FAULT TREE ANALYSIS OF ADJACENT TRACK ACCIDENTS
ON SHARED-USE RAIL CORRIDORS

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ABSTRACT
Adjacent track accidents have been identified as an important hazard on shared-use rail corridors. They are train accidents in which derailed railroad equipment intrudes upon ("fouls") an adjacent track, disrupting operation and potentially causing a collision with trains operating on the fouled tracks. Derailments without intrusion may cause equipment and infrastructure damage, passenger casualties and disturb system operation; however an intrusion may be even more severe due to the potential involvement of multiple trains. Opportunities for adjacent track passenger train accidents have increased in recent years due to expanded passenger service on shared trackage, right-of-way, or corridors and also because of increased multiple track in connection with capacity expansion projects. This paper presents a probabilistic risk assessment methodology to analyze adjacent track accident risk. An event tree is created to identify scenarios for adjacent track accidents and a fault tree analysis is performed to identify basic events that contribute to such accidents. The quantitative probability of adjacent track accident is derived using Boolean algebra based on the results of the fault tree analysis.

Keywords: Adjacent Track Accident, Rail Safety, Shared-Use Rail Corridor, Probabilistic Risk Assessment, Fault Tree Analysis
INTRODUCTION
Adjacent Track Accidents
Adjacent track accidents (ATA) have resulted in several recent high-profile railroad incidents. In one case, a grain train derailed and equipment intruded on ("fouled") the adjacent track. An oncoming petroleum crude oil train collided with this equipment derailing 21 tank cars causing a number of them to release product and catch on fire (1) (Figure 1a). In another incident, a passenger train derailed and fouled the adjacent track leading to a collision and derailment of another passenger train approaching on the adjacent track resulting in 65 passenger injuries (2) (Figure 1b).

FIGURE 1 Adjacent track accident scene for (a) two freight trains and (b) two passenger trains (2)

These examples of ATAs represent a potential hazard to both freight and passenger train operation in which one or more derailed rail cars or locomotives intrude upon adjacent tracks and collide with, or are collided by, another train operating on the adjacent tracks at the time of the initial accident (3). The potential for passenger train ATAs has increased in recent years due to expanded passenger services in which these trains share trackages, right-of-way, or corridors with existing freight railroad lines. Although train derailment rate has decreased substantially since 2000 (4, 5), the chance for these types of incidents increases as railroads install additional multiple track sections in order to increase capacity. These so called “Shared-Use Rail Corridors (SRC)” are expanding as passenger rail operations have increased in the United States (6 – 9). Consequently, ATAs have been identified as an increasingly important hazard on these SRCs (6). Derailments without an intrusion may cause equipment and infrastructure damage, passenger casualties and disturb system operations, but ATAs can result in all of these and in addition may lead to more severe consequences due to involvement of multiple trains.

Under normal conditions, the loading gauge (aka clearance plate) of rolling stock in a train stays within the clearance envelope of the track it is on (Figure 2a). However, if a derailment occurs the derailed equipment will generally exceed the clearance envelope of the track it is on (Figure 2b), and possibly intrude on an adjacent track’s clearance envelope. If the latter occurs, it is referred to as an intrusion (Figure 2c). When an intrusion occurs, there is a possibility that another train operating on the adjacent track, either at or approaching the intrusion site, will result in a collision with the derailed equipment (Figure 2d).
An ATA consists of three sequential events: 1) an initial derailment in multiple track territory, 2) intrusion of the derailed equipment onto an adjacent track, and 3) the presence of another train on that track. Two variants of this type of ATA are the focus of the research presented in this paper. In the first type an intrusion occurs and there is a train is on an adjacent track at the same time and location resulting in an immediate collision as the derailing equipment impacts the other train. In the second scenario, an intrusion occurs when a train on an adjacent track is approaching the intrusion site leading to a potential collision with the debris from the first derailment.

There are other ATA scenarios such as a direct collision between two trains on adjacent tracks. These are generally caused by shifted lading, or car components that for some reason exceed the loading gauge (raking collisions in Federal Railroad Administration (FRA) terminology). Another type is a collision of two trains at turnouts (side collisions in FRA terminology). These types of ATA require a modified approach that is beyond the scope of this paper and will be considered elsewhere.

**Research Objectives**

This paper develops a probabilistic risk assessment methodology to address ATA risk. An event tree is created to identify scenarios for ATA and fault tree analysis (FTA) is performed to identify failure paths and basic events that contribute to such accidents. Boolean algebra is used to derive the probability of ATA from the resulting fault tree.

**LITERATURE REVIEW**

Fault-tree analysis has been extensively applied to railroad safety in a variety of contexts. Li et al. uses FTA on rear-end train collision accidents and developed models to calculate the probability of rear-end train collisions (10). Wang et al. used FTA to address the risk of train derailments on urban rail transit systems (11). Huang et al. combined FTA and fuzzy theory in general railroad safety analysis (12). Jafarian and Rezvani also used the fuzzy fault tree to analyze train derailments and identify significant causes (13). European railway agencies apply FTA to various railroad hazards in order to allocate preventive resources most effectively. The Rail Safety and Standards Board (RSSB) (14-16) conducted FTA on six major types of train derailment.
accidents in Europe and used historical train accident data to identify causes with the most effect on each type of accident.

An example fault tree for train-to-train collisions developed by RSSB is shown in Figure 3. It is color-coded based on the relative ranking for each accident cause, which is supported by data from RSSB’s train accident database. Accident causes highlighted in red have the highest risk ranking, meaning that these are causes most in need of attention. Accident causes highlighted in yellow have medium risk and the ones in green have low risk.

FIGURE 3 RSSB fault tree for train-to-train collision (14)

There is some prior research addressing risk assessment of adjacent track accidents. Lin et al. proposed a semi-quantitative method to evaluate general ATA risk (3). Cockle developed a semi-quantitative risk assessment model to evaluate ATA risk specifically between high-speed rail and conventional railroad systems (17). Barkan used NTSB data to develop a statistical estimate of the distribution of the lateral displacement from track center of rolling stock derailed in accidents (18). English expanded and extended this work and developed a quantitative probabilistic model (19). Based on English’s result, Clark et al. proposed an analytical approach to assess the risk of high-speed track being fouled by freight derailments (20). To date however, neither fault tree analysis nor other probabilistic risk assessment techniques have been used to address ATA risk. Since ATAs are a complex process involving multiple events, there is a need for comprehensive understanding of their mechanisms in order to more precisely assess and ultimately reduce the risk.

METHODOLOGY

Probabilistic Risk Assessment

As discussed above an ATA is a sequential event (Figure 2a – 2d) that can be formally described using an event tree (Figure 4). The initial event is the derailment of the first train(s), denoted as D, and may be due to an initial derailment or a collision. Thus, D is the probability of a derailment or a head-on or rear-end collision at a location. The intrusion, when the adjacent track is fouled by equipment derailed in the initial accident, is denoted as I. It is a conditional probability, given that an initial derailment occurs. The adjacent train presence is defined as the presence of another train on an adjacent track(s) either next to, or approaching, the intrusion location, denoted as T. Its probability is conditional on the occurrence of an intrusion. The black
square nodes represent divergence points whether an event occurs or not. Each divergence on the event tree implies a probability element.

**TABLE 4 Event tree for ATA**

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>The train does not derail. The railroad system operates as normal</td>
</tr>
<tr>
<td>S2</td>
<td>The train derails but does not intrude the adjacent track. Although the railroad system is interrupted, but this is not in the scope of adjacent track accident. Thus, it is considered a “success” in this particular event tree.</td>
</tr>
<tr>
<td>S3</td>
<td>The train derails and intrudes the adjacent track, but there is not other trains on adjacent track at the time of accident. Although the multiple tracks are affected, there is no collision between trains on adjacent tracks in the end, so it’s considered a system success in terms of ATA.</td>
</tr>
<tr>
<td>F1</td>
<td>The train derails and intrudes the adjacent track, and then collides with another train on the adjacent track.</td>
</tr>
</tbody>
</table>

**FIGURE 4 Event tree for ATA**

A “success” in the event tree is defined as an event that does not occur, which is the safer alternative. A “failure” means that the event does occur and represents the unsafe alternative.

For instance, the black node on the left in Figure 4 indicates whether an initial derailment occurs. If it does, it is considered a “failure” because the occurrence leads to an intrusion, which is the next stage of an ATA. Therefore, in Figure 4, the path for the probability of the occurrence of the initial derailment, D, goes downward (the direction of occurrence), while the path for its complement probability, \( \bar{D} \), goes to the right (the direction of non-occurrence and results in a success scenario (no accidents)). This may be counter-intuitive because in reliability engineering, a “success” usually means that a component or procedure functions or “occurs”, but in ATA risk, prevention of the event is the desired outcome. We therefore define the “success” of the system as the non-occurrence of an ATA (scenarios S1, S2 and S3 in Figure 4), and system failure as the occurrence of an ATA (scenario F1 in Figure 4).

The event tree is divided into four scenarios. When an initial derailment does not occur, the train runs normally and the system is safe (success scenario S1). The probability of S1 is simply the non-occurrence of the initial derailment (denoted as \( \bar{D} \)). The subsequent probability components are not examined in this case because the first event does not occur. If the initial derailment occurs but the intrusion does not, the derailed train will not collide with trains on adjacent tracks. Although this scenario may still cause damage and system disturbance, it will not result in an ATA and is labeled as success scenario S2. The probability is the occurrence of the initial derailment, multiplied by the non-occurrence of intrusion (denoted as \( D \cdot \bar{I} \)). When both the initial derailment and an intrusion occur, the derailed train is exposed to a hazardous situation in which a train on the adjacent track may not stop before colliding with the derailed train. The probability of no train on the adjacent track is at or approaching the intrusion occurs is denoted...
as $D \cdot I \cdot \bar{T}$. This is labeled as \textit{success} scenario S3. Even though the intrusion has occurred in this scenario, but because there is no train on the adjacent track, this scenario does not result in a collision between derailed equipment and adjacent train and therefore is not considered as system failure. The probability that there is a train at or approaching the location where and when the intrusion occurs, resulting in a direct collision, is denoted as $D \cdot I \cdot T$ and labeled as \textit{failure} scenario F1. Scenarios F1 is the focus of this research. In the next subsection, FTA will be used to further analyze the factors contributing to ATAs.

\textbf{Fault Tree Analysis (FTA)}

FTA is a deductive process to identify all potential failure paths and basic events that lead to a top event \((21)\). In this study, the top event is the ATA (scenario F1 in the previous subsection). A fault tree diagram provides a logical and graphical presentation of various combinations of the basic events that can lead to the top event \((22)\). The fault-tree consists of events and logic gates. Different logic gates represent different calculation processes. For example, an AND gate means that all events connected by the gate need to occur for the upper level event to occur. On the other hand, an OR gate means that the upper event will be triggered when at least one of the events connected by the gate occur. Table 1 shows the common symbols used in fault-tree analyses. Basic events are the lowest level events that contribute to the occurrence of the top event. Intermediate events are the ones between the top events and basic events. Conditioning events specify the order for a sequence of events to occur. External events are those that contribute to the occurrence of the top event from outside the defined system.

The development of the ATA fault tree is based on: a) existing fault trees developed for train accidents on typical railroad systems, b) analysis of previous ATA reports, and c) expert judgment. Fault trees have previously been developed for various types of train accidents as discussed in the literature review and these were used as a reference for developing an ATA-specific fault tree. For example, train accidents in Europe have been broken down into causes (aka, "deducted") by RSSB \((15)\). We used a similar approach based on FRA Rail Equipment Accident cause codes and data to deduct the initial derailment into accident causes. All of the basic events were systematically considered to identify each stage in an ATA and the fault tree can be expanded as more information becomes available.
<table>
<thead>
<tr>
<th>Name</th>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basic Event</td>
<td>![Symbol]</td>
<td>A basic event that is not broken down into more detailed events</td>
</tr>
<tr>
<td>Intermediate Event</td>
<td>![Symbol]</td>
<td>An event that occurs because of one or more basic events acting through a logic gate that connects with it</td>
</tr>
<tr>
<td>External Event</td>
<td>![Symbol]</td>
<td>An event which is normally expected to occur</td>
</tr>
<tr>
<td>Conditioning Event</td>
<td>![Symbol]</td>
<td>Specific conditions or restrictions that apply to any logic gate</td>
</tr>
</tbody>
</table>

### Logic Gates

<table>
<thead>
<tr>
<th>Name</th>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>And</td>
<td>![Symbol]</td>
<td>The output event occurs if all input events occur</td>
</tr>
<tr>
<td>Or</td>
<td>![Symbol]</td>
<td>The output event occurs if at least one of the input events occurs</td>
</tr>
<tr>
<td>Priority And</td>
<td>![Symbol]</td>
<td>The output event occurs if all input events occur in a specific order</td>
</tr>
<tr>
<td>Transfer</td>
<td>![Symbol]</td>
<td>The fault tree is developed further and connected to other fault trees</td>
</tr>
</tbody>
</table>

Figure 5 shows the fault tree for an ATA. Since the initial derailment, the intrusion, and the adjacent train presence events need to occur in a specific order, they are connected by the “Priority And” gate. Branches for the three intermediate events are described as follows:
1 FIGURE 5 Fault-tree for ATA
Initial derailment (D)
The initial derailment results from various train derailment causes. Thus, the intermediate event is deducted into five types of accident causes: infrastructure, equipment, signal and communication, human factor, and miscellaneous. This is based on the accident codes developed by the Federal Railroad Administration (23). Each type of accident cause is further deducted into sub-accident causes. These sub-accident cause groups are treated here as basic events. However, any sub-accident cause group can be further deducted into more detailed failure modes based on the resolution of analysis and data available. Transfer gates can also be used for each sub-accident cause to create more detailed fault trees, which are outside the scope of this paper.

Intrusion from derailed equipment (I)
The major impact of intrusion events is the excessive displacement of derailed equipment. Some studies have analyzed the probability distribution of lateral displacement of equipment in derailments (18, 19). When lateral displacement exceeds the track center spacing of two adjacent tracks, installation of crash walls or containment may prevent intrusion by keeping the derailed equipment off adjacent tracks. Crash walls are earth berms, concrete walls or other types of barrier constructed between tracks that can prevent such intrusions (24 – 26). Containment is some structure located directly on the infrastructure to prevent the train from rolling over and intruding on adjacent tracks, such as a parapet or guard rail (27). Crash walls and containment act in similar ways to reduce the occurrence of intrusion. However, they will not protect the adjacent track from intrusion if they are not present at a particular site, or if they are installed but are overcome by derailed equipment during the intrusion.

Adjacent Train Presence (T)
When an intrusion occurs, there may be another train on the adjacent track, which results in a collision between the derailing train and the adjacent train. Sometimes the train on adjacent track is approaching when an intrusion occurs, which may also result in the collision due to the failure to stop the adjacent train short of the intrusion. Two possible reasons contribute to the inability to stop a train in time: failure of intrusion detection systems or insufficient time or distance to brake the train. Intrusion detection systems are special fences or chains equipped with sensors that are set between adjacent tracks to detect intrusion events. When an intrusion is detected, a warning signal is sent immediately to the train engineer so that they can start braking the train. The failure or absence of the intrusion detection system increases the probability that a train will be unable to stop short of the intrusion. Braking itself may also fail due to mechanical problems or human factors.

Boolean Algebra Probability Calculation
After the fault tree is constructed, the probability of top event occurrence can be calculated using Boolean algebra. In the fault tree, each intermediate and basic event is denoted by two-letter abbreviations, except the initial derailment (D), intrusion (I), and train presence on the adjacent track (T). In the fault tree, the OR-gate represents the union of input events, the Boolean expression for the OR-gate is \( Q = A \cup B \), or \( A+B \). The And-gate represents the intersection of input events, and the Boolean expression for the AND-gate is \( Q = A \cap B \), or \( A \cdot B \). By definition, the occurrence of an ATA is the intersection of the initial derailment, intrusion, and adjacent train presence:
\[ ATA = D \cdot I \cdot T \]

The probability of the initial derailment is the cumulative probability of infrastructure (DT), equipment (DE), signal and communication (DS), human factor (DH), and miscellaneous (DM) caused derailments. Each corresponds to the cumulative probability of lower level events shown in the fault tree (Figure 5), assuming all basic events are mutually independent:

\[ D = DT + DM + DS + DE + DH \]
\[ = (T1 + T2 + T3 + T4 + T5 + T6 + T7) + M1 + S1 + (E1 + E2 + E3) + (H1 + H2 + H3 + H4 + H5 + H6 + H7) \]

The probability of an intrusion is the multiplication of the probabilities of the crash wall failure (IC), excessive lateral displacement toward the adjacent track (ID) and containment failure (IF). Each corresponds to the cumulative probability of lower level events shown in the fault tree (Figure 4), again assuming all basic events are mutually independent:

\[ I = IC \cdot ID \cdot IF = (LW + DW) \cdot ID \cdot (DC + LC) \]
\[ = (LW + (WA + WD)) \cdot ID \cdot ((CA + CD) + LC) \]

Finally, the probability of the adjacent train presence is the cumulative probability of the failure to stop clear of the initial derailment (TF) and direct presence of a train on adjacent track (TT). Each corresponds to the cumulative probability of lower level events shown in the fault tree (Figure 5), assuming all basic events are mutually independent:

\[ T = TF + TT = (ID + FB) + TT = (ID + (EB + H2)) + TT \]

The probability of an ATA can therefore be expressed in Boolean algebra as:

\[ ATA = D \cdot I \cdot T \]
\[ = (T1 + T2 + T3 + T4 + T5 + T6 + T7) + M1 + S1 + (E1 + E2 + E3) + (H1 + H2 + H3 + H4 + H5 + H6 + H7) \cdot ((LW + (WA + WD)) \cdot ID \cdot ((CA + CD) + LC) \cdot ((ID + (EB + H2)) + TT) \]

The result can be used to identify the minimal set of basic events so that the occurrence of these events guarantees the occurrence of the top event. The probability of the union of all minimal cut sets is the probability of ATA. This is the foundation of the quantitative evaluation of the probability of ATA. Once the data for each element of the fault-tree is acquired, the probability of ATA can be calculated.

**DISCUSSION**

**Data Sources and Analysis Requirements**

In order to implement the fault-tree analysis and its corresponding probabilistic model, existing accident databases such as the Federal Railroad Administration’s Rail Equipment Accident database (23) and Rail Safety and Standard Board’s Safety Management Information System (SMIS) database (28) can be used to estimate the derailment rate for a specific rail line or network. Additional sources needed to estimate the probabilities of intrusion and adjacent train presence may include the database for lateral displacement of derailed equipment, data collection...
for the intrusion detection, and records of close calls (or near misses) where a collision that could have occurred did not. Additional analyses needed include quantitative assessment of the factors affecting intrusion probability, the effectiveness and reliability of crash walls and containment in preventing intrusion, effectiveness and reliability of intrusion detection systems, and stochastic modeling of train presence at a specific location.

**Fault-Tree Analysis and New Rail System Planning**

When planning a new rail system, safety is a critically important consideration, specifically, minimization of potential hazards and mitigation of consequences if they do occur. Before addressing those hazards, identifying their cause is an essential first step. Only when all factors and possible ways for those factors to result in the hazard are explored can its risk be effectively addressed. The FTA developed in this research serves purpose of ATA hazard exploration. For a new rail system with multiple track sections or potential shared-use rail corridors, the FTA and corresponding probabilistic model can be implemented to evaluate the risk of ATA on the new system. Certain factors that affect ATA risk are evaluated and weighed against each other to determine proper design of the factors. Additionally, ATA risk mitigation can be evaluated using the FTA and corresponding probabilistic models. For example, the spacing between two adjacent tracks affects intrusion probability. Wider track spacing reduces the risk of an ATA due to reduced intrusion rate. However, at many locations, the space for railroad right-of-way and construction is constrained, or land acquisition is difficult or impractical. In order to mitigate ATA risk at locations where two tracks are close, construction of crash walls, containment, or intrusion detection may be considered. Different scenarios can be proposed based on the combination of track spacing, containment, crash walls and intrusion detection. The model can then be implemented to evaluate the risk of an individual scenario. System designers can then discuss and determine the optimal solution to design and construct the new rail system accordingly. This practice allows proper design of route, infrastructure, rolling stock, and operating plans for a new system.

**Fault Tree Analysis and Existing Railroad Network Safety Improvement**

The FTA proposed in this research can also be used to improve existing or expanded multiple track sections. Multiple track sections can be divided into segments based on route characteristics, traffic composition, presence of crash walls and other relevant factors. FTA can be implemented to evaluate segment-specific ATA risk. Segments where ATA risk is high will be identified and prioritized for risk mitigation. Similar to the design of a newly planned rail system, FTA can also evaluate the effectiveness of risk mitigation strategies on existing railroad corridors.

**CONCLUSIONS AND FUTURE WORK**

This paper explores and identifies elements that contribute to the occurrence of ATA, and constructs a fault-tree to show how each element affects the probability of ATA. Boolean algebra is used to develop the logical relationship among contributing elements. The importance and potential application of FTA are discussed. The FTA developed in this research serves as a foundation for further development of quantitative risk assessment and the evaluation of risk mitigation strategies for ATA. Future work will involve development of minimal cut sets (which are sets of basic events that guarantee the occurrence of ATA) and quantitative derivation of the general probabilistic equation for ATA risk.
ACKNOWLEDGMENTS
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