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Derailment-based Fault Tree Analysis on Risk Management of Railway Turnout Systems

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Abstract. Railway turnouts are fundamental mechanical infrastructures, which allow a rolling stock to divert one direction to another. As those are of a large number of engineering sub-systems, e.g. track, signalling, earthworks, these particular sub-systems are expected to induce high potential through various kind of failure mechanisms. This could be a cause of any catastrophic event. A derailment, one of undesirable events in railway operation, often results, albeit rare occurs, in damaging to rolling stock, railway infrastructure and disrupt service, and has the potential to cause casualties and even loss of lives. As a result, it is quite significant that a well-designed risk analysis is performed to create awareness of hazards and to identify what parts of the systems may be at risk. This study will focus on all types of environment based failures as a result of numerous contributing factors noted officially as accident reports. This risk analysis is designed to help industry to minimise the occurrence of accidents at railway turnouts. The methodology of the study relies on accurate assessment of derailment likelihood, and is based on statistical multiple factors-integrated accident rate analysis. The study is prepared in the way of establishing product risks and faults, and showing the impact of potential process by Boolean algebra.

1. Introduction

Derailment is an undesirable phenomenon causing damage to rolling stock and infrastructure as well as service disruptions, and which might also cause casualties and harm the environment. Moreover, these effects might result in serious reputation and financial losses to railway companies and organisations, as well as social, mental and economic consequences to the public. Although EU members have claimed that train operating safety is constantly improving and the number of derailments across the EU has been slightly improved, there appear to have been around 500 derailments per year in the last ten years, of which 7% (35 derailments) involved catastrophic consequences [1]. On average, catastrophic derailments potentially result in 30 fatalities per year, each of which costs, on average, 10M£ [2].

As for the situation in the UK, Network Rail has 21,000 track miles and 19,000 turnouts [3]. In other words, it can be said that there is one turnout per 1,14 track mile. As a result, a large number of derailments, accounting for 46% potentially higher-risk train accidents over the last 10 years, has occurred at British turnouts [4]. Causes of a derailment are often truck and turnout component failures, malicious operational failures, loading faults, environmental conditions, human factors, interaction problems or a combination of them [5].

2. Literature Review and Related Studies

The purpose of Fault tree analysis (FTA) lies in revealing a single system failure mode and qualitative information on how a relevant event may occur and what consequences this event can cause [6]. Many studies on various aspects of railway safety are formed of FTA-including methodologies. Pei et al. [7] proposed a fault tree analysis method combined with quantitative analysis to investigate high-speed railway accidents. Li et al. [8] discussed the train crash accident from a broader viewpoint, and analysed the train crash accident related safety issues through the fault tree model of the train rear-end. Leveson [9] used FTA to reach a detailed diagram of the contributing causes of accidents. Yao [10] introduced an improved intelligent system for railway safety-focused risk analysis on the basis on fuzzy-FTA. Jafarian and Rezvani [11] also used fuzzy based FTA to examine train derailments and to acquire an exact estimation of event occurrence rates and its distribution function along with significant causes. Lin et al. [12] proposed probabilistic risk assessment methodology based on FTA for analysing adjacent track accidents risk. More specifically, this proposal has a structure, identifying scenarios for adjacent track accidents to fulfil a quantitative probability analysis derived from Boolean algebra on the basis of the results of the fault tree analysis.

On the other hand, the investigation of natural hazard has been getting popular within the industry over the last few years. Saadin eat al. [13] investigated to what degree a HSR line between Singapore and Malesia, on-going project, will be affected during operation by severe weather conditions such as rainfall, lightning, wind and very high temperatures. Dindar et al. [14] examined the diversity of railway turnout related derailment risk arising from natural hazards and build relations between derailment accidents and environmental conditions. Baker et al. [15] studied the effects of high summer temperatures due to climate change on buckling. As for managing risk, only two management frameworks aimed to reduce risk of natural hazard at RTSs have been proposed [16] [17]. Along with proposed management techniques, risk analysis methods were discussed to identify what the techniques such as FTA, event tree, Bayesian risk analysis, are suitable to what parts of RTSs [18] [19]. This study has suggested FTA to manage risk induced by environmental conditions for turnouts.

Thus, this research establishes a risk analysis based on FTA for investigating the impact of nature on RTSs. The establishment is built on investigation of accident cases along with aforementioned researches; ref. 12, 14 and 18, and thus, the gap of this related research area is filled.

3. Fault Tree Analysis in Railway Researches

Fault tree analysis is a deductive technique which enables the building of causal relations resulting in a given undesired event. This analysis approach begins with a defined system failure event and reveals backward its causes, down to the primary independent faults, concentrating on a single system failure mode [20].

To complete the construction of a fault tree, it is firstly necessary to use a system flow diagram for an understanding of how the system functions. The diagram depicts the pathways by which goals are transmitted through components of the system. The steps in fault tree construction are as follows:

I.   The selection of the system failure event of interest, known as the top event. The following event or events is/are considered with regard to its/ their effect on the top event.

II.   Identification of contributing events, which might directly cause the top event to occur. As such, four possibilities exist:

    a. primary failure of the device (e.g. aging, fatigue)
    b. secondary failure of the device (e.g. earthquake)
    c. no input to the device
    d. human error in actuating or installing the device

If one of these events alone is enough to contribute to the system fault, they are linked to the top event through 'an OR function`. If all of the events are required for system fault, they are related to the top event through 'an AND function' [21]. These functions are illustrated in figure 1, modified from [22].
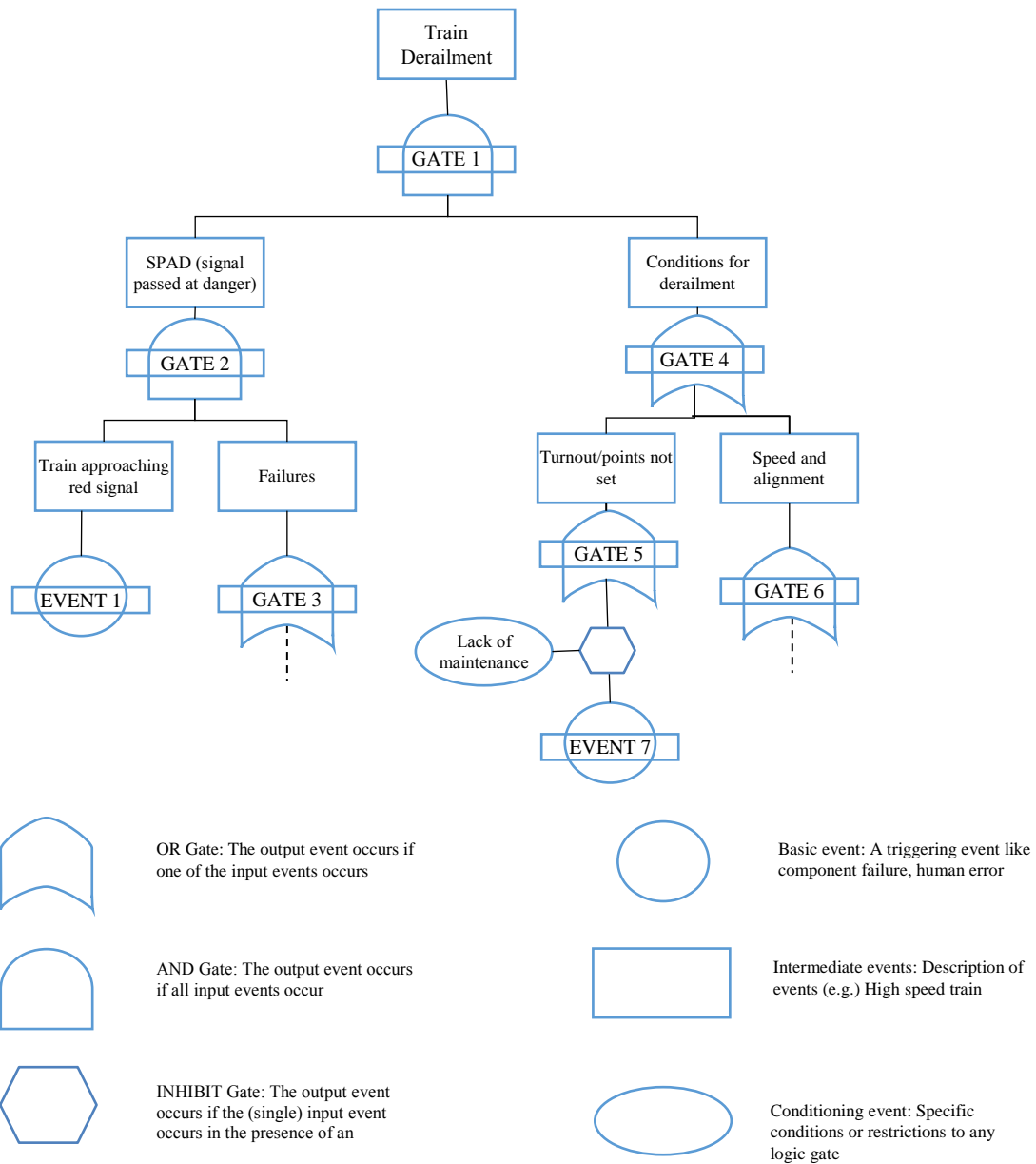
Figure 1 The structure of FTA

Basic events (BEs), one of the common symbols used in FTA in figure 1, are the lowest level events within a branch. BEs bring about the occurrence of the top event in FTA. Intermediate events (IEs) help to describe events located between BEs and the events. Conditioning events (CAs) are a restriction on a logic gate in the diagram

4. Environmental Failures Mechanisms in RTSs

Extreme environmental conditions such as high temperature, floods, and storm tides are known to be responsible for many derailments at RTSs [23]. Thus, it is necessary to take measurements against the associated potential effects of extreme weather.

Table 1 Environmental-based Failure Mechanism Resulting in Derailment on Turnouts [24]

Failure type	Environmental reason	Features
Buildup of ice or snow	Snow precipitation	Filling the gap between stock rail and switch blade
Progressive shear failure	High water content	Squeezing near subgrade surface
		Depression under ties
Changes in Aerodynamics	High wind or Tornado	Blowing railway trains off turnouts
Excessive plastic deformation	Repeated freezing and thawing	Ballast pocket
Electricity failures	Flood/Heavy rain	Unusable of switch motor
Attrition with mud pumping	High water contact at subgrade surface	Poor drainage
		Muddy ballast
		Inadequate sub-ballast
Frost action	Low temperature/ Frost susceptible soil	Often occurs winter/spring season
Buckling	High temperature	Turnout geometry problems
Swelling/Shrinkage	Changing moisture content	Rough track surface
Brittle components	Extreme cold temperature	Component failures
		Separated or broken components
Washout	A heavy downpour of rain	Turnout geometry problems
Aerodynamic Forces	High wind	Poor designed trackbed
	Subsurface water	Soil washed or blown away
Slides	Existence of mud	Muddy track

Table 1 is prepared by considering accident reports of the Federal Railroad Administration (FRA) and shows common reported failure types associated with their environmental reasons and features. For instance, when high water content exists in trackbed layers for some reason, it is highly likely that this contributes to irregularities in track geometry, resulting in progressive shear failure, attrition, washout etc. On the other hand, extreme low temperature might cause brittle tracks and broken or separated rail at RTSs, as illustrated in table 1.

5. FTA Structure and Discussion

5.1. Assignment of Gates in the FTA for RTSs

The consideration of changes in temperature in railway industry is vital to ensure a smooth railway operation. The changes contribute to temperature-induced influences on the derailment as buckling, thermal expansion of track, uneven thermal expansion or contraction, brittle. Thus, it might be said that there are two temperature based variants, namely high temperature (T_h) and low temperature (T_l). However, excessive plastic deformation resulted primarily from fluctuation in temperatures that causes repeated freezing and thawing in trackbed. Thus, fluctuation in temperatures is symbolised as (T_f)

Precipitation might fall in either solid or liquid phases, or transition. As the number of turnout related derailments by environmental based reasons is quite low and data is scarce, the authors decided only consider two variants which makes FTA as calculatable as possible. Therefore, these two forms can be called and abbreviated as solid precipitation (SP), liquid precipitation (LP). SP and LP are one of the most common cause of derailments at RTSs, resulting in many events associated with flooding, runoff and antecedent rains which lead to soft and saturated trackbed, or create washouts undermining RTSs, or cause accumulations of snow and ice. In addition to SP and LP, the high amount of precipitation in a short time might result in flood causing electricity faults. Therefore, flood is denoted as F.

Accidents associated with high winds have also been reported commonly. If they reach aerodynamically enough speed, rolling stocks at RTSs can be blown off tracks and cause derailment.

5.2. Scenarios and structure of the FTA for RTSs

The environmental based faults on RTSs is discussed in Section 4, and variants of environmental impacts is discussed in Section 5.1. To implement the FTA and its corresponding probability model for RTSs, those sections are considered, which allows to estimate the derailment rate for a specific turnout. However, it is should not be forgotten that the rates are likely to be quiet low as the number of derailment is not high. The structure of FTA is shown in figure 2. The suggested FTA consists of 5 IEs, 6 different CEs, 12 BEs and a top event that is environmental cause related derailment at RTSs. CEs are assigned to some events. For instance, excessive plastic deformation (T4), responsible for turnout trackbed fault, can occurs given that repeated freezing and thawing in trackbed (T_f) exist. Therefore, the basic event, excessive plastic deformation, is related to T_f in the FTA. On the other hand, washout (T3), which is the sudden erosion of trackbed underlying a turnout, only occurs when a gush of water exists. Therefore, it is no need to tie it with a condition.

Assuming that all basic events in the FTA are mutually independent each other, each probability has to correspond to the cumulative probability of lower level events. A basic event with a conditioning event or more is calculated as follow (Distributive Law);

$$X \cap (Y \cup Z) = (X \cap Y) \cup (X \cap Z) = X \cdot (Y + Z) = X \cdot Y + X \cdot Z \qquad (1)$$
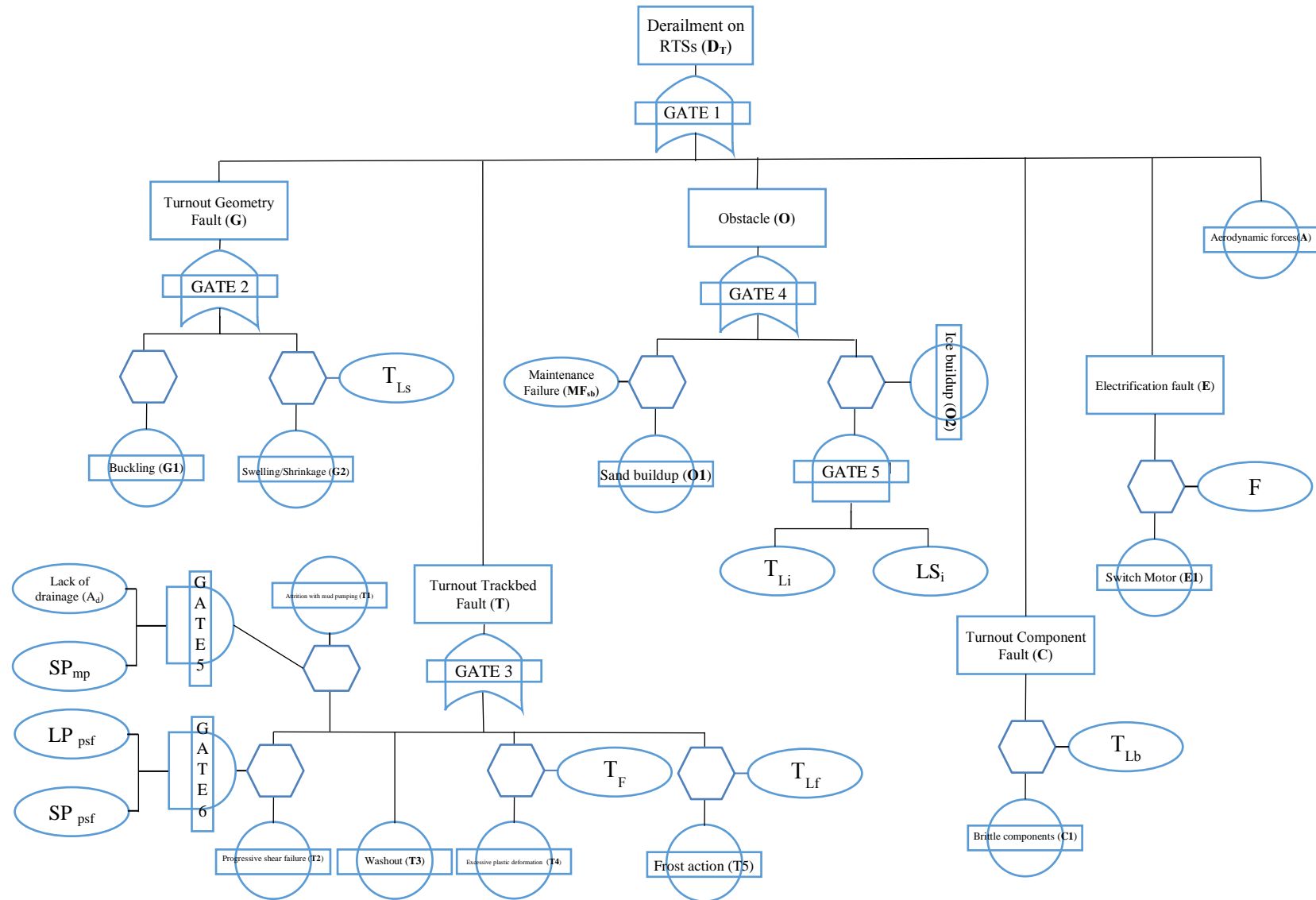
Figure 2 The structure of FTA aiming to environmental causes of derailments at RTSs

Thus, probability of derailment can be calculated as follow:

$$D_T = G + T + O + C + E + A$$

$$D_T = (G_1 + T_{Ls}G_2) + ((A_{md} + SP_{mp})T_1 + (LP_{psf} + SP_{psf})T_2 + T_3 + T_F\,T_4 + T_{Lf}\,T_5\,) + (MF_{sb}O_1 + (T_{Li} + LS_i)O_2) + T_{Lb}C_1 + FE_1 + A$$

Therefore, the probability of D_T is found out in Boolean algebra as

$$D_T = G_1 + T_{Ls}G_2 + T_1A_{md} + T_1SP_{mp} + T_2LP_{psf} + T_2SP_{psf} + T_3 + T_F\,T_4 + T_{Lf}\,T_5 + MF_{sb}O_1 + O_2T_{Li} + O_2LS_i + T_{Lb}C_1 + FE_1 + A$$

where the variables are as defined in Figure 2.

6. Conclusion

This study investigates environmental causes of derailments at RTSs. In order to do this, various elements and variables that contribute to the occurrence of faults and failures and thereby the top event, derailment, explored and determined systematically. The FTA is developed by using Boolean algebra, which allows for calculation of branches of the tree, and revealing the logical relationship between contributing elements in the FTA. On the other hand, impacts of all risk elements created only by the nature on derailment risk at RTSs are discussed. This is the first work contributing to many future studies in this fields, and enables them to involve quantitative derivation of probabilities.

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