrial processes involve the manufacturing, transportation and use of vast quantities of highly hazardous materials, thus it is imperative that the risk of unintentional release of such HAZMAT is minimized. The processes and activities involved in the rail industry are multifaceted and increasingly complex and the incentive to maximize profits is often in conflict with the demands of the organization's safety management system requirements. Risk assessments can provide appropriate information to identify the areas and activities that present higher risk levels, thereby influencing land-use planning processes, providing for adequate emergency planning, and preventing catastrophic incidents. Risk analysis tools provide a standard diagnostic and risk mitigation process that can be applied across all industries. If backed by national and international legislation, these processes could become commonplace, and their widespread application could remove any real or perceived competitive disadvantage from the identification and implementation of necessary additional preventative and mitigative control measures.

2. Methodology

2.1 Event tree analysis

Quantitative risk analysis methods attempt to achieve a probabilistic analysis by assigning numerical values to the likelihood of an event occurring, and the likelihood that the event will affect the likelihood or outcome of other events. Such an analysis requires an understanding of the relative importance of the various sub-systems in a specific operation or activity. It additionally requires an understanding of the inter-relatedness of the sub-systems in each operation.

Event tree analysis is a quantitative risk modeling technique that works by starting with a single initiating event and creating a tree that assesses probabilities of all the possible outcomes. From the starting branch, this tree is created by making paths of outcomes after answering yes and no questions about the event.[3] If using this method as a quantitative risk analysis tool, two assumptions are made: the first regarding assigning probability values of input events, and the second relating to the interdependency among the inputs. [4] This is a very efficient way to assess the cause of a disaster. It includes an initiating event (the starting point), probable subsequent events, and the outcome from the order of events. The outcome probability for each event can be measured by multiplying the probabilities which are assigned to each event. The probable subsequent events are interdependent to one another and on prior events. One major drawback of this tool is that accurate, validated probability values are difficult to assign. A diagram of an event tree is provided below in Figure 1.

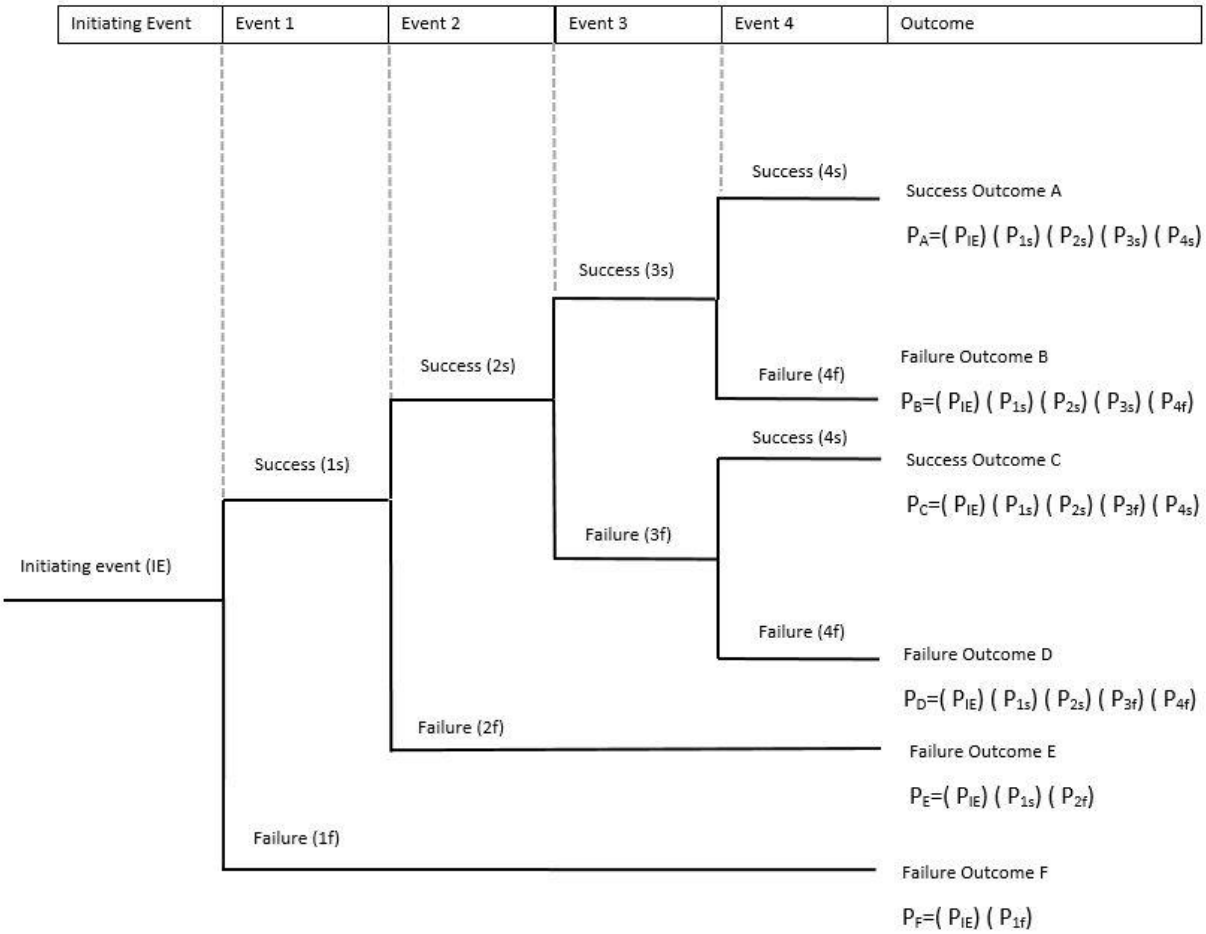

Figure 1. Example of an event tree diagram (from www.wikiwand.com/en/Event_tree_analysis)

2.2 Root Cause Analysis (RCA)

In contrast to the quantitative methods, qualitative methods do not assign numerical values to probabilities of events in the sub-systems of an operation. Instead, qualitative methods, such as RCA, identify an unwanted event or incident associated with an activity, then list the various possible causes and identify how the cause are related to each other (e.g., event or action 1 may cause event 2), thus developing a critical path allowing the incident to occur. In short, qualitative RCA methods identify, list, and illustrate graphically the interrelatedness of causes, which helps to identify the root causes of an incident and illuminate aspects of the organization's safety management system that are weak or non-existent. An RCA is developed by first briefly describing the incident, then analyzing a timeline of events that led to the incident and identifying the different causal factors associated with the incident, driving down to the latent or root cause, which is associated with a failure or a weakness in the organization's safety management system. All the causes and roots from the incident down to the root causes (and their interrelationships) are represented graphically. The resulting diagram illustrates the different paths (or roots) from the incident (at the top) to the root causes of the incident (at the bottom).[5] An example RCA chart is provided in Figure 2 below.

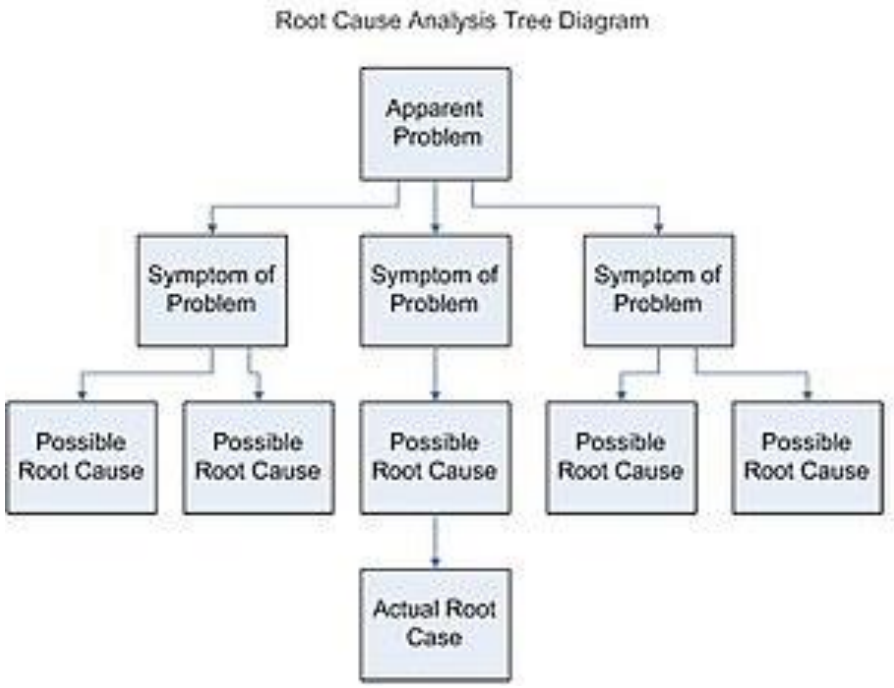

Figure 2. Example of an RCA chart. (From https://en.wikipedia.org/wiki/Root_cause_analysis)

RCA technique is useful, not only for early failure identification, but also to identify and eliminate or mitigate hazards and risks before they occur. Additionally, these methods can be used to understand why a process is performing well and the successful root cause can be implemented in other processes that are lacking it.[9] This is a repeatable, logical, step-by-step process, so it can be applied to confirm the results of another risk assessment tool. Some disadvantages of this technique include the many assumptions that are necessarily made while performing the RCA. This method requires focusing on simplifying the causes and roots when in reality, the actual situation or set of causes (and their interrelationships) can be much more complex.[10]

2.3 Bow Tie Analysis

Bow tie analysis is a qualitative method used to identify where new or enhanced preventative or mitigative controls would be beneficial, especially when there is a high-risk level, a critical lack of control identified, or lack of a robustly implemented risk assessment and management system in the organization. A bow tie diagram (Figure 3) identifies potential hazards associated with an unwanted event, visually models the critical paths a hazard could take to cause a significant consequence and identifies the preventative and mitigative controls that are needed to reduce the process safety risk.[6].

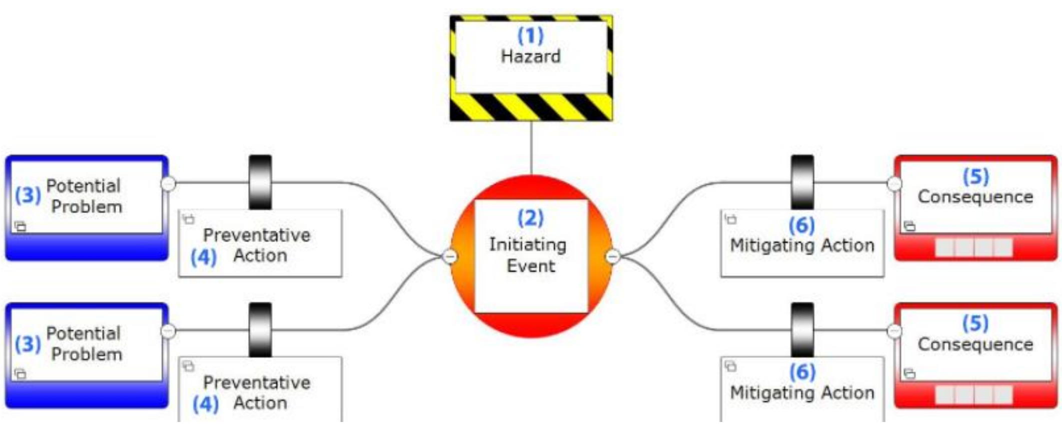

Figure 3. Bow Tie Analysis Representation

A bow tie analysis presents many advantages over other risk analysis tools, including the fact that it: 1) is flexible (it can be applied to any kind of risk and is used in a variety of industries); 2) highlights the direct link between the controls and relevant elements of the safety management system; 3) it can be targeted to evaluate risks in a specific activity or area; and 4) it provides information in an easy to understand visual format.

This method has also gained acceptance as a credible risk and safety management tool, as it provides a graphical representation of incident scenarios, which is useful for comprehensive risk analysis and safety assessment. Further, many studies have confirmed that this technique can present the direct and logical relationship between hazards, tasks, safety controls, risks, and consequences of incidents. On the other hand, the disadvantages of bow ties must also be noted. Bow tie analysis does not produce a quantitative assessment of the risks, unless the analysis is linked to fault tree analysis or event tree analysis, and a thorough understanding of the unwanted event, hazards, controls, and consequences is essential. Since no standards exist for this technique, there are a variety of inconsistent representations of and approaches to bow ties. Lastly, this technique does not evaluate whether the safeguards and controls in place are sufficient or operating effectively.[7]

Bow tie analysis is a highly effective risk assessment tool because it uses both event tree and fault tree diagrams. A bow tie diagram is created using both an event tree diagram on the right side and a fault tree diagram on the left side.[6] We have chosen this method to evaluate the rail case study incident because of its many advantages over other common methods of risk analysis. The causes and consequences of an event are represented on the left and right side of the diagram respectively, allowing users to visualize and understand the events and the timeline in a more effective way. [8]

This paper describes the application of a bow tie analysis to the Lac-Mégantic rail disaster in order to illustrate the main causes of the incident and determine additional preventative and mitigative control measures that should be developed.

The Lac Mégantic rail disaster of 2013 is one of the worst rail disasters in Canadian history. On July 5, 2013, around 10:50 p.m. a MMA train, (Montreal, Maine & Atlantic Railway) stopped at Nantes, Quebec. It was carrying 7.7 million liters of petroleum crude oil in 72 Class 111 tank cars. [11] Shortly before 1 a.m. on July 6, 2013, the train started to roll uncontrolled. It traveled 7.2 miles and reached speeds of 65mph. About 15 minutes later, while reaching the center of the town, Lac- Mégantic, Quebec, 2 boxcars and 63 tank cars carrying petroleum crude oil derailed. As a result, approximately 6 million liters of petroleum crude oil spilled. There were explosions and fires which destroyed 50 vehicles, 40 buildings, and the railway tracks at the west end of the Mégantic Yard. This caused the death of 47 people. [12] The train was left unattended and parked on a descending grade on the main track. The engineer applied a handbrake on all locomotives but only shut down the lead locomotive. Railway rules require hand breaks alone to be strong enough to hold the train alone, and this must be tested. On the night of the test, the locomotive air brakes were left on, resulting in the train being held by both the hand brakes and the air brakes. During the trip, the engineer indicated that the lead locomotive was having mechanical issues and that there was excessive black and white smoke coming from the smokestack. They expected it to settle and agreed to deal with it the next morning. Eight months before this incident, the lead locomotive was sent to the repair shop due to engine failure. Due to cost and time concerns, the engine was repaired with a metal-like epoxy material that lacked the necessary strength and durability. This material failed and that led to oil leaks and engine surges. The oil began to accumulate in the body of the turbocharger where it overheated and caught fire. First responders to the fire shut down the locomotive's fuel supply and they moved the electrical breakers to the off position. Due to the fuel supply being shut off, the air compressor was no longer able to supply air to the air brake system and as air leaked from the brake system, the main air reservoir was slowly depleted, and that eventually reduced the effectiveness of the air brakes. That night, the air pressure dropped to a point at which the air brakes and hand brakes were no longer strong enough to hold the train and that was when the train began to roll downhill toward Lac-Mégantic. Train derailment collisions caused breaches in the tank cars. As a result, oil spilled out, hotspots and sparks caused ignitions, followed by fires and explosions. There was damage to the environment, 2000 people were forced to evacuate, almost all 63 tank cars were destroyed and most of downtown Lac-Mégantic was ruined.

There are many causes associated with this incident. We have identified the initiating event, hazards, preventative controls, mitigative controls, and consequences and created a bow tie diagram (Fig.2) to illustrate the application of a qualitative risk analysis of the disaster.

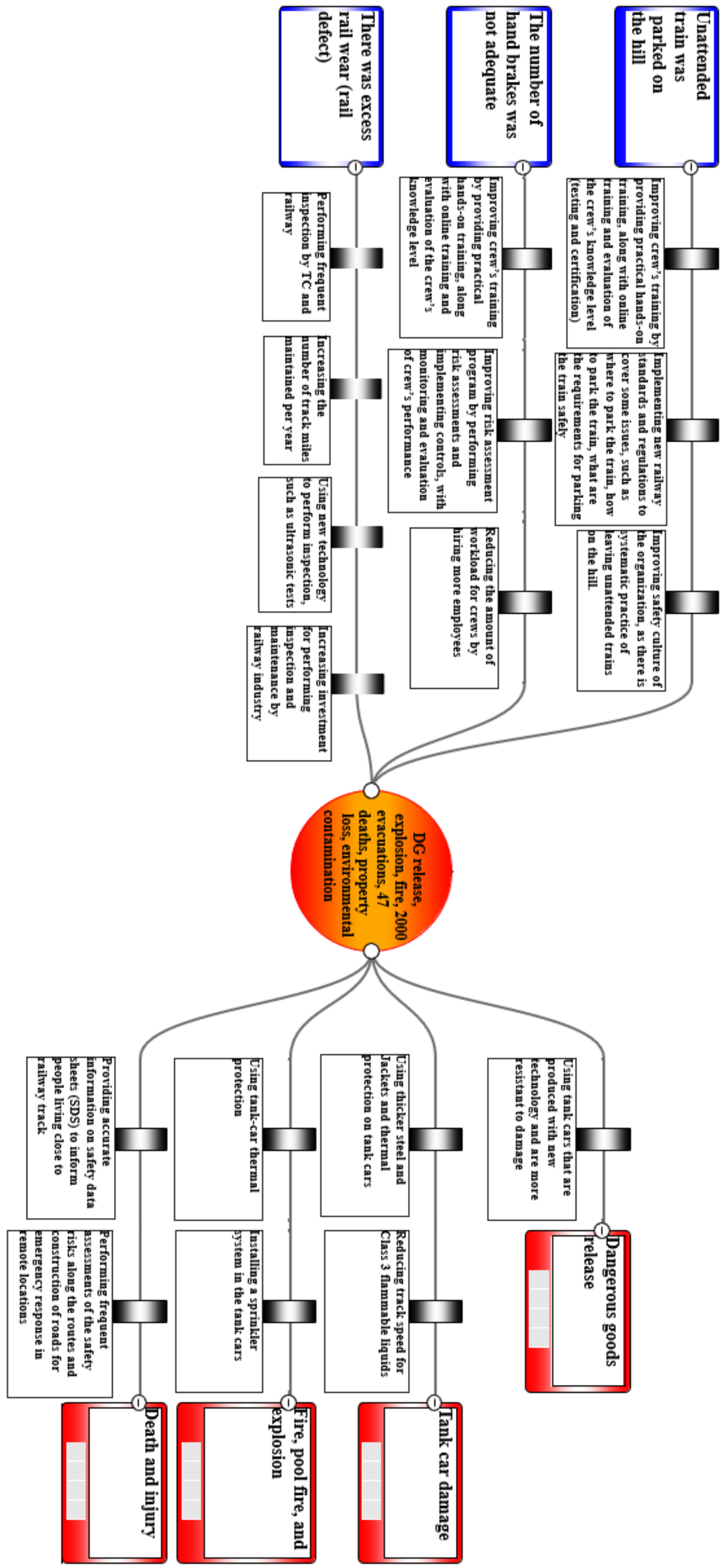

Fig.4 The bow tie diagram developed for the Lac-Mégantic derailment

3. Results and discussion

After reviewing the available Lac Mégantic incident documents and reports, the three top hazards (or threats) identified for the derailment were the unattended train parked on a descending grade, the number of handbrakes was not adequate and there was excess rail wear (rail defect). The preventative measures that could have prevented the initiating event include the following:

- Better crew training could have prevented the train from being parked on an incline. Such training may include online or practical training. Specifically, the crew could have been better trained regarding their assessment of safe places to park the train. The requirements pertaining to train parking should have been provided in written form, and the crew's training level should have been tested regularly through an objectively developed assessment protocol. Much of this discussion leads back to the issue of corporate or institutional safety culture, which can only be addressed at the upper management level.
- The inadequate number of handbrakes, or the inability to foresee the risk of relying on a single braking system, could also be solved by improving the crew's training, improving the organization's risk assessment program, and reducing the workload on attendant crews by hiring more employees.
- Regarding the issue of the rail defect, more frequent inspections could be performed by Transportation Canada and the number of track maintenance operations per year could be increased. New technology could be used to perform inspections, such as ultrasonic and other non-destructive testing methods, and there could be an increase in investment for performing inspection and maintenance by the railway industry.

Many significant consequences resulted from this derailment, such as tank car damage, dangerous goods (DG) release, fire, explosions, death, injuries, and environmental pollution. People, the environment, assets, and production were all impacted in this event. We believe that by putting in mitigative measures such as: reducing track speed for Class 3 flammable liquids, thicker steel, using jackets and thermal protection on tank cars, using tank cars that are produced with new technology and are more resistant to damage, using tank car thermal damage protection, frequent assessments of the safety risks along the routes, construction of roads for emergency response in remote locations, and providing accurate information on safety data sheets (SDS) to inform people living close to the railway track. With the introduction of these measures, the consequence of this incident could have been drastically reduced.

4. Conclusion

In this paper, we applied a bow tie analysis tool to better understand the causes, preventive measures, and consequences in the Lac-Mégantic train derailment, as well as to give a qualitative visual representation of the event and causes of this incident. We studied the Lac-Mégantic train derailment because it is one of the biggest rail incidents in Canadian history and it had a significant impact on people, the environment, assets, and production (PEAP). We found the top 3 technical causes to be the unattended train parked on a descending grade; inadequate number of handbrakes; and rail defects. Human factors, organizational safety culture, and engineering-related factors were all key contributors to this incident. To further develop this research, dynamic quantitative risk assessment tools could be used for a more accurate assessment of the risk in this incident.

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