Fault Tree Analysis of Adjacent Track Accidents on Shared-Use Rail Corridors

Chen-Yu Lin, Mohd Rapik Saat, and Christopher P. L. Barkan

Adjacent-track accidents (ATAs) have been identified as an important hazard on shared-use rail corridors. In these train accidents derailed railroad equipment intrudes on (fouls) an adjacent track, disrupts operations, and potentially causes a collision with trains operating on the fouled tracks. Derailments without intrusion may cause equipment and infrastructure damage, passenger casualties, and disturbances to system operation; however, an intrusion may be even more severe because of the potential involvement of multiple trains. Opportunities for ATAs have increased in recent years because of expanded passenger and transit service on freight railroad trackage, right-of-way, and corridors and because of increased multiple tracks related to capacity expansion projects. This paper presents a probabilistic risk assessment methodology for analyzing ATA risk. An event tree is created to identify scenarios for ATAs, and a fault tree analysis is performed to identify basic events that contribute to such accidents. The quantitative probability of an ATA is derived by using Boolean algebra on the basis of the results of the fault tree analysis.

In the past several years, adjacent-track accidents (ATAs) have resulted in several high-profile railroad incidents. In one case, a grain train derailed, and equipment intruded on (fouled) the adjacent track. An oncoming crude oil train collided with this equipment, derailing 21 tank cars and causing a number of them to release product and catch fire (Figure 1*a*) (*1*). 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 and resulting in 65 passenger injuries (*2*) (Figure 1*b*).

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 struck 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 because of expanded passenger services for which these trains share trackage, right-of-way, and corridors with existing freight railroad lines. These shared-use rail corridors are expanding as passenger rail and transit operations increase in the United States (*4–10*). Although the train derailment rate has decreased substantially since 2000, the chance of these types of incidents increases as railroads install additional multiple track sections to increase capacity (*11, 12*). Consequently, ATAs have been identified as an increasingly important hazard on shared-use rail corridors (*4*). Derailments without an intrusion may cause equipment and infrastructure damage, passenger casualties, and disturbances to system operations, but ATAs can result in all of these; in addition, they may lead to more severe consequences because of the involvement of multiple trains.

Under normal conditions, the loading gauge (i.e., clearance plate) of rolling stock in a train stays within the clearance envelope of the track on which it runs (Figure 2*a*). However, if a derailment occurs, the derailed equipment will generally exceed the clearance envelope of that track (Figure 2*b*) and possibly intrude on an adjacent track's clearance envelope. If the latter occurs, it is referred to as an "intrusion" (Figure 2*c*). When an intrusion occurs, another train operating on the adjacent track may be at, or approaching, the intrusion site, with the result being a collision with the first derailed train (Figure 2*d*).

An ATA consists of three sequential events: (*a*) an initial derailment in multiple track territory, (*b*) an intrusion of the derailed equipment onto an adjacent track, and (*c*) the presence of another train on that track. Two variants of this type of ATA are the focus of the research presented here. In the first scenario, an intrusion occurs, and a train is on an adjacent track at the same time and location, with the result being an immediate collision, as the derailing equipment strikes the other train. In the second scenario, an intrusion occurs when a train on an adjacent track is approaching the intrusion site and leads to a potential collision with equipment from the first derailment.

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

RESEARCH OBJECTIVES

This paper develops a methodology for probabilistic risk assessment 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 an ATA from the resulting fault tree.

LITERATURE REVIEW

FTA methodology has been extensively applied to railroad safety in a variety of contexts. Li et al. used FTA on rear-end train collision accidents and developed models to calculate the probability of

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(a) (b)

FIGURE 1 ATA scenes for (*a*) two freight trains on December 30, 2013, in Casselton, North Dakota (Source: M. Vosburg), and (*b*) two passenger trains on May 17, 2013, in Bridgeport, Connecticut (*2*).

rear-end train collisions (*13*). Wang et al. used FTA to address the risk of train derailments on urban rail transit systems (*14*). Huang et al. combined FTA and fuzzy theory in general railroad safety analysis (*15*). Jafarian and Rezvani also used the fuzzy fault tree to analyze train derailments and to identify significant causes (*16*). European railway agencies apply FTA to various railroad hazards to allocate preventive resources most effectively. The Rail Safety and Standards Board (RSSB) conducted FTA on six major types of train accidents in Europe and used historical train accident data to identify causes with the most effect on each type of accident (*17–19*).

An example fault tree for train-to-train collisions developed by RSSB is shown in Figure 3. It is color-coded on the basis of 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, which means that they are most in need of attention. Accident causes highlighted in yellow have medium risk, and the ones in green have the lowest risk.

Some prior research has addressed risk assessment of adjacent track accidents. Lin and Saat proposed a semiquantitative method to evaluate general ATA risk (*3*). Cockle developed a semiquantitative risk assessment model to evaluate ATA risk specifically between high-speed rail and conventional railroad systems (*20*). Barkan used National Transportation Safety Board data to develop a statistical estimate of the distribution of the lateral displacement from track center of rolling stock derailed in accidents (*21*), and English et al. expanded and extended this work to develop a quantitative probabilistic model (*22*). From the result of English et al., Clark et al. proposed an analytical approach to assess the risk of high-speed track being fouled by freight derailments (*23*). To date, however, neither FTA nor any other probabilistic risk assessment techniques have been used to address ATA risk. Because an ATA is a complex process involving multiple events, a comprehensive understanding of their mechanisms is needed to assess more precisely, and ultimately, reduce the risk.

METHODOLOGY

Probabilistic Risk Assessment

As discussed earlier, an ATA is a sequential event (Figure 2, *a* to *d*) that can be formally described by using an event tree (Figure 4). The initial event is the derailment of the first train(s), denoted *D* in the figure, and is the result of an initial derailment or a collision. Thus,

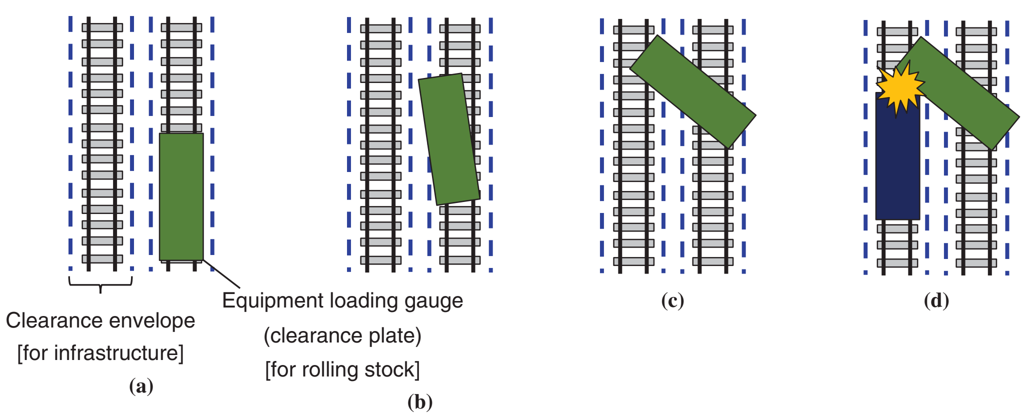


FIGURE 2 ATA event scenarios and typical sequence: (*a*) normal operation, (*b*) derailment, (*c*) intrusion, and (*d*) collision.

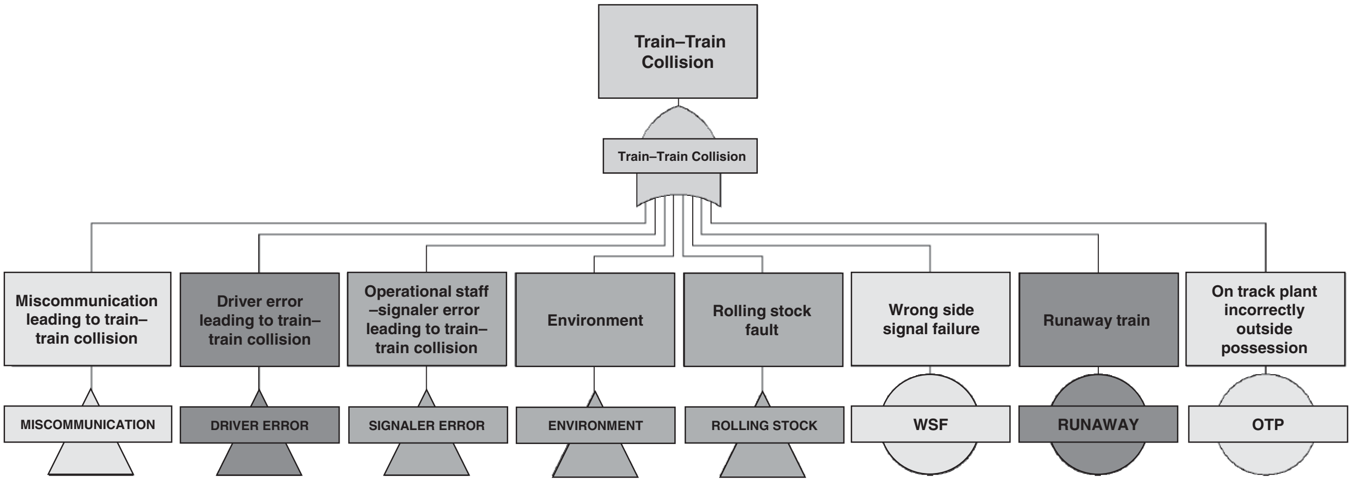


FIGURE 3 RSSB fault tree for train-to-train collision.

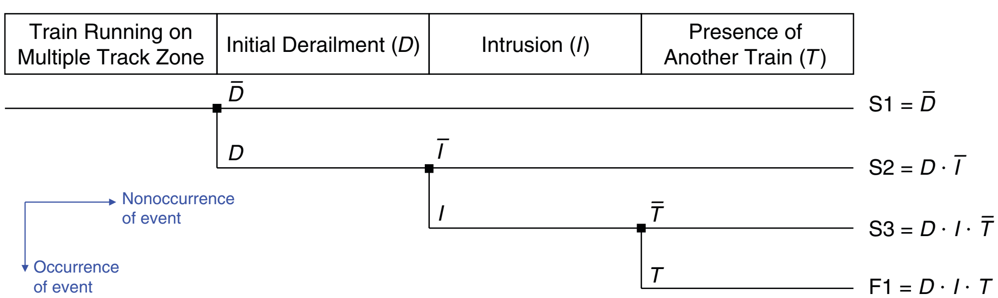
D is the probability of a derailment or a head-on or rear-end collision at a location. The intrusion, when the adjacent track is fouled by equipment derailed in the initial accident, is denoted I. It is a conditional probability, given that an initial derailment occurs. The adjacent train presence is defined as the presence of another train on an adjacent track or tracks either beside, or approaching, the intrusion location, denoted T. Its probability is conditional on the occurrence of an intrusion. The black square nodes represent divergence points whether or not an event occurs. Each divergence on the event tree implies a probability element.

A "success" in the event tree is defined as an event that does not occur (i.e., the safer alternative). A "failure" means that the event occurs; it represents the unsafe alternative. For instance, the black node on the left in Figure 4 indicates whether an initial derailment occurs. If a derailment occurs, the event 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 nonoccurrence) and results in a success scenario (no accident).

This situation may be counterintuitive 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. Therefore, the current authors define "success" of the system as the nonoccurrence of an ATA [Scenarios (Success 1) S1, S2, and S3 in Figure 4] and system "failure" as the occurrence of an ATA [Scenario Failure 1 (F1) in Figure 4]. The event tree is divided into four scenarios, and each of them is introduced below.

Scenario S1

When an initial derailment does not occur, the train runs normally and the system is safe (Scenario S1). The probability of S1 is simply the nonoccurrence of the initial derailment (denoted $\bar{D}$). The



Define success (S) to be the nonoccurrence of the accident (safe operation), and failure (F) to be the occurrence of the accident (system failure).
The descriptions for each scenario are as follows:
S1. The train does not derail. The railroad system operates as normal.
S2. The train derails but does not intrude on the adjacent track. Although the railroad system is interrupted, this is not in the scope of "adjacent track accident." Thus, it is considered a "success" in this particular event tree.
S3. The train derails and intrudes on the adjacent track, but there are no other trains on adjacent track at the time of accident. Although multiple tracks are affected, there is no collision between trains on adjacent tracks in the end, so it is considered a system success in terms of ATA.
F1. The train derails and intrudes on the adjacent track, and then collides with another train on the adjacent track.

FIGURE 4 Event tree for ATA.

subsequent probability components are not examined in this case because the first event does not occur.

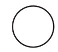
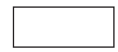
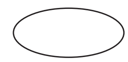
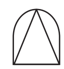
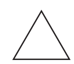
Scenario S2

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 Scenario S2. The probability associated with this scenario is the occurrence of the initial derailment multiplied by the nonoccurrence of intrusion (denoted $D \cdot \overline{I}$).

Scenario S3

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 be able to stop before colliding with the derailed train. This hazardous situation may be caused by the engineer (driver) of the second train being unaware of the intrusion or insufficient braking distance if the engineer is aware. The probability that no train on the adjacent track is at or approaching the intrusion is denoted $D \cdot I \cdot \overline{T}$. Although the intrusion has occurred, no train is on the adjacent track, so this scenario does not result in a collision and therefore is not considered a failure.

TABLE 1 Common Symbols Used for Fault Trees

Name	Symbol	Description
Events		
Basic event		A basic event that is not broken down into more detailed events
Intermediate event		An event that occurs because of one or more basic events act through a logic gate that connects with it
External event		An event that is normally expected to occur
Conditioning event		Specific conditions or restrictions that apply to any logic gate
Logic Gates		
AND		The output event occurs if all input events occur.
OR		The output event occurs if at least one of the input events occurs.
PRIORITY AND		The output event occurs if all input events occur in a specific order.
TRANSFER		The fault tree is developed further and connected to other fault trees.

Scenario F1

The probability that a train is at, or approaching, the location where and when the intrusion occurs that results in a direct collision, is denoted $D \cdot I \cdot T$, and is labeled Scenario F1, which is the focus of this research. In the next subsection, FTA is used for further analysis of the factors contributing to ATAs.

Discussion of FTA

FTA is a deductive process to identify all potential failure paths and basic events that lead to a top event (*24*). In this study, the top event is the ATA (Scenario F1). A fault tree diagram provides a logical and graphical presentation of various combinations of the basic events that can lead to the top event (*25*). 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 that gate must occur if the upper level event is to occur. In contrast, an OR gate means that the upper event will be triggered when at least one of the events connected by the gate occurs. Table 1 shows the common symbols used in FTA. 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 the basic events. Conditioning events specify the order of occurrence for a sequence of events. 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 classified into causes (or "deducted") by RSSB (*18*). Here, a similar approach based on FRA rail equipment accident cause codes and data is used to deduct the initial derailment into accident causes. All 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.

A fault tree was developed for an ATA (Figure 5). Because the events of initial derailment, intrusion, and presence of an adjacent train need to occur in a specific order, they are connected by the PRIORITY AND gate. Branches for the three intermediate events are described next.

Initial Derailment, D

The initial derailment, *D*, 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. These categories are based on the accident codes developed by FRA (*26*). Each type of accident cause is further deducted into subaccident cause groups, which are treated here as basic events; however, any subaccident cause group can be further deducted into more-detailed failure modes on the basis of the resolution of the analysis and data available. Transfer gates can also be used for each subaccident cause to create more-detailed fault trees but are beyond the scope of this paper.

Intrusion from Derailed Equipment, I

The major impact of intrusion (*I*) events is the excessive displacement of derailed equipment. Some studies have analyzed the probability distribution of lateral displacement of equipment in derailments (*21, 22*). 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 barriers constructed between tracks to prevent such intrusions (*27–29).* Containment is some structure located directly on the infrastructure to prevent the train from rolling over and intruding onto adjacent tracks, such as a parapet or guard rail (*30*). Crash walls and containments act in similar ways to reduce the occurrence of intrusion. 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, another train (T) may be on the adjacent track; this condition results in a collision between the derailing train and the adjacent train. Sometimes the train on the adjacent track is approaching when an intrusion occurs, another condition that may result in a collision because of failure of the adjacent train to stop 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 to the train on the adjacent track so that the engineer 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 because of mechanical problems or human factors.

Boolean Algebra Analysis of ATA Fault Tree

After the fault tree is constructed, the probability of top event occurrence can be calculated by 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 $\mathrm{A} \cdot \mathrm{B}$. By definition, the occurrence of an ATA is the intersection of the initial derailment (D), intrusion (I), and adjacent train presence (T), as follows:

$$\mathrm{ATA} = D \cdot I \cdot T$$

The probability of the initial derailment is the cumulative probability of derailments caused by infrastructure (DT), equipment (DE, where E is equipment), signal and communication (DS, where S is signal), human factor (DH, where H is human factor), and miscellaneous (DM, where M is miscellaneous). Each probability corresponds to the cumulative probability of lower-level events shown in the fault tree (as defined in Figure 5), under the assumption that all basic events are mutually independent, as follows:

$$\begin{aligned} D &= \mathrm{DT} + \mathrm{DM} + \mathrm{DS} + \mathrm{DE} + \mathrm{DH} \\ &= (\mathrm{T1} + \mathrm{T2} + \mathrm{T3} + \mathrm{T4} + \mathrm{T5} + \mathrm{T6} + \mathrm{T7}) + \mathrm{M1} + \mathrm{S1} \\ &\quad + (\mathrm{E1} + \mathrm{E2} + \mathrm{E3}) + (\mathrm{H1} + \mathrm{H2} + \mathrm{H3} + \mathrm{H4} + \mathrm{H5} + \mathrm{H6} + \mathrm{H7}) \end{aligned}$$

where the variables are as defined in Figure 5.

The probability of an intrusion is the multiplication of the probabilities of the crash wall failure (IC, where C is crash wall failure), excessive lateral displacement toward the adjacent track (ID, where D is displacement), and containment failure (IF, where F is containment). Each of these probabilities corresponds to the cumulative probability of lower-level events shown in the fault tree (Figure 5), again under the assumption that all basic events are mutually independent, as follows:

$$\begin{aligned} I &= \mathrm{IC} \cdot \mathrm{ID} \cdot \mathrm{IF} = (\mathrm{LW} + \mathrm{DW}) \cdot \mathrm{ID} \cdot (\mathrm{DC} + \mathrm{LC}) \\ &= (\mathrm{LW} + (\mathrm{WA} + \mathrm{WD})) \cdot \mathrm{ID} \cdot ((\mathrm{CA} + \mathrm{CD}) + \mathrm{LC}) \end{aligned}$$

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

$$T = \mathrm{TF} + \mathrm{TT} = (\mathrm{ID} + \mathrm{FB}) + \mathrm{TT} = (\mathrm{ID} + (\mathrm{EB} + \mathrm{H2})) + \mathrm{TT}$$

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

$$\begin{aligned} \mathrm{ATA} &= D \cdot I \cdot T \\ &= (\mathrm{T1} + \mathrm{T2} + \mathrm{T3} + \mathrm{T4} + \mathrm{T5} + \mathrm{T6} + \mathrm{T7}) + \mathrm{M1} + \mathrm{S1} \\ &\quad + (\mathrm{E1} + \mathrm{E2} + \mathrm{E3}) + (\mathrm{H1} + \mathrm{H2} + \mathrm{H3} + \mathrm{H4} + \mathrm{H5} + \mathrm{H6} + \mathrm{H7}) \\ &\quad \cdot ((\mathrm{LW} + (\mathrm{WA} + \mathrm{WD})) \cdot \mathrm{ID} \cdot ((\mathrm{CA} + \mathrm{CD}) + \mathrm{LC})) \\ &\quad \cdot ((\mathrm{ID} + (\mathrm{EB} + \mathrm{H2})) + \mathrm{TT}) \end{aligned}$$

where the variables are as defined in Figure 5.

The result can be used to identify the minimal cut set of basic events such that they guarantee the occurrence of the top event. The probability of the union of all minimal cut sets equals the probability of ATA and provides the foundation for their quantitative evaluation. Once the data for each element of the fault tree are acquired, the probability of ATA can be calculated. The assumption of mutually independence between all basic events needs further testing and verification to increase the accuracy of quantitative assessment of probability.

DISCUSSION OF IMPORTANT ASPECTS OF FTA

Data Sources and Analysis Requirements

To implement the FTA and its corresponding probabilistic model, existing accident databases such as FRA's database of rail equipment accidents (*26*) and RSSB's database of the safety management information system (*31*) 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) for which a collision might have occurred but 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,

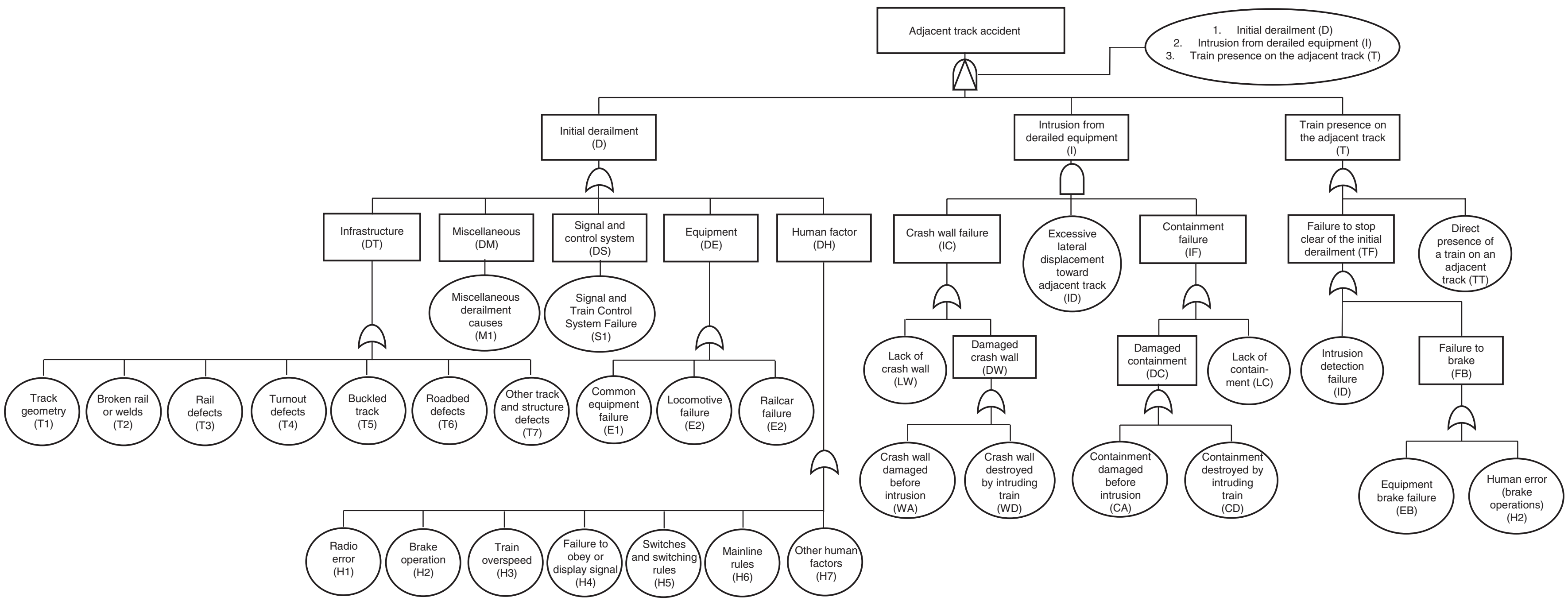


FIGURE 5 Fault tree for ATA.

effectiveness and reliability of intrusion detection systems, and stochastic modeling of train presence at a specific location.

FTA and New Rail System Planning

When a new rail system is being planned, safety is a critically important consideration, specifically minimization of potential hazards and mitigation of consequences if they do occur. Before these hazards can be addressed, potential causes must be systematically identified. Only when all factors and possible ways for those factors to result in a hazard are explored can the risk be comprehensively addressed. The FTA described in this paper provides a foundation for evaluation of exploration of ATA hazards.

For a new rail system with multiple track sections or potential shared-use rail corridors, the FTA and the corresponding probabilistic model can be implemented to evaluate the ATA risk on the new system. Factors affecting ATA risk are evaluated and the relationships between them compared to determine proper design of the new rail system. In addition, ATA risk mitigation can be evaluated by using the FTA and the corresponding probabilistic models. For example, the spacing between two tracks affects intrusion probability. Wider track spacing reduces the risk of an ATA because of the 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. 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 on the basis of a combination of track spacing, containment, crash walls, and intrusion detection. The model can be implemented to evaluate the risk of an individual scenario, and system designers can then determine the optimal solution to design and construct the new rail system. This practice allows proper design of the route, the infrastructure, rolling stock, and operating plans for a new system.

FTA and Existing Railroad Network Safety Improvement

The FTA presented here can also be used to improve existing or expanded multiple track sections. These can be divided into segments on the basis of the route characteristics, traffic composition, presence of crash walls, and other relevant factors, and the FTA can be used to evaluate segment-specific ATA risk. Segments whose ATA risk is high can be identified and prioritized for risk mitigation. The FTA can, as with the design of a new rail system, evaluate the effectiveness of risk mitigation strategies on existing railroad corridors.

CONCLUSIONS AND FUTURE WORK

This paper explored and identified elements that contribute to the occurrence of ATAs and developed a formal structure to evaluate the risk by using an FTA in which each element affects the probability of ATAs. Boolean algebra was used to develop the logical relationship between contributing elements. The importance and potential application of FTA in the content of ATA risk analysis was discussed. The FTA analysis serves as a foundation for further development of quantitative risk assessment and the evaluation of risk mitigation strategies for ATA. Future work will involve quantitative derivation of probabilities for minimal cut sets (the sets of basic events that guarantee the occurrence of an ATA) and the general probabilistic equation for ATA risk.

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