A systems approach to reducing train accident risk

By Brian Tomlinson

Executive summary: This case study explains the systems approach taken by Network Rail to achieve a reduction in train accident risk over a five-year period. It identifies the most effective safety risk reduction options using a combination of qualitative and quantitative techniques, shows how data-driven analysis can be used to identify key failure modes and causes, and establishes key performance indicators to monitor safety risk reduction activities.

Tags: railway, train accident, transportation, complex system, failure modes, key performance indicators, passenger and freight networks, safety, risk reduction, United Kingdom

Section 1: Background and introduction

Railways across the world transport large numbers of passengers and quantities of freight over extensive geographic networks. With trains operating at high speeds and having significant mass, any accident can have catastrophic consequences. Over many years, both transformational and incremental steps have been taken to introduce improved safety measures on railways. While rail is now acknowledged to be one of the safest forms of transport, the potential risk of a train accident remains ever present.

A railway is a complex safety critical system comprising many sub-systems, such as trains, track, structures, earthworks, signalling, electrification and level crossings. As with most complex systems, there are many internal and external interdependencies that can affect system performance. Examples of external factors that can impact railways include the weather/temperature and outside parties, such as road vehicle users and adjacent landowners.

The overall safety of the railway as a system is dependent on the infrastructure manager, train operators and station operators: (a) having a detailed understanding of risk; (b) identifying and implementing effective controls; (c) monitoring their effectiveness; and (d) implementing actions as part of a continual improvement cycle. This is illustrated in **Figure 1**.

This case study will explain in practical terms the systems approach taken by Network Rail, the infrastructure manager for most of the main line railways in Great Britain, to achieve a significant reduction in train accident risk over a five-year period, known as Control Period 5 (April 2014 to March 2019). This includes:

- The in-depth analysis undertaken of the sub-system failure modes and causal factors;
- The identification and analysis of an extensive range of risk reduction options; and
- Implementation of those activities that would have the most significant impact on reducing risk within the funding available.

This approach has contributed to Britain's railway being one the safest in Europe.

Section 2: Analysis and insights

Obtaining a deeper understanding of risk

An accident involving the derailment of a train or collision with another train or object can have very serious consequences, potentially resulting in multiple

Figure 1. Fundamental principles of Network Rail's Health & Safety Management System.

fatalities and injuries and/or the release of dangerous goods being transported. There are many precursor events that could result in a train accident. Within the rail industry, the extent of these are known and include events such as Signals Passed At Danger (SPADs), broken rails and objects on the line. **Figure 2** shows the nine main precursor event groups that comprise train accident risk. It also expands upon one of these groups, the track system, to provide examples of potential failure modes.

As well as the immediate cause, accidents often have several causal and contributory factors. Through the thorough application of accident investigation techniques, a deeper understanding of these factors can be obtained. This can be further used to identify common themes and improve the overall understanding of the risks and the implementation/effectiveness of their controls.

At the end of Control Period 4 (March 2014), Network Rail already had an existing portfolio of ongoing workstreams aimed at reducing train accident risk, such as the introduction of new technology and actions to address investigation recommendations. As part of the overall planning process for Control Period 5, the question arose as to which workstreams, either existing or newly proposed, would have the greatest impact on reducing train accident risk within the funding available.

In 2013 and 2014 a series of 'Deep Dive' risk reviews were undertaken by Network Rail, in relation to each of the train accident risk categories, to review the strategies, policies, initiatives, risk exposure, targets and performance; and to develop corresponding improvement plans. In particular, the 'Deep Dive' reviews undertook extensive analysis of data from a wide variety of data sources to identify trends and correlations of failure/event data with attributes such as year/month/day/time, weather/temperature, detection method and asset type/location. The outputs of this analysis were combined with industry risk model data provided by RSSB (a not-for-profit company owned by major industry stakeholders whose core purpose is to actively help the industry work together to drive improvements in the GB rail system) and intelligence from assurance activities and investigation findings to obtain a much deeper understanding of risk associated with each of the precursor events to a train accident. **Figure 3** provides two example outputs from the 'Deep Dive' analysis undertaken at the time.

Within each 'Deep Dive' risk review a high-level narrative PESTLE (Political, Economic, Sociocultural, Technological, Legal and Environmental) analysis was undertaken to obtain a greater understanding of the potential impact on risk due to both internal and external factors. An overall summary of this is provided in Appendix 1. Examples of external factors that can impact safety include changes in the economy,

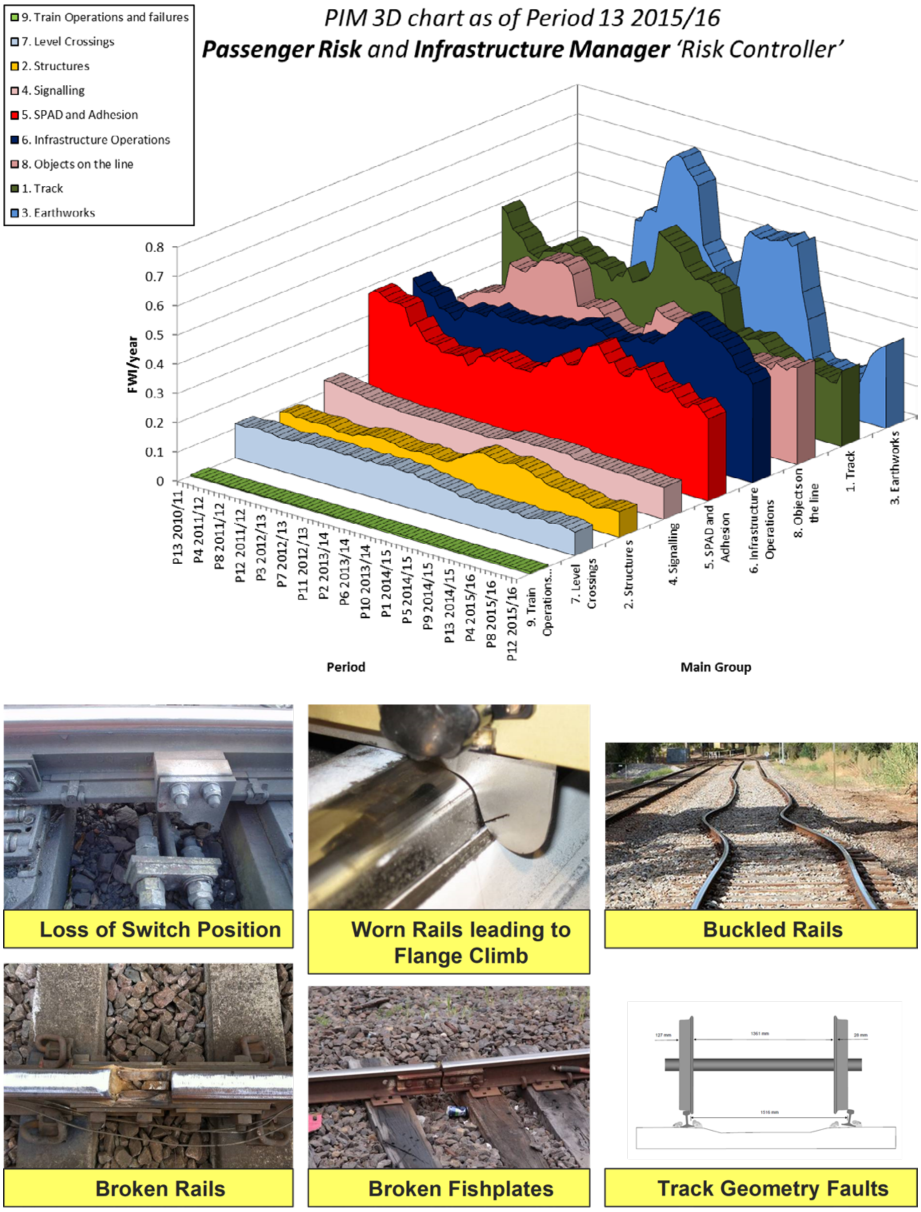

Figure 2. Trend in train accident main precursor event groups (2010 to 2015) and examples of track system failure modes.

funding allocation, security threat level, government, industry structure, new technology, climate change and external risks from other inter-dependent complex systems, such as electricity generation and supply.

Identification and evaluation of risk reduction options

Within railway systems, the risk controls have been established and refined over many years. As a result, nowadays there are fewer opportunities to make transformational improvements to reduce residual risk; although they do exist, for example through the adoption of improved technology and/or more affordable solutions. As there is no dominant category of sub-system risk, the train accident risk reduction strategy needs to be based on the optimum balance of many incremental workstreams/ initiatives applied to a wide range of the precursor event types.

In August 2015, following on from the 'Deep Dive' reviews, a significant study was undertaken to identify current and future planned workstreams/initiatives that would, or could, reduce train accident risk. This was conducted in conjunction with the relevant subject matter experts considering: the existing workstreams; expanding/ enhancing existing workstreams; or adopting new technology/ approaches. The outputs of the rail industry Safety Risk Model (SRM), in conjunction with the analysis of train accident precursor events known as the Precursor Indicator Model (PIM), were used as a basis to identify the relative magnitude and trend in risk of each of the precursor events.

In workshop sessions, subject matter and risk experts used their existing knowledge and the intelligence gained from 'Deep Dive' reviews to estimate the reduction in risk that could potentially be expected if each of the workstreams/initiatives were to be progressed. As part of this exercise their relative effectiveness was considered, taking into consideration the hierarchy of risk controls: eliminate risk; apply engineering control; apply procedural control.

To complete the analysis, each of the identified potential workstreams/initiatives was prioritised by assessing its estimated benefits and costs over a 30-year period considering development, implementation, ongoing costs and associated timescales. The chart in **Figure 4**, shows the output of the cost benefit analysis of more than 70 workstreams/initiatives that were identified. This enabled those initiatives providing the greatest risk reduction to be identified, along with those that had the highest benefit-cost ratio.

Risk reduction plan

The outputs of the 2015 study were used to formulate a train accident risk reduction plan, comprising those workstreams considered to give the optimum risk reduction within the funding available. The plan was initially based on

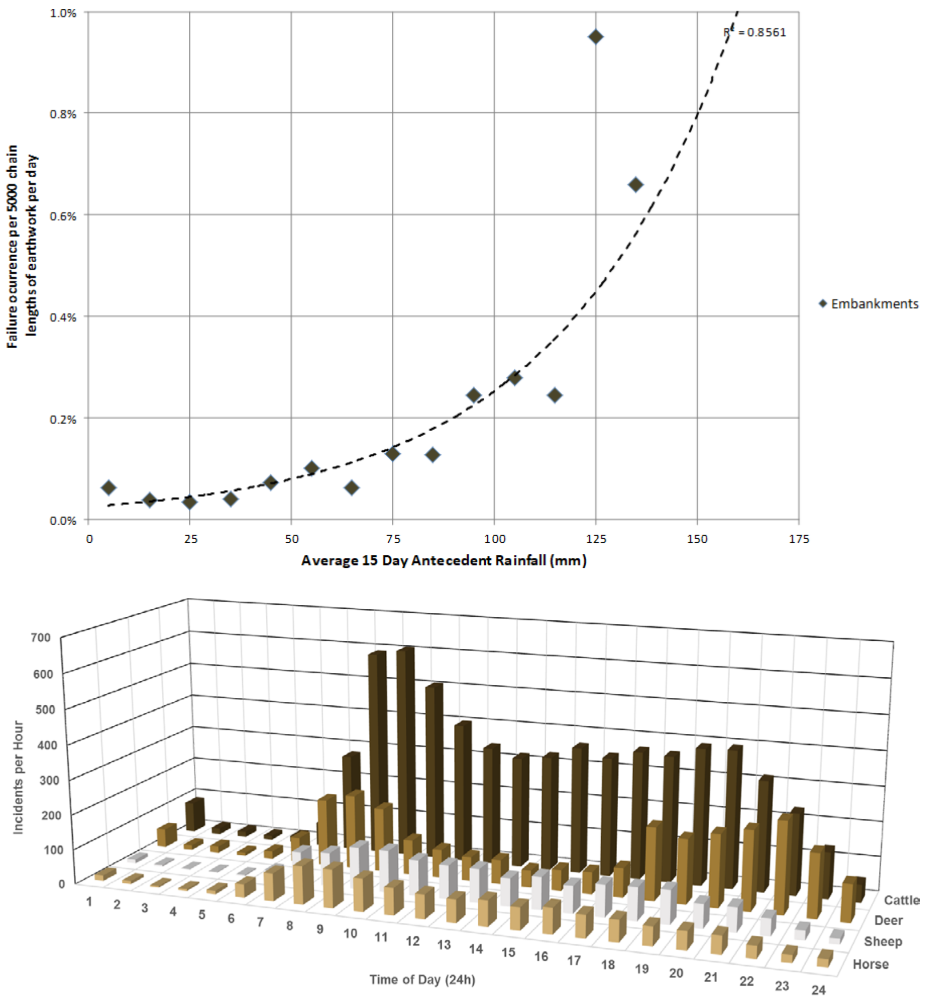

Figure 3. Example outputs of analysis from 'Deep Dive' reviews (correlation of embankment failure rate with 15-day antecedent rainfall, numbers and types of animal reported on the line vs. time of year)

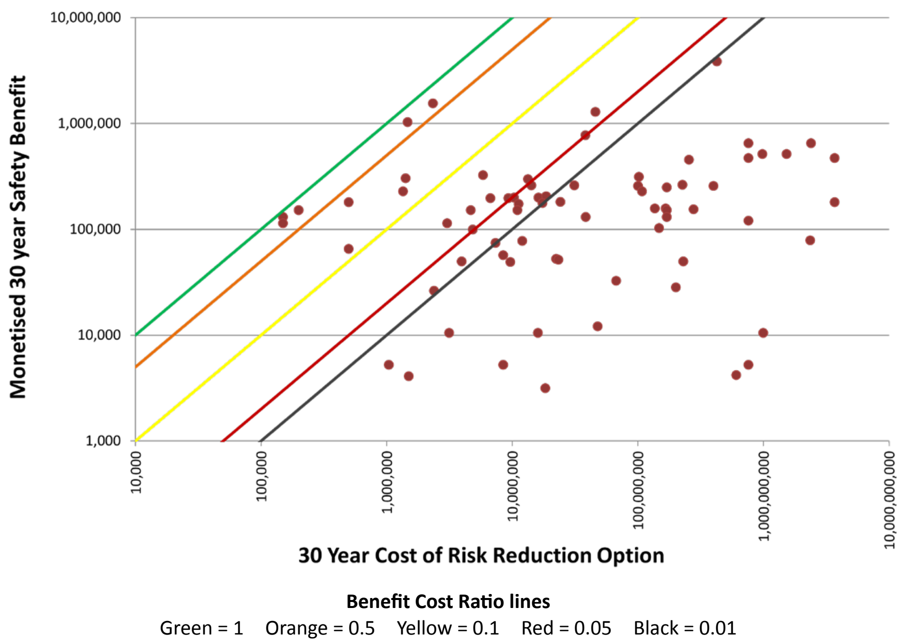

Figure 4. Chart showing the cost benefit of each of the risk reduction workstreams (indicated by the red circles).

a series of activity milestones to record when key stages of the workstreams had been completed or to track the number of risk reduction interventions that have been made. The results of the 'Deep Dives', optioneering study, cost benefit analysis and formulation of the risk reduction plan were all presented to senior stakeholders within the company to obtain their support for the proposals.

Over the following three years, progress against each of the workstreams was tracked through a composite weighted activity (leading) indictor, known as the Train Accident Risk Reduction (TARR) metric, to drive continual improvement year-on-year. The original components of the TARR metric were based on those workstreams considered to provide an improved risk control (such as the introduction of tubular stretcher bars at switches and crossings) or known areas where risk control improvement was required (such as drainage, fencing and vegetation management).

Each year the components of the TARR metric were updated to capture new risk reduction initiatives and, from 2018/19, this included the introduction of Region/Route-specific workstreams more closely focused on key risk areas. The relative weightings of the component workstreams were also reviewed, and adjusted if necessary, following evaluation of actual performance against plan and relative trend in risk (**Figure 5**).

Monitoring performance

Throughout the remainder of Control Period 5, several key performance indicators were closely monitored to assess the impact on train accident risk:

- The performance of the TARR metric itself to measure the achievement of the target volumes and milestones in the risk reduction plan. The metric

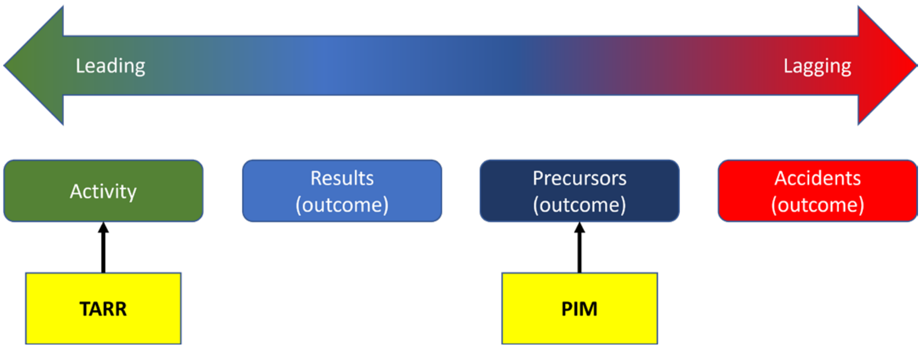

Figure 5. Diagram showing that the Train Accident Risk Reduction (TARR) metric is a leading activity indicator compared to outcome indicators, such as monitoring precursor events or accidents.

attained or exceeded the annual plan in each of the three years after the metric was established;

- The number of failures/events relating to precursor component groups. Improved techniques to visualise this data were applied based on the deeper understanding of risk acquired through the 'Deep Dive' reviews. A good example of this is shown in **Figure 6** with the application of 'control limits' to identify where performance was outside the normal range of variance observed; and
- The Precursor Indicator Model (PIM) performance. The PIM provides a calculation of risk (normalised by the number of train miles) for train accident precursors derived from:
  - The frequency of train accident precursor events that have been reported; and
  - An estimation of their 'average' potential consequences from data contained within the rail industry Safety Risk Model (rather than from the actual consequences of the event itself) or from those events that are risk ranked, such as Signals Passed At Danger (SPADs) and asset failures.

Outcome at the end of Control Period 5

Over the control period, an overall reduction in risk of 37% was achieved against a baseline target of 19%. Each of the targets for the main precursor event groups was also met. This is shown in **Figures 7** and **8**.

While the PIM results showed a significant overall reduction in train accident risk in Control Period 5, more detailed analysis of the model outputs highlighted that trends in some of the train accident precursor events (such as track, earthwork and signalling failures) have more variation as they are more susceptible to the effects of adverse weather and temperature (which can vary in severity from year-to-year). When these precursor trends were analysed over a longer duration, a 31% overall reduction in risk over the control period was calculated. This was still an appreciable reduction in risk compared to the original 19% target.

In terms of absolute risk reduction, the greatest reduction in risk was achieved in the track system, earthworks and objects on the line main precursor event groups. While there was some variable impact on risk due to weather/temperature effects (and other factors both internal and external to the railway system), it was concluded that there was a genuine causal reduction in risk resulting from several of the TARR workstreams. Examples of these include:

- The contribution of the tubular stretcher bar installation programme and improvement in the identification of switch wear towards reducing track system switch and crossing failure risk;
- The contribution of improvements in trainborne monitoring towards reducing track system twist & geometry fault and broken rail risk;
- The impact of increased focus on drainage maintenance on reducing track system and earthwork failure risk;
- The contribution of scour mitigation measures and improvements in competence towards reducing rail bridge failure risk;
- The contribution of level crossing closures and other safety improvements towards reducing level crossing risk; and
- The impact of increased focus on vegetation maintenance on reducing risk due to trees on the line.

While most of the train accident risk precursors showed either a consistent or improving trend, there were a very small number showing a gradual worsening trend within the control period. An example of this was the risk associated with non-rail vehicles on the line, despite implementation of road vehicle incursion mitigation measures being a key TARR volume. This is another example of a risk that can be significantly influenced by external factors.

Section 3: Discussion and transferrable learning

Reflecting on this case study, there were several key factors that needed to be present to successfully achieve the overall outcome objective. These are:

- A risk breakdown structure of the railway system and identification of precursor events based on known and theoretical failure modes;

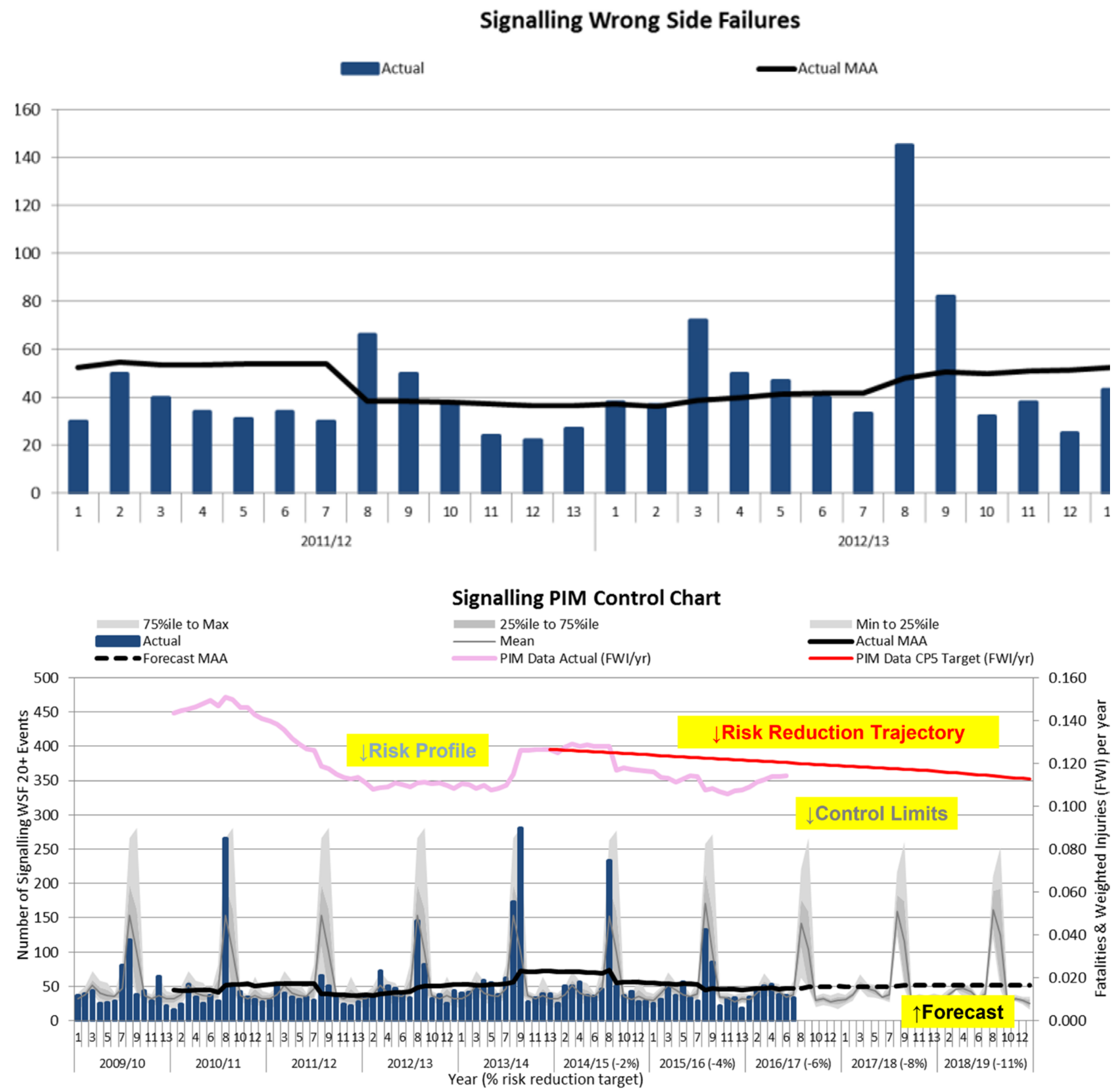

Figure 6. Analysis of signalling wrong side failure data (before 'Deep Dive' on the left, after 'Deep Dive' on the right which includes the risk trajectory and highlights seasonal variation by the application of control limits).

- Availability of relevant failure data and key data attributes, assurance outcomes and investigation findings to enable the 'Deep Dive' analysis to be undertaken;
- The existence of the industry Safety Risk Model containing information on both event frequency and consequence relating to precursor events;
- Access to subject matter experts for each of the engineering and operational failure modes and experts in risk, analysis and systems engineering;
- Estimation of indicative estimates of cost, timescales and benefits associated with each of the risk reduction workstreams/initiatives;
- A good understanding of the impact of both internal and external factors that impact risk;
- Senior level buy-in, leadership, commitment and support throughout;
- Continued performance monitoring through a combination of both lagging and leading key performance indicators;
- Acknowledgment that the strategy needed regular review and refinement; and
- The ability to respond proportionately to events arising without undermining the overall risk reduction strategy.

There are also a few areas where, upon reflection, further improvements and refinements to the methodology applied could be made:

- Further study and analysis of inter-dependencies and commonality between precursor events, including across sub-

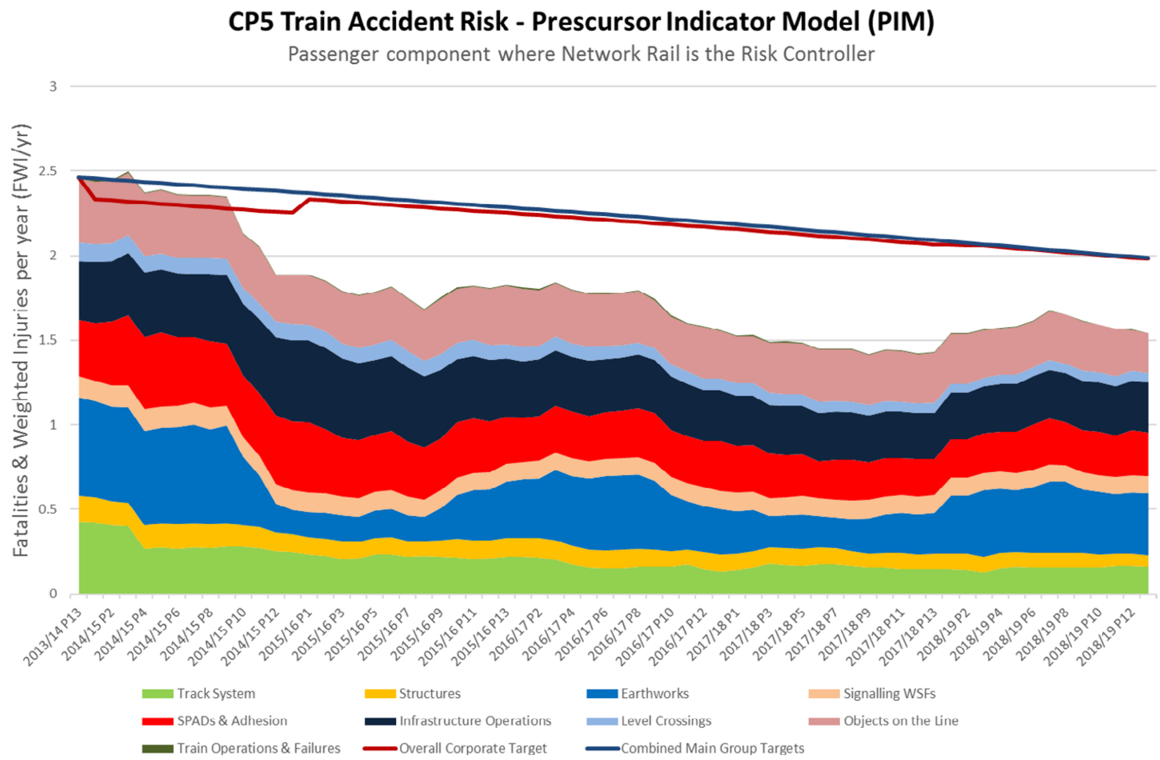

Figure 7. Train accident risk PIM results for Control Period 5.

	Target reduction in risk in CP5 (%)	Actual reduction in risk in CP5 (%)	CP5 Target Met	Proportion of total risk at CP4 exit (%)	Proportion of total risk at CP5 exit (%)
Overall PIM	**19**	**37**	Yes		
Track System	18	62	Yes	17.4	10.5
Structures	29	56	Yes	6.2	4.3
Earthworks	35	37	Yes	23.5	23.7
Signalling WSFs	11	19	Yes	5.1	6.6
SPADs & Adhesion	13	23	Yes	13.6	16.7
Infrastructure Operations	10	15	Yes	14.1	19.2
Level Crossings	28	47	Yes	4.5	3.8
Objects on the Line	7	39	Yes	15.4	15.1
Train Operations & Failures	No target set	59	Not applicable	0.2	0.2

Figure 8. Risk reduction in Control Period 5 for each of the main precursor event groups.

system boundaries and closely involving other industry parties;

- An improved feedback loop between activities undertaken to reduce risk and the potential outcome on accident precursors to identify those that are making the greatest impact and those that are not impacting risk in the manner originally envisaged;
- Provision of improved cost data/estimates and sensitivity analysis, for example three-point estimates; and
- Wider and more detailed consideration of other external factors that could impact risk, such as those identified in the PESTLE analysis (see **Appendix 1**) and the UK Cabinet Office's National Risk Register.

In terms of transferrable learning to other sectors and industries, this case study:

- Provides a practical methodology to identify the most significant and cost-effective safety risk reduction options for a complex system, comprising many sub-systems impacted by both internal and external factors, using a combination of qualitative and quantitative techniques;
- Shows how a data-driven approach can be taken to assessing a very complex system to understand its key failure modes and causes, supported by risk modelling and analysis; and
- Identifies how to establish a suite of key performance indicators that monitor activity being undertaken to reduce safety risk. These indicators can then be refined year-on-year to target further improvement in safety performance.

An overall summary of the methodology applied is shown in **Figure 9**.

These techniques could be adopted by any safety critical industry that has established safety reporting processes in place and/or knowledge of system failure modes (actual and envisaged) and their effects. They are simple to understand and apply, which makes them suitable for transferrable application. Also, there is potential for further development and refinement of the methodology applied and to apply it to other system capabilities within an organisation, such as environment, performance, security, etc.

Appendix 1 – PESTLE analysis of factors impacting train accident risk

Political

The main line railway in Great Britain comprises the infrastructure managers (of which Network Rail is the largest), train and freight operating companies and station operators. Changes in government, train operators or wider-industry structure can impact the organisational structure, priorities and funding – which in turn can impact safety. The railway also has a high media profile that can potentially impact decision making.

Economic

Network Rail receives its funding from the Department for Transport in five-year Control Periods. The level of funding impacts the investment in maintaining, renewing and enhancing the infrastructure and the operational running of the railway – this can have a direct impact on safety. Funding, therefore, must be used in the most cost-effective way to achieve the organisation's objectives.

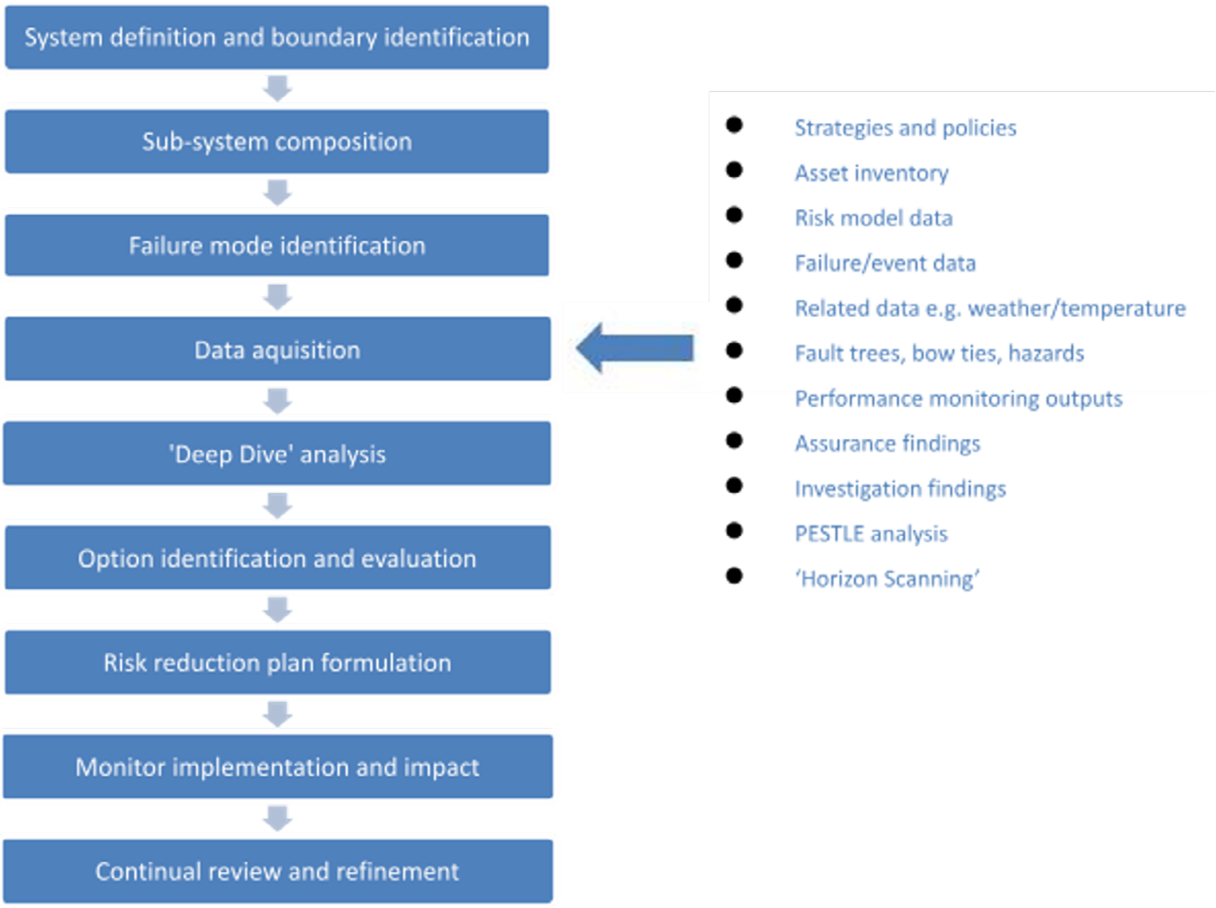

Figure 9. Overview of methodology applied to reducing train accident risk.

Insufficient or inappropriate allocation of funding could result in a deterioration of asset condition.

Sociocultural

The railway is a safety critical system and safety is a strong cultural value held by all people who work for the railway. Passengers and members of the public can each have a different perception of risk and, as such, sometimes do not act safely. An example of this is at level crossings where unsafe behaviour is frequently observed. This is considered when determining the risk controls that need to be applied.

Technological

Technology makes an extremely important contribution towards improving railway safety. Most of the significant reductions in risk that have been achieved over the years have been made through advances in technology. Network Rail has made significant investment in research and development in order to identify and adopt successful new technology to reduce safety risk. One important area is seeking more cost-efficient and reliable engineering solutions. Through greater automation of activities, such as track inspection, the risk of human error and risk to workers can be reduced. Other technological developments include the introduction of new signalling systems, use of drones and intelligent infrastructure monitoring.

Legal

In addition to the general health and safety legislative requirements that apply to the railway, such as the Health & Safety at Work Act, there is also a wealth of railway-related safety legislation. Changes in legislation have a positive impact on safety, underpinned by the use of engineering safety management processes and risk assessment.

Environmental

As the railway largely operates in an external environment, its performance can be impacted by the weather and its effects. Rainfall, snow, high/low temperatures, wind, fog and leaf fall can all affect the safe performance of the railway. Examples include flooding of the line, poor adhesion between train wheels and the rails, objects blown onto the line, buckled rails in hot temperatures and earthwork failures. Climate change will therefore have a key impact on railway safety. In reducing carbon, the railway is moving towards more electric trains and alternative/supplementary means of powering trains, for example using batteries or hydrogen.

Acknowledgements

This was work supported by the Safer Complex Systems mission of Engineering X, an international collaboration founded by the Royal Academy of Engineering (the Academy) and Lloyd's Register Foundation (LRF). The opinions expressed in this publication are those of the author(s) and do not necessarily reflect the views of the Academy or LRF.

Affiliations

Brian Tomlinson, Chief Systems Engineer, Technical Authority, Network Rail