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Identification of Appropriate Risk Analysis Techniques for Railway Turnout Systems

Serdar Dindar[1], Sakdirat Kaewunruen[2] and Min An[3]

Abstract:

The construction of railway turnout entails a complex geometry and multi-disciplinary engineering science, which makes it one of the most critical railway infrastructures. As such, these characteristics pose various risks in rail operation. A considerable number of derailment incidents at the turnouts are reported annually worldwide. Not only do these incidents cause operational downtime and financial loss, they also give rise to casualties and sometimes loss of life. One of the fundamental reasons for this may well be the fact that the railway industry pays little attention to the risk elements of railway turnouts. The paper, as state-of-the-art, provides an overview of how to deal with the many different risks arising from railway turnout systems by identifying the most/more suitable risk analysis methods for the systems. In order to do this, a large number of related articles, reports and review papers are critically analysed by virtue of comparison, experiences and deductions. As a result, various qualitative and quantitative based risk analysis methods are proposed to fully understand a number of technical phenomena, e.g. aging, degradation and signalling faults, in a railway turnout system.

Keywords: risk analysis, turnout systems, risk monitoring and management, rail infrastructure, system thinking approach

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1 Introduction

As an essential feature to enable rail operational flexibility, railway turnouts are special track systems used to divert a train from a particular direction or a particular track onto other directions or other tracks. It is a structural grillage system that assembles steel rails, points (or called ‘switches’), crossings (or called ‘frogs’), steel plates, rubber pads, insulators, fasteners, screw spikes, beam bearers (either timber, polymer, steel or concrete), ballast and formation. A railway turnout is a must-have structure in railway corridor whose crossing imparts a significant discontinuity in the rail running surface. It is important to note that its structure and components pose different risk profiles to railway operations. High demand in railway operation, the railway operators have to increase the axle load, traffic density and speed of the operations. The dynamic wheel/rail interaction on such imperfect contact transfer can cause detrimental impact loads on railway track and its components. The transient vibration could also affect surrounding building structures. In addition, the large impact emits disturbing noises to railway neighbours. Railway turnouts are one of the highest percentages contributing railway infrastructure component failure.

Although the safety of railway systems is relatively high and is continually being improved, a considerable number of severe accidents still occur globally. The total number of train accidents for the last five years (2009 to 2014) in the EU has been reported as around 12,000. Derailment is illustrated to be the most occurring type of accident, accounting for almost 9% of the total [1].

Derailments have been estimated to cost all EU member states more than 200 million Euros annually [2]. Financial losses frequently result from damage to wagons or railway components or operational shutdown. In addition to financial losses, even if the number of fatalities and injuries appears low, it can be said that fatalities still result from extreme disasters, such as the derailment of a fuel wagon at Viareggio in 2009, causing 34 fatalities. A recent research reveals an average of 3.9 fatalities per year resulting from various derailing incidents across the EU [3].

Since the author is of the opinion that most derailments occur on turnouts, this paper focuses only on the hazards involved here and is intended to address almost all types of causes, identifying useful risk analysis methods for the major problems.

2 Risk and Safety

A railway has very complex geometry as a large number of components interrelate with each other. Derailment arises mainly from poorly understood railway systems as a result of this complexity [4]. One of these systems is turnout, which describes a mechanical installation by means of which flanged vehicles are able to be diverted from one track to another.

As a turnout system is very complex, attention should be paid not only to railway component failures in the system, but also operational failures, (e.g. train radio communication system failures, environmental factors (e.g. poor weather conditions) and interaction problems (e.g. searches when determining the likelihood of any accident in each individual turnout system). This is because each has a unique technical characteristic. Therefore, it might be said that every turnout has various different types of potential causes posing risk of derailment regardless of how well they are constructed, monitored or maintained.

In this circumstance, risk analysis, a significant step in risk management, plays a key role in reducing or, if possible, eliminating derailments in particular cases. There is a large number of different types of risk analysis techniques from which to choose, and each might have an advantage over the others in the railway industry for one reason or another. An analyst should choose a method giving more realistic outcomes, otherwise, undesired results, loss of time and cost overruns can be expected [5].

Hence, to fully understand the existing risk at a turnout, it is necessary to identify appropriate types of risk analysis methods in the railway industry for this intended purpose.

3 Scope, Significance and Originality

A derailment based on component failures might be attributed to link wagon-based components, such as bearing failures or axle failures caused by loading problems, or any other component of track geometry. As mechanical design engineering is more interested in this type of cause than is railway engineering, the paper is limited to just railway component failures, any type of operational failures, interaction problems, environmental problems and human factors. There is increasing concern in risk analysis of railway systems as uncertainties cannot always be quantified and especially cannot related directly to vulnerable assets and components, which is unlike those energy infrastructures with identifiable failure modes [6 - 9]. The risk and vulnerability arising from the complex nature of turnout components and assets in various operational environments has thus been evaluated and firstly highlighted in this paper. The insight into the risk integration and prioritisation can lead to the development of adaptive measures for maintenance of turnout systems. The suitable methodologies can be integrated into the design and preparation stages so that the turnout infrastructure resilience can be economically built in, improving public safety and reliability [9]

4 Risk Management Principles

4.1 Objectives

Risk management might have several purposes, which are grouped into following serving areas [10];

- A sufficient safety level demonstration through risk analyses
- A basis for risk communication to all stakeholders including public, investors, various railway companies in project.
- A basis for decision-making helping to balance risks against costs associated with risk reducing measures.

4.2 Process

In Risk Management in the railways sector, there is a range of terms frequently used to describe a particular situation or action. The following are some of these terms and their definitions

A hazard is something (e.g. an object, property of a substance, phenomenon or an activity) that can cause adverse effects [11]. For instance, a sharp blade profile might be termed a hazard since it might result in derailment and is, therefore, an adverse effect. Thus, hazard identification may be said to be important in order to minimise or eliminate the adverse consequences of hazard. As for risk, it is addressed to the chance that a hazard will give rise to an accident, which results in causalities such as property damage or financial or life loss [12]

An accident is generally regarded as an unwanted event that brings about physical harm to people (health or life) or damage to property. Although there is a reasonable degree of consensus as to whether an accident is an unplanned event, the term ‘incident’ is sometimes used to express such events where no injury occurs [13] However, incidents are generally seen as wake-up calls that could alert supervisors and employees to risks or hazards that they had previously not considered while risk is the chance that a hazard will give rise to an accident, which results in causalities such as property damage or financial or life loss [14].

The structure of the overall risk management process is illustrated in Fig. 1 [15].

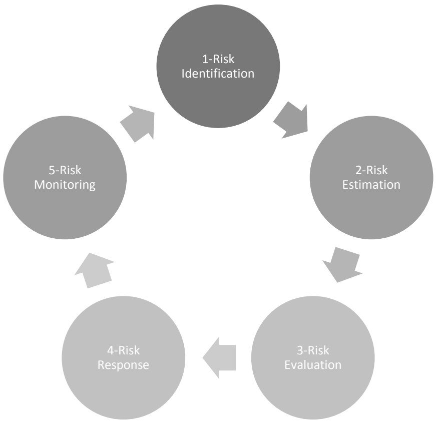

Figure 1 Risk Management Process [15]

- Risk Identification is formalised after any hazard has been identified. Where an identified hazard is eliminated and/or its consequences are assumed negligible, analysis might be discontinued.
- Risk Estimation is the result of chosen risk analysis technique. Thus, it is significant to determine error-free in regards to both the frequency of a hazard event and the severity of associated consequences. Frequency and severity values are often estimated through either quantitative or qualitative methods.

- Risk Evaluation ascertains whether or not risk warrants a response or is acceptable[4] . This stage is conducted using qualitative or quantitative methods, or both.
- Risk Response includes risk avoidance or elimination, retention, transfer and reduction.
- Risk Monitoring reveals whether the responses are performing adequately throughout the lifecycle of the component, system or activity.

5 Risk Analysis Process and Techniques

5.1 System definition and hazard identification

The overall approach of hazard identification in railway industry is a deductive process by which possible events are imagined [16]. This process is highly likely to rely on the experience and qualifications of the analysts [17]. There are a number of possible ways to support the process;

Brainstorming is the simplest way to identify hazards through which a simple list of hazards is produced. This kind of identification concentrates on identifying imaginable and unimaginable hazards within the scope of the domain of the particular concept of railway operation or systems [18].

The new hazard types in railway industry aren’t generally expected to emerge as the industry uses almost the same systems for a long time and, as a result, has well-known the common types hazards. One of the reason for this is the industry largely relies on *checklists* for a particular case. General experience from various organisation, stakeholders is gathered to build checklists which often consists of generic hazards or areas where it is particularly significant to pay attention hazards [19].

The two can be combine each other to predict the hazards. This approach is called as what-if, generation of scenarios. Besides being an informal method for identifying hazards, it might be quite often used in railway design projects for financial matters rather than accidents [20].

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[4] Risk tolerance is still a developing area of research in the railway industry. For instance, rails and axles are crucial components, since any failure may result in a catastrophic derailment. However, in some cases, it can be decided that a risk falls into the unacceptable region, taking into account cost-benefit analysis.

The HAZOP methodology (Hazard and Operability Study) is a structured technique of hazard identification and failure modes, considering deviations applied to predetermined keywords describing railway components, system, process or operations being performed [21].

5.2 Risk analyses

5.2.1 Risk matrix

The risk matrix approach is often semi-quantitative and referred to as preliminary risk analysis. The approach is easy to use and perform properly, provided that the following drawbacks are resolved [22]

- calibration for intended application is required;
- the parameters, such as likelihood and frequency, are based on subjective definitions, which could result in comprehending complexities;
- the risk results are only reasonable for systems to which the risk matrices can be applied.

In order to properly conduct a risk analysis based on risk matrix, the three steps, *Determine the possible consequences, Likelihood of occurrence and Risk scoring matrix* should be followed [23].

5.2.2 Failure Mode and Effect Analysis (FMEA)

This is a qualitative method, due to its inductive nature, which aims to identify potential failure modes of the components and to analyse the effects of those failure modes in an engineering system [24, 25]. The system components to analyse individually could be selected according to the degree of disability of system operation or by accidents with significant external consequences. Whilst a single system component is considered at a time, the other components are assumed to work at the same time [26]. As a result, FMEA is asserted as not fit for critical combinations of component failures [27].

The analysis proceeds as follows:

- Break down the system into independent subsystems;
    - Identify the various operational modes for each subsystem, e.g. maintenance
    - Determine its configurations when operating in such modes, e.g. a rail-grinder in progress.

- Compile a suitable table for each subsystem in each of its operational modes. The table should not neglect any of the subsystem components and include its failure modes and the effects on the subsystem.

5.2.3 Reliability Block Diagram – RBD

A Reliability Block Diagram (RBD) is a diagrammatic method performing the system availability and reliability analyses on complex and large systems using block diagrams to show the components (or failure events) and network relations in the system [28].

5.2.4 Fault Tree Analysis – FTA

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 [29]. FTA concentrates on a single system failure mode and is able to give qualitative information on how a relevant event may occur and what consequences this event can cause [30].The steps in fault tree construction are as follows:

- 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.
- Identification of contributing events, which might directly cause the top event to occur. As such, four possibilities exist:
    - primary failure of the device (e.g. aging, fatigue)
    - secondary failure of the device (e.g. earthquake)
    - no input to the device
    - human error in actuating or installing the device

5.2.5 Event Tree Analysis – ETA

Event Tree analysis (ETA) provides an inductive approach to evaluate the consequences of an initiating event and the likelihood of each of the possible sequences which may occur [31]. This approach is constructed using forward logic. The failure, partial failure or success of different systems and subsystems is often represented by the branch points on the tree structure.

5.2.6 Markov Analysis – MA

Markov analysis is a stochastic technique that enables the computation of the probability of failure or repair characteristics of individual components in a specific state at a given time [32]. In contrast to simulation-based analysis, this is a well-suited approach for rare events, and, thus, allows such events to be analysed within a reasonable amount of time.

MA is based on the Markov Process, a stochastic process governed by transition probabilities. A Markov Process is characterised by two main concepts: its system and transaction states. The former constitutes the system at any given moment of time, while the latter governs the changes of a state that happen within a system.

5.2.7 Hazard Function – HF

It has been seen that Hazard Function (failure rate) can be applied satisfactorily in the railway and transportation sectors [33]. It is a function showing the probability of railway components, system, process or operation failure at time `t` given these are functioning up to time `t`.

5.2.8 Bayesian Analysis

The striking difference between Bayesian and frequentist methods is in the definition of probability [34]. According to a frequentist, probability is considered as a long-run frequency. In other words, it is asserted that the probability of a fair coin toss landing heads up is half of the whole possibility, 0.5, in the long run. Conversely, a Bayesian expresses a belief in the degree that the coin lands heads. This definition of probability is often termed subjective probability. While probability is used by a frequentist to express the frequency of certain types, which happens over repeated trials, a Bayesian, in practice, uses it to express belief in a statement about unknown quantities [35].

In Bayes Analysis (BA), when further information is provided, the structure of the model can be updated [36]. This feature may be helpful, as the statistical uncertainty is largely present and the amount of available data is sparse. The other advantage of BA is to integrate experimental data with reliability data at all available levels through Bayes' theorem [37]. The theorem underlies how to update beliefs for prior probabilities.

5.2.9 Monte Carlo (MC) Simulation

Monte Carlo (MC) is a problem-solving technique used to understand the impact of risk and uncertainties by running multiple trial runs, called simulations, using random variables [38]. The simulations are the process of running a model, aiming to obtain numerical results, numerous times with a random selection from the input distributions for each variable. The outcomes of these numerous scenarios might give a most likely case to approximate the probability of certain outcomes, as well as a statistical distribution to reveal the risk or uncertainty involved [39].

6 Comparative Evaluations and Discussions

To assess emerging risks in the railway sector, a large number of possible risk analysis methods applicable for a turnout have been comprehensively reviewed and critically discussed in this paper. This research is significant and cannot be matched by simple multiple-criterion decision making framework, without the insights into multi-layer asset vulnerabilities derived from expert opinions. As some of the methods depend largely on statistical techniques, a set of illustrative examples has been given to understand their characteristics in order to deal with the variables for analysis. Additionally, the limitations of the presented methods are discussed through the paper.

One of the problems is that analysis is often of scarce, incomplete or, sometimes even has missing data [40]. The weakness in building a satisfying database arises mainly from building new lines, the new materials used in railway tech, and climate and traffic density changes over the years [41]. As a result, many precise safety estimates for the ensuing years need to be carried out, as many of the changes mentioned above have already occurred or will.

These changes have been seen to give rise to component failure rates due to lack of precise maintenance strategies based on insufficient risk analysis techniques. In the case of complex and sparse data, it is argued that quantitative based methods, e.g. Monte Carlo or Hazard Function, should be chosen to provide better information of possible risk factors and their consequences [42, 43]. In contrast to a deterministic approach, the well-built stochastic approaches of MC and HF might allow railway operators to eliminate undesirable time and financial losses. This is because the probabilistic component failure models of the MC and HF techniques are entirely appropriate to complex engineering systems such as switch blade of a turnout. The blade mechanism often requires an intense care and maintenance as its geometry generally tends to be changed in use.

Furthermore, a recent study [44] has illustrated that such methods have another advantage over others for any type of infrastructure, particularly large scale systems, man-made, networked and operated from long distance, since their results provide much more solid information on total system vulnerability as a function of the input variables.

Considering the above papers and their conclusions, their methods could be well-adapted into any risk analysis attempt at understanding to what degree each component of a turnout system could have an effect on the safe passage of wagons through the turnout. This kind of research should be directed at optimising the maintenance intervals of system components in a particular type of the turnout. Considering how different is each response to safety failures, consequently contributing to the overall system vulnerability of the turnout, stochastic modelling using one of the two approaches is likely to suit.

However, the core problem of object-oriented modelling for complex engineering systems is related to slow simulation speed and the large number of input parameters [45]. Additionally, the authors prescribe that the sub-systems of a turnout should be taken into specific account in the railway industry risk management chain. Instead, the industry currently often prefers to accept the system as whole or simply classify it as crossing and switch [46]. From this perspective, these kinds of classifications make investigating risks and vulnerabilities inadequate and they need to evolve to approach sound estimates. Such an evolution would be able to take measures against risk and vulnerabilities due to a better understanding of how these arise in the complexity of turnout systems.

The importance of ensuring how accurate and appropriate data are collected is vital. Given the subsystem levels of a railway turnout as the aim of the risk assessment study, it is expected to have two possible sources of data which might be used for the assessment: 1) data through the analysis of similar railway systems, such as crossing, and then allocation/contribution of failures to the subsystems of a turnout, and 2) data through elements and components of the subsystems of a turnout [47]. The latter is known as the bottom-up approach, while the former is the top-down approach. It is significant to underline that this classification is based, not on the organisation of the data, but the source of the data.

A failure to display signals at a turnout is a good example of this as the top-event probability in a fault tree model. If the logical aggregate of turnout subsystems related to signalling process estimates a failure, then it should be considered a bottom-up approach. On the other hand, if a failure to display signals is based on observation, e.g. the identification of procedural faults, and if the basic event probabilities, e.g. human-oriented operational failure of signalling, are the sole allocation of top-event probability based on various criteria, then the same FT model would be considered a top-down approach.

The results of these two approaches are highly likely to vary in the same study. Effort in deciding the structure of the study could be unrealistic. ASA`s recent study of a complex engineering system [47] revealed that a sound estimation might be achieved with the application of both to a study, and then the aggregate of the study outcomes and overall failure probability can be reached using techniques such as Monte Carlo.

Expert review is still one of the essential elements in understanding risk components in railway studies [48]. In the literature, it is noticed that over 500 railway review-based risk analysis or management articles, reports and conference proceedings appear to have been published since 2010.

The implementation of expert review into risk analysis is often quite difficult, or even impossible in some cases [49], e.g. hazard function. On the contrary, more simple methods, such as FMEA, FTA or risk matrix could be more suitable to review implementation [50]. Furthermore, the majority of these methods are generally designed with a top-down approach. It is also important to choose methods for eliciting and aggregating expert opinion. The elicitation and aggregation processes of expert assessments are classified into two groups: behavioural and mathematical approaches [51]. The former aims to produce some type of group consensus among experts, while the latter is performed by the decision maker using a set of mathematical methods.

In 2004, a research study based on the review implications provided solid information as to what aggregation techniques are effective in satisfying outcomes, by investigating 90 studies in different fields [52]. However, the results show that there seems to be no prominent all-purpose aggregation method for expert opinion, even if mathematical methods of aggregation, e.g. Bayes, often yield better results than behavioural methods.

One of the suitable methods for expert reviews, risk matrix is one of the common methods for risk assessment and risk classification in the railway domain, e.g. BS EN 50126-1:1999; BS EN 50126-2, 2007; BS ISO/IEC 26702, 2007. However, the technique has some concerns regarding [53-55]:

- calibration to the particular application,
- the dependence of results on the system level to which it is applied,
- vulnerability on the determination of parameter classes,
- challenges of directly taking barriers or risk reduction factors into account in the risk matrix.

On the other hand, the risk matrix is a well-accepted and easy-to-use tool, and can be useful for risk prioritisation, allowing these problems to be eliminated [56-57]. The elimination can be made through combination with another method which could additionally take into account the effect of barriers and their related risk reduction [58-59]. One of the most prominent candidates for combination is FTA, as used by risk priority numbers in the railway domain. Indeed, risk matrix has lost its reliability because accessible and improved large railway databases enable the performing of well-built sensitive quantitative analysis. A study of train control systems has been conducted for a comparison of risk matrix with a set of risk analysis methods, including semi quantitative (upgraded risk matrix methods) and quantitative [60]. Although the results of a basic risk matrix are seen to be unrealistic in regards to safety estimation, a proposed semi-quantitative method alongside the use of risk matrix is determined as the best approach. However, the research might be considered as incomplete and open to criticism, considering it does not include FTA-based or any advanced qualitative techniques, e.g. Bayes, in comparison. In the case of such a comparison, the paper is highly likely to have given a different conclusion.

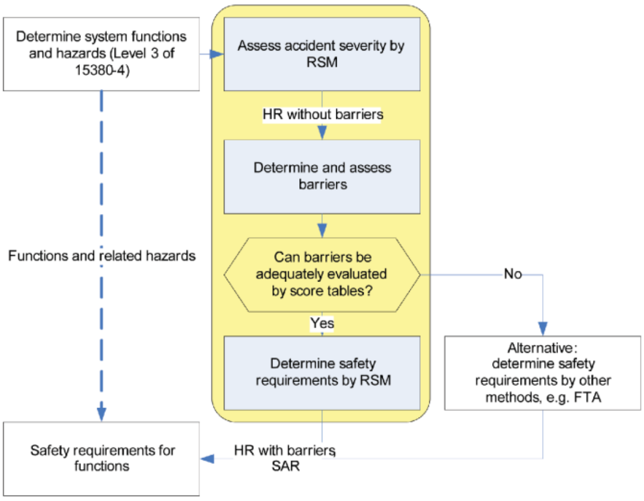

Figure 2 Overview of the combination model [61]

Figure 2 shows the overall approach, jointly with additional and alternative steps. As seen in the figure, when barriers cannot adequately be evaluated by score tables, FTA can be added into the chain to determine what is needed, e.g. safety requirement in this case. Therefore, the final output comprises the assumptions on which the analysis rests, which may result in SAR (safety-related application rules) and HR (hazard rates) related to the functional failures (as hazards) of the technical system.

Some methods take proactively preventative measures, whereas others, e.g. ETA, do not. For instance, the focus of FTA is on provision against multiple causes leading to a number of undesired events. In other words, the events are likely to occur in the future and the probability of their occurrences is assumed to be reduced through FTA. On the other hand, the focus of ETA could be on mitigation measures leading to multiple consequences after any event occurs. Hence, the use of failure tracing methods is widely different from one to the other, since actions are taken either actively or proactively.

In fact, the two are complementary and are generally used together by focusing on opposite sides of an undesired event.

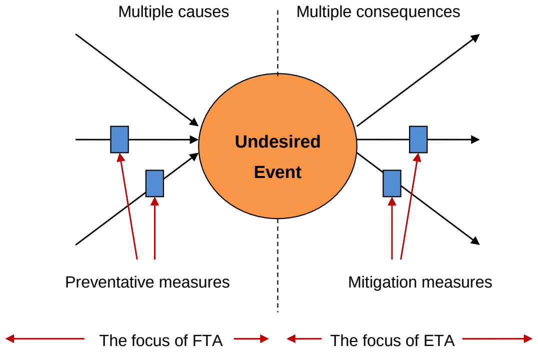

Figure 3 Bow-tie technique

The figure above shows how they fit together. This is often called the bow-tie technique. Only a single ‘undesired event’ is shown in the figure; in the reality of the railway sector, multiple causes are highly likely to result in many different events, initially, each then escalating with multiple consequences. Each event can be analysed through FTA and ETA. In a nutshell, ETA is interested in stopping an event escalating, whereas FTA is concerned with analysing faults which could lead to it happening. Both can be applied qualitatively or, if data are available and satisfying, quantitatively.

The bow-tie could be used successfully to access the adequacy of controls and identify areas for risk reduction in properly operating railway turnouts. The aim could be to test the robustness and number of existing safeguards and identify improvements.

For instance, the technique might be useful for risk assessment of driver-to-signaller train radio communication system failures which are responsible for derailments at the turnouts, as stated in the second section. It inherently has a graphical representation, which might result in easy understanding of the relationships between the causes of unwanted events and their control. The assessment is highly likely to identify procedural controls, along with integrity and functional requirements, and establish issues requiring information, assessment or action where the effectiveness of a control might be questioned.

However, the bow-tie might not be the panacea for all risk management problems. If a particular level of risk is required to be revealed in absolute terms, the technique might not help directly. Similarly, there could be better ways than using bow-ties to model the complex interrelationship between risk controls.

Additionally, there is another issue for classical risk analysis methods, e.g. FTA and ETA, typically decomposing a system into subsystems and basic elements. Investigating risks for a turnout system with strong interdependencies in nature has to go beyond the convention cause–consequence analysis in order to concentrate on spill-over clusters of failures. Indeed, the sum of the behaviour of individual components in a turnout cannot be expected to describe implicitly the behaviour of the whole system. This renders questionable the suitability of such risk analysis techniques. Moreover, pre-defined causal chains, e.g. defined by ETA, are likely to be inappropriate to identify hidden risks.

It is ultimately worth noting that each technique might provide different parameters or outputs that may be particularly useful regarding intended solutions of the problem. Therefore, a risk analysis method should be chosen, not only based on hazard, but also the consideration of the capabilities of each technique.

As a summary of outputs, desired outputs can be simple lists of individual failures (FMEA, RM), numerical estimates of system failure probabilities (MA, RBD, FTA), listings of event scenarios and their likelihoods (ETA), numerical system failure probabilities and sensitivities to input variables (BA, MC), or unique combinations resulting from a combination of these methods (e.g. use of both FTA and ETA).

As regards successful application of compressive risk analysis methods, British boards, e.g. London Underground Board (LUB) and The Rail Safety and Standards Board (RSSB), appear to be very successful and, in 2015, were ranked top among the EU-25 countries across all state-specific national reference values [62].

Using a good example of bow-tie techniques, London Underground Board and the UK national railway network currently rely on their own risk models, namely the LUQRA (London Underground Quantitative Risk Assessment) and the RSSB SRM (Safety Risk Model), respectively. The general common purposes of the models are, briefly: assessment of risk and risks of change, understanding current risks, identification of mitigation measures and key risk contributors and risk-based improvement planning [63-64]. The main difference between the two is that the LUQRA is designed by considering more serious injury and fatality relative to minor injuries.

In contrast to using the same structured model with bow-tie techniques, their judgements are different to each other. For instance, both the RSSB and the LU use separate fault/event tree models for derailment at various different speeds. Other situations affecting the results, e.g. how far the derailed train moves away from the centre of the track or how many people there are on the derailed train, are considered through the ET model, which means there are many approximations and assumptions made by different analysts in terms of the points of detail which are less or more important for accident consequences [65].

Additionally, despite the models being at system levels, the LUQRA quantifies first at the system and then at line-level, considering line-specific factors, and, lastly, aggregates the line representations of risk to the overall system representation, whereas the other begins with the whole system representation and then disaggregates it to reach risk representations for individual routes [66-68].

The models take into account: train accidents, including collusion and derailment, movement accidents, including various interfacing problems, and other malicious non-movement accidents. However, the RSSB SRM does not inherently include accidents most seen in underground lines, such as flooding and arching, whereas the LUQRA does.

Furthermore, the data used by the both models, is: 1) derived from historic data; 2) normalised per relevant unit of railway activity; 3) evaluated to make a decision on whether changes in the railway or its operation may have influenced the normalised rate of occurrence of such events; and 4) multiple backups of current relevant volumes concerning railway activity to achieve the best estimation of forecasting the frequency of such an event today. However, in the RSSB SRM, database updates are carried out more often and its database covers a shorter time period.

Upon the request of the Office of Rail Regulation in the UK, a report [65] has been published to reveal the one closest to reality through comparison of the general nature of the outputs, produced by both models, using recent actual safety performance. The outputs of the models in the report covers: 1) top event frequencies and annual risks, 2) probability/consequence of top event outcomes, 3) frequencies/number curves.

Comparison between the actual experience of recent years and the current risk model predictions shows that the LU QRA`s average estimates for five years from 2006-2007 to 2010-11 are somewhat higher than the reality. The LU QRA predicts about an average six passenger fatalities per year for the events, while the RSSB SRM estimates an average of around 11. However, the actual average numbers per year for the LU QRA and the RSSB SRM are 0.8 for LU and 6.8 for National Rail, respectively. This pessimistic attribute of the LU QRA can be explained by: 1) risk models of included top events not having been updated for some time; 2) the statistical data applied in quantifying the model being derived from longer time periods than tend to be used by RSSB; 3) beginning with a picture of the whole system and then disaggregating it, which could be somehow more beneficial for complex scenarios.

On the other hand, both models provide a distorted picture of risk, mainly arising from the following concerns: 1) incompleteness – leaving out rare but significant events previously experienced in the UK; 2) limited database - using only own database; 3) backward looking - addressing only past events rather than predicting and integrating current underlying risk; 4) uncalibrated process - leading to under-estimating or consistently over-estimating safety risks.

To address these in turn: where the models might be incomplete and limited, global events can be incorporated into their database with proper modelling to obtain UK-appropriate estimates of frequencies and consequences. As regards backward looking, the models make an assessment of risk, doing a scale up/down of current incident rates through multiplication of current activity volumes with recent normalised rates. Although RSSB might occasionally make changes to the recently observed rate, both may need to identify the sensitivity of risk to various aspects of safety performance improvement in accordance with their activities. As regards the data calibration of the models, the LU might err on the side of pessimism in its risk estimates, as smaller units of railway increase the areas where the model could tend towards using longer term incident data.

All the methods to use in a railway turnout system are evaluated in the following table [69-72];

Technique	**Life cycle phases**	**Strengths**	**Weakness**	**Availability prediction**	**Common cause failures**	**Effects of uncertainty in data**	**Proactive use**
RM	All phases	Quick preparation; suitable in the case of subjective data, e.g. expert opinion on only ties degradation of a turnout.	Inadequate for complex systems; cannot identify dependencies such as signalling errors.	Yes	No	No	Yes
FMEA	After design is finalised.	good for identifying single point failures. e.g. electrification process of a switch mechanism.	Human error not addressed; unable to reflect system redundancies, interactions, and Common Cause Failures.	No	No	No	Yes
RBD	Throughout life part. Design phase.	As for FTA	As for FTA	Yes	Yes	No	No
ETA	All phases	Excellent tool to model temporal escalation of events such as high speed based derailment; ideally suited to model efficiency of safety critical tasks and emergency response; provides numerical estimate of likelihood of an escalated event such as operational faults;	Dependencies highly on the correct capture of event escalation; needs scarce data for such complex systems as aging any railway components through FTA.	No	Yes	Yes	Yes
MA	Essentially, design stages	Good for complex systems; good tool for identifying process inefficiencies.	Unable to reflect redundancies and Common cause failures.	Yes	Depends on model	Yes	No
HF	Design of emergency Preparedness plans	Very thorough Technique: evaluates existing safeguards and identifies ultimate	For a human-based failures, Quantification may be misleading since such failures are quite difficult to	Yes	Depends on model	Yes	Yes

	and evaluation of safety critical tasks	consequences. May be good tool to arrive safety-based maintenance model of a turnout.	model; due to its reliance on scarce date to model, gathering of data might be difficult.				
MC	To establish properly reliability of system, ideally during consolidated design, but could be used in all phases	Once model built, input distributions are quickly updated to yield new results; an Intuitive process, helping users to add some qualitative data into a mathematical model which describes the risk parameter; provides a range of consequences, enabling better estimation of risk.	Creation of a mathematical model can be challenging; relies on computerised methods, e.g. spread sheeting; satisfaction of the analysis highly depending on complexity.	Depends on model	Depends on model	Yes	Yes
FTA	Throughout all stages of operation.	May be excellent for complex systems where interaction and combination of events and failure needs to be considered; uses properly statistical data of component failures of a turnout to evaluate probability for unwanted top event; provides visual model of a safety system; provides ranked lists of critical turnout components; an excellent tool based on a qualitative or quantitative application to model redundancies and fault tolerance (vulnerability).	In spite of Databases unsuitable for specific application, e.g. Aging of rail track, failure information might be supported using FORM methods; unable to model temporal events of a turnout such as changing weather conditions. Dependencies on correct capture of faults and failure mechanisms and interaction to predict system behaviour.	Yes	Yes	Yes	Yes

7 Concluding Remark

Railway turnout is a complex system, which is used to divert a train from one track to another. Its geometry and gradient constraints make it one of the most critical railway infrastructures. Significant complexity of railway turnout results in emerging risks during rail operations. This has been proven by a large number of train derailments at or nearby railway turnouts and crossings. Such incidents cause operational downtime and financial losses, and sometimes the loss of lives. The proper estimation of the high level of risk posed by railway turnout systems is essential for companies and organisations in order to operate the entire railway system without any safety concerns. With the increasing interest in railway transportation, the risk in railway turnout systems as a most problematic one, one which might be expected to increase and require more complex analysis.

This review paper assists in evaluating the existing understanding and practices of risk analysis and modelling, and in revealing the gaps in the industry. It has been seen that the industry uses a wide range of risk analysis modelling and gains different outcomes. Research showed that railway industry needs to pay special attention to monitor and manage interconnected risks, in order to improve public safety and operational reliability. The paper thus presents the state-of-the-art risk management techniques considering systems thinking approach, diversity of emerging risks and variety of risk analysis methodologies. Comparative evaluation of the techniques has been comprehensively discussed with relation to railway incidents. The practical guidelines have been summarised for railway practitioners so that risk management processes can be enhanced for rail transport with special respect to railway switches and crossings. As a complex system, a railway turnout is evaluated to be appropriately fitted for downward models. Furthermore, it has been found out that there are many problems updating existing risk levels and model calibration. Solutions to these, such as integration of databases, calibration, etc. can be recommended, but their impacts and significance require further research.

There is no question that risk analysing, modelling and management of railway systems provide an invaluable tool for railway companies and organisations to forecast various scenarios and then minimise their effects. Addressing areas arising from the discussions, the following might be underlined as envisaged to be worth future development.

- The benefits of greater ability to select, evaluate and discuss relevant aspects of risk analysis modelling to meet suitable safety criteria of railway turnout systems, e.g. using a continuous updating process whereby a large number of outputs in each particular case is obtained by using many different methods and inputs, and then comparing the outputs with reality annually to optimise and calibrate the expectation.
- The reaction of more integrated environments for different risk analysis; the different levels of various risk factors, such as railway components aging and environmental-based, can be integrated with each other to forecast more accurately the likelihood of occurrence at turnout systems, thereby revealing the quantitative relation between them. In this example, the integration of both factors might lead to different risk levels, even across the same railway line, which might provide a better understanding of the real level of risk rather than levelling out the overall risk.
- The outcomes of building more effective databases. Where any discovered new events are expected to occur and data are incomplete, as often seen following technology transfers, it might be better to incorporate the external data into the existing models with proper modelling to derive UK-appropriate estimates of frequencies and consequences.
- The effect of the same detailed Mapping Top Events of estimations throughout the industry, i.e. any hazard on one side can, in some cases, be subdivided into more than one category on the other. Standardised titles and subtitles might be beneficial to approximate accurate risk levels in a particular case.
- Various quantitative cost-benefit optimisations of all those points above to learn what needs to be extended.

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9 References

1. Eurostat. Eurostat statistical database. In., Series Eurostat statistical database. EU.

2. European Comission. Final report summary - d-rail (development of the future rail freight system to reduce the occurrences and impact of derailment). NEWCASTLE UPON TYNE: EU-Project reference: 285162.

3. ERA. Assessment of freight train derailment risk reduction measures: B2 – risk model and potential effectiveness of measures, report for , report no: Ba000777/07, rev: 02. Cheshire, the UK: ERA.

4. Chattopadhyay G, Raman D, Alam M. A study of derailment in australia: Analysing risk gaps with remote data monitoring. In: Engineering asset management. London: Springer 2011; p. 21-31.

5. Mullai A. Risk management system – risk assesment frameworks and techniques, the european union within the bsr interreg iii b programme. Turku, Finland: DaGoB publication.

6. Kaewunruen S, Chiravacharadej J, Chucheepsakul S. Nonlinear free vibrations of marine risers/pipes transporting fluid. Ocean Engineering, 2005; 32 (3-4):417-40.

7. Shortridge JE. Scenario discover with multiple criteria: An evaluation of the robust decision-making framework for climate change adaptation. Risk Analysis, in Press, 2016.

8. Nateghi R, Guikema SD, Wu YG et al. Critical assessment of the foundations of power transmission and distribution reliability metrics and standards. Risk Analysis, 2015; 36 (1):4-15.

9. Kaewunruen S, Sussman J, Matsumoto A. Grand challenges in transportation and transit systems. Front. Built Environ. 2:4. doi: 10.3389/fbuil.2016.00004, 2016.

10. Chapman C, Ward S. Project risk management: Processes, techniques and insights. Hobooken, New York: Wiley; 2 edition; 2003.

11. HaS Exacutive. A brief guide to controlling risks in the workplace, risk assessment. London: HSE.

12. McNeil AJ, Frey R, Embrechts P. Quantitative risk management: Concepts, techniques and tools. New Jersey: Princeton University Press; 2014.

13. Dixit B. Measuring safety through a composite safety index. In The International Rail Safety Conference (IRSC). Dublin; 2007.

14. Stringfellow MV. Accident analysis and hazard analysis for human and organizational factors. Newyork MIT.

15. Scott B, Ponniah D, Smith S. Risk response techniques employed currently for major projects for major projects. Construction Management and Economics, 1999; 17 (2):205-13.

16. Mazouni M, Bied-Charreton D, Aubry J. Proposal of a generic methodology to harmonize preliminary hazard analyses for guided transport. System of Systems Engineering, 2007; 7:1-6.

17. Carter G, Smith S. Safety hazard identification on construction projects. Journal of Construction Engineering and Management, 2006; 132 (2):197-205.

18. Min A, Yao C, Baker CJ. A fuzzy reasoning and fuzzy-analytical hierarchy process based approach to the process of railway risk information: A railway risk management system. Information Sciences, 2011; 181 (18):3946–66.

19. Høj NP, Kröger W. Risk analyses of transportation on road and railway from a european perspective. Safety Science, 2002; 40 (1):337–57.

20. Fernie L. Hima In., Series Hima Meeting IEC61508 and IEC61511 standards: ; 2014.

21. Bian K, Wang H. Hazard and operability analysis on risk factors of railway dangerous goods transport. In ICTE 2015: pp. 2746-2753. Dailan, China; 2015.

22. Braband J. On the justification of a risk matrix for technical systems in european railways. In: Forms/format 2010- formal methods for automation and safety in railway and automotive systems. Berlin Springer Berlin Heidelberg; 2011; p. 185-97.

23. Board RSaS. Guidance on the preparation and use of company risk assessment profiles for transport operators. London: RSSB.

24. Recht JL. System safety analysis: Failure modes and effects analysisNat. Saf. News

25. Stamatis DH. Failure mode and effect analysis: Fmea from theory to execution. Milwaukee: ASQ Quality Press; 2003.

26. Zio E. An introduction to the basics of reliability and risk analysis. London: World Scientific Publishing; 2007.

27. Sankar N, Prabhu B. Modified approach for prioritization of failures in a system failure mode and effects analysis. International Journal of Quality & Reliability Management, 2001; 18 (3):324 - 36.

28. Birolini A. Reliability engineering: Theory and practice. London: Springer Science & Business Media; 2010.

29. Sadiq M, Rahmani MKI, Ahmad MW et al. Software risk assessment and evaluation process (sraep) using model based approach. Networking and Information Technology (ICNIT), 2010 International Conference on, IEEE, 2010; 12 (2):171 - 7.

30. Shital AT, H. Lambert J. Decision analysis and risk models for land development affecting infrastructure systems. Risk Analysis, 2012; 32 (7):1253–69.

31. Ericson CA. Hazard analysis techniques for system safety. London: John Wiley & Sons; 2005.

32. Andrews JD, Dunnett SJ. Event-tree analysis using binary decision diagrams. Reliability, IEEE Transactions, 2000; 49 (2):230 - 8.

33. Sapoznikov V, Sapoznikov V, Anders E et al. Safety and reliability in signalling systems. In In: Theeg G., Vlasenko S., Railway Signalling & Interlocking – International Compendium, Eurailpress. Hamburg; 1st edition 2009.

34. Perkins J, Wang D. A comparison of bayesian and frequentist statistics as applied in a simple repeated measures example. Journal of Modern Applied Statistical Methods, 2004; 3 (1):227-33.

35. Glickman ME, Dyk DAv. Basic bayesian methods. Topics in Biostatistics, 2007; 404:319-38.

36. Gelman A, Carlin JB, Stern HS et al. Bayesian data analysis. London: CRC Press, Taylor & Francis Group; 2003.

37. Graves TL, Hamada MS. A demonstration of modern bayesian methods for assessing system reliability with multilevel data and for allocating resources. International Journal of Quality, Statistics, and Reliability, 2009; 1155 (10):1-10.

38. Couto PRG, Carreteiro J. Monte carlo simulations applied to uncertainty in measurement. In: Theory and applications of monte carlo simulations: InTech; 2013; p. Chapter 2.

39. Xinhua L, Yongzhi L, Hao L. Theory and application of monte carlo method. Software Engineering and Knowledge Engineering: Theory and Practice, 2012; 105 (1):841-8.

40. Rabatel J, Bringay S, Poncelet P. So_mad: Sensor mining for anomaly detection in railway data. Advances in Data Mining. Applications and Theoretical Aspects, 2009; 5633 191-205.

41. Rail N. New lines programme: Demand forecasting technical note. London: Network Rail: Planning and Regulation Department.

42. Marsegurra M, Zio E. Basics of the monte carlo method with application to system reliability. Hagen: Basics of the Monte Carlo Method with Application to System Reliability; 2002.

43. Billinton R, Li W. A system state transition sampling method for composite system reliability evaluation. IEEE Transactions on Power Systems, 1993; 8 (3): 761-70.

44. Zio E, Wolfgang K. Vulnerability assessment of critical infrastructures the IEEE Reliability Society.

45. Eusgeld I, Kröger W, Sansavini G et al. The role of network theory and object-oriented modeling within a framework for the vulnerability analysis of critical infrastructures. Reliability Engineering & Systems Safety, 2009; 94 (5):954-63.

46. RSSB. A guide to rssb research in safety policy and risk management. London: RSSB.

47. Nejad HS, Mathias DL. Top-down vs. Bottom-up risk assessment: Consistent, contradictory or complimentary? In Reliability and Maintainability Symposium (RAMS), 2013 Proceedings - Annual; 2013.

48. Sang BW, Kwak L, Woo PJ. Development and application of hazard analysis & risk assessment models for the korea railway. In International Railway Safety Conference. Denver; 2008.

49. Beale CJ. Uncertainty in the risk assessment process – the challenge of making reasonable business decisions within the framework of the precautionary principle. In: Hazards xx: Process safety and environmental protection, harnessing knowledge, challenging complacency: IChemE; 2008; p. 1-15.

50. Nedeljakova I. Review of risk assessment methods. Journal of Information, Control and Management Systems, 2007; 5 (2):277-84.

51. R.T. Clemen, R.L Winker. Combining probability distributions from experts in risk analysis. Risk Analysis, 1999; 19 (2):187-203.

52. Ouchi F. A literature review on the use of expert opinion in probabilistic risk analysis. New York: Policy Research Working Paper.

53. Korombel A, Piotr T. Qualitative risk analysis as a stage of risk management in investment projects: Advantages and disadvantages of selected methods-theoretical approach. Journal of Interdisciplinary Research 2011; 01 (02):51-4.

54. Kelly B, Dubey B, Richard H et al. A risk-based approach to sanitary sewer pipe asset management. Science of the Total Environment, 2015; 505:1011-7.

55. Cox LAT. What's wrong with risk matrices? Risk Analysis, 2008; 28 (2):497-512.

56. Corinne A, Marshall MI. The risk matrix: Illustrating the importance of risk management strategies. Journal of Extension, 2006; 44 (2).

57. Duijm NJ. Recommendations on the use and design of risk matrices. Safety Science, 2015; 76:21–31.

58. Braband J. Rapid risk assessment of technical systems in railway automation. In the Australian System Safety Conferrence. Darlinghurst, Australia.; 2012.

59. Zhao N, Zhao T, Tian J. Reliability centered preliminary hazard analysis. In Reliability and Maintainability Symposium, RAMS. Fort Worth, TX; 2009.

60. Jo H-J, Hwang J-G, Kim Y-K. Risk assessment method for guaranteeing safety in the train control system. Urban Transport XIII: Urban Transport and the Environment in the 21st Century, 2007:567-77.

61. Braband J. On the justification of a risk matrix for technical systems in european railways. In: Forms/format 2010- formal methods for automation and safety in railway and automotive systems. Berlin Springer Berlin Heidelberg; 2011; p. 185-97.

62. Board RSaS. Annual safety performance report 2013/14 London: RSSB.

63. Limited LU. Standard 1-526:The assessment and management of health, safety & environmental risk”,. Issue 3, June 2009: Head of TfL Management Systems.

Stamatelatos M, Dezfuli H, Apostolakis G et al. Nasa technical report server, probabilistic risk assessment procedures guide for nasa managers and practitioners. In., Series Nasa technical report server, probabilistic risk assessment procedures guide for nasa managers and practitioners. NASA; 2011.

64. Board RSaS. Original railtracksafety & standards directorate safety risk model model: Briefing note –report no. Sp-rsk-3.1.3.9. London: RSSB.

65. Taig T, Hunt M. Review of lu and rssb safety risk models: A report produced for the office of rail regulation. London: TTAC Limited.

66. Board TRSaS. Platform train interface strategy. London: RSSB.

67. Dennis C, Sizer P, Pitman S. Rssb board meeting: Train accident risk. London: RSSB.

68. System TM. Lighting of london underground asset. London: Mayor of London.

69. Rasche T. Risk analysis methods – a brief review. Queenisland: University of Quennisland, Minerals Industry Safety and Health Centre.

70. Skorupka D. Identification and initial risk assessment of construction projects in poland. Journal of Management in Engineering, 2008; 24 (3):120–7.

71. Marhavilas PK, Koulouriotis D, Gemeni V. Risk analysis and assessment methodologies in the work sites: On a review,classification and comparative study of the scientific literature of the period 2000 to 2009. Journal of Loss Prevention in the Process Industries, 2011; 24:477-523.

72. Stamatelatos M. Probabilistic risk assessment: What is it and why is it worth performing it? NASA Office of Safety and Mission Assurance, 2000; 4 (05):00.