DEVELOPING AN UNDERSTANDING OF THE RELATIONSHIP BETWEEN RAILWAY SAFETY & OPERATIONAL PERFORMANCE

by

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Abstract

Railway risk and delays are most often analysed apart with no common language for collecting data making it difficult to analyse or compare railway safety and operational performance. This study attempts to develop an understanding of the relationship between the two performance measures by comparing them on a common scale (in this case using monetary terms/values) while building on existing approaches in the industry.

To achieve this, a causal loop diagram (CLD) is firstly used to show the existing known relationships between risk and delays by documenting their causes using data from the Rail Safety and Standard Board (RSSB) and Network Rail respectively. This part of the research identified differences in the classification of some events although these datasets are collated from the reporting of the same incidents on the network. Also identified are the common causes of risk and delays.

The common causes which are identified are defined for the purpose of this research as the common performance influencing factors (CPIFs). The existence of CPIFs shows that there are incidents/events that can impact both the safety and operational performance of the railways. Understanding the relationship between the two measures and being able to compare them on a common scale can potentially be beneficial to stakeholders especially in finding solutions to reduce the occurrence of CPIF related incidents on the network.

As the CPIFs can lead to both risk (typically measured by Fatalities and Weighted Injuries) and delay consequences (usually measured by delay minutes), it is appropriate to convert their values into a common measure, and this is possible using existing monetary values for both measures. That enabled this research to categorise on a common scale the impact CPIFs have

on railway safety and operational performance. This thesis develops an approach to help convert delays into monetary values.

It is noted that the values which are taken from published sources are a representation of what delays and risks on the network cost the industry. Given the approach adopted, this creates a reasonable estimate of the relative significance of an event for both risk and performance but would need to be supplemented with real life data from particular routes and contracts to be used to support decision making. This is attempted in the thesis by using route data on trespass incidents for which scenarios were developed to demonstrate the use of the approach in the stakeholder decision making process.

In conclusion, the thesis develops our understanding of the relationship between railway safety and operational performance by identifying the common causes of risk and delays on the network (i.e., CPIFs). The identification of the CPIFs have made it possible to develop an approach for comparing risk and delays on a common scale. In addition, the researcher also identified the need for a consistent language and data collection/analysis approach (e.g., an 'event – based' reporting system). It is hoped that over time, this would enable a much clearer understanding to be developed and be more efficient in terms of data capture.

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Abbreviations

CaSL	Cancellation and Significant Lateness
CLD	Causal Loop Diagram
CPIFs	Common Performance Influencing Factors
ERTMS	European Rail Traffic Management System
FWI	Fatalities and Weighted Injuries
ORR	Office of Rail and Road
PIM	Precursor Indicator Model
PPM	Public Performance Measure
RSSB	Rail Safety and Standards Board
SMIS	Safety Management Intelligence System
SPADs	Signals Passed at Danger
SRM	Safety Risk Model
TOCs	Train Operating Companies
VPF	Value for Preventing a Fatality

1 INTRODUCTION

1.1 Background

Over the years of its existence, the focus of performance on Great Britain's railway[1] has often shifted between safety and the operational performance of services on the network. This was mainly influenced by customer preferences or demand for reliable services and the occurrence of accidents. For instance, railway companies in the 19th century are known to have continually prioritised short term operational/business performance over safety in order to minimise costs (Rolt, 1998 and Wolmar, 2008). A good example of this is the withdrawal of Sunday services in the 1860s by several companies to save money (Wolmar, 2008). Meanwhile within the same era, railway companies were reluctant to introduce automatic braking systems until compelled by government legislation (Rolt, 1998) following an accident at Armagh in 1889.

In recent times, Network Rail – responsible for the infrastructure management of Britain's railway network – collects and analyses data on passenger train service performance while the Rail Safety and Standards Board (RSSB) collects and analyses data on safety performance. These datasets have been studied independently over the years with the aim of improving performance or safety without any dedicated work published on exploring the relationship of one with the other.

Hitherto, railway safety and operational performance are both measured in terms of divergence from a planned ideal (e.g., minutes late, or people harmed) and in some cases these failures

[1] Here on referred to as GB's railway or GB rail.

have common causes (e.g., a broken rail leading to train derailment, causing delays to other trains and harm to the passengers). So, as safety and performance are both emergent properties of complex systems, it is surprising that there is little work looking at the nature of the relationship between the two.

This thesis therefore aims to identify what can be quantified in the relationship between railway safety and operational performance by developing a valuation approach that values safety risk and delays on a common scale. It is suggested that the approach could be useful to the stakeholders of rail industries to inform decision making.

1.2 Research Scope

GB's railway is considered amongst the safest major railway networks in Europe with no record of passenger fatalities for the last 13 consecutive years (Global Railway Review, 2019, Rail Safety and Standards Board, 2020). However, only 74% of rail passenger journeys in 2019 were rated satisfactory with regards to the punctuality/reliability of train services (Transport Focus, 2020). Improving railway operational performance is currently a key focus of GB's rail industry and safety on the network is an equally important focus.

By presenting a case study of the GB railway network, there is an opportunity to use derived key performance indicators which can help define the parameters required to establish a more detailed understanding of the relationship between railway safety and operational performance[2]. Focusing on passenger rail, key organisations such as the Department for Transport (DfT), the Office of Rail and Road (ORR), RSSB, the passenger train operating companies (TOCs) and Network Rail are responsible for the safe, reliable and efficient operation of trains on GB railways. Hence these organisations are considered as potential units of analysis for the research.

One of the key purposes of this thesis is to stir up a discussion within research and academia on the subject of developing an understanding of the relationship between railway safety and operational performance. ORR, Network Rail and RSSB have publicly available data on the safety and operational performance of GB's railway making it possible to undertake this research. However, a major challenge is the format of reporting for which these datasets are presented; making it difficult to reliably compare the performance measures on a common scale. The approach developed is however considered reliable, repeatable and accurate with the use of requisite data.

1.3 Research Objectives

The main aim of the research in this thesis is to facilitate the understanding of the relationship between railway safety and operational performance by comparing them on a common scale

[2] For the purpose of this thesis, the term safety performance and operational performance are in reference to the "quality" of safety and operation of passenger train services on Britain's railway network respectively. Throughout the thesis, "safety and operational performance" and "safety and performance" are used interchangeably to mean safety and operational performance of the railways. However, when 'performance' is mentioned alone (i.e., without 'safety'), this is a specific reference to the general or overall performance – including both safety and operational performance – of the rail network

while building on existing approaches in the industry. Underpinning the research are the following research objectives

i. To explore publicly available data on GB railway safety and operational performance in order to identify the factors that influence these two performance measures.
ii. To demonstrate the possible interactions between the influencing factors that form a relationship useful to develop an understanding.
iii. To identify the various industry approaches for managing and measuring the impacts of network disruptions /events /incidents on railway performance (i.e., safety and operation).
iv. To develop a valuation approach for comparing risk and delay on a common scale (i.e., in monetary terms)
v. To use the valuation approach to better facilitate the rail industry stakeholder decision making
vi. To identify insights that are useful to GB's railways and railways in other countries

These objectives will be achieved by addressing the following research questions

1. What are the influencing factors of safety and operational performance and how do they interact with each other?
2. What are the approaches for managing and measuring the impacts of network disruptions /events /incidents on railway performance?
3. How do you develop an approach for comparing risk and delay on a common scale?
4. How can the stakeholder decision making process be better facilitated with the use of the valuation approach?

5. What is/are the insight(s) from this research that is/are beneficial to GB's railways and the railways in other countries?

The answers to these research questions will be sought through literature review as well as through the examination and analyses of publicly available data.

1.4 Research Approach

To achieve the research goal, the thesis adopts a systems thinking approach by exploring and analysing various reasons for delays and risk to passenger train services on GB's rail network. Systems thinking acknowledges the relationship between components by looking at connected wholes rather than separate parts (INCOSE, no date). The approach is utilised in systems engineering, which is the design and management of complex systems – in this case railway systems.

The thesis is therefore developed on the logic that safety and performance are both emergent properties of complex systems; yet there is little work exploring the nature of the relationship between the two. The research begins with the question of the functionality of the perceived relationship between safety and operational performance. That is *"how exactly does this relationship work and what influences the performance of railway safety and operational performance?"*

The response to these questions is achieved by exploring delay incident data and records of hazardous events on the railway network to identify those common to both measures. The results help in visually presenting the interactions between the influencing factors showing the relationship between safety and operational performance. An experiment to quantify the impact of the common influencing factors is then developed to help assign a common financial scale to calculate the relative values of impact of events/interventions on safety and performance. This is aimed at providing industry stakeholders a valuation approach that values safety risk and delays on a common scale which could be useful to the stakeholders to facilitate the process of making better informed decisions. The results from the experiment are applied to a real-life scenario to demonstrate the benefit or use of the approach to stakeholders within the industry.

Figure 1 below illustrates the thought process adopted for the research. The alphanumeric numbers in the diagram represent the research questions 'R' and the chapters 'C' within the thesis to which the thought process is linked.

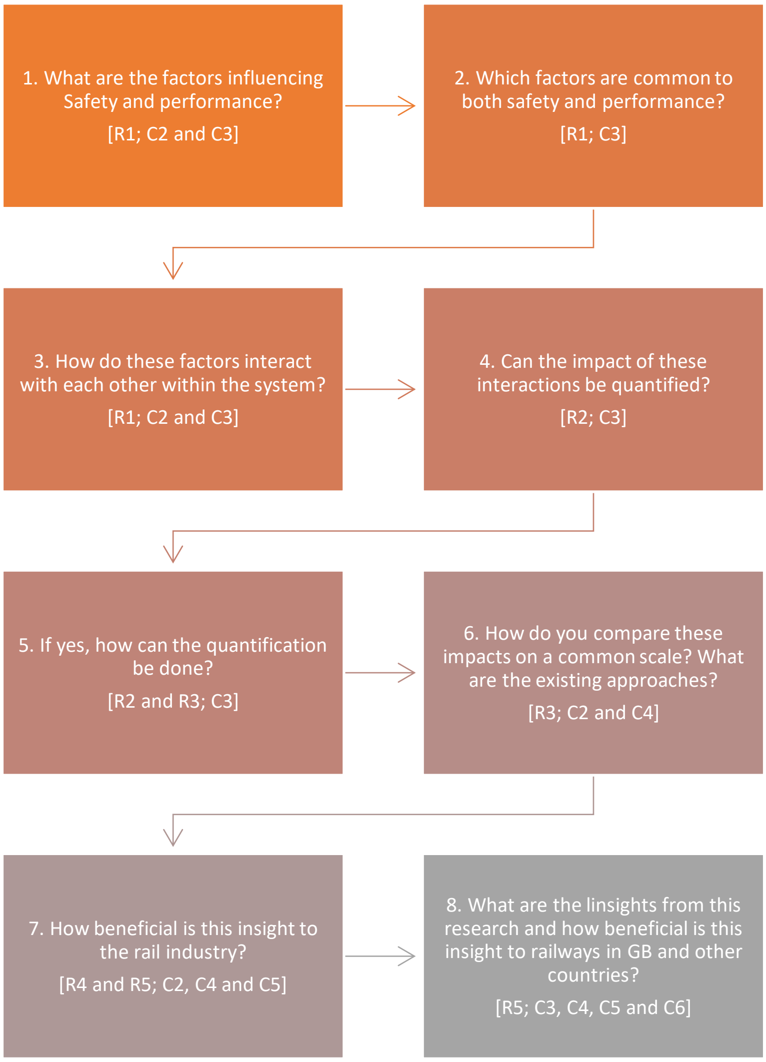

Figure 1: Conceptual Framework / Research Approach

1.5 Thesis Structure

The structure of the thesis is as follows

Chapter 1

This is the first chapter and an introduction to the thesis. It provides a background to what the thesis seeks to achieve, which is to develop an understanding of the relationship between railway safety and operational performance. The chapter also outlines the objectives and provides a conceptual framework as to how the aim of the research study will be achieved.

Chapter 2

This chapter presents a review of literature on current practices in relation to managing risk and delays on GB's railway network. It also explores how safety and performance are managed in other industries (e.g., aviation and the oil and gas industries). From the literature, it is discovered that managing the two performance measures together is not popular in the transport industry but is however a very common practice in management – and also well researched.

Chapter 3

This is the first of three major chapters in this thesis. It involves the exploration of railway safety and operational performance data which leads to identifying some of the challenges faced with analysing the two datasets due to the separate management approach adopted by the industry. A causal loop diagram is used to demonstrate the relationship between safety and operational performance based on the insights from exploring the data. Also, in order to analyse both performance measures, 12 common performance influencing factors are identified from the data exploration process. The term 'CPIF' is coined and referenced to the 12 influencing factors throughout the thesis. The data is then analysed for which risk and delay values are estimated for each CPIF.

Chapter 4

As the second major chapter of the thesis, it presents a description of the process for converting risk and delays into monetary values in order to compare them on a common scale. The converted risk and delay values are analysed (i.e., in monetary terms) from which insights on the value attached to safety and performance by the rail industry can be drawn. A flow diagram for converting risk and delays into monetary values for comparison on a common scale is also presented in this chapter.

Chapter 5

This is the third and final major chapter of the thesis. The chapter adopts a case study approach to validate the work done so far by applying the valuation approach to real-life data. Scenarios are developed using industry data on trespass incidents to help demonstrate how stakeholders can use the approach to make better informed decisions in the decision-making process. The chapter also highlights some of the challenges faced with the use of publicly available data and recommendations on the need for a common 'event-based' reporting system is reiterated.

Chapter 6

This is the concluding chapter which presents a signpost on how the study achieved the research objectives set out in Chapter 1 of the thesis. It presents a summary of findings from which conclusions are drawn and the contributions to knowledge presented. Recommendations and suggestions for further studies are also presented in this chapter of the thesis.

Appendix

The Appendix contains additional information (e.g., data and graphs) that can be referred to for further information regarding this study.

1.6 Publications

The following publications and conference presentations/proceedings were carried out during the course of this PhD.

- Wemakor, W.D., Jack, A. and Schmid, F., 2018. Establishing the relationship between railway safety and operational performance. In: Ricci S. and Brebbia, C. A. (eds). *Transport and the City*. Southampton, Boston: WIT Press, pp.103-120.

This paper presents an analysis of publicly available data to suggest how railway safety has in a more general way impacted railway performance and by extension derive lessons for emerging and developing economies. The key finding from this research was that there are various factors that influence the safety and operational performance of railways that go beyond the managerial control of train operating companies.

This thesis therefore builds upon this finding by exploring the various underlying factors of risk and delays on GB's railway network – see Chapter 3 – in order to develop an understanding of the relationship between railway safety and operational performance.

- Wemakor, W., Jack, A. and Schmid, F., 2018, April. Modelling the Relationship (s) between safety and operational performance. In *2018 Joint Rail Conference* (pp. 1-8). American Society of Mechanical Engineers.

This paper provides an overview of performance models and presents a model framework that incorporates both elements of safety and operational performance in an attempt to facilitate the understanding of railway safety and operational performance.

The model framework from the paper has been significantly modified and updated in order to introduce the Common Performance Influencing Factors (CPIFs) which have been used and reported in this research in Chapter 3 of the thesis.

2 Review of Literature on Safety & Operational Performance

2.1 Overview

Providing a safe, reliable and efficient railway for customers of GB railway is at the heart of its operations. However, the industry is faced with various challenges in its daily operation which range from train or infrastructure malfunctions to a trespasser on the line resulting in risk and delays to services. The ability of the industry to reduce the frequency of such incidents as well as mitigate the impacts with respect to disruptions to services (be it a risk or delay incident) is paramount.

This thesis is among the first of its kind to explore safety and operational performance data together for the enhancement of the rail industry. The chapter therefore reviews literature on the relationship between the two parameters in management and other industries such as the aviation and oil & gas industries. It also presents a discussion on how safety and operational performance are managed on GB's rail network by reviewing the industry's reports and publications to help identify the various data types and sources available for the study.

2.2 The Relationship between Safety and Operational Performance

Many organisations and industries such as the manufacturing, transport and oil & gas industries pride in the safety of their operations and consider it a vital component of their operation process. Therefore, there are various processes and management systems in place to enhance the safety of the workers, the safety of the production of goods or services and the safety of consumers. However, studies in relation to the relationship between safety and operational performance – the two major performance goals – are almost non-existent in the railway industry where others have thoroughly investigated this phenomenon (e.g. the manufacturing industry) with the debate on whether the two performance measures are contradictory (Westgaard and Winkel, 2011) or complementary (Das et al., 2008).

According to Brown (1996) – supported in a recent study by Hasle et al. (2021) – safety with regards to management has generally been studied as a stand-alone phenomenon even though it occurs in the context of a wider work setting impacted by decisions made by either the operation or safety managers. This is similar in the railway industry, whereby the literature on safety ranges from examining the safety culture of the railway industry as a whole (Clarke, 1998, Clarke, 1999, Farrington-Darby et al., 2005), to studies on the precursors that have led to train accidents (Kyriakidis et al., 2012) as well as the development of safety models, some of which have evolved from Reason's Swiss Cheese model (Reason, 1990, Leveson, 2004). Likewise, there are studies focused only on the operational performance of the railways with particular interest on the impacts of reforms and deregulation on performance (Cantos et al., 2010, Friebel et al., 2010) as well as focus on the effective operation and maintenance activities to derive a performance measurement system (Stenström et al., 2014).

Pagell et al. (2015) argue that safety and operations are neither inherently contradictory nor complementary but rather that managerial choices determine whether conflict occurs between operating a safe process and an effective process. This argument supports Hansen and Zhang (2004) study on the relationship between the National Air Space (NAS) safety and efficiency performance measures from the perspective of human factors and ergonomics. The study showed a positive relationship between operation errors and operational performance suggesting that safety and efficiency are complementary goals.

Pagell et al. (2015) then goes on to state that the relationship between being safe and effective is a function of the routines used to manage the production system. Therefore, they suggest that the approach for a complementary safety and effectiveness is the utilisation of a Joint Management System (JMS[3]) routine by both safety and operations managers. This is similar to DiMatteo (2014) suggestion of an asset integrity management approach for the oil and gas industry. The asset integrity management suggested by DiMatteo (2014) combines risk-based inspections[4] and reliability-centred maintenance[5] approaches with data management in order to improve both the safety and operational performance of oil and gas companies. It is argued that when safety and operations are jointly managed the system is stable – i.e., safe and effective. However, there's conflict between safety and operations when the functions are managed as separate and unequal silos (Pagell et al., 2015).

In the railway industry, there is the general perception that safety (i.e., the occurrence of incidents that can potentially lead to accidents) and operational performance (i.e., the efficiency and reliability of train services) go hand-in-hand or are complementary. However, others in the industry argue the two are in conflict. There are a very limited number of studies in the literature to support either argument. A study by Harrison and Weltz (2016) tests the hypothesis that the occurrence rates of personal accidents correlate with instances of train delays; constituting a case study to improve the understanding of the effects from train delays on safety risk across

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[3] JMS is a formal set of routines that allow for the shared planning, measurement, monitoring and continuous improvement of both safety and operations (Pagell et al, 2014) PAGELL, M., JOHNSTON, D., VELTRI, A., KLASSEN, R. & BIEHL, M. 2014. Is safe production an oxymoron? *Production and Operations Management,* 23**,** 1161-1175.

[4] Risk-based inspections (RBI) is a methodology used to reduce risk through the application of a strategic inspection program which optimizes inspection resources.

[5] Reliability-centred maintenance is based on principles similar to the RBI. It analyses conditions and performance data to determine which maintenance tasks to perform and when for more complex machineries when there are many failure modes and consequences.

Britain's rail network. Another study by the author of this thesis (Wemakor et al., 2018) presents an analysis of publicly available data to test the hypothesis that safety and operational performance are independent. The results suggested that there are various factors that influence the safety and operational performance of railways that go beyond the managerial control of train operating companies (TOCs).

This thesis (which is a continuation of the later study) contributes to bridging the gap in literature by further exploring the relationship and developing a new approach for comparing railway risk and delays on a common scale. This should be beneficial for stakeholders in making better informed decisions. The subsequent sections of the chapter therefore review industry publications and reports on how safety and operational performance are managed on GB's railway. This is in order to identify current practices and available data sources.

2.3 Great Britain's Approach to Railway Safety and Operation

GB's railway is often described as one of the safest major railway networks in Europe (Rail Safety and Standards Board, 2019a). It is noted among the safest in the world with recent reports of no fatal train accident for the thirteenth conservative year[6] (Global Railway Review, 2019, Rail Safety and Standards Board, 2020). This performance can be attributed to the industry's continuous commitment to provide a safe, reliable and efficient rail network for its users

[6] A ScotRail train derailed near Stonehaven, south of Aberdeen, in Scotland on 12 August 2020. The accident killed three people and six others injured (Holden, 2020). HOLDEN, M. 2020. 3 Dead, 6 Injured as ScotRail train derails near Stonehaven. *Rail Advent*, 12 August 2020.

through various investments and interventions such as investing in new technologies for traffic management systems e.g., European Rail Traffic Management System (ERTMS) (Network Rail, 2021a).

The GB railway network is operated on "vertical separation" (Abbott and Cohen, 2017), which means the operation of services is separated from the management of the infrastructure[7]. However, the structure of the railway is a lot more complicated than maintaining the tracks and running train services to ensure a safe, efficient and reliable service. According to the Williams Rail Review (2019), the current structure of GB's railway demonstrates a complex blend of both the private and public sectors. The report identifies the major or key features of the railways to include the funding bodies (e.g., the Department for Transport), network infrastructure (owned and operated by Network Rail), passenger train services (e.g., train operating companies), freight operators, the train fleet (mainly owned by the private sector rollingstock companies) and the Office of Rail and Road (ORR). In addition to these are other railway bodies such as the British Transport Police (BTP), the community rail partnerships, Transport Focus, the Rail Safety and Standards Board (RSSB) and the Rail Delivery Group (RDG). These organisations operate together to ensure the safe, reliable and efficient operation of train services on GB railway.

[7] Great Britain plans to reform the rail industry by introducing Great British Railways (GBR), a state-owned public body, from 2023. The organisation will oversee rail transport in Great Britain by replacing Network Rail as the operator of the rail infrastructure and will also control train operations by setting fares and timetables.

The major interest to this study is the organisations with a direct link of responsibilities to either the safety or operational performance (or both) of passenger services on the network. These are mainly the passenger train operators, Network Rail and RSSB.

2.3.1 Managing operations on Great Britain's railway network

As mentioned earlier, in GB, the operation of train services is separated from the management of the infrastructure in accordance with the EU Directive 91/440 – a legislative instrument which provided the framework for the operation of the government-owned railways in the European Union[8]. This Directive required that open access to track be granted to train companies other than those that own the track infrastructure. However, this has been replaced with the EU Directive 2012/34 (U.K. Government Legislation, no date). This new directive is similar to the earlier one but creates greater competition by allowing railway companies to run services on any member state infrastructure in order to foster a more efficient rail network (European Union, 2012).

Network Rail is therefore responsible for the operation and maintenance of GB's rail network whereas the freight and passenger train operating companies (FOCs and TOCs respectively) are responsible for providing train services. However, Network Rail and the train operators work together along with the local communities in which they operate in order to improve train performance on the 14 routes created by Network Rail. The routes are supported by the 5

[8] The United Kingdom officially left the European Union with a Brexit deal on 1 January 2021. However, GB maintains its operations of a vertically separated railway

Network Rail regions (see Figure 2 below), each led by a managing director (Network Rail, 2021c).

Figure 2: A map of Network Rail's routes and regions in GB

Delays are identified as a problem for the daily operation of trains that highly affect rail network performance (Berger et al., 2011). These delays are often caused by incidents on the network that can be anything ranging from a trespasser or buckled rail to a fallen tree blocking a line (Network Rail, 2021b). According to the Comptroller and Auditor General (2008), GB's rail network experienced almost 800,000 incidents that caused 14 million minutes of delay to rail journeys in 2006-07. This cost passengers a minimum of £1 billion in terms of time lost (Comptroller and Auditor General, 2008).

Information with regards to incidents are an important aspect of train operations in the rail industry. On GB's rail network, such information is obtained via reports from maintenance teams, traincrew, platform staff as well as members of the public in addition to Network Rail's remote monitoring system on the rail network that alerts them (Network Rail, 2021b). The information is often relayed to passengers in order to enhance passenger experience on the network. It is also stored in a database referred to as TRUST which is analysed (and also made available by Network Rail to developers on request) in order to improve performance on the rail network.

2.3.1.1 Measuring Operational Performance & Potential Data Sources:

Railway operational performance can be described in terms of the punctuality and reliability of train services on a network. On GB's railway network, this is measured by the Public Performance Measure (PPM) and delays to trains. PPM is a key performance metric for the evaluation of the overall performance and reliability of train services. It combines punctuality and reliability into a single performance measure and is defined[9] as "the percentage of trains which ran their entire planned journey calling at all scheduled stations and arriving at their terminating station within 5 minutes (for London & South East and regional services) or 10 minutes (for long distance services)" (Network Rail, 2021d). A train is said to be on time if it

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[9] This definition of the PPM is part of a new, precise and more detailed measure of railway performance introduced by Network Rail from 1April 2019. The new measure reports cancellations and the proportion of trains arriving to the minute at every station on the timetable, known as a 'station stop'.

arrives less than one minute later than its advertised time whereas a train is said to have either a 'half' or 'full' cancellation when it fails to stop at one or more scheduled station stops or completes less than 50% of its planned journey respectively (Network Rail, 2021e).

These measures of performance are recorded by Network Rail, the principal railway infrastructure management company of GB rail network. Network Rail has publicly available data on the occurrences and causes of delay. Reported as Historic Delay Attributions, this is the main source of operational performance data for this study.

2.3.2 Managing safety on Great Britain's railway network

GB's railway runs a risk and evidence-based approach to safety management which can be traced back to 1840 when the first Railway Regulatory Act established both a Railway Inspectorate and a requirement to report all injurious accidents to the Board of Trade (Harrison, 2019, Dacre, 2021b). Within 50 years, block signalling, interlocking and continuous braking on passenger trains had been made mandatory by the 1889 Railway Regulatory Act following the Armagh disaster on 12 June 1889 (Rolt, 1998, Wolmar, 2008). This was the beginning of a new safety regime on GB's railway.

The next century saw many more improvements ranging from continuous welded rail to automatic train protection systems – the development of new technologies which often came out of investigations (Wolmar, 2009). Currently, safety on GB's railway is partly the responsibility of RSSB, an independent body tasked with improving the rail industry's health and safety performance in order to reduce risk to rail employees, passengers and the public at large. It achieves this by tracking accident precursors – e.g., signals passed at danger – and analysing risk through its various reporting systems developed for the industry (Rail Safety and

Standards Board, 2019a). RSSB's safety reporting and intelligence systems for managing safety on GB's railway include

- The Safety Management and Intelligent System (SMIS) – online health and safety reporting and business intelligence software (Dacre, 2021a). It provides the industry with a rich evidence base that it draws on to better understand risk and take safety-related decisions (Dacre, 2021b).
- The Confidential Incident Reporting and Analysis Service (CIRAS) – captures health, safety, security and environmental concerns raised by individual workers. It also seeks a constructive response from the companies concerned (Baker, 2019).
- Close Call - this system enables the rail industry to record and manage conditions and behaviours that under different circumstances could have led to injury or harm. The information is used to mitigate risk and understand broader safety issues (Duggan, 2021).
- R2 (the vehicle database to improve maintenance planning) – this is the UK's central asset management system for railway vehicles and components, designed to improve maintenance planning. It holds details of every vehicle registered to operate on the UK railway and tracks the life history of each vehicle and their major component (Hundal, 2019).

The data collected from these systems are analysed and shared with the rail industry to help make informed judgement and take safe decisions. For instance, by identifying key risk areas, better policies can be formulated, and investments or operational decisions made so as to address these issues. Likewise, Network Rail, TOCs and other industry bodies play a role in ensuring safety on the GB railway network. In this regard, the RSSB has published a document – "Taking Safe Decisions" – which provides the industry with guidance on aspects of good practices grounded in risk-based evidence (Gilmartin, 2019a). Such information is useful in operation of services in the industry.

Within the "Taking Safe Decisions" document is a framework which outlines the stages in planning and decision making when contemplating change (Gilmartin, 2019b). The framework acknowledges that a change initiated by either safety improvements or for commercial/other reasons could potentially have safety concerns and should be investigated before and after the change is implemented (see Figure 3 below). However, these changes could potentially have operational concerns which will also need to be considered in the decision-making process.

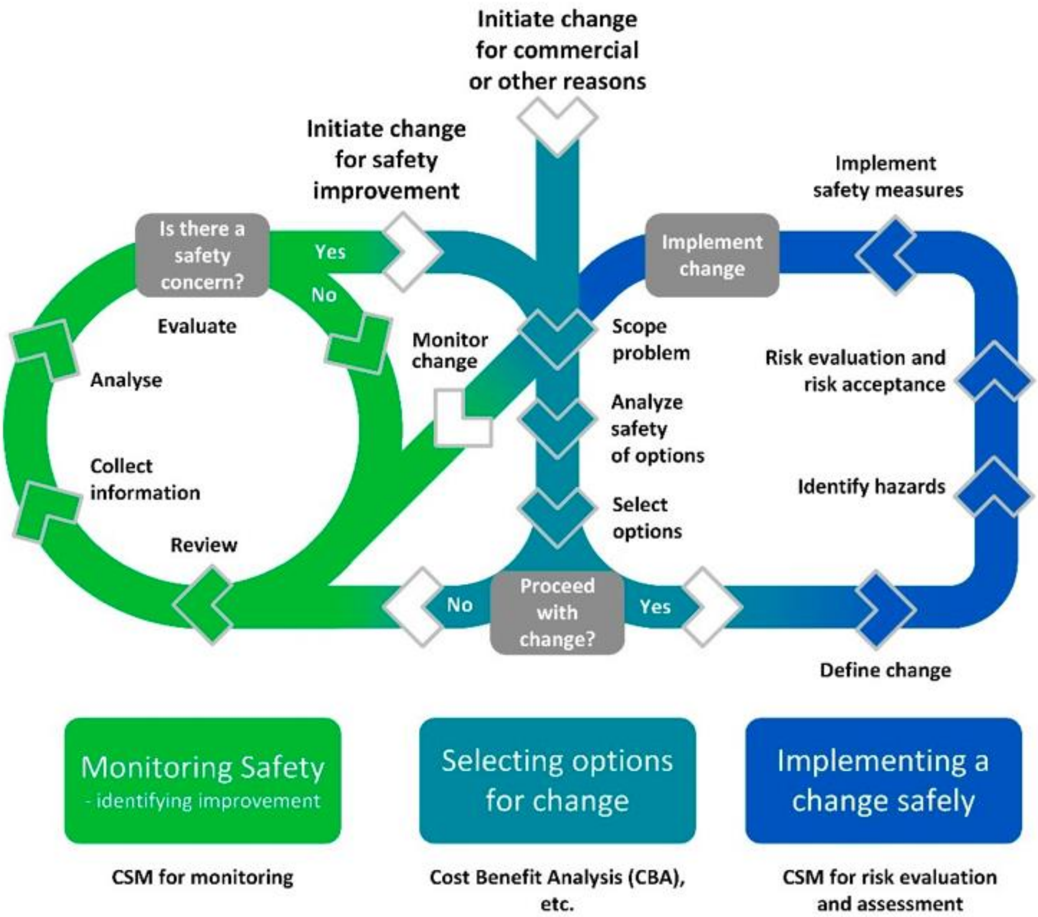

Figure 3: RSSB's Taking Safe Decisions Framework (RSSB, 2019: TSD – worked examples)

2.3.2.1 Measuring Safety Performance & Potential Data Sources:

Safety is generally measured by the number of accidents and their consequences which may occur at home, the workplace, school or on any mode of transport. Similarly, safety on GB's railway is measured by 'risk' which is defined as a combination of the number of times something happens (i.e. the frequency of an event) and its likely consequence ((Harrison, 2019). In rail, it is presented in units of Fatalities and Weighted Injuries (FWI), and often normalised by expressing the number per million train miles/kilometres.

According to the Rail Safety and Standards Board (2011), "the FWI measure takes account of the severity of each accident by weighting the lower severity injuries by a number that is considered to be statistically equivalent to a fatality". For example, 10 major injuries are equivalent to 1 fatality therefore has a weight of 0.1. Table 1 below shows the injury weightings that are currently in use in the industry.

Table 1: GB rail industry injury weightings for calculating FWI (Source: Annual Health and Safety Report 2018/19 (RSSB, 2019))

Injury Degree	Weighting	Number of Injuries Weighted as equal to a Fatality
Fatality	1	1 (fatality)
Major Injury	0.1	10
Minor Injury (Class depends on seriousness of injury)	0.005 (Class 1)	200
	0.001 (Class 2)	1000
Shock/Trauma (Class depends on seriousness of event resulting in shock/trauma)	0.005 (Class 1)	200
	0.001 (Class 2)	1000

Since FWI is the recognised unit of measure for risk in the GB rail industry, this measure will also be used in the research that follows.

The reporting of occurrences in the operation and maintenance of infrastructure on GB's railway network is a major source of rail safety data. As identified earlier, SMIS is "the rail industry's national database for recording safety-related events that occur on the rail network in Britain" (Macmillan, 2020). This software developed by RSSB, is used by the rail industry to collect a wide range of incidents including all injuries and safety events reportable under the Reporting of Injuries, Diseases and Dangerous Occurrences Regulations (RIDDOR) 1995 (Dacre, 2021a, Department for Transport, 2018).

Unfortunately, the SMIS data is not publicly available. However, the Safety Risk Model (SRM) also developed by RSSB, is publicly available and provides a network-wide risk profile of GB's mainline railway (Gilchrist and Harrison, 2021). The SRM was used to help develop the SMIS as it identified risk areas of interest. It is used by the railway industry to monitor safety performance and to manage change safely on the network. It also provides a trusted starting point for quantified risk analysis (Harrison, 2019). Therefore, the SRM serves as a good source of safety data – specifically Table C2 of the risk profile – for the purpose of this study.

The SRM consists of hazardous events that collectively define the overall risk on Britain's rail network (Harrison, 2019). According Gilchrist and Harrison, a hazardous event is any event which could result in death, physical injury or shock/trauma such as collision between two trains, a train derailment, person falling from platform, passenger slip/trip or fall, etc. These hazardous events are broken down into precursors which are a particular cause, type or location of the hazardous event e.g., train derailments caused by broken rail. The risk estimates of the SRM – derived from historical accident data, fault and event-tree modelling, structured expert judgement from technical specialist and statistical methods (Harrison, 2019) – also serves as a trusted source of risk values for the thesis.

2.4 Summary

It is argued that safety and operational performance are neither inherently complementary nor contradictory but rather jointly managing them is what makes these performance measures complementary goals. Focusing on GB's railway industry, the literature identifies that safety and operational performance are managed separately with the responsibility of each measure falling on RSSB and Network Rail respectively. It can therefore be said that there is the potential for trade-offs of one performance measure over the other in the decision-making process by the managers within these organisations and the industry at large. However, RSSB provides the "Taking Safe Decision" framework which incorporates safety in the operation and decision-making process for organisations in the industry. For example, organisations like Network Rail, train operating companies, rolling stock operating companies, etc.

The literature also shows that the reporting of safety incidents is more structured with varying systems for collation and analysis than there is for delay related incidents. That is, RSSB has developed some safety reporting and intelligence systems (e.g., SMIS, CIRAS, etc.) for the collation and analyses of safety data. Whereas Network Rail's reporting of incidents is made available in the TRUST database via information provided by reports from maintenance teams, traincrew, platform staff as well as the public in addition to Network Rail's remote monitoring system on the rail network. This could potentially cause a challenge in an attempt to analyse both datasets for the purpose of exploring the relationship between safety and operational performance.

The following chapter (i.e., Chapter 3) will therefore explore the available data (i.e., data from the Historic Delay Attributions and SRM Table C2) identified in this chapter in order to demonstrate the relationship between the two major performance measures of the rail industry.

It will also highlight the challenges faced when analysing the safety and performance datasets together.

3 Data Exploration & Modelling of Risk & Delay on Great Britain's Railway Network

3.1 Overview

There have not been many studies in literature on the relationship between railway safety and operational performance. As identified in Chapter 1, this thesis seeks to contribute to the subject matter by comparing risk and delays on a common scale. Following from the review of industry publications and reports in Chapter 2, it is noted that the available sources of railway safety data is different from the operational performance data. Although these datasets are collated from the reporting of incidents on the network, the responsibility of collating and analysing the performance measures are separated.

This chapter begins by exploring the safety and operational performance data from RSSB and Network Rail respectively. The aim is to identify common factors that influence risk and delays affecting the performance of GB's railway network. The chapter then adapts a Causal Loop Diagram (CLD) to demonstrate the relationship between the two measures using the identified influencing factors from the datasets. Finally, the impacts of the common influencing factors on GB's railway performance are quantified and analysed. This is aimed at providing insights that will be beneficial to converting risk and delays into monetary values in order to measure them on a common scale.

3.2 Data Exploration

As stated earlier in Chapter 2, risk and delays are the respective variables used to measure network performance levels with respect to railway safety and operational performance. These measures of performance (i.e., risk and delays) are mainly influenced by the occurrence of various events on the network which are recorded by the industry as either reasons for delays or hazardous events. By exploring the recorded data made available by Network Rail and RSSB, it is possible to identify events that influence both railway safety and operational performance on GB's rail network.

To begin with, 213 reasons for delays to passenger trains are identified from the 2016/17 delay dataset of Network Rail's Historic Delay Attribution. These are compared with 116 passenger train related hazardous events (recorded in RSSB's Table C2 of the risk profile) contributing to risk on the network. *[See Appendix 1 for list of delay reasons and hazardous events]*.

In comparing the data, each hazardous event is matched against the reasons for delays in order to group identical occurrences. It must be noted that, as these performance measures are managed by two different entities, there are slight variations in the description of some reported events. For example, RSSB reports point failures in the category of "track faults" whereas Network Rail considers these as "non-track asset faults". Therefore, to successfully group occurrences, individual discretions are made based on the description provided for the event within the dataset.

By grouping individual events of risk and delays into common event categories based on their descriptions, it is possible to identify the common factors that influence both risk and delays. These event categories are referred to as the 'CPIF' (i.e., Common Performance Influencing Factors) throughout this thesis. The names for the CPIF are adopted from both the hazardous event groups and delay categories in the risk and delay datasets respectively.

Table 2 below shows a list of CPIFs and specific factors that influence risk and delays. The risk and delay factors are respectively hazardous events and reasons for delay considered to have a similar description worth placing in the same group (i.e., CPIF). Therefore, although hazardous events are matched with delay reasons to form the CPIF groups, the number of factors for risk and delays vary due to the difference in description for similar events. For example, the CPIF “Level Crossing Incidents” has delay factors recorded in the delay dataset as “level crossing incidents including misuse” whereas the risk factors recorded are “Misuse Error, Violation, Proper Use, Passenger train collision with road vehicle on level crossing” among others.

Table 2: A table showing the identified CPIFs and a list of factors that influence risk and delays on Britain’s railway network (Adapted from RSSB’s SRM Table C2 and Network Rail’s Historic Delay Attributions)

CPIFs	Risk Factors	Delay Factors
Rolling Stock Faults/ Failures	Rolling stock door incidents (includes door faults), Rolling stock faults – other, Rolling stock (PT SPADs)	Door and Door system faults, Confirmed train cab based safety system fault (including GSMR), Confirmed Pantograph ADD, shoe beam or assoc. system faults including positive PANCHEX activations; Technical failures above the Solebar; Electric Loco failure, defect, attention; Diesel Loco failure, defect, attention; Technical failures below the solebar, Steam locomotive failure/defect/attention, International/Channel Tunnel locomotive failure/defect/attention; Wagons, coaches and parcel vehicle faults; Brake and brake systems faults including wheel flats where no other cause had been identified, Sanders and scrubber faults, Coupler and Coupler system faults, On train TASS/TILT failure, Delay due to ETCS/ERTMS on-board overriding driver command
Driver Errors	Train Driver braking errors, Other train driver errors, Train Driver over speeding errors, Train Driver errors resulting in SPADs	Driver
PT SPADs	Uncategorised driver error, Driver fails to check signal aspect, Driver fails to react to cautionary aspect, Driver fails to locate signal, Driver misreads by viewing wrong signal, Driver misjudges train behaviour, Driver misjudges environmental conditions, Driver views correct signal but misreads aspect, Driver anticipates signal clearance, Driver misreads	Incorrect route taken or route wrongly challenged by driver including SPADs

	previous signal, Driver ignorance of rules/instructions, Unknown driver misjudgement, Driver violation of rules/instructions	
Signaller Errors	Signaller communication errors, Correct information given but misunderstood by driver/signaller, Ambiguous or incomplete information given by driver/signaller, Wrong information given by driver/signaller, Signaller operating errors	Signaller, including wrong routing and wrong ETCS/ERTMS instruction, delayed by signaller not applying applicable regulating policy
Env. & Weather	Environment, Other environmental (PT SPADs), Subsidence/landslip (Track faults)	Failure to lay sandite or operate Railhead Conditioning train as programmed; Rail / wheel interface, adhesion problems (including ice on the running rail); Adhesion problems due to leaf contamination, cautioning due to railhead leaf contamination, Leaf fall neutral
Structural Failures	Structural failures resulting from subsidence or landslips, Structural failures – other	Earth slip/subsidence/breached sea defences (not the result of severe weather on the day of failure), Structures - Bridges/tunnels/buildings/embankments (not bridge strikes)
Track Faults	Defective S&C, Movement of points under train, Miscellaneous/unknown causes on S&C, Broken fishplate, Track twist, Gauge spread, buckled rail, Broken rail, Broken rail in tunnel	Points failure, Points failure due snow/frost where heaters fitted but not operative or defective, Points failure caused by snow or frost where heaters are not fitted, Track defects (other than rail defects) inc. fish plates, wet beds etc., Broken/ cracked/ twisted/ buckled/ flawed rail
Possessions	OTP inside possession	Possession over-run from planned work, Engineers train late or failed in possession, OTM DAMAGE, Engineers on-track equipment failure outside possession
Trespass Incidents	Adult/Child trespasser struck while crossing track at station, Adult trespasser electric shock in station	Trespass (including non-intentional), Disorder/drunks or trespass
Station Incidents	Passenger/MOP boarding/ alighting, Passenger/MOP fall from platform or bridge in station, Passenger/MOP struck while on platform, Staff struck while on platform, Passenger burns not on train, Fire in station, Passenger/MOP electric shock in station, Passenger injury due to being hit by objects/vehicles not on platform, Passenger/MOP struck while crossing track in	Passengers joining/alighting, Fatalities and or injuries sustained on platform result of struck by train or falling from a train, Station evacuated due to fire alarm, Mishap - Station Operating causes, Other Station Operating causes

	station, Staff fall between platform and train in station, Explosion in station, Passenger/MOP exposure to hazardous substances in station, Passenger fall during evacuation at station, Passenger exposed to noise	
Level Crossing Incidents	Misuse Error, Violation, Proper Use, Level crossings, Passenger train collision with road vehicle on level crossing, MOP pedestrian struck/crushed by train on level crossing, Passenger struck/crushed by train on station crossing, MOP slip, trip or fall on level crossing, MOP struck/trapped by level crossing equipment	Level Crossing Incidents including misuse
Vandalism	Train collisions caused by objects placed on the line by vandals, Train struck by objects thrown by vandals through train window, Train derailment cause by vandalism, Train fires caused by arson/vandalism	Vandalism or theft (including the placing of objects on the line), Vandalism or theft, Cable vandalism or theft, Fire caused by vandalism

Following from the exploration of the data that led to identifying CPIFs, a Causal Loop Diagram (CLD) – a type of systems dynamic tool – is used to demonstrate the relationship of factors that influence railway safety and operational performance. The 12 identified CPIFs in Table 2 are used as one of four types of nodes in the CLD to virtually demonstrate the relationship between safety and performance.

3.3 Causal Loop Diagrams

According to Forrester (1994), systems dynamics is the combination of theory, methods and philosophy required to analyse the behaviour of systems. Stock and flow, and the CLD are typical examples of system dynamic tools. While the stock and flow depict the structural understanding of a system (i.e., the causal structure that produces the observed behaviour), the

CLD on the other hand shows the cause-and-effect relationships between the variables of a system. This makes the CLD a suitable tool for this study in order to show the interactions between component variables (i.e., risk and delays).

Spector et al. (2001) assert that systems dynamics can be effectively used to promote the understanding of complex domains. A good example of such complex domains is the railway system and specifically for this study, GB's railway system.

The concept behind a causal loop diagram is to "provide a language for articulating our understanding of the dynamic interconnected nature of our world" (Tip, 2011, p.5). This is achieved by linking key variables and indicating the causal relationship between them. Tip (2011) explains that, by stringing together several loops, a coherent story can be developed for a specific issue in order to provide a better understanding of the general situation. In this case, by stringing together loops of factors influencing risk and delays, a coherent story can be developed to provide a better understanding of the relationship between railway safety and operational performance on GB's rail network.

A main challenge of the CLD is the degree of complexity it may entail; potentially defying the purpose of its representation (Spector et al., 2001). This challenge is addressed by presenting appropriate chunks in terms of clusters, sectors or parts of the system to facilitate understanding (Davidsen, 1996). In a like manner, this study focuses on sections of the railway system to facilitate the understanding of relationships by breaking down the complex system into manageable parts.

For instance, the CLD in this study looks at the safety and operational performance of GB's railway system with focus on events that are potentially hazardous and disrupt passenger train services in order to show the relationships between the two variables. However, it excludes aspects such as maintenance, governance, interventions among others to minimise the complexity of the relationship.

3.3.1 Modelling risk and delays

A CLD is made up of nodes (variables) and edges (links representing a connection or relation between the two connected nodes). From the exploration of the risk and delay datasets, four (4) main levels of nodes are defined in order to develop the CLD to demonstrate the relationship. These are

i. the performance measures (risk and delay),
ii. types of risk and delay,
iii. CPIF (event categories) and
iv. events (reasons for delay and hazardous events).

3.3.1.1 Performance measures

This is the first level in the CLD representing the performance measures of safety and operational performance. These are risk and delay on GB's railway network represented in bold capital letters in the centre of the CLD *[see Figure 4]*.

3.3.1.2 Types of risk and delay

The second level in the CLD constitutes the types of risk and delay on GB's railway network. RSSB's Precursor Indicator Model (PIM)[10] identifies six types of precursors to accidents (i.e.,

[10] PIM measures the underlying risk from train accidents by tracking changes in accident precursors, and is calibrated against the Safety Risk Model

risks) on the network. These are infrastructure failures[11], Signals Passed at Danger (SPADs), train operations & failures, infrastructure operations, level crossings and object on the line. These were adopted for the CLD and illustrated in boxes with links (red arrows) to the "RISK" variable *[see Figure 4]*.

Similarly, the types of delay identified from the Network Rail delay database include Network Rail-on-TOC delays, TOC-on-TOC delays and TOC-on-self delays. These are also illustrated in boxes with links (yellow arrows) to the "DELAY" variable in the CLD *[see Figure 4]*.

3.3.1.3 CPIF

The 12 identified CPIFs (from the data exploration) are represented as the third level of variables in the CLD. Each CPIF has a link to a type of risk and delay showing how they influence risk and delays on the network. These links are represented by red arrows showing risk interactions whereas yellow arrows represent delay interactions between the variables. That is, the interactions between CPIFs and types of risk and delay *[see Figure 4]*.

3.3.1.4 Risk & delay factors

The fourth and final level of variables in the CLD is risk & delay factors. These are the identified reasons for delays (shown in yellow fonts) and hazardous events (shown in red fonts) on the network. In the CLD, there are links from these factors to the CPIFs. These are represented with blue short dashed arrows to show the interactions between the factors and

[11] According to the PIM, infrastructure failures comprise of track, signalling, structural and earthworks related incidents. Whereas infrastructure operational failures comprise of operating incidents affecting level crossing, objects foul on the line, signaller errors, routing, track issues and other operating incident issues.

CPIFs *[see Figure 4]*. It shows that the factors (i.e., reasons for delays and hazardous events) contribute to the occurrence of CPIFs on the network.

Illustrated in Figure 4 below is a CLD showing how risk and delays are influenced by the identified factors from the risk and delay datasets. It highlights the interactions between the factors demonstrating how the occurrence of CPIFs influence both risk and delays. In the diagram, there are 3 main links that connect the various levels of variables described above. These are

i. interactions between the types of delay & risk and performance measures
ii. interactions between CPIFs and the types of delay & risk
iii. interactions between the risk & delay factors and CPIFs.

Also, the '+' sign at the head of the red and yellow arrows shows that an increase in frequency of the CPIF variables can lead to an increase in risk and delay respectively. For instance, an increase in the CPIF variable "Track faults" as a result of the frequent occurrence of one or more related risk and delay factors, will potentially lead to reports of an increase in infrastructure failures on the network (a type of risk). Likewise, this will potentially lead to reports of an increase in Network Rail related delays (a type of delay) to the operation of passenger train services. We observe that this single CPIF event has the potential to increase both risk and delay levels on GB's rail network.

An advantage of this CLD is that it helps the reader to visualise the influence of events on network risks and delays. The reader can see how the occurrence of events categorised as CPIF will potentially lead to both risk and delays that impact the performance of the network. Therefore, if the impact of CPIFs on risk and delays are quantified, then they can be analysed to provide insights that can further be used to measure risk and delays on a common scale.

The following section therefore discusses the approach to estimating the impact of CPIFs on GB's network performance.

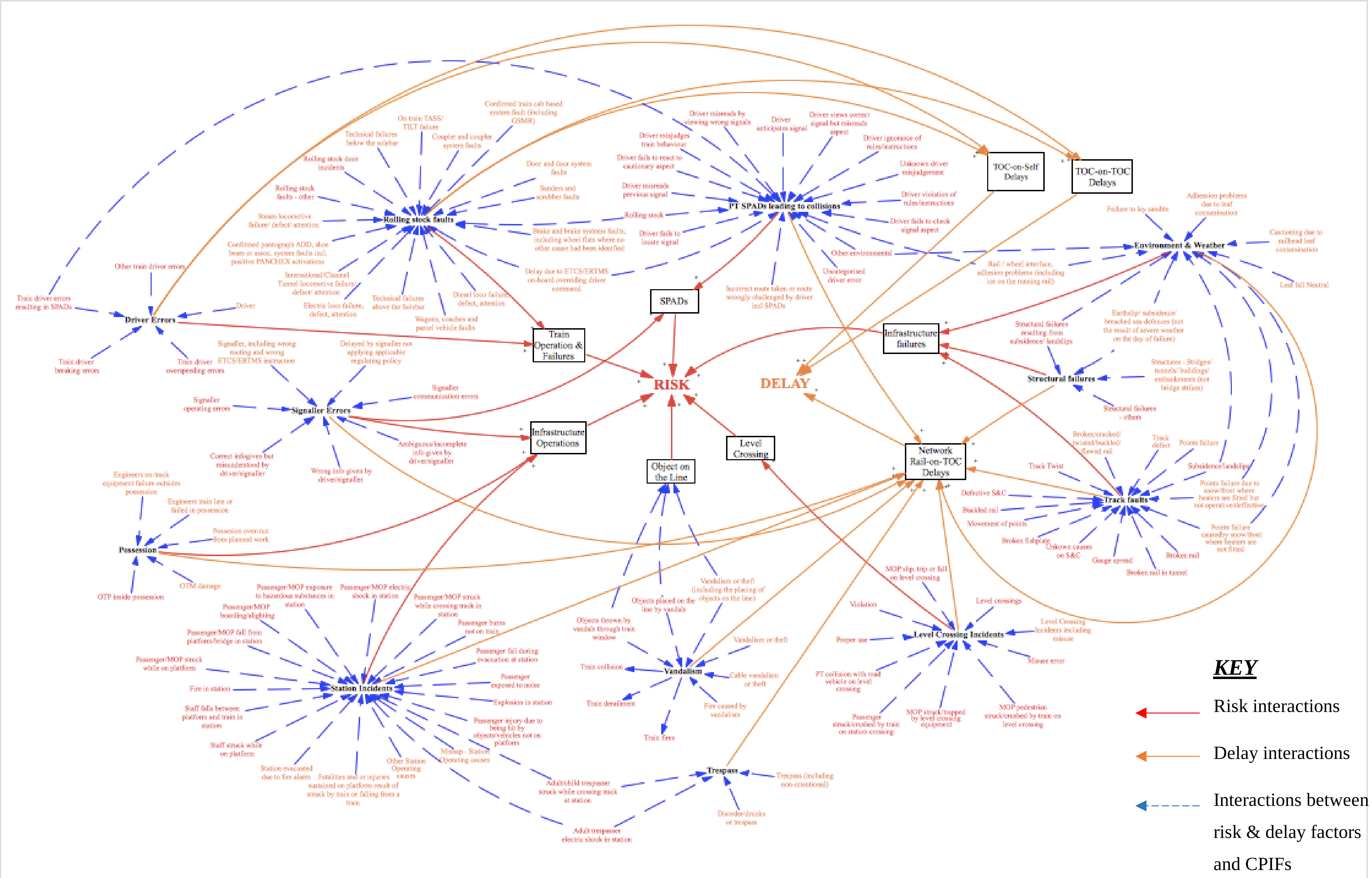

Figure 4: A Causal Loop Diagram of factors influencing risk and delays on GB's railway network (Author's construct using data from RSSB's SRM Table C2 and Network Rail's Historic Delay Attributions)

3.4 Estimating the risk & delay of CPIFs on GB's railway network

3.4.1 CPIF risk values

In Chapter 2, it was established that the FWI is the recognised unit of measure for risk on GB's rail industry. Hence it will be used in throughout the thesis.

To be able to quantify the risk and delay contributions of CPIFs on the network, the average risk as well as the delay per event within each CPIF group is calculated. To calculate the average risk, the risk contribution for the risk factors (i.e., hazardous events) identified in Table 2 are taken from RSSB's Table C2. *[See Appendix 2 for list of risk contributions of risk factors within the CPIFs]*.

The FWI values (i.e. risk values) are refered to as the risk contribution of the risk factors from which the average risk is calculated. Therefore, based on the risk factors for each CPIF, the average risk contribution is calculated and attributed to the CPIF as the average risk. That is,

$$Average\ risk\ (CPIF\ type)\ = \frac{Sum\ of\ risk\ contributions}{Number\ of\ risk\ factors}$$

For example, the CPIF "Rollingstock Faults/Failures" has the following risk factors and associated risk contributions: Rolling stock door incidents – includes door faults (1.67FWI), Rolling stock faults – other (1.66FWI) and Rolling stock – PT SPADs (0.003FWI). Therefore,

$$Average\ risk\ (\text{Rollingstock Faults/Failures})\ = \frac{(1.67 + 1.66 + 0.003)FWI}{3} = 1.11FWI$$

The results of the average risk are shown in Table 3 below.

Table 3: Average risk contribution for each CPIF

CPIFs	Average Risk (FWI)
Rolling Stock Faults/ Failures	1.11
Driver Errors	0.35
PT SPADs	0.02
Signaller Errors	0.01
Env. & Weather	0.70
Structural Failures	0.42
Track Faults	0.03
Possessions	1.23
Trespass Incidents	6.37
Station Incidents	1.31
Level Crossing Incidents	2.89
Vandalism	0.07

In this research, the average risk value is used to give a representative value of the potential risk of an event as defined above. However, it is acknowledged that the use of average risk values may not always reflect the full extent of the risk contribution of an individual event.

3.4.2 CPIF delay values

Similarly, the average delay per event is calculated by using the information on the occurrence of delay events (i.e., reasons for delay) and the associated delay minutes reported in Network Rail's Historic Delay Attribution database. As the dataset does not aggregate events to show frequency, Microsoft Excel's Pivot Table tool is used to count the number of events and sum up the minutes of delay associated with each event to get the frequency and delay minutes for each reason for delay per year. *[See Appendix 2 for frequency and delay minutes of delay factors within the CPIFs]*.

To calculate the average delay minutes for the CPIFs identified in Table 2, the delay minutes of the delay events within each CPIF are summed up and then divided by the sum of frequency. That is

$$Average\ delay\ (CPIF\ type)\ =\ \frac{Sum\ of\ delay\ minutes}{Sum\ of\ frequency\ of\ delay\ events/factors}$$

For example, the CPIF "Rollingstock Faults/Failures" has 15 delay factors with a total delay minute of 3,722,267.73 minutes occurring at a total frequency of 540,493 times in 2016/17. This implies that,

$$Average\ delay\ (\text{Rollingstock Faults/Failures})\ =\ \frac{3{,}722{,}267.73\ mins}{540{,}493} = 6.89\ mins$$

It must be noted that, the average risk of a CPIF is the annual average risk contribution. This is irrespective of the frequency of events within a year as the risk data does not provide any information on the frequency of hazardous events. However, for the average delay of a CPIF, this is the average minutes of delay for each occurrence of an event (specific to that particular CPIF) within a year.

In addition, each CPIF has records of thousands of delay events (with the exception of PT SPADs recording 229 events) with the associated minutes of delay. Therefore, to ensure that the calculated average delay gives a suitable representation of the events on the railway network, it is calculated assuming a lognormal distribution and a "*Two – Sigma*[12] *(*2σ*)"* approach is adopted to give an idea of the spread of individual sampled events from the calculated average values that will be used in the analysis. *[See Appendix 4 for distribution graphs]*.

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[12] σ is the symbol for standard deviation. Therefore, 2σ refers to 2 times the standard deviation. This approach is used in calculating confidence interval whereby 95% of random variations or distribution of the data will fall within 2σ.

3.4.2.1 Justifying delay averages

Firstly, a sample of the data for each CPIF dataset (i.e., data without 0 delay values) is used for the approach. Due to the skewness of the delay datasets (i.e., positively skewed data), the natural logarithm of the delay minutes for each event is calculated in Microsoft Excel by using the function 'LN'. Once the sample delay data is converted to natural logarithm values, the mean and standard deviation of the data are calculated using the Microsoft Excel functions 'AVERAGE' and 'STDEV.S' respectively. These are then used to calculate the mean and "Two – Sigma" values by calculating the exponent of the log mean and standard deviations using the Microsoft Excel function 'EXP' (i.e., performing the reverse transformation). That is,

$$Two - Sigma\ (2\sigma) = \ EXP\ [Log\ Mean\ \pm (2\ \times\ Log\ Standard\ Deviation)]$$

The results of both the average delay (calculated from the raw data) and the exponent of the log mean of the sample data are presented in Table 4 below. *[See Appendix 3 for Microsoft Excel formulas]*. Also shown in the table are the bounds/intervals obtained from calculating the 2σ values. The values in the table can be read as for each CPIF mean value (i.e., exponent of the log mean of the sample data), the researcher is confident that 95% of the data is spread between the 2σ lower and upper bounds.

Table 4: Average Delay results for both raw data and logarithm of sample data (Source: Network Rail's Historic Delay Attributions)

CPIFs	Average Delay (mins)	Sample Data		
		Exponent of Log Mean (mins)	Lower 2σ Bound (mins)	Upper 2σ Bound (mins)
Rolling Stock Faults	6.89	5.22	0.99	27.66
Driver	5.84	4.62	0.84	25.45
PT SPADS	9.35	5.74	0.73	44.80
Signaller Errors	3.77	3.64	1.23	10.73
Environment & Weather	2.49	2.01	0.49	8.29
Structural Failures	3.85	2.06	0.32	13.41
Track Faults	5.37	4.04	0.78	21.04
Possessions	4.66	5.41	1.05	27.86
Trespass Incidents	5.93	5.00	1.18	21.22
Station Incidents	3.06	2.90	0.89	9.38
Level Crossing Incidents	5.88	4.67	1.13	19.31
Vandalism	6.95	5.51	1.08	28.00

For example, the range for 95% of the Rolling Stock Faults data based on 2σ is from 0.99 mins to 27.66 mins with a mean of 5.22 mins. This means that the data is widely spread around the mean which is often expected of a skewed dataset.

3.4.3 Analysis of CPIF risk & delay values

The researcher has chosen to use the exponent of the log mean of the sample dataset as the calculated "Average Delay per Event" value for the rest of the thesis. This is because the new mean represents most of the data (i.e., 95%) however, there are some extreme events which are not then considered in the analysis of the data. Figure 5 below shows the estimated average risk and delay of CPIF events.

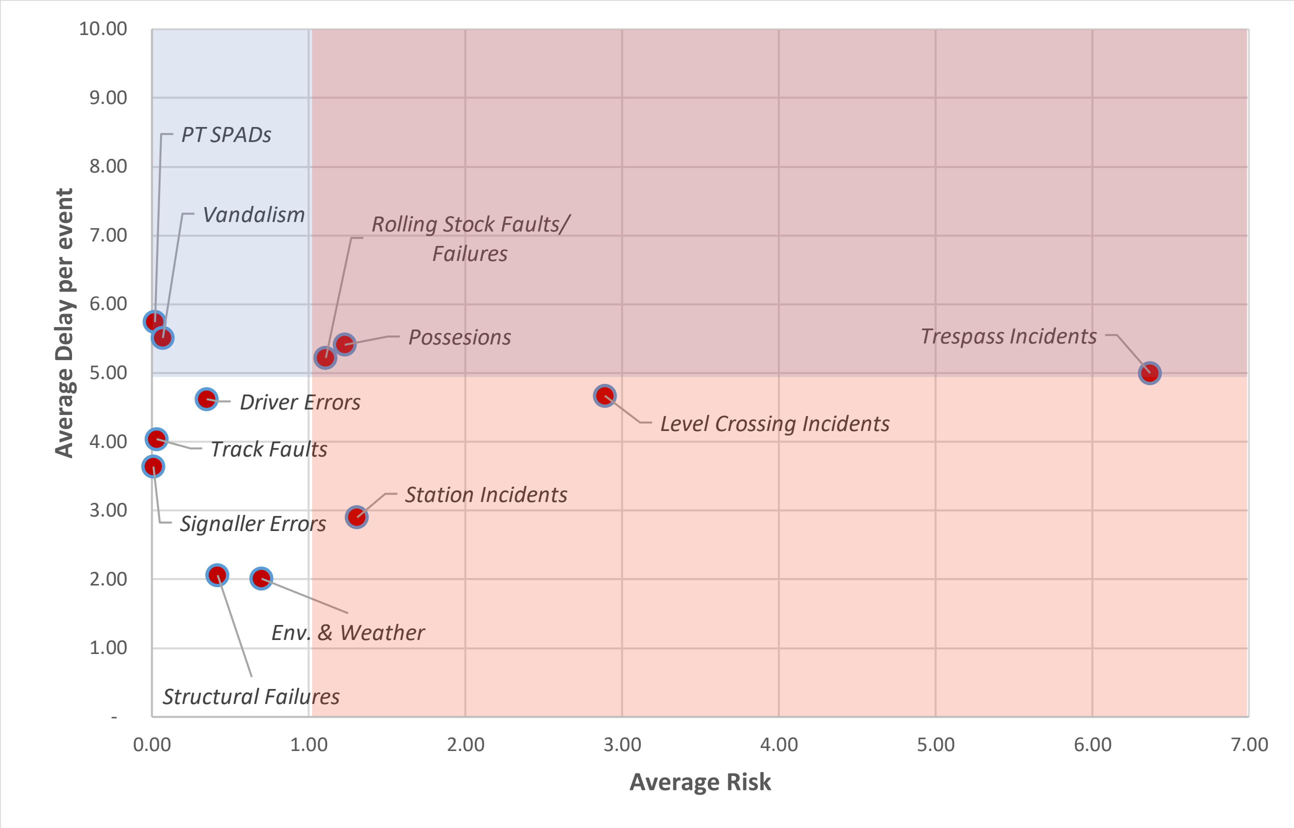

Figure 5: A scatter graph showing the average risk and delay per minute of CPIFs with standard deviation error bars (Author's construct adapted from RSSB's SRM Table C2 and Network Rail's Historic Delay Attributions)

Based on Network Rail's definition of punctuality, where the number of trains arriving within 5 minutes of scheduled arrival time is used, the blue shaded area (across the top of Figure 5) represents delay values which are higher than 5 minutes. CPIFs within this area (e.g., PT SPADs, rolling stock faults, etc) are considered in this study to have high delay values that can influence network performance when such events occur frequently. Likewise, the red shaded area in Figure 5 represents risk values higher than 1.0 FWI. CPIFs within this area (e.g., rolling stock faults/failures, possessions, etc) are also considered in this study to have high risk values.

In addition, another factor is considered for the classification of CPIFs with regards to delays to ensure that the classification is a reflection of the data. The additional factor considered is the threshold for which compensations are paid to passengers for delays to their journeys.

According to the Department for Transport (2020), Delay Repay 15 (DR15) compensate passengers for a delay of 15 – 29 minutes while passengers are eligible for Delay Repay 30 (DR30) when they are delayed by 30 minutes or longer. Based on these definitions, CPIFs are considered in this study to have high delay values if the upper 2σ value in Table 4 is more than 15mins.

Since majority of the data are spread within the 2σ bounds, it means that there is a higher chance of a single event within these CPIF groups to contribute to greater than 15 minutes delays on the network. Therefore, with reference to Figure 5 and Table 4, the CPIFs can be grouped in 4 main categories:

i. low risk low delay
ii. low risk high delay
iii. high risk high delay
iv. high risk low delay

Table 5 shows a list of CPIFs, their categorisation and associated risk and delay contributions on the network. From the table, it is observed that the CPIFs classified as high delay have a minimum average delay per event of 4 minutes. Therefore, high delay CPIFS are defined in this thesis as events that contribute to a minimum of 4 minutes delay per event on the network.

Table 5: Categorisation of risk and delays of CPIF (Author's Construct adapted from RSSB's SRM Table C2 and Network Rail's Historic Delay Attributions)

Event Categorisation	CPIF	Av. Risk (FWI/year)	Av. Delay per Event (Minutes)	Upper 2σ Bound (Minutes)
Low Risk, Low Delay	Env. & Weather	0.70	2.01	8.29
	Signaller Errors	0.01	3.64	10.73
	Structural Failures	0.42	2.06	13.41
Low Risk, High Delay	Track Faults	0.03	4.04	21.04
	PT SPADs	0.02	5.74	44.80
	Vandalism	0.07	5.51	28.00
	Driver Errors	0.35	4.62	25.45
High Risk, High Delay	Rolling Stock Faults/ Failures	1.11	5.22	27.66
	Level Crossing Incidents	2.89	4.67	19.13
	Trespass Incidents	6.37	5.00	21.22
	Possessions	1.23	5.41	27.86
High Risk, Low Delay	Station Incidents	1.31	2.90	9.38

It should be noted that, although 'Structural Failures' and 'Driver Errors' are categorised as low risk CPIF events, they are considered by the author as events with medium risk levels (shaded orange in Table 5). This is because their risk contributions are within a similar range and are higher than that of the other low risk level CPIFs but lower than the high-risk level CPIFs. The author also considers 'Env. & Weather' as a medium risk level CPIF in comparison to the other CPIFs.

In Table 5 above, the average risk shown is per year whereas the average delay is per event within the year. Therefore, to be able to compare the risk and delay data of CPIF events, the average delays per year of each CPIF needs to be calculated. This is achieved by multiplying the average frequency of each CPIF from the delay data by the average delay per event. That is

$$Average\ delay\ per\ year\ (CPIF\ type) = Average\ frequency \times Average\ delay\ per\ event$$

For example, the CPIF 'Rollingstock Faults/Failures' has an average frequency of 36,033 and an estimated average delay per event of 6.89 minutes. This implies that,

$$Average\ delay\ per\ year\ (\text{Rollingstock Faults/Failures}) = 36{,}033 \times 5.22 = 188{,}092.26\ mins$$

Table 6 below shows average delay per year for each CPIF. It also shows the average frequency of delay events per year within a CPIF group.

Table 6: Average delays of CPIF per year (Author's Construct adapted from Network Rail's Historic Delay Attributions)

CPIFs	Average Frequency	Av. Delay per Event (Minutes)	Av. Delay (Minutes/ year)
Rolling Stock Faults/ Failures	36,033	5.22	188,092.26
Driver Errors	253,036	4.62	1,169,026.32
PT SPADs	229	5.74	1,314.46
Signaller Errors	74,232	3.64	270,204.48
Env. & Weather	18,605	2.01	37,396.05
Structural Failures	25,760	2.06	53,065.60
Track Faults	61,439	4.04	248,213.56
Possessions	20,811	5.41	112,587.51
Trespass Incidents	75,022	5.00	375,110
Station Incidents	23,717	2.90	68,779.30
Level Crossing Incidents	16,851	4.67	78,694.17
Vandalism	9,023	5.51	49,716.73

From Table 6 above, it is observed that ‘PT SPADs’, classified earlier as a low risk high delay CPIF records the lowest average delay in the year despite having the highest average delay per event (5.74 mins). This is attributed to the fact that ‘PT SPADs’ had the least frequency of events; an average of 229 occurrences in the entire year. If ‘PT SPADs’ recorded more events in the thousands like the other CPIFs, it could easily be the CPIF with the highest average delay like the CPIF ‘Driver Errors’.

The low record of ‘PT SPADs’, especially in the delay dataset can also be attributed to the fact that these events are not adequately captured like they are in the risk dataset. However, over the years the railway industry has invested in risk control measures (e.g., installation of Train Protection and Warning Systems) to reduce the rate of SPADs on the network. This, according to the safety trends on SPADs in the industry, has resulted in its low risk value. In return, it can be argued that it has also contributed to the low record of ‘PT SPADs’ related delays on the network.

Figure 6 below shows CPIFs average risk and delay per year. In the diagram, ‘Driver Errors’ and ‘Trespass Incidents’ are obvious outliers with the highest average delay and risk per year respectively.

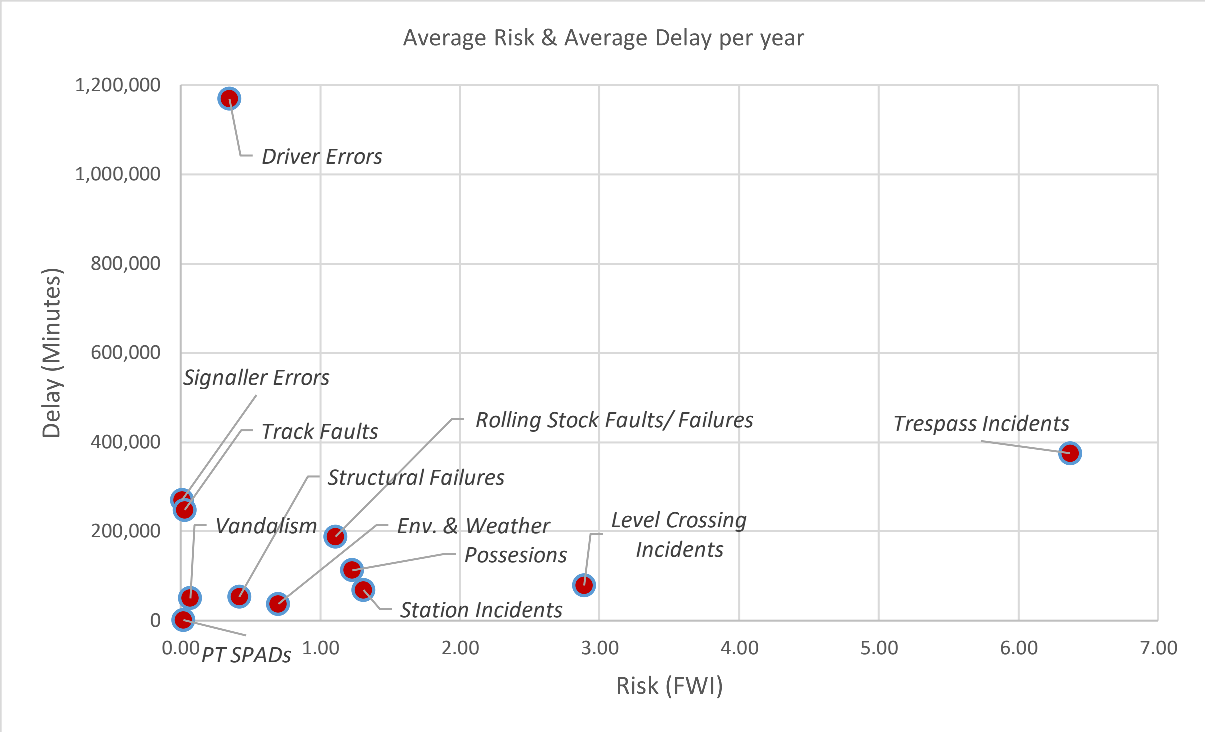

Figure 6: A scatter graph showing the average risk and average delay per year of CPIFs (Author's construct adapted from RSSB's SRM Table C2 and Network Rail's Historic Delay Attributions)

Identified as a low risk high delay CPIF, it is not surprising that 'Driver Errors' has the highest delay per year as it also has the highest average frequency of 253,036 occurrences per year. In the delay dataset, events within this CPIF are recorded as 'driver' with specific related reasons for delay, ranging from driver errors, station overshoot by driver, route knowledge issues, driver shortages, taking breaks, being late for duty among others. However, with respect to the risk dataset, driver related events are particularly focused on potential errors made by drivers during train operations and often associated with driver fatigue. For example, braking errors and over speeding errors as shown in Table 2 above.

This difference in the reporting of events for risk and delays is a challenge faced in this study as it makes it difficult to have full confidence in the values produced when comparing them.

Regardless, this section of the chapter has attempted to estimate the annual values of risk and delays of CPIFs on GB's rail network.

In addition to the findings from the diagram in Figure 6, Trespass Incidents do not only have the highest value of average risk per year (6.37 FWI) but also the second highest value of average delay per year (375,110 mins). This is in line with its earlier classification as a high-risk high delay CPIF in Table 5. Therefore, its record of an average frequency of 75,022 occurrences per year is alarming. This is because as a high risk high delay CPIF, it can potentially cause major disruptions to passenger train services which affects the performance of GB's railway network.

Currently, trespass incidents are of major concern to the railway industry – especially Network Rail (Network Rail, 2019) – due to the high volumes of delays this causes. There are various on-going safety campaigns and interventions by the industry to help curb the rate of trespass incidents on the network. For example, in 2018 the rail industry, Network Rail and the British Transport Police launched the "You Vs Train" campaign to raise awareness about the dangers of trespassing (Network Rail, 2021j). If these safety campaigns and interventions are successful at mitigating the occurrence of trespass incidents on the network, risk and delays could significantly improve. A decrease in risk and delays attributed to trespass incidents will, in the long run, improve the safety and operational performance of GB's railway network.

3.5 Summary

Risk and delays are loosely analysed together as there is no common language for the reporting and collation of the data. This chapter has attempted to compare risk and delay on GB's railway network by exploring the risk and delay datasets publicly made available by RSSB and Network

Rail respectively. This has resulted in identifying 12 influencing factors that are common to both risk and delays.

A CLD was developed with the help of the identified CPIFs from the datasets by stringing together loops of factors influencing risk and delays. The aim is to demonstrate how the occurrence of events on the network (especially CPIF related events) can potentially influence both risk and delays that impact the overall performance of the network. It is immediately realised that, by quantifying the impact of CPIFs on risk and delays it is possible to better analyse and provide insight that could further be used to develop a valuation approach to measure risk and delays on a common scale.

A major challenge with this chapter is the differences in reporting in the available datasets which makes it difficult to analyse both risk and delay as the datasets are collated and managed independently. The chapter therefore demonstrates how to manoeuvre through the datasets to analyse the risk and delays. That is, by actually clustering together similar definitions for hazardous events and reasons for delays, the term 'CPIFs' has been coined to represent the 12 identified common performance influencing factors.

In quantifying risk and delay values for the CPIFs, a lot of averages are calculated hence the standard deviations are calculated by adopting a lognormal approach in order to measure the dispersion/variations with the data being used. It is therefore suggested that future work on the subject area could include extending the calculations to include a Monte-Carlo analysis which might produce a statistical delay model. This model can incorporate the lognormal model in the calculations rather than using the mean as done in this chapter.

The next chapter, Chapter 4, converts the estimated values of risk and delays into a common language (i.e., monetary values) by using existing industry practices. This seeks to ensure for easy comparison and use by industry stakeholders in making informed decisions.

4 Monetary Valuation of Risk & Delay of the Common Performance Influencing Factors

4.1 Overview

The associated value attached to risk and delay by the railway industry from the general perception of an existing relationship between safety and operational performance is unknown. One of the key objectives of this thesis is to develop an understanding of the perceived relationship by comparing risk and delays on a common scale. This is to be achieved by using already existing approaches in industry which are discussed and demonstrated in this Chapter.

The chapter therefore begins with a discussion on the various techniques for assigning monetary values to performance measures in the transport industry. The purpose for this is to help identify a technique for converting delays into monetary terms. Risks on the other hand have an annual calculated value by RSSB used for converting risk values into monetary terms.

A description of the process of converting risk and delays into monetary values is presented and then followed by the analysis of comparing them on a common scale. This helps provide insights into the value attached to safety and performance by the rail industry. A flow diagram is presented at the end of the chapter showcasing a summary of the valuation approach for converting and comparing risk and delays on a common scale (i.e., monetary terms).

4.2 Techniques for Monetizing Transport Impacts

Performance measures used by transport agencies have varying purposes. These range from monitoring system performance to affecting budget allocation and project selection (Weisbrod et al., 2007). Nonetheless, monetary values are applied to the indicators of performance measures, especially the quantitative measures of performance (e.g., infrastructure preservation or congestion reduction), to estimate the full range of performance benefits.

Over the years, efforts have been made to monetize quantitative performance metrics. These efforts have been extended towards projects focusing on mobility or safety objectives in order to assign monetary values to project benefits (Weisbrod et al., 2007). Methods like cost-benefit analysis (CBA) are used to measure and compare the value of benefits relative to investment cost. These are practices common to the GB rail industry whereby safety benefits are incorporated into CBA by multiplying the expected risk reduction associated with a measure by the value of preventing a fatality (Rail Safety and Standards Board, 2019b).

However, there is not an outlined approach by the industry for monetizing delays on GB's railway network. According to Weisbrod et al (2007, 2009) there are 6 techniques for monetizing transport impacts in the industry. These are as follows

- *Damage Costs* – indicates the total estimated amount of economic losses produced or avoided by a project / program. For example, the damage cost of a railway train crush will include rollingstock damage, lost productivity when people are injured, disabled or killed, etc.
- *Control or Prevention Costs* – this technique is the cost estimated based on what it would cost to prevent, control or mitigate an incident after it occurred. For example, the benefits of air pollution reduction programs valued by considering the opportunity cost of compliance with Clean Air Acts.
- *Compensation Rates* – this technique uses legal judgement and other compensation rates for damages as a reference for accessing non-market costs. For example, if crash victims

are compensated at a certain level, this amount can be considered as a representative estimate of the cost of damages, pain & discomfort.

- *Revealed Preferences* – also referred to as "Shadow Pricing", this technique infers values for non-market goods from the effect on market prices, property values and wages. An example is the additional travel-related costs that are voluntarily incurred by visitors. This could provide a measure of the value associated with having improved access to destinations such as recreational sites (e.g., the park or other public lands).
- *Contingent Valuation (also called Stated Preferences)* – this technique relies on surveying a representative sample of individuals to deduce how much they value a particular factor or non-market good. For example, residents may be asked how much they are willing to pay for improvement in air quality or what will be the acceptable compensation for the loss of a recreational site. These surveys need to be very carefully structured and interpreted to obtain accurate results. This is because there is the potential for survey respondents to overestimate the extent to which they are willing to actually pay for and use new transportation services or improvements.
- *Direct Projected Income Growth* – the technique uses an economic model to calculate the income benefit that will occur as a result of implementing various proposed projects or programs. It is expressed in terms of worker income (wage) growth or total gross product (i.e., value added income) growth.

From the list outlined above, 'Compensation Rate' is identified as the most suitable technique for monetizing delays on GB's railway network. This is because it is already common practise within GB's railway industry for Network Rail and TOCs to pay compensation for delays to train services on the network. Although the 'Compensation Rate' technique as described above is originally focussed on compensation paid for damages, it will be used in this thesis in terms of compensation paid for delays to train services. This will provide a financial/monetary value (i.e., GB Pounds) that is a representative estimate of the cost of delays on the network.

4.3 Monetary Valuation Approach / Monetization Process

Identified in the literature review in Chapter 2 on GB's railway, risk is measured as a Fatality Weighted Injury (FWI) and is converted by industry into monetary terms using the Value of Preventing a Fatality (VPF[13]). The VPF is calculated by RSSB on an annual basis and is used in this section of the chapter to calculate the monetary values for risk.

Delays, on the other hand, have not got any specific value calculated on an annual basis to help convert the performance measure into monetary terms. However, there are monetary values associated with delays within the industry. These are in the form of compensations paid by either Network Rail or Train Operating Companies (TOCs).

Based on the discussion on the various techniques for assigning monetary values to performance measures in the transport industry, the compensation technique is used in this section of the chapter to calculate the monetary values for delays.

It must be noted that, due to the differences in managing risk and delays, different approaches are adopted for monetizing risk and delays. The value or cost of risk in GB's rail industry is

[13] This represents the maximum amount considered reasonable to pay for a safety measure that will reduce by one the expected number of preventable premature deaths in a large population (Department for Transport cited in Thomas and Vaughan, 2014)

calculated by RSSB based on a DfT methodology which uses economic indicators (i.e., increases in GDP per head and the willingness to pay). Meanwhile delay costs are calculated from Schedule 8 as set by ORR targets and rates. The cost formulation is complicated including targets for punctuality and varying between routes and potentially over time.

Consequently it is challenging to compare these like for like. Therefore, it may be appropropriate to apply a weighting to one of these – however what should that weighting be? Selections and justification of a weighting/normalisation value remains a topic for future research in this area. For the purposes of this thesis, the compensation and VPF approaches are used without adjustment in order to monetize delay and risk on GB's railway network respectively. See sections 4.3.1 and 4.3.2 below for the detail description of each process.

4.3.1 Monetizing CPIF risk values

Firstly, the calculated average risk values of the CPIFs identified in Chapter 3 are multiplied by the 'Value of Preventing a Fatality' (VPF). As mentioned earlier in the paragraph above, the VPF is published by RSSB on an annual basis and can be taken to be the monetary value of a single fatality weighted injury (FWI). For this research, the June 2018 VPF of ***£1,946,000*** (Rail Safety and Standards Board, 2018) is used in calculating the value of risk on the network. This is shown as follows:

$$Monetary\,Value\;(CPIF\;type)\;=\;Annual\;Av.risk\;\times\;£1{,}946{,}000$$

The result for each CPIF is shown in Table 7 below.

Table 7: A table showing the monetary values of risks for CPIFs on the network (Source: Author's construct adapted from RSSB's SRM Table C2)

CPIFs	Annual Av. Risk (FWI)	Monetary Value
Rolling Stock Faults/ Failures	1.11	£2,160,060
Driver Errors	0.35	£681,100
PT SPADs	0.02	£38,920
Signaller Errors	0.01	£19,460
Env. & Weather	0.70	£1,362,200
Structural Failures	0.42	£817,320
Track Faults	0.03	£58,380
Possessions	1.23	£2,393,580
Trespass Incidents	6.37*	£12,396,020
Station Incidents	1.31	£2,549,260
Level Crossing Incidents	2.89	£5,623,940
Vandalism	0.07	£136,220
TOTAL	*14.51*	***£28,236,460***

**The researcher is aware that the 6.37 FWI for Trespass Incidents appears to be understated as there are usually almost 40 FWIs among trespassers. However, Table C2 of the SRM only has records for station related trespass incidents. Hence the low value recorded.*

4.3.2 Monetizing CPIF delay values

Schedule 4 & 8 are the performance regimes in place between Network Rail and train operators. Specifically, Schedule 4 compensates train operators for the impact of planned service disruptions whiles Schedule 8 compensates train operators for the impact of unplanned service disruptions (Office of Rail and Roads, 2019).

The following assumptions are made in order to apply a monetary value to the CPIF delays

1. Delays in the delay dataset used for this study are Schedule 8 delays.
2. Schedule 8 compensations paid to TOC by Network Rail in 2017/18 are divided by the total value of Network Rail delay minutes for 2017/18 in order to estimate Network Rail's average cost of compensation per minute delay. The researcher is aware that the use of averages limits the applicability of the results to any particular decision, but it does provide a methodology where actual delay data and costs could be used by the relevant decision makers.
3. TOC compensations paid to passengers is divided by the total value for TOC-on-Self delay minutes in 2017/18 in order to estimate TOC's average cost of compensation per minute delay. Similarly, the researcher's use of averages only provides a broad estimate/token of the value of TOC delays limiting the applicability of the results to any particular decision. However, the approach provides a methodology where actual data and costs could be used by the relevant decision makers to make informed decisions.

Table 8 shows information on the compensations paid by Network Rail and TOCs in 2017/18. The estimated monetary value – i.e., average cost of delay compensations paid by both Network Rail and TOCs – are presented as *'compensation paid per minute'* in Table 8. These values are used in the calculations for applying monetary values to CPIF delays on the network.

Table 8: A table showing the compensation information used to calculate the monetary values of CPIF delays on the network (Source: Ames (2019), Department for Transport (and ORR data portal)

Network Rail on TOC 2017/18 Delays	8,847,772 minutes
Network Rail compensation paid to TOCs (Schedule 8)	£180,500,000
Network Rail paid compensation per minute delay	***£20.40***
TOC-on-Self 2017/18 Delays	3,590,979 minutes
TOC compensation paid to passengers	£80,710,000
TOC paid compensation per minute delay	***£22.48***

As rolling stock faults/failures and driver errors are TOC responsible delays, these delays *(shaded grey in Table 9)* are multiplied by £22.48 (i.e., TOC paid compensation per minute delay) to estimate their monetary values. The other CPIFs are multiplied by £20.40 in order to estimate their monetary values as these are Network Rail responsible delays. Since PT SPADs *(shaded in blue in Table 9)* are either Network Rail or TOC responsibility, the delay monetary value is calculated using the sum of TOC and Network Rail paid compensation per minute delay (*i.e., £22.48 + £20.40 = £42.88*). The results of the estimated monetary values for delays are shown in Table 9 below.

Table 9: A table showing the monetary values of delays for CPIFs on the network

CPIF	**Annual Av. Delay (Minutes)**	**Value per minute delay**	**Monetary Value**
Rolling Stock Faults/ Failures	188,092.26	£22.48	£4,228,314.00
Driver Errors	1,169,026.32		£26,279,711.67
PT SPADs	1,314.46	£42.88	£56,364.04
Signaller Errors	270,204.48	£20.40	£5,512,171.39
Env. & Weather	37,396.05		£762,879.42
Structural Failures	53,065.60		£1,082,538.24
Track Faults	248,213.56		£5,063,556.62
Possessions	112,587.51		£2,296,785.20
Trespass Incidents	375,110		£7,652,244.00
Station Incidents	68,779.30		£1,403,097.72
Level Crossing Incidents	78,694.17		£1,605,361.07
Vandalism	49,716.73		£1,014,221.29
TOTAL	*2,625,200.44*		***£56,957,244.68***

4.3.3 Analysis of risk and delays on a common scale

Having calculated the monetary values for risk and delays, it becomes possible to compare the performance measures on a common scale (i.e., in monetary terms). Figure 7 below shows the CPIFs annual contribution to risk and delays on the network. Similar to the findings in Chapter 3, the diagram in Figure 7 shows that Driver Errors and Trespass Incidents have the highest railway operational and safety costs respectively. However, in comparing the risk and delay values in the diagram, it is observed that the cost of railway delays is generally higher than the cost of risk on the network.

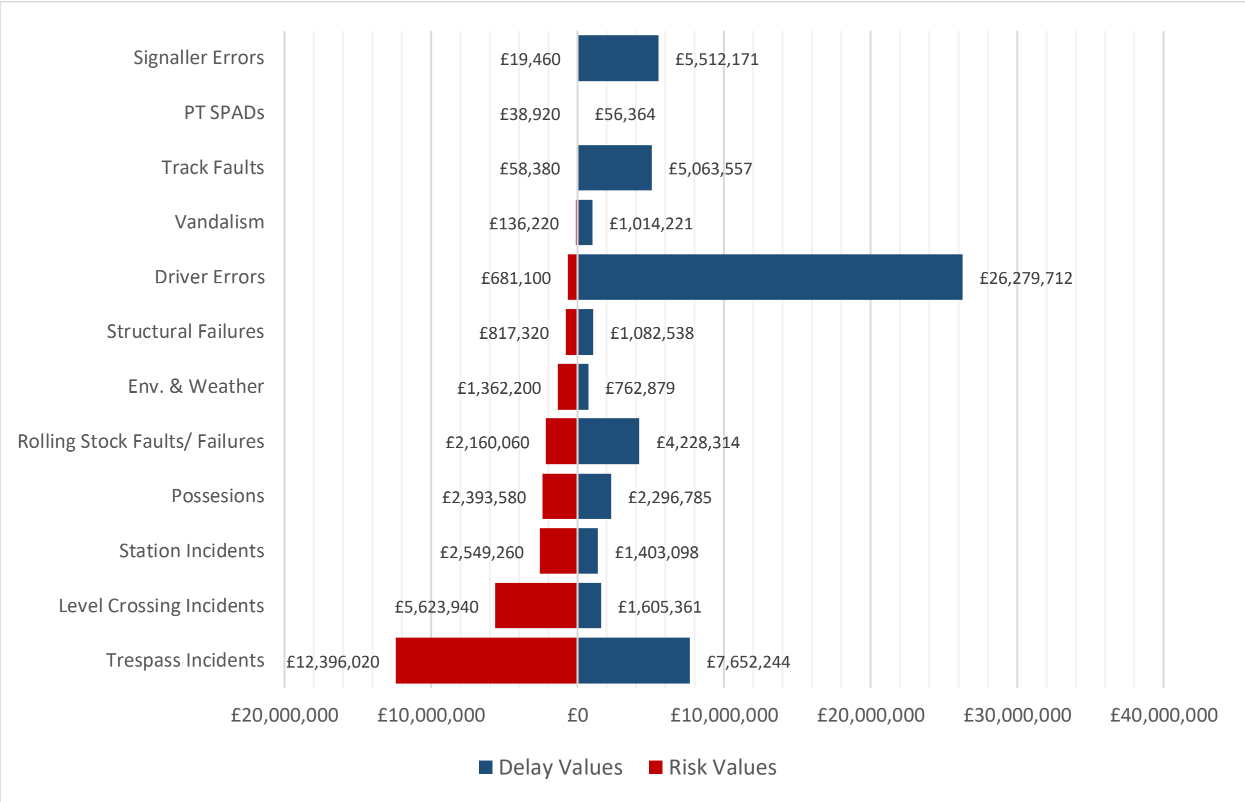

Figure 7: Annual monetary values of CPIFs showing the contribution of risk and delays on the network

From the diagram above, 58% of the 12 CPIFs have a higher cost of delay than risk. These are made up of events related to Signaller Errors, PT SPADs, Track Faults, Vandalism, Driver

Errors, Structural Failures and Rolling Stock Faults/Failures. The remaining 42% of the CPIFs have a higher cost of risk than delay on GB's railway network. These include events related to Env. & Weather, Possessions, Station Incidents, Level Crossing Incidents and Trespass Incidents; all of which are Network Rail responsible events.

It can be determined that, the TOC responsible CPIFs – excluding PT SPADs – have higher financial impacts on railway operational performance than on safety performance on GB's railway network. These CPIFs (i.e., Driver Errors and Rolling Stock Faults/Failures) have an estimated total annual cost of £30,508,206 for delays and an estimated total annual cost of £2,841,160 for risk. This implies that, should railway stakeholders be interested in investing in technology or solutions aimed at reducing the occurrence of Driver Error and Rollingstock Faults/Failures related events on GB's railway network, there is the potential to reduce the cost of railway disruptions by £33,349,186.

The CPIF monetary values are beneficial for use in the Cost – Benefit Analysis approach which is widely used in the railway industry. An awareness of the risk and delay impact of CPIFs as well as their associated monetary values can be useful for stakeholders in making better informed decisions with regards to interventions aimed at improving railway performance. This is because for CPIF related interventions/solutions, stakeholders will have the opportunity to analyse risk and delays simultaneously by comparing them on the same scale.

Also, it must be noted that the relative significant values presented for risk and delays in the valuation approach are a reflection of the VPF and compensation. This perhaps shows that incentive regimes such as the ORR places a higher value on performance than the value placed on safety. The ORR reviews performance values on GB's railway every 5 years while the VPF is published annually by RSSB for industry. Hence, a review of the values and incentive regime policies are therefore suggested for the further development or improvement of the valuation approach.

Moreover, based on the finding that delay costs are higher than risk, it can be argued that further investments should focus more on improving performance than safety as this will deliver greater economic benefit. As part of further studies, it is recommended that, a complete cost benefit analysis should be undertaken by researchers to prove this. Meanwhile, the section below presents a flow diagram that illustrates the approach for comparing risk and delays on a common scale.

4.4 Flow Diagram

The flow diagram in Figure 8 below illustrates the approach to comparing risk and delays on a common scale. Improving railway performance is one of the key targets for stakeholders of GB's railway industry. This involves operational investments such as the improvement of asset reliability to reduce delays on the network or investments in safety technology to reduce risks on the network. These investments are often targeted at reducing the frequency of specific events on the network which may be either risk or delay related or may impact both risk and delays just like CPIFs. Therefore, the first step to comparing risk and delays on a common scale is to identify if the investment is targeted at an event (or events) that has an impact on both safety and operational performance (e.g., CPIFs).

If the event is a CPIF, then proceed to apply the valuation approach. That is, by identifying both the risk and delay impact of the event, monetary values can be estimated for comparison. As already discussed, a monetary value is applied to risk by multiplying annual risk values (FWI) by the VPF whereas the compensation rate technique is adopted in order to apply a monetary value to delays. The delay monetary value is calculated by multiplying the minutes of delay by its specific amount of compensation per minute delay (i.e., Network Rail or TOC compensation paid).

Now risk and delays can be compared in monetary terms. The safety and operational performance costs of the CPIF event have been calculated. The cost values can then be used in the Cost-Benefit Analysis (CBA) approach widely used by industry stakeholders in order to make informed decisions. *[See flow diagram below]*.

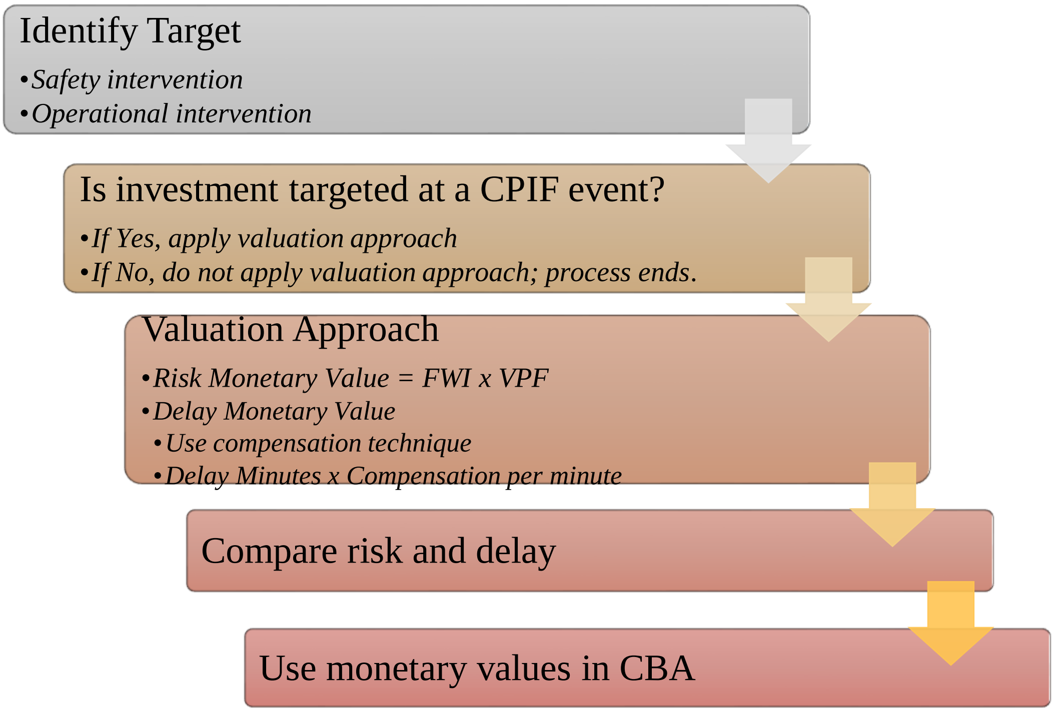

Figure 8: A flow diagram illustrating the approach to compare risk and delays on a compare scale.

4.5 Summary

The main contribution of this Chapter is that it has converted **risk** and **delays** of the identified CPIFs into monetary values for comparison on a common scale. This has been achieved by using available data and some existing techniques in the industry. To monetize risk, the VPF which is an annual estimate by RSSB of the cost of preventing a fatality is multiplied by the risk values of each identified CPIF. For delays, the ‘Compensation Rate’ technique is adapted for the monetization process.

This involves using the compensations paid by Network Rail and train operating companies which are a representative estimate of the cost of delays on the network. The compensations are then multiplied by the delays of the CPIFs to obtain the monetary values. It must be noted that, depending on the type of delay (i.e., Network Rail or TOC delay), the delay value is multiplied by either the amount of Network Rail or TOC compensation paid or the sum of both.

By comparing risk and delays on a common scale (i.e., GB Pounds), it is observed that the cost of delays is higher than the cost of risk on GB’s railway network. Majority of the CPIFs (58%) have a higher cost of delay than risk. However, for CPIFs with a higher cost of risk than the cost of delay, these are identified as CPIFs with Network Rail responsible events. These include Env. & Weather, Possessions, Station Incidents, Level Crossing Incidents and Trespass Incidents.

Based on this finding, it must be noted that the relative significant values presented for risk and delays in the valuation approach are a reflection of the VPF and compensation. Hence, as part of further studies, it is considered necessary to review both the VPF and compensation values along with related policies for further development of the valuation approach.

Lastly, this chapter has also presented a flow diagram of the approach to comparing risk and delays on a common scale. The approach creates a reasonable estimate of the relative significance of an event for both safety and performance but would need to be supplemented with actual data from particular routes and contracts to be used to support decision making. This will be demonstrated and discussed in Chapter 5, the next chapter.

5 Case Study: Application to Trespass Incidents

5.1 Overview

This chapter adopts a case study approach to demonstrate how to use the step-by-step approach provided in Chapter 4 to compare railway risk and delay in monetary terms. Within the approach, it also demonstrates how stakeholders can use the monetary values in decision making by using trespass incident data from RSSB's SMIS and Network Rail's TRUST systems, which are recorded by route. Actual data is used to demonstrate the applicability of the approach.

The case study discusses the characteristics of the Network Rail routes for which the trespass data is provided. The valuation approach is then discussed step-by-step alongside the presentation of key information such as route strategic plans specific to trespasses. A discussion of the valuation approach is presented highlighting the use of the risk and delay monetary values in Cost – Benefit Analysis (CBA) of rail projects by stakeholders. The case study highlights the need to have a common language for collating risk and delay data.

5.2 Network Rail Routes

As discussed in Chapter 2, Network Rail has 14 routes operating within five regions which are led by regional managing directors. However, the trespass incidents route data used for the case study (i.e., SMIS and TRUST data) are based on eight passenger service routes as the operational structure of Network Rail has changed[14] since the data was collected. The eight passenger service routes used by Network Rail before the change were:

(i) Anglia – This service route covers five main corridors through Greater London, Cambridgeshire, Essex, Norfolk and Suffolk. It is currently part of Network Rail's Eastern region (Network Rail, 2021c).

(ii) London North Eastern and East Midlands (LNE & EM) – This is the largest service route (Network Rail, 2018) and it covers the North East, Yorkshire, Lincolnshire, Bedfordshire, parts of Cambridgeshire and the whole of the East Midlands. The route is currently split into 3 (i.e., East Midlands, North East and East Coast routes) to form part of Network Rail's Eastern region (Network Rail, 2021c).

(iii) London North Western (LNW) – The London North Western service route is the biggest single route within Network Rail (Network Rail, 2016a). It stretches from London to Carlisle, including the major towns and cities of the West Midlands and North West of England. Currently, Network Rail has split the route into 3 routes (i.e., North West, Central and West Coast routes) which form the North West and Central region (Network Rail, 2021c).

(iv) Scotland – This route supports all the TOCs in Scotland (Transport Scotland, 2016) which includes Caledonian Sleeper, CrossCountry Trains, London North Eastern Railway (LNER), First TransPennine Express and ScotRail (Network Rail, 2021f).

[14] Network Rail's change to its operational structure led to the creation of the 5 regions in June 2019 [Available at: https://www.networkrail.co.uk/running-the-railway/our-routes/ (Accessed on 03 November 2021)]

(v) South East – This service route covers the network from London across Kent, parts of Surrey, East and West Sussex. This route is currently split into the Kent and Sussex routes which form part of Network Rail's Southern region.

(vi) Wales – The Wales service route operates and maintains the track across Wales and the border counties of England. It is currently part of Network Rail's Wales and Western region(Network Rail, 2021g).

(vii) Wessex – This service route is one of the busiest and most congested routes on Britain's railway network (Network Rail, 2016b). It covers the major commuter area of south-west London as well as from London Waterloo to the south and south-west of England. It currently forms part of Network Rail's Southern region (Network Rail, 2021h).

(viii) Western – This route stretches from London Paddington to Penzance, through Bristol and up to the boundaries with Wales, Worcester and Basingstoke. Currently, these boundaries have been adjusted which means the route now stretches up to the boundaries with Wales, the Cotswold and Hampshire. The route forms part of Network Rail's Wales and Western region (Network Rail, 2021i).

5.3 Application of CPIF Valuation Approach to Compare Risk & Delays on a Common Scale

As outlined in Chapter 4, there are 5 main steps of the CPIF valuation approach *(See the flow diagram in* Figure 8 *of Chapter 4)*. This section of the thesis discusses the steps to compare risk and delays of 'trespass incidents' on a common scale as well as highlighting how stakeholders can use this in the decision-making process.

5.3.1 Identify Target

Trespass incidents are a persistent issue in the railway industry. According to Network Rail (2021j), the number of incidents spike at specific times throughout the year especially from late July to early September which is usually the summer holiday period. Trespass incidents cause significant delays to train services on GB's railway network. Network Rail is seeking to reduce trespass on the railway in the current control period 6 (CP6) through both investment and public education campaigns.

In 2019/20 a total of 10,374 trespass incidents were recorded in Network Rail's TRUST dataset with an associated 986,228 minutes of delays. Over the same period 6,721 trespass incidents were recorded in RSSB's SMIS dataset, but the data has no associated risk values reported (i.e., risk contribution per incident or even total). However, according to RSSB's Safety Risk Model (SRM), trespass contributes a risk of about 33.6 FWI/year (Dacre, 2014).

As both datasets have route information and Network Rail has adopted a route-based approach in delivering its plans for CP6, the data will be explored on a route basis. Table 10 below shows the data on recorded trespass incidents by Network Rail routes.

Table 10: A table showing the 2019/20 trespass incidents by routes recorded in Network Rail's TRUST database and RSSB's SMIS database

Network Rail Routes	Number of Recorded Incidents		TRUST Delays (minutes)
	SMIS	TRUST	
Anglia	876	1,043	78,746
LNE & EM	1,659	2,197	199,417.70
LNW	901	2,629	273,553
Scotland	633	761	54,741.50
South East	1,047	1,372	168,907.50
Wales	456	597	28,100
Wessex	627	862	106,097.50
Western	513	902	76,664.50
TOTAL	***6,712***	***10,363***	***986,227.70***

5.3.2 Is investment/intervention targeted at CPIF event?

Trespass incidents are one of the identified common performance influencing factors of railway safety and operational performance in this research. According to Network Rail (2019), trespass incidents are of major concern. Hence route specific interventions have been put in place in CP6 to address the issue of trespasses. These interventions are summarised in Table 11 below.

Table 11: A table showing Control Period 6 route strategic plans aimed at tackling trespass incidents on the railway network (Source: Network Rail, Freight and National Passenger Operators Route Strategic Plan, Feb 2019)

Network Rail Routes	CP6 Route Strategic Plan Information	Trespass Investment? or Is Target a CPIF (e.g., trespass)?	Key Purpose or Type of Intervention
Anglia	Funding of small BTP team throughout CP6 to carry out patrols across known route hotspots in order to identify issues such as easy access points that could be used for trespass & vandalism. An additional investment option of £3.6m OPEX on security plans to mitigate trespass & fatality incidents in order to improve performance	YES	To improve operational performance
LNE & EM	Investing in infrastructure through interventions including fencing and ticketing controls to limit access to the railway and reduce potential trespass. For CP6, there's a £6m available fencing budget allocated to route hot spots, animal incursion and cable theft hardening. The route has an additional supplementary plan with 4 investment option packages. Each package includes the provision of lineside fencing (budget of £45m) projected to reduce trespass incidents by 40%.	YES	Safety and performance intervention

LNW	Seeks to manage trespass incidents jointly with TOCs and industry partners to implement both technological and educational initiatives. According to the asset strategy, 24% of fencing assets on this route remain in poor/ very poor conditions	YES	To improve passenger safety
Scotland	Seeks to improve off-track asset management such as drainage, vegetation and fencing management to reduce the likelihood of incidents arising from subsidence, flooding, adhesion, OLE short circuit trips, signal sighting and collision risk from animal incursion and trespass	YES	Safety intervention
South East	An additional investment option on Improving Safety and Compliance Packages which includes fencing to reduce trespass, level crossing closures, enhancement etc. Package A has a CAPEX of £23.1m and Package B has a CAPEX of £40.4m	YES	To protect railway services (operational performance intervention)
Wales	10th priority additional investment option is on performance and resilience. This is a £1.25m budget for demolition of redundant lineside buildings will potentially reduce delays due to safety incidents, trespass and arsons	YES	Passenger safety and performance – to reduce delays due to safety incidents
Wessex	Committed to reducing trespass and vandalism incidents by continuing in its activities from CP5 which include expansion of 'complimentary policing', continued community engagement promoting railway safety, close liaison with the BTP, intelligence to better task trespass & vandalism activities, and the investment in physical barriers and new technologies e.g., drones & smart CCTV	YES	Safety intervention
Western	Has no specific plans to deal with or manage trespass incidents	NO	No information

N.B. – Green shaded rows are routes with specific investment interventions & budgets/expenditures for trespasses whiles unshaded routes have no known specific investment budgets/expenditures for the trespass interventions. The orange shaded row highlights the lack of investment/interventions to deal with trespass incidents on this specific route.

5.3.3 Valuation Approach – converting risk and delays into monetary values

5.3.3.1 Risk Monetary Values

As per the flow diagram in Chapter 4, risk monetary value is determined by multiplying the risk (FWI) by the Value of Preventing a Fatality (VPF). According to the Office of Rail and Roads (2021), the VPF for 2019 as published by the Department for Transport and used by RSSB is £2,017,000. Therefore, the risk monetary value on each route is calculated as

$$Monetary\,Value\,(Trespasses) = Risk\,(FWI) \times £2{,}017{,}000$$

Since the risk value for trespass incidents in 2019/20 was recorded at 19.99FWI (Rail Safety and Standards Board, 2021), it can be divided by the total recorded number of trespass incidents recorded in SMIS (i.e., 6,712) in order to determine the value of risk per event (i.e., 0.002978248 FWI). Thus, the risk of trespass incidents for each route can be calculated by multiplying the number of incidents by the risk per event in order to calculate the FWI to be used in the risk monetary value equation. Table 12 below shows the estimated trespass risk and monetary values for each of the NR routes rounded to the nearest pound (£).

Table 12: A table showing the monetary values of risks for the 2019/20 trespass incidents by Network Rail routes (Source data: RSSB's SMIS)

Network Rail Routes	Number of Incidents	Risk Value (FWI) (Number of Incidents x 0.002978248)	Monetary Value (FWI x VPF)
Anglia	876	2.608945248	£5,262,242
LNE & EM	1659	4.940913432	£9,965,822
LNW	901	2.683401448	£5,412,421
Scotland	633	1.885230984	£3,802,511
South East	1047	3.118225656	£6,289,461
Wales	456	1.358081088	£2,739,249
Wessex	627	1.867361496	£3,766,468
Western	513	1.527841224	£3,081,656
Total	***6,712***	***19.99***	***£40,319,830***

Risk per event = 0.002978248 FWI *2019 VPF = £2,017,000*

5.3.3.2 Delay Monetary Values

To estimate delay monetary values, the compensation approach is adopted as discussed in Chapter 4. As trespass incidents are considered a Network Rail responsibility, the estimated value for Network Rail paid compensation per minute delay (£20.40) is used in the calculations for this case study. That is, the delay monetary value for trespass incidents on each of the Network Rail routes are calculated as

$$Monetary\,Value\,(Trespasses) = Delay\,Minutes \times £20.40$$

The results are shown in Table 13 below with the values rounded to the nearest pound (£).

Table 13: A table showing the monetary values of delays for the 2019/20 trespass incidents by Network Rail routes (Source data: Network Rail's TRUST)

Network Rail Routes	Delay Minutes (rounded to the nearest whole number)	Monetary Value (Delay Minutes x £20.40)
Anglia	78746	£1,606,418
LNE & EM	199418	£4,068,121
LNW	273553	£5,580,481
Scotland	54742	£1,116,727
South East	168908	£3,445,713
Wales	28100	£573,240
Wessex	106098	£2,164,389
Western	76665	£1,563,956
Total	***986,230***	***£20,119,045***

5.3.4 Compare Risk and Delays

Having calculated the monetary values for risk and delays, it is now possible to compare risk and delays on a common scale (i.e., in monetary terms). Figure 9 below shows the cost of trespass risk and delays on GB's railway network by Network Rail's routes. It is observed that, the cost of trespass risk, with the exception of the London North West route, is higher than that of delays on all the routes. This is in line with the findings in Chapter 4 which notes that 42% of the CPIFs (including Trespass Incidents) have a higher cost of risk than delay on GB's railway network.

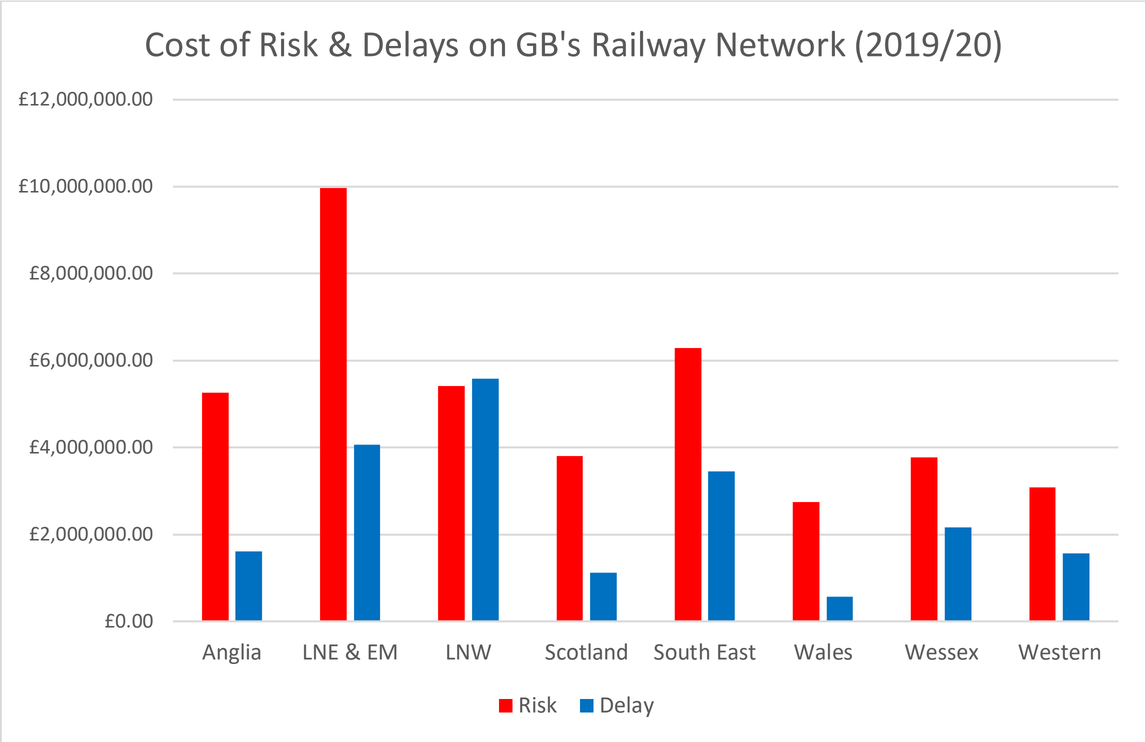

Figure 9: A bar graph showing the estimated cost of risk and delays on GB's railway network in 2019/20

The total cost of risk from trespass on the network is estimated at £40,319,830 of which the London North East & East Midlands route make up 25% (£9,965,822). The route also makes up 20% of the total cost of delays (i.e., £4,068,121 of the £20,119,045 total cost) on the network resulting from trespass incidents. In total, the London North East & East Midlands route is the most affected route by trespass incidents with a total cost from both types of event of £14,033,943. As the largest service route on the network, this shows that trespasses are both a safety and performance concern. Accordingly, the route has a specific budget aimed at tackling trespass incidents to improve the safety and performance of train services in CP6.

Although for some routes (i.e., Anglia and South East – see Table 11 above) these interventions are from an operational perspective of seeking to reduce delays by mitigating trespass incidents, this approach of comparing risk and delays on a common scale makes it possible to also acknowledge the safety aspect. For instance, the value of safety risk on the South East route is almost twice that of the delay cost whereas the value of safety risk on the Anglia route is more than thrice that of the delay cost *[See Figure 9 above]*. This valuation approach therefore makes it possible to estimate the safety monetary value of trespasses which can be considered as additional (unforeseen) cost to industry.

5.3.5 Use of Monetary Values in Cost Benefit Analysis

This stage of the valuation approach demonstrates the use of the monetary values in support of stakeholder decision making. Based on the route strategic plan information provided in Table 11 above, two main scenarios - i.e., the "Do–Nothing" and "Do–Something" scenarios – are developed to demonstrate the impacts of trespass incidents on GB railway's safety and operational performance at the end of CP6. Within these scenarios, the stakeholder will be able to calculate either cost or benefits (in terms of cost savings) of investments/interventions which are required when calculating the cost-benefit of rail projects.

5.3.5.1 Do – Nothing Scenario

In the "Do-Nothing" scenario, it is assumed that each of the routes fail to invest or intervene (either directly or indirectly) to reduce trespass incidents within their jurisdictions. The result of this action is also assumed to be a 10%[15] increase in the number of trespass incidents across each of the routes. Using both SMIS and TRUST data on trespass incidents, it is possible to calculate the risk and delay minutes which adds 10% to the existing cost of trespass incidents at the end of CP6.

That is, by using a 10% increase for the number of trespass incidents in both the SMIS and TRUST data, the calculated risk per event as well as the average delay per event on each route can be used for the scenario. The results are then converted into monetary values to determine the cost of trespass incidents at the end of CP6. The monetary conversion is based on the assumption that the 2019 value of preventing a fatality is the same at the end of CP6 (i.e., £2,017,000). Likewise, the Network Rail paid compensation per minute delay is also the same at the end of CP6 (£20.40).

Table 14 and Table 15 below respectively show the projected risk and delay minutes as well as the estimated cost of trespass incidents (rounded to the nearest pound (£)) on each of the Network Rail routes for the do-nothing scenario.

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[15] This value has no empirical basis. It is a pure assumption for which if no action is taken to address the issue of trespasses, the researcher assumes that there will be an increase in the number of incidents overtime. Therefore, an assumption of the 10% increment to represent the expected change in the number of incidents by the end of CP6.

Table 14: A table showing the projected risk at the end of CP6 based on the do-nothing scenario of a 10% increase in trespass incidents.

Network Rail Routes	Number of Incidents	Risk per event	Risk (FWI)	2019 VPF	Monetary Values
Anglia	964	0.002978248	2.86983969	£2,017,000	£5,788,467
LNE & EM	1825		5.435004619		£10,962,404
LNW	991		2.951741508		£5,953,663
Scotland	696		2.073754023		£4,182,762
South East	1152		3.430048123		£6,918,407
Wales	502		1.493889154		£3,013,174
Wessex	690		2.054097586		£4,143,115
Western	564		1.680625298		£3,389,821
Total	***7,384***		***21.99***		***£44,351,813***

Table 15: A table showing the projected delays at the end of CP6 based on the do-nothing scenario of a 10% increase in trespass incidents.

Network Rail Routes	Number of Incidents	Average Delay per Event (Minutes)	Delay in Minutes	Compensation per Minute Delay	Monetary Values
Anglia	1147	75	86,047.50	£20.40	£1,755,369
LNE & EM	2417	91	219,919.70		£4,486,362
LNW	2892	104	300,757.60		£6,135,455
Scotland	837	71	59,434.10		£1,212,456
South East	1509	123	185,631.60		£3,786,885
Wales	657	47	30,864.90		£629,644
Wessex	948	123	116,628.60		£2,379,223
Western	992	85	84,337		£1,720,475
Total	***11,399***		***1,083,621***		***£22,105,869***

In this scenario, the London North East & East Midlands route remains the route most affected by trespass incidents. By experiencing a 10% increase in trespass incidents by the end of CP6, the route has an estimated cost of £10,962,404 for risk and an estimated £4,486,362 for delays. This is a corresponding 10% increase in cost which amounts to an estimated total cost of

£15,448,766 to the railway network. In a cost-benefit analysis, the route will be noted to have incurred an additional cost of about £1,414,823 by the end of CP6 for not tackling the issue of trespass incidents. *[See Figure 10 below]*

5.3.5.2 Do – Something Scenario

In the "Do-Something" scenario, the case study adopts the various investments and interventions (either directly or indirectly) by each Network Rail route outlined in Table 11 to reduce trespass incidents within their jurisdictions. According to the route strategic plan, the London North East & East Midlands route seeks to provide lineside fencing with a budget of £45m. This is projected to reduce trespass incidents by 40% and is the only trespass intervention related projection in the report.

Routes like Anglia, South East and Wales also have similar interventions for trespasses with a total budget of almost £68m for all the three routes. The researcher therefore develops an assumption of a 40% reduction in trespass incidents on each of these roues. It must be noted that, the 40% is applied to each of the routes irrespective of the specific amount of money budgeted. This is aimed at simplifying the calculations for the purpose of demonstrating the applicability of the valuation approach.

However, the researcher acknowledges that not all investments will yield the same outcome. Therefore, to demonstrate the variation in the levels of achievement of investment for interventions, a 25% reduction is assumed for routes that have no known budget specific interventions aimed at reducing trespass incidents *[See Table 11]*. This value has no specific empirical basis, but the researcher considers it as a reasonable value for developing a forecast of trespass incidents. That is, for the purposes of this scenario, the assumption is that trespass interventions on GB's railway network will result in about 25% to 40% reduction in trespass incidents by the end of CP6.

Based on the assumption developed, it is assumed that routes such as Anglia, London North East & East Midlands, South East and Wales have a 40% reduction in trespass incidents by the end of CP6 due to the specific interventions and investment/expenditures directly aimed at reducing trespass incidents. The routes London North West, Scotland and Wessex are assumed to have a 25%[16] reduction in trespass incidents by the end of CP6. Western on the other hand is assumed to have a 5%[17] reduction in trespass incidents due to the lack of information on any trespass investments or interventions.

The results of the do-something scenario are shown in Table 16 and Table 17 using the same approach adopted in the do-nothing scenario to calculate risk and delays. This also involves the use of the 2019 VPF (£2,017,000) and the Network Rail paid compensation per minute delay (£20.40) in calculating the monetary values of risk and delays respectively at the end of CP6.

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[16] An assumption for 25% reduction in trespasses is developed for these routes to create a variation in the impact of investment on trespasses on the network (i.e., to create different levels of achievement). Since the LNW, Scotland & Wessex routes have no known specific budget/expenditure to deal with trespass incident, they are considered for the lower range of the researcher's assumption of 25%-40% reduction in trespasses as a result of investments in trespass interventions.

[17] A 5% reduction in trespasses is assumed because despite the fact that the route has no specific interventions, it is assumed that nationwide campaigns and education by Network Rail is considered to have had an impact on this route since this is a "do-something" scenario

Table 16: A table showing the projected risk at the end of CP6 based on the do-something scenario.

Network Rail Routes	Percentage Reduction	Number of Incidents	Average risk per event	Risk (FWI)	2019 VPF	Monetary Values
Anglia	40%	525.60	0.002978248	1.5653671	£2,017,000	£3,157,345.45
LNE & EM	40%	995.40		2.96454797		£5,979,493.26
LNW	25%	675.75		2.01255103		£4,059,315.42
Scotland	25%	474.75		1.4139232		£2,851,883.09
South East	40%	628.20		1.87093534		£3,773,676.58
Wales	40%	273.60		0.81484863		£1,643,549.69
Wessex	25%	470.25		1.40052108		£2,824,851.02
Western	5%	487.35		1.45144912		£2,927,572.88
Total		***4,530.90***		***13.49***		***£27,217,687.39***

Table 17: A table showing the value of the projected delay at the end of CP6 based on the do-something scenario.

Network Rail Routes	Percentage Reduction	Number of Incidents	Average Delay per Event	Delay in Minutes	Compensation per Minute	Monetary Values
Anglia	40%	625.80	75	46,935	£20.40	£957,474
LNE & EM	40%	1318.20	91	119,956.20		£2,447,106.48
LNW	25%	1971.75	104	205,062		£4,183,264.80
Scotland	25%	570.75	71	40,523.25		£826,674.30
South East	40%	823.20	123	101,253.60		£2,065,573.44
Wales	40%	358.20	47	16,835.40		£343,442.16
Wessex	25%	646.50	123	79,519.50		£1,622,197.80
Western	5%	856.90	85	72,837		£1,485,864.60
Total		***7,171.30***		***682,921.45***		***£13,931,597.58***

In this scenario, the London North East & East Midlands route still remains the route most affected by trespass incidents. However, by experiencing a 40% decrease in trespass incidents by the end of CP6, the route has an estimated cost of £5,979,493 for risk and an estimated £2,447,107 for delays. These reductions in cost account for a total savings of about £5,607,343 at the end of CP6 that account for investment benefits in a cost-benefit analysis. *[See Figure 10 below]*.

5.3.5.3 Discussion

Illustrated in Figure 10 below are the total cost of risk and delays from trespasses on each of the routes. In the diagram, the gap between the 2019/20 cost line and the do-nothing scenario cost line represents the additional costs incurred by the routes at the end of CP6 if not tackling the issue of trespass incidents. Likewise, the gap between the 2019/20 cost line and the do-something scenario cost line represents the cost-savings made by the routes at the end of CP6 by reducing the number of trespass incidents.

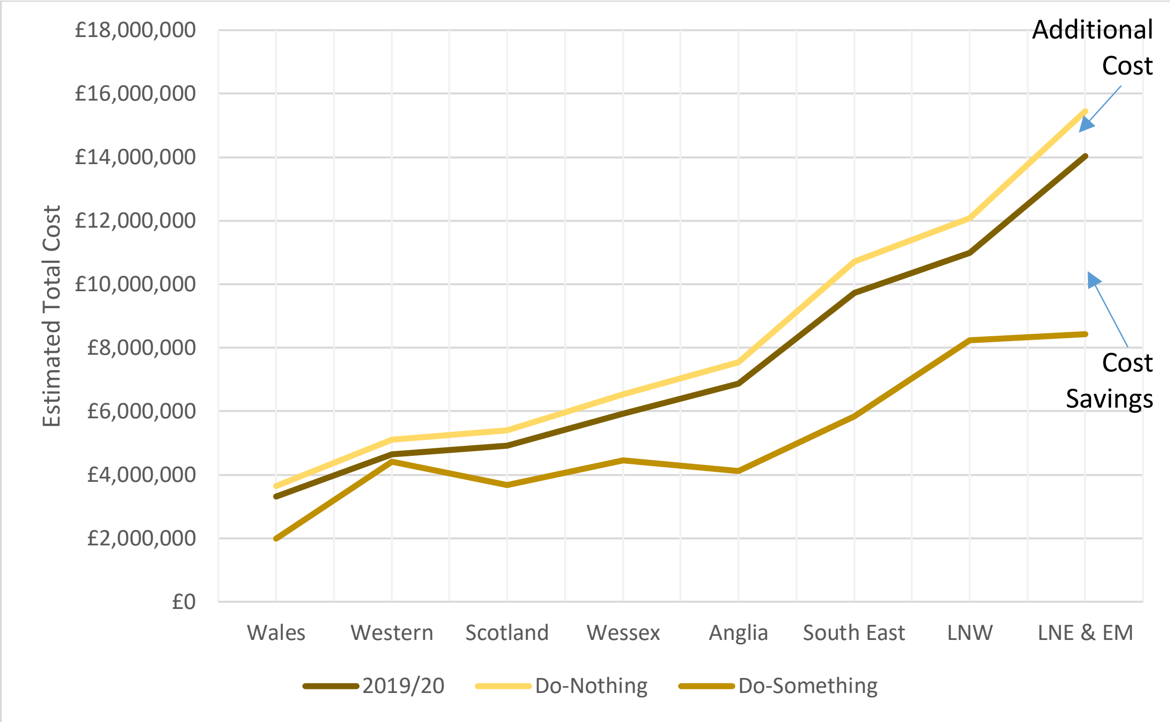

Figure 10: A line graph showing the estimated total cost of risk and delays on the network based on the 2 scenarios at the end of CP6

The Wales route followed by the Western route have the least estimated cost of risk and delays from trespass incidents recorded in the 2019/20 datasets (i.e., £3,312,490 and £4,919,237 respectively). There is a budget in place to tackle the issue of delays on the Wales route resulting from safety incidents such as trespasses while Western route has no interventions and could gradually become the route with the most trespass incidents. This is shown in the Do-Something scenario whereby it fails to maintain one of the lowest costs (See Figure 10 above).

There is the issue of the LNW route having a higher delay cost than risk cost which is out of character for the Trespass CPIF discussed in this research. This can be attributed to the fact that the LNW route is the biggest single route in the network and operates approximately 4,100 trains per day (Network Rail, 2016a). Therefore, disruptions to passenger services are likely to have a higher consequence than others as more services will be affected.

Also, the LNW route is the only route with a high disparity in the recorded number of trespass incidents on the network. This could be an attributing factor since the SMIS data used for this case study only has a record of 901 trespass incidents for the LNW route whereas the TRUST data recorded 2,629 (*See* Figure 11 *below*).

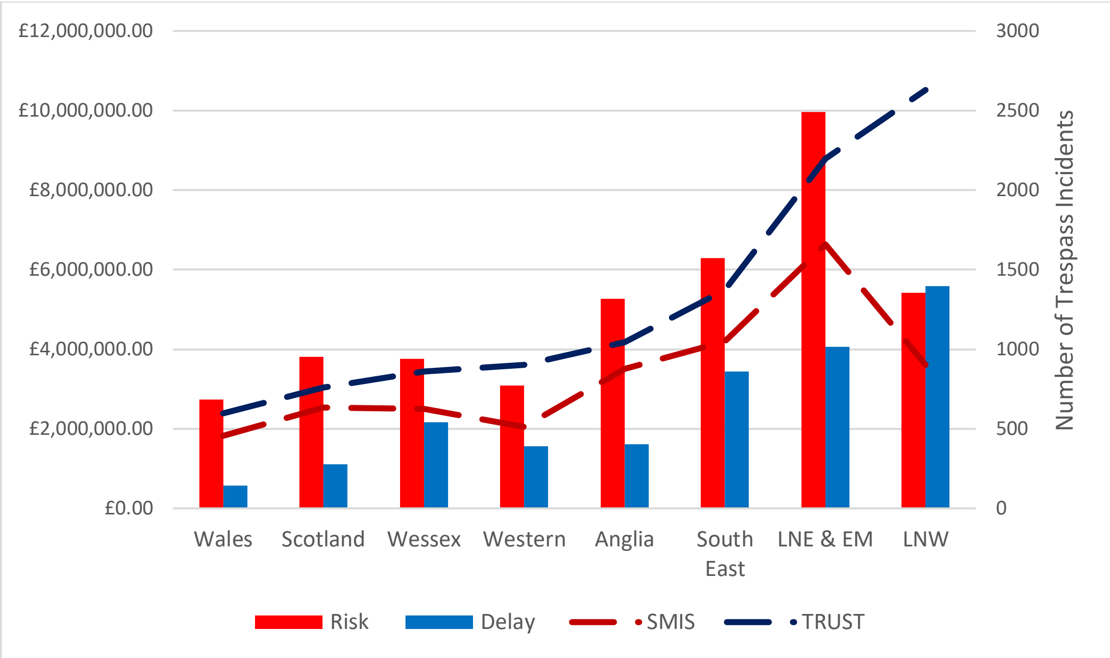

Figure 11: A mixed graph showing the number of trespass incidents and estimated cost of risk and delays on GB's railway network in 2019/20

The difference in the number of recorded incidents is not only seen for the LNW route but for all the other routes on the network. The disparities in the number of incidents recorded could be attributed to the different purposes and modes by which the data is collected by RSSB and Network Rail.

Moreover, there is also the challenge of finding available data in specific formats required to be able to compare risk and delays. For instance, in this case study, the approach requires specific information such as risk and delay values by route. The data used had records of delay minutes per incident which therefore made it easy to compute by route but had no risk contributions by neither incident nor route.

As highlighted throughout the thesis, it is important to have a common ‘event-driven’ reporting system for collating risk and delay data (especially for CPIF events). This will enhance the confidence in the use of the datasets and also encourage other researchers to explore the subject area in order to further develop an understanding of the relationship between railway safety and operational performance.

5.4 Limitations of the CPIF Valuation Approach

A major challenge of the CPIF valuation approach is data availability in the required form to facilitate the conversion of risk and delays into monetary values. In addition, the approach does not use the existing standards in WebTAG[18] which adopts the weighting and scoring or multi-

[18] WebTAG is a transport analysis guidance by the DfT which provides information on the role of transport modelling and appraisal. It contains various guidance on the conduct of transport studies and how the transport appraisal process supports the development of investment decisions to support a business case

criteria analysis techniques in valuing costs and benefits. However, it does present the basis, although simplified, for converting risk and delays into monetary terms for comparison on a common scale.

Therefore, to ensure the robustness of the CPIF valuation approach, researchers could further build upon the approach incorporating the standards (i.e., use WebTAG) while bearing in mind the limitations of the data in order to help predict and forecast events accurately for the development of scenarios to justify investments/ interventions.

5.5 Summary

By adopting a case study approach, the chapter demonstrates a step-by-step process of the application of the valuation approach which seeks to aid stakeholder decision making. The case study uses real-life data of trespass incidents recorded in SMIS and TRUST datasets of RSSB and Network Rail respectively. In the process, the trespass risk and delay minutes recorded by route are converted into monetary terms highlighting the cost of trespass incidents on GB's rail performance.

Trespass risk have a greater financial impact than delays on most of the routes. This is in line with the findings in Chapter 4 which highlights trespass incidents as the CPIF with the highest risk monetary value on the network in comparison to delays. The risk delay cost ratio for trespass incidents is estimated at approximately £12.9m to £7.6m. Driver Errors on the other hand is the CPIF with the highest delay monetary value on the network with a risk delay cost ratio of approximately £0.7m to £26m.

However, the wide disparity in the recorded number of trespass incidents in the SMIS (901) and TRUST (2,629) datasets for the London North West route has resulted in a higher estimated cost of delay than risk. This result is also attributed to the characteristics of the route as the impact of disruptions on delays is expected to be higher on more congested/busy routes than others. The disparities in the recorded datasets reiterates the point made throughout this thesis for the need to have a common ‘event-driven’ reporting system for risk and delays. This is to inspire confidence in the data and also encourage other researchers to partake in research on understanding the relationship between railway safety and operational performance.

Although this case study may help highlight the need to have a common ‘event-driven’ reporting system, it serves as a validation process for the applicability of the valuation approach to be used by stakeholders in making informed decisions. By converting risk and delays into monetary values for comparison, the case study uses two scenarios to demonstrate how risk and delay monetary values can be used in the cost benefit analysis process of rail projects. This means that, for CPIF events such as trespass incidents, the valuation approach makes it possible to capture both the safety and operational cost/cost-savings in the CBA process of rail projects.

A major challenge of this approach is the availability of data in the form required to help with the conversion of risk and delays into monetary values for comparison and use by stakeholders in making better informed decisions. In addition, researchers could further build on the approach to help predict and forecast events accurately for the development of scenarios to justify investments/ interventions.

6 CONCLUSIONS

6.1 Overview

Railway risk and delay are reported, collated and managed separately and this has led to variations in the two datasets. This poses a challenge when comparing and analysing safety and operational performance for the purpose of developing an understanding of the relationship between the performance measures.

The reporting of safety incidents, managed by RSSB, is more structured with varying systems for collation & analysis in comparison to that of delay incidents managed by Network Rail. However, the literature review in Chapter 2 explains that safety and operational performance are neither inherently complementary nor contradictory but rather jointly managing them is what makes these performance measures complementary goals.

By exploring the two datasets, this research has identified that there are factors that influence both safety and operational performance. These factors are categorised into 12 groups referred to as the "CPIFs". Therefore, an improvement to how risk and delay incidents are collated and analysed by industry will inspire confidence in the data for future works that seek to improve railway safety and operational performance.

Moreover, by quantifying the impact of CPIF events on risk and delays combined with the use of available data & existing industry techniques, a valuation approach has been developed to compare risk and delays on a common scale. The approach creates a reasonable estimate which captures the safety and operational cost/cost-savings potential to the stakeholder in making decisions.

This chapter addresses the aims and objectives by demonstrating the answers to the research questions in this thesis. It explains the significance and implications of the findings and also highlights the research contributions to knowledge. Also, the limitations to the research are discussed and suggestions for further research are laid out.

6.2 Evaluation of research against research questions

The main aim of this research is to facilitate the understanding of the relationship between railway safety and operational performance by comparing them on a common scale while building on existing approaches in the industry. The following section discusses how the research in this thesis responds to the research questions posed in Chapter 1.

6.2.1 What are the influencing factors of safety and operational performance and how do they interact with each other?

In GB's railway industry, safety and operational performance are mainly influenced by events occurring on the network which both disrupts and poses a danger to the operation of train services. These events vary from incidents such as objects on the line to driver errors and signal failures. They are recorded in various RSSB reporting systems for safety related incidents (referred to as hazardous events) and Network Rail reporting systems for delay related incidents (referred to as reasons for delays).

Some of the information from these reporting systems is made publicly available by each of the organisation responsible for the management of the data. RSSB's Safety Risk Model (SRM) and Network Rail's Historic Delay Attributions which are made publicly available are identified in Chapter 2 as the sources for exploring the safety and operational performance data in order to identify the factors influencing risk and delays in Chapter 3.

There are 12 identified common performance influencing factors which are referred to as ***CPIFs*** throughout this thesis. These are ***Rolling Stock Faults, Driver Errors, Passenger Train Signals Passed at Danger (PT SPADs), Signaller Errors, Environment & Weather, Structural Failures, Track Faults, Possessions, Trespass Incidents, Station Incidents, Level Crossing Incidents and Vandalism.*** The CPIFs cause both risk and delay events that occur on GB's railway network.

The interactions between the influencing factors are demonstrated using a causal loop diagram leading to the identification of three main levels of interactions. These are

i. The interactions between the types of delay & risk and the performance measures.
ii. The interactions between CPIFs and the types of delay & risk.
iii. The interactions between the risk & delay factors and CPIFs.

These interactions in the causal loop diagram are demonstrated in Chapter 3 with links which show the main relationships between safety and operational performance on GB's rail network.

6.2.2 What are the approaches for managing and measuring the impacts of network disruptions /events /incidents on railway performance?

The occurrence of events on GB's network affect the performance of train services. This research has focused on the impact of these events on safety and operational performance on GB's railway network. According to the literature in Chapter 2, safety is measured by risk which is defined as the combination of the number of events and their consequences presented in units of fatalities and weighted injuries (FWIs). Railway operational performance on the other hand is measured by the punctuality and reliability of train services (i.e., PPM) as well as the delay to trains on the network. The impacts of network disruptions /events /incidents are measured by risk and delays to passenger train services with respect to safety and operational performance.

Data associated with risk and delays to trains as a result of network disruptions/events/incidents are managed separately by RSSB and Network Rail respectively. The literature has shown that, there are different systems and procedures used in the reporting and management of incidents by these organisations. While the reporting of safety incidents is more structured with varying systems for collation and analysis (e.g., SMIS, CIRAS, etc.), delay incidents are reported in the TRUST database via information provided by reports from maintenance teams, traincrew, platform staff as well as the public.

6.2.3 How do you develop an approach for comparing risk and delay on a common scale?

The 12 identified CPIFs from this research indicate that the events within these categories have an impact on both safety and operational performance when they occur. This means that, by quantifying the risk and delay of the CPIFs events *(demonstrated in Chapter 3)*, it is possible to develop a valuation approach with the help of existing industry techniques in order to compare risk and delay on a common scale *(demonstrated in Chapter 4)*.

RSSB provides an annual value for preventing a fatality on the railway network. This value is incorporated in the approach for the calculation of risk monetary values. There is no specific value attached to delays on the network by GB's railway industry. A compensation technique is therefore adopted by using the average compensation paid by Network Rail and train operating companies for delays on the network. This is also incorporated in the approach for the calculation of delay monetary values. Once the risk and delays have been converted into monetary values, they are potentially comparable. A flow diagram which provides a step-by-step guide for the use of the valuation approach is illustrated in Chapter 4. To use this information for specific decision-making would require the use of actual values of risk and delay that is enshrined in the respective local contracts.

6.2.4 How can the stakeholder decision making process be better facilitated with the use of the valuation approach?

The valuation approach creates a reasonable estimate of the relative significance of an event for both safety and performance. Chapter 5 of this thesis demonstrates the applicability of the valuation approach by adopting a case study of trespass incidents on GB's railway network. A step-by-step process of the approach is explained using real-life data of trespass incidents recorded in SMIS and TRUST datasets of RSSB and Network Rail respectively.

By converting the risk and delays into monetary values for comparison, the case study uses two main scenarios – the *'Do Nothing'* and *'Do Something'* scenarios – to demonstrate how risk and delay monetary values can be used in the cost benefit analysis process. This means that, for CPIF events such as trespass incidents, the valuation approach makes it possible to capture both the safety and operational cost/cost-savings in the CBA process of rail projects.

6.2.5 What is/are the insight(s) from this research that is/are beneficial to GB's railways and the railways in other countries?

This research demonstrates that there are factors that influence both risk and delays on the network. Therefore, addressing these factors as issues on the network can have a beneficial impact on both safety and operational performance. However, the data required to help facilitate the understanding between the performance measures has variations in the reporting language. This makes it difficult to compare like with like. Migrating to a common 'events driven database' would involve transition issues to keep historical data credible but would move the industry toward a more coherent and balanced analysis including more demonstrably balanced investment decisions.

The comparison of risk and delays on a common scale has revealed that, the industry attaches a higher relative significant value to performance than safety. However, some particular Network Rail responsible event related CPIFs like Level Crossings, Trespass Incidents, etc. have a higher relative significant value to safety than performance. As these values are a reflection of VPF and compensations; it shows that incentive regimes place a higher value on performance than the value placed on safety. A review of these values and related policies by researchers/industry is considered necessary for further development of the valuation approach (i.e., to boost confidence in the use of the approach).

6.3 Contributions to Knowledge

The major contribution of this research is that it provides for the first time, a study to facilitate the understanding of the relationship between railway safety and operational performance by comparing risk and delay on a common scale. This has been achieved by first developing a model framework of the interaction between the influencing factors of safety and operational performance. The research has identified 12 common performance influencing factors (i.e., the CPIFs) and quantified their impacts on railway performance in terms of risk and delays. There is an opportunity for the model and the process for quantification to be further developed by researchers into a combined risk and delay statistical model which can be used for the simulation of CPIFs on the network.

Secondly, the research provides a valuation approach developed by using the quantified risk and delay of the CPIFs collected using existing industry techniques. The approach is used for comparing safety and operational performance of CPIFs and has been demonstrated to be beneficial for use in the stakeholder decision making process. There is also an opportunity to replicate the approach for further development with the aid of the step-by-step guide provided in the thesis.

In addition, the research highlights the fact that there are two different data collection and analysis systems which poses as a challenge to researchers seeking to analyse the data together for the improvement of railway safety and operational performance. Driven on single events, there is an opportunity to enhance industry efficiency and effectiveness by moving toward a common reporting system – at least for all CPIFs.

Lastly, this research contributes to filling the gap in literature for published studies on the relationship between railway safety and operational performance. There are already two publications from this research and this thesis will be used towards a third publication.

6.4 Limitations

A significant challenge faced by this study was the inconsistency of data groupings of the two main datasets – delays and risk. It was observed that the measures for collecting safety performance and operational performance data vary considerably in definition/categorisation and clearly are not designed to the same guidelines. A typical example of this is the categorisation of events that constitute track and non-track asset failures. Also, the datasets were presented in different ways thereby making it difficult to easily compare both datasets. For example, risk data is generally presented annually for the overall risk on the network. Delay data, on the other hand, is presented periodically for delays on the network by TOCs.

This sort of differences made it difficult to reconcile the datasets with confidence and at the same time create the potential for misleading results. However, this challenge set the foundation for the recommendation of a framework for collecting performance and safety data in the railway industry in a consistent manner. This is further discussed in the recommendation section of this chapter.

6.5 Recommendation & Future Works

One of the findings from this study is that the occurrence of events – especially events within the CPIF – have an impact on both safety and operational performance. This research did not address whether it is appropriate for there to be differences in the relative values for risk and delays set by industry and the regulator (ORR) but suggests that with the insights derived from this research, it is a reasonable policy issue and in the best interest of policy makers to consider whether change in one value should lead to an adjustment in the other.

To successfully carry out this suggestion, and as identified earlier in the study, the industry needs a common reporting system for events that lead to different effects, including safety and performance. This would facilitate better industry decision making and future research with respect to safety and operational performance. It is therefore recommended that existing reporting guidelines relating to risk and delays conducted by RSSB and Network Rail respectively are reviewed. By evaluating current practices, it will then be possible to identify areas and processes that require improvement to support the development of more robust approaches.

Moreover, the development of a common reporting system, based on underlying causes/events has the potential to improve reporting, understanding and management of many other factors across the railway system. This could be taken on by interested researchers to develop a framework suitable for reporting events that affect the overall system. This would require work on definitions, reporting mechanisms and processes, and the treatment of historic data during any transition period. For a strategic framework that incorporates the recording of both risk and delay minute values, it is important that the framework enables individuals or systems responsible for capturing events to record all the system effects arising from the event.

In addition, the framework should present the datasets in a clear and consistent manner which enables a user to interrogate the data at different levels for different purposes. That is to say, the data should be broken down and filtered by attributes such as routes, TOCs, periodicity, annually, etc. Network Rail and RSSB could consider integrating their actors/actions in this regard in order to deliver a consistent approach to the reporting of incidents on the network and their consequent outcomes.

In addition to the reporting issues, the valuation approach can be further developed. Researchers could explore the use of Monte-Carlo analysis to provide potentially predictive models.

Finally, the findings from this research could be integrated into industry decision making guidance like the Taking Safe Decisions. Further research, and workshops with industry stakeholders would help develop the approach into an effective decision support tool on its own or can be integrated into already existing tools/systems. Likewise, case studies can be generated from stakeholder workshops in order to help validate the approach and boost confidence in its usage within the industry and beyond once the issues with data reporting are addressed.

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APPENDICES

Appendix 1: List of 213 reasons for delay to passenger trains from Network Rail's Historic Delay Attribution (2016/17) and a list of 116 passenger train related hazardous events from RSSB's Table C2 used in this study.

Hazardous Events	Reason for Delay
Train collisions caused by objects placed on the line by vandals	Level crossing failure incl. barrow/foot crossings & crossing treadles
Struck by objects thrown by vandals through train window	Axle Counter Failure
Train derailment cause by vandalism	Overhead line/third rail defect
Train fires caused by arson/vandalism	AC/DC trip
Abnormal dynamic forces - only considered for PT	OHLE/third rail power supply failure or reduction
Subsidence/landslip	Points failure
Track maintenance staff errors	Points failure due snow/frost where heaters fitted but not operative or defective
Defective S&C	Points failure caused by snow or frost where heaters are not fitted
Misc. track faults - only considered for FT	Telecom equipment failures legacy (inc.NRN/CSR/RETB link)
Movement of points under train	Telecom equipment failure
Track twist	Telecom radio failures IVRS/GSM-R
Buckled rail	Track circuit failure
Broken rail	Signal failure
Broken fishplate	Signalling Functional Power Supply Failure
Gauge spread	Train Describer/Panel/ARS/SSI/TDM Remote Control failure
Broken rail in tunnel	Block failure
Miscellaneous/unknown causes on S&C	Power Supply and Distribution System Failure
Cyclic top - only applicable to FT	AWS/ATP/TPWS/Train stop/On track equipment failure
Track faults - passenger trains	Signalling lineside cable fault
Rolling stock door incidents (includes door faults)	Token Equipment Failure
Rolling stock faults - other	Infrastructure Balise Failure
Structural failures - other	HABD/PANCHEX/WILD Failure (no fault found/wrong detection)
Structural failures resulting from subsidence or landslips	Network Rail staff oversight or error (Maintenance / Infrastructure)
Passenger train SPADs resulting in collision+	ETCS/ERTMS Equipment Failure (excl. communications link and balises)
Driver fails to check signal aspect	Regulation Decision Made with Best Endeavours
Driver fails to react to cautionary aspect	Delayed by signaller not applying applicable regulating policy
Other environmental	Signaller, including wrong routing and wrong ETCS/ERTMS instruction
Driver fails to locate signal	Signal Box not open during booked hours
Driver misreads by viewing wrong signal	Incorrect simplifier
Driver misjudges train behaviour	TSR speeds for Track-work outside the Rules of the Route
Signaller communication errors	Condition of Track TSR outside the Timetable Planning Rules
Driver misjudges environmental conditions	Broken/cracked/twisted/buckled/flawed rail
Driver views correct signal but misreads aspect	Track defects (other than rail defects) inc. fish plates, wet beds etc.
Driver anticipates signal clearance	Bumps reported - cause not known
Driver misreads previous signal	Reactionary Delay to "P" coded TSRs
Correct information given but misunderstood by driver/signaller	Delays a result of track patrolling blocks
Driver violation of rules/instructions	Takeback Pumps
Ambiguous or incomplete information given by driver/signaller	Delay accepted by Network Rail as part of commercial agreement where no substantive delay reason is identified
Driver ignorance of rules/instructions	Animal Strike or Incursion within the control of Network Rail
Uncategorised driver error	Other Infrastructure causes

Wrong information given by driver/signaller	Infrastructure Safety Issue Reported by Member of the Public - No Fault Found
Information not given by driver/signaller	Infrastructure Fault Report Proven to Be Mistaken
Rolling stock	Preventative Maintenance to the infrastructure in response to a Remote Condition Monitoring Alert
Signaller operating errors	NR staff oversight or error (Maint / Infrastructure)
Unknown driver misjudgement	Msc items (inc. trees) causing obstructions not result T&V, weather or fallen/thrown from trains
Passenger train SPADs resulting in derailment or level crossing collision	ARS software problem (excluding scheduling issues and technical failures)
Passenger train SPAD resulting in derailment or level crossing collision	Formal Inquiry Incident - other Operators
Passenger train SPADs/ runaways resulting in derailment, train collision or level crossing collision	Delay caused by Operating staff oversight, issues or absence (excluding signallers and Control)
Train Driver errors resulting in SPADs	Failure of TRUST or SMART system preventing recording and investigation of delay
Train Driver braking errors	Fire or evacuation due to fire alarm of Network Rail buildings other than stations not due to vandalism
Other train driver errors	Conn held where the prime incident causing delay to the incoming train is a FOC owned incident & serv is more freq than hourly
Train Driver over speeding errors	Other Network Rail operating causes
Misuse Error	VSTP Schedule/ VSTP Process (TSI created schedule)
Violation	Delayed as a result of Route Control decision or directive
Proper Use	Technical failure associated with a Railhead conditioning train
Footpath crossings	Late start or delay to Railhead Conditioning Train (RHC) including any reactionary delay to other trains
MOP pedestrian struck/crushed by train on footpath crossing	
MOP slip, trip or fall on footpath crossing	Possession over-run from planned work
Level crossings	Engineers train late or failed in possession
Passenger train collision with road vehicle on level crossing	OTM DAMAGE
MOP pedestrian struck/crushed by train on level crossing	ESR/TSR Work not comp/canx pssn (restriction did not exist prior to pssn)
Passenger struck/crushed by train on station crossing	Reactionary Delay to 'P' coded Possession
MOP slip, trip or fall on level crossing	Trackside sign blown down, missing, defective, mis-placed
MOP struck/trapped by level crossing equipment	WTT schedule and or LTP Process including erroneous simplifiers
Passenger train collisions	Planned engineering work - diversion/SLW not timetabled (outside the Timetable Planning Rules)
Automatic Half Barrier Crossing	Train schedule/STP Process including erroneous simplifiers
User Worked Crossing Protected with Telephone	Failure to maintain vegetation within network boundaries in accordance with prevailing Network Rail standards
Automatic Open Crossings Locally Monitored	Unattributed Cancellations
User Worked Crossing	Unexplained late start
User Worked Crossing Protected by Miniature Warning Lights	Unexplained station overtime
Manual Controlled Barrier	Unexplained loss in running
Manual Controlled Barrier with CCTV	No Cause ascertainable for a Sub-Threshold Delay causing Threshold Reactionary (where agreed by both parties)
Automatic Barrier Crossings Locally Monitored	No Cause Identified After investigation by both Parties
Manual Controlled Gate	Delays not properly investigated by Network Rail
Footpath Crossing	Delays un-investigated
Open Crossing	Special working for leaf-fall track circuit operation
Automatic Half Barrier Crossing	NZ Pumps T
User Worked Crossing Protected with Telephone	Planned underpowered or short formed service and or vehicle, incl. exam set swaps
Automatic Open Crossings Locally Monitored	Depot operating problem
User Worked Crossing	Technical Fleet Holding Code
User Worked Crossing Protected by Miniature Warning Lights	Confirmed train cab based safety system fault (including GSMR)

Manual Controlled Barrier	Confirmed Pantograph ADD, shoe beam or assoc. system faults inlc. positive PANCHEX activations
Manual Controlled Barrier with CCTV	Door and Door system faults
Automatic Barrier Crossings Locally Monitored	Technical failures above the Solebar
Footpath Crossing	Reported fleet equipment defect - no fault found
Manual Controlled Gate	Electric Loco failure, defect, attention
Open Crossing	Diesel Loco failure, defect, attention
Passenger/MOP slip, trip or fall in Station	Technical failures below the solebar
Adult/Child trespasser struck while crossing track at station	Steam locomotive failure/defect/attention
Passenger/MOP boarding/alighting	International/Channel Tunnel locomotive failure/defect/attention
Passenger/MOP fall from platform or bridge in station	Wagons, coaches and parcel vehicle faults
Passenger assaults	Brake and brake systems faults; including wheel flats where no other cause had been identified
Adult trespasser electric shock in station	Loco/unit/vehicles late off depot (cause not known)
Passenger/MOP struck while on platform	Sanders and scrubber faults
Staff slip, trip or fall in station	Confirmed train borne safety system faults (not cab based)
Staff struck while on platform	Engineers on-track equipment failure outside possession
Workforce assault	Weather - effect on T&RS equipment
Passenger/MOP electric shock in station	Coupler and Coupler system faults
Workforce boarding/alighting	On train TASS/TILT failure
Passenger injury due to being hit by objects/vehicles not on platform	Train Operations Holding Code
Passenger/MOP struck while crossing track in station	Dangerous Goods incident
Staff fall between platform and train in station	Planning issues including loco diagrams or RT3973 restriction not requested
Public assaults	Tail lamp/head lamp out or incorrectly shown
Explosion in station	Late presentation from Europe
MOP contact with other objects on railway premises i.e., banged head on station sign	Delay in running believed due to Operator but no info available from Operator
Staff asphyxiation in station	Attaching/detaching/shunter/watering
Passenger burns not on train	Waiting passenger connections authorised by TOC but out with TOC/Network Rail connection policy
Fire in station	Special Stop Orders - authorised by TOC Control (including any delay at point of issue)
Passenger/MOP exposure to hazardous substances in station	Train-crew/loco/stock/unit diagram issues
Passenger fall during evacuation at station	Train cancelled or delayed at Train Operators request
Passenger exposed to noise	Seat reservation problems
Passenger on-train incident	Connection authorised by TOC but outwits Connection Policy
Worker on train incident	Late presentation from the continent
Inside possession	Delay believed to be due to Operator but no information available from Operator
Environment	Special Stop Orders
YD&S	Train Operating Company Directive
	Delay due to ETCS/ERTMS on-board overriding driver command
	Delays incurred on non-Network Rail running lines incl. LT causes (except T&RS)
	Mishap-Train Operating Company cause
	Other Passenger Train Operating Company causes
	Train Crew Causes Holding Code
	Train crew not available
	Driver adhering to company professional driving standards or policy
	Incorrect route taken or route wrongly challenged by driver incl SPADs
	Waiting connections from other transport modes
	Driver
	(Senior) Conductor/Train Manager

	Traincrew rostering problem
	Tail lamp or headlamp missing, not lit or wrongly displayed
	Train catering staff (including Contractors)
	Driver adhering to company professional driving standards or policy
	Rail / wheel interface, adhesion problems (including ice on the running rail)
	Leaf fall Neutral
	Trespass (including non-intentional)
	Fatalities or injuries caused by being hit by train (including non-intentional)
	Police searching the line
	Security alert affecting Network Rail
	Animal Strike or incursion not within the control of Network Rail
	External power supply failure NR Infrastructure
	Fire external to railway infrastructure
	Gas/water mains/overhead power lines
	External trees, buildings or objects encroaching onto Network Rail infrastructure (not due to weather or vandalism)
	Swing bridge open for river or canal traffic
	Sunlight on signal or dispatch equipment
	Fire or evacuation due to fire alarm of Network Rail buildings due to vandalism (not including stations)
	Other external causes the responsibility of Network Rail
	BRIDGE HIT
	Vandalism or theft (including the placing of objects on the line)
	Cable vandalism or theft
	Level Crossing Incidents including misuse
	Road related - excl bridge strikes/level crossing incident
	Fires starting on Network Rail Infrastructure
	Train striking bird (pheasant or smaller)
	Disorder/drunks or trespass
	Vandalism or theft
	Fatalities and or injuries sustained on platform result of struck by train or falling from a train
	Passenger taken ill on train
	Ticket irregularities or refusals to pay
	Fire caused by vandalism
	Police searching train
	Communication cord or emergency train alarm operated
	Security alert affecting stations and depots
	Driver adhering to company professional driving standards or policies during severe weather that are not fleet related
	Severe weather affecting passenger Fleet equipment including following company standards/policies or Rule book instructions
	Passenger charter excludable events occurring on the LUL or other non-NR running lines
	Other passenger or external causes the responsibility of TOC
	Incorrect train dispatch by station staff
	Late TRTS given by station staff
	Station Staff unavailable - missing or uncovered
	Station staff split responsibility - unable to cover all duties
	Station staff error - e.g., wrong announcements misdirection
	Station delays due to special events e.g., sports fixtures
	Passengers joining/alighting
	re-booked assistance for a person with reduced mobility joining/alighting,
	Lift/escalator defect/failure
	Station evacuated due to fire alarm

	Waiting connections - not authorised by TOC Control
	Special stop orders - not authorised by TOC Control
	Waiting connections from other transport modes
	Passengers taken ill on platform
	Passenger dropped object whilst boarding/alighting from train and train delayed at TOC request
	Un-booked assistance for a person with reduced mobility joining/alighting,
	Loading or unloading reserved bicycles
	Loading or unloading un-reserved bicycles
	Loading excessive luggage
	Locating lost luggage
	Customer Information system failure
	Station flooding (incl. issues with drains) not the result of weather, where the water has not emanated from NR infrastructure
	Mishap - Station Operating causes
	Other Station Operating causes
	Delay at unstaffed station to non-DOO train
	Loading Supplies (including catering)
	Earthslip/subsidence/breached sea defences (not the result of severe weather on the day of failure)
	Structures - Bridges/tunnels/buildings/embankments (not bridge strikes)
	Severe flooding beyond that which could be mitigated on Network Rail infrastructure
	Lightning Strike - damage to protected systems
	Points failure caused by severe snow where heaters are working as designed
	Severe heat affecting infrastructure the responsibility of Network Rail (excluding heat related speed restrictions)
	Severe snow affecting infrastructure the responsibility of Network Rail
	Severe weather, not snow affecting infrastructure the responsibility of Network Rail
	Non severe weather - snow/ice/frost affecting infrastructure equipment
	Lightning strike against unprotected assets
	Critical Rail Temperature speeds, (other than buckled rails)
	Flooding not due to exceptional weather
	Ice on conductor rail/OHLE
	Visibility in semaphore signalled areas, or special workings for fog and falling snow implemented by Network Rail - in all signa
	Blanket speed restriction for extreme heat or high wind in accordance with the Group Standards
	Failure to lay Sandite or operate Railhead Conditioning train as programmed
	Adhesion problems due to leaf contamination
	Cautioning due to railhead leaf contamination

Appendix 2: List of risk contributions of risk factors as well as frequency and delay minutes of delay factors within the CPIFs (Source: RSSB Table C2 and Network Rail's Historic Delay Attributions, 2016/17)

CPIF	Risk Factors	Risk Contribution (FWI)	Delay Factors	Frequency	Minutes
Rolling Stock Faults/ Failures	Rolling stock door incidents (includes door faults)	1.666172079	Door and Door system faults	76,361	423,457.88
	Rolling stock faults - other	1.652757651	Confirmed train cab-based safety system fault (including GSMR)	38,670	245,840.59
			Confirmed Pantograph ADD, shoe beam or assoc. system faults inlc. positive PANCHEX activations	13,234	95,324.70
			Technical failures above the Solebar	110,468	723,315.56
			Electric Loco failure, defect, attention	12,923	106,216.23
			Diesel Loco failure, defect, attention	44,729	423,031.32
			Technical failures below the solebar	147,232	1,007,679.79
			Steam locomotive failure/defect/attention	568	5,288.50
			International/Channel Tunnel locomotive failure/defect/attention	8	127
			Wagons, coaches and parcel vehicle faults	12,144	122,832.07
			Brake and brake systems faults; including wheel flats where no other cause had been identified	56,874	436,316.57
			Sanders and scrubber faults	2,163	16,018.80
			Coupler and Coupler system faults	17,603	101,076.73
			On train TASS/TILT failure	4,755	15,638
	Rolling stock (PT SPADs)	0.003353839	Delay due to ETCS/ERTMS on-board overriding driver command	2,761	104
Driver Errors	Train Driver braking errors	0.433368226	Driver	253,036	1,489,070.85
	Other train driver errors	0.290957037			
	Train Driver over speeding errors	0.035001517			
	Train Driver errors resulting in SPADs	0.657584409			
PT SPADs	Uncategorised driver error	0.006052994	Incorrect route taken or route wrongly challenged by driver incl SPADs	229	2,141
	Driver fails to check signal aspect	0.077003355			

	Driver fails to react to cautionary aspect	0.074878764			
	Driver fails to locate signal	0.024145459			
	Driver misreads by viewing wrong signal	0.01973335			
	Driver misjudges train behaviour	0.019162378			
	Driver misjudges environmental conditions	0.015684832			
	Driver views correct signal but misreads aspect	0.013263169			
	Driver anticipates signal clearance	0.013015249			
	Driver misreads previous signal	0.010821478			
	Driver ignorance of rules/instructions	0.006575229			
	Unknown driver misjudgement	0.001162826			
	Driver violation of rules/instructions	0.007003366			
Signaller Errors	Signaller communication errors	0.015863807	Signaller, including wrong routing and wrong ETCS/ERTMS instruction	88,969	348,652.71
	Correct information given but misunderstood by driver/signaller	0.009810328			
	Ambiguous or incomplete information given by driver/signaller	0.006955143			
	Wrong information given by driver/signaller	0.004007682			
	Signaller operating errors	0.001846363	Delayed by signaller not applying applicable regulating policy	59,494	210,820.26
Env. & Weather	Environment	1.688370977	Failure to lay Sandite or operate Railhead Conditioning train as programmed	6,969	19,460
	Other environmental (PT SPADs)	0.024673443	Rail / wheel interface, adhesion problems (including ice on the running rail)	36,517	82,360.07
	Subsidence/landslip (Track faults)	0.390263466	Adhesion problems due to leaf contamination	4,636	34,651.69
			Cautioning due to railhead leaf contamination	4,397	25,862.64
			Leaf fall Neutral	40,505	69,488.90
Structural Failures	Structural failures resulting from subsidence or landslips	0.40128129	Earthslip/subsidence/breached sea defences (not the result of severe weather on the day of failure)	27,864	49,840.60
	Structural failures - other	0.446914891	Structures - Bridges/tunnels/buildings/embankments (not bridge strikes)	23,656	148,690.40

Track Faults	Defective S&C	0.063899265	Points failure	102,487	701,313.61
	Movement of points under train	0.038403257	Points failure due snow/frost where heaters fitted but not operative or defective	170	1,200.50
	Miscellaneous/unknown causes on S&C	0.00393118	Points failure caused by snow or frost where heaters are not fitted	394	2,634.00
	Broken fishplate	0.020513506	Track defects (other than rail defects) inc. fish plates, wet beds etc.	126,017	578,405.59
	Track twist	0.035793536			
	Gauge spread	0.017387671			
	Buckled rail	0.032309623	Broken/cracked/twisted/buckled/flawed rail	78,128	364,693.00
	Broken rail	0.022062222			
	Broken rail in tunnel	0.014198941			
Possessions	OTP inside possession	1.225503623	Possession over-run from planned work	33,767	251,594.28
			Engineers train late or failed in possession	16,988	43,286.45
			OTM DAMAGE	8,106	48,463.35
			Engineers on-track equipment failure outside possession	24,383	44,264.14
Trespass Incidents	Adult/Child trespasser struck while crossing track at station	9.255835197	Trespass (including non-intentional)	108,282	675,903.60
	Adult trespasser electric shock in station	3.492124514	Disorder/drunks or trespass	41,761	214,169.36
Station Incidents	Passenger/MOP boarding/alighting	6.68230324	Passengers joining/alighting	82,522	230,144.08
	Passenger/MOP fall from platform or bridge in station	5.512015843	Fatalities and or injuries sustained on platform result of struck by train or falling from a train	9,295	45,310.26
	Passenger/MOP struck while on platform	2.283889433			
	Staff struck while on platform	1.22464606			
	Passenger burns not on train	0.012137744			
	Fire in station	0.009664167	Station evacuated due to fire alarm	1,207	5,982.76
	Passenger/MOP electric shock in station	0.87045174	Mishap - Station Operating causes	1,621	8,224.78
	Passenger injury due to being hit by objects/vehicles not on platform	0.547627072	Other Station Operating causes	23,942	72,858.23
	Passenger/MOP struck while crossing track in station	0.546122422			
	Staff fall between platform and train in station	0.449674736			

	Explosion in station	0.15			
	Passenger/MOP exposure to hazardous substances in station	0.009064614			
	Passenger fall during evacuation at station	0.0026537			
	Passenger exposed to noise	0.000422014			
Level Crossing Incidents	Misuse Error	6.40596057	Level Crossing Incidents including misuse	16,851	99,014.53
	Violation	3.248547561			
	Proper Use	1.556454009			
	Level crossings	7.602248201			
	Passenger train collision with road vehicle on level crossing	3.191138064			
	MOP pedestrian struck/crushed by train on level crossing	2.99595576			
	Passenger struck/crushed by train on station crossing	0.546122422			
	MOP slip, trip or fall on level crossing	0.30268941			
	MOP struck/trapped by level crossing equipment	0.149480661			
Vandalism	Train collisions caused by objects placed on the line by vandals	0.160333647	Vandalism or theft (including the placing of objects on the line)	20,544	141,451.44
	Struck by objects thrown by vandals through train window	0.0746	Vandalism or theft	11,248	64,952.56
	Train derailment cause by vandalism	0.027577778	Cable vandalism or theft	3,928	42,740.91
	Train fires caused by arson/vandalism	0.013670044	Fire caused by vandalism	373	1,687.35
		66.81509804		*1,798,779*	*9,841,601.64*

Appendix 3: Description of Microsoft Excel formulas used.

The AVERAGE function in Microsoft Excel calculates the arithmetic mean of a group of numbers. It ignores logical values, empty cells and cells that contain text. Therefore, the data was properly sorted and only the sample data (i.e., data without 0mins delay values) was used in the calculation. *[Available at* https://www.excel-easy.com/examples/average.html *Accessed on 13 September 2021]*

The EXP function returns is raised to the power of a number. EXP is the exponent and is the inverse of LN, the natural logarithm of a number. *[Available at* https://support.microsoft.com/en-us/office/exp-function-c578f034-2c45-4c37-bc8c-329660a63abe *Accessed on 20 September 2020]*

The LN function returns the natural logarithm of a number. *[Available at* https://support.microsoft.com/en-us/office/ln-function-81fe1ed7-dac9-4acd-ba1d-07a142c6118f *Accessed on 20 September 2020]*

The STDEV.S function in Microsoft Excel calculates the standard deviation based on the sample. This function was used to calculate the standard deviation of the sample data (i.e., delay data without 0mins record) for each CPIF group. The function uses the formula

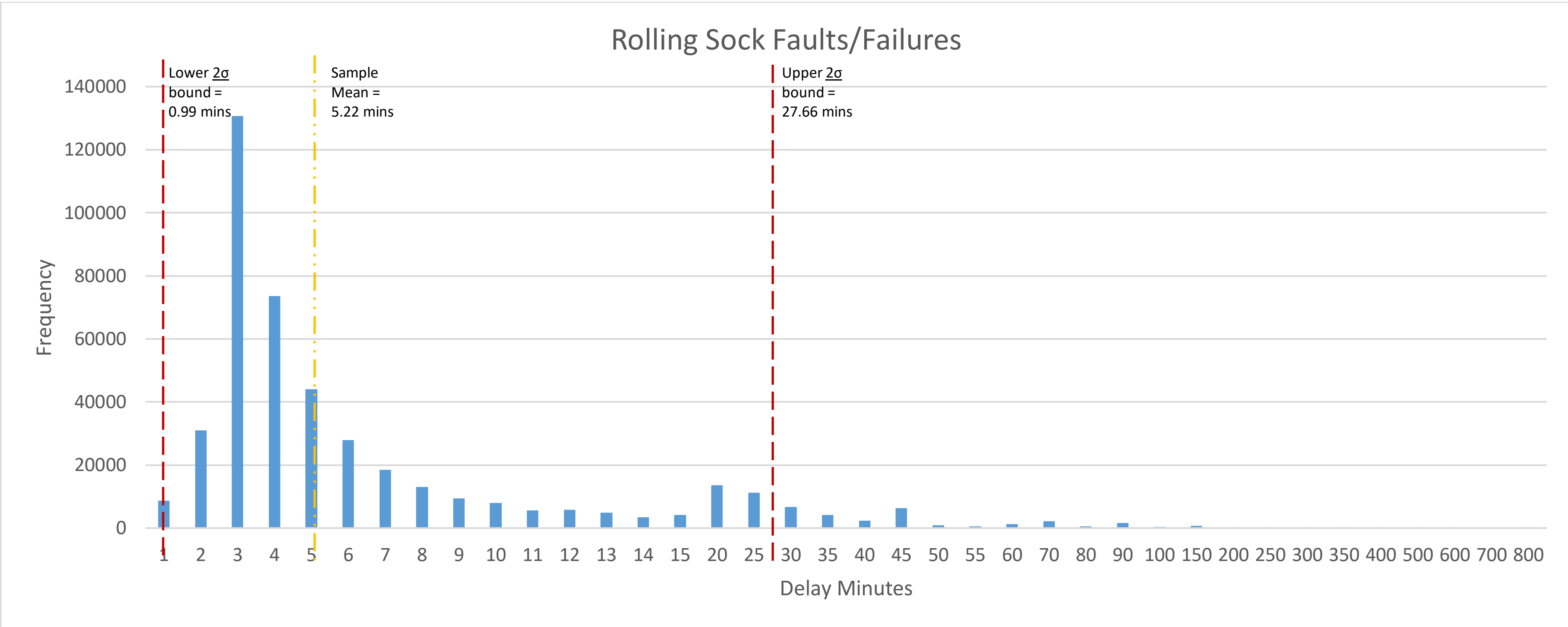
$$s = \sqrt{\frac{\sum(x_i - \bar{x})^2}{n-1}}$$

Where s is the standard deviation; $\bar{x}$ is the sample mean and n is the sample size. *[Available at* https://www.excel-easy.com/examples/standard-deviation.html *Accessed on 16 July 2021]*

Appendix 4: Sample delay data distribution for each CPIF group.

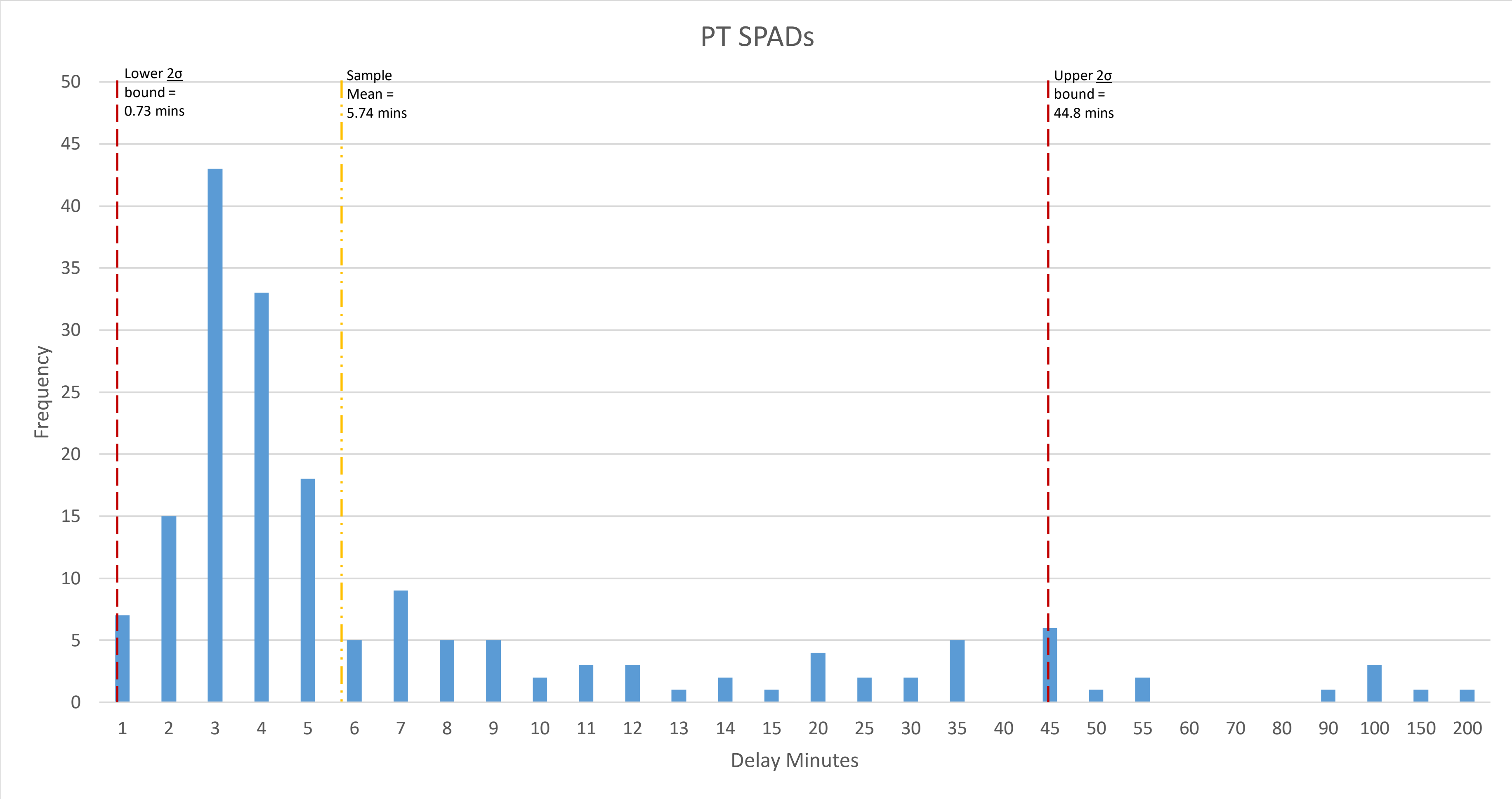
Illustrated below are histograms showing the delay frequency distribution for each CPIF group. It also shows the CPIF mean value (i.e., exponent of the log mean of the sample data) and the 2σ lower and upper bounds within which the researcher is confident that 95% of the data is spread.

a) Rolling stock faults/failures sample delay data distribution graph

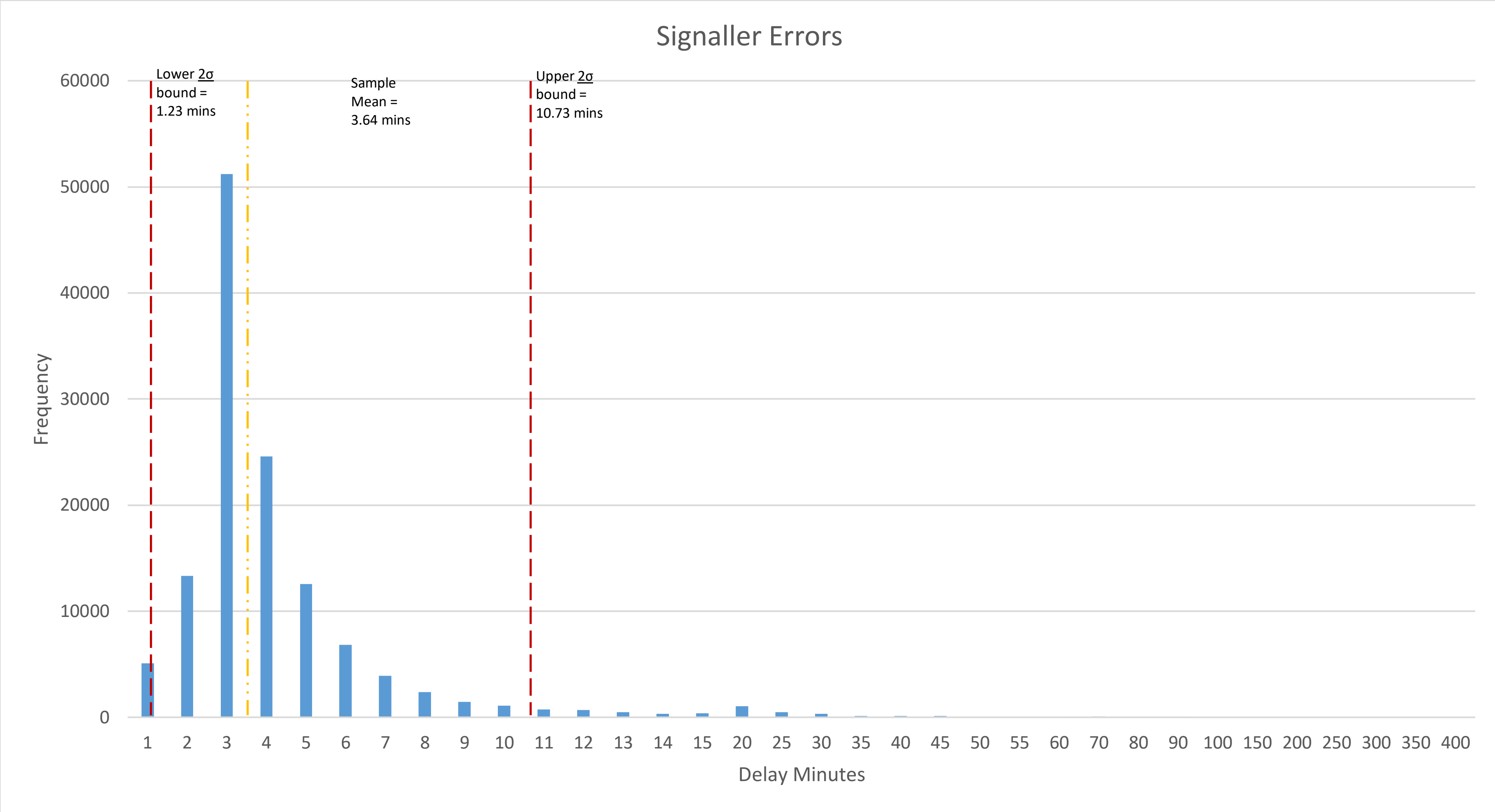


b) Driver errors sample delay data distribution graph

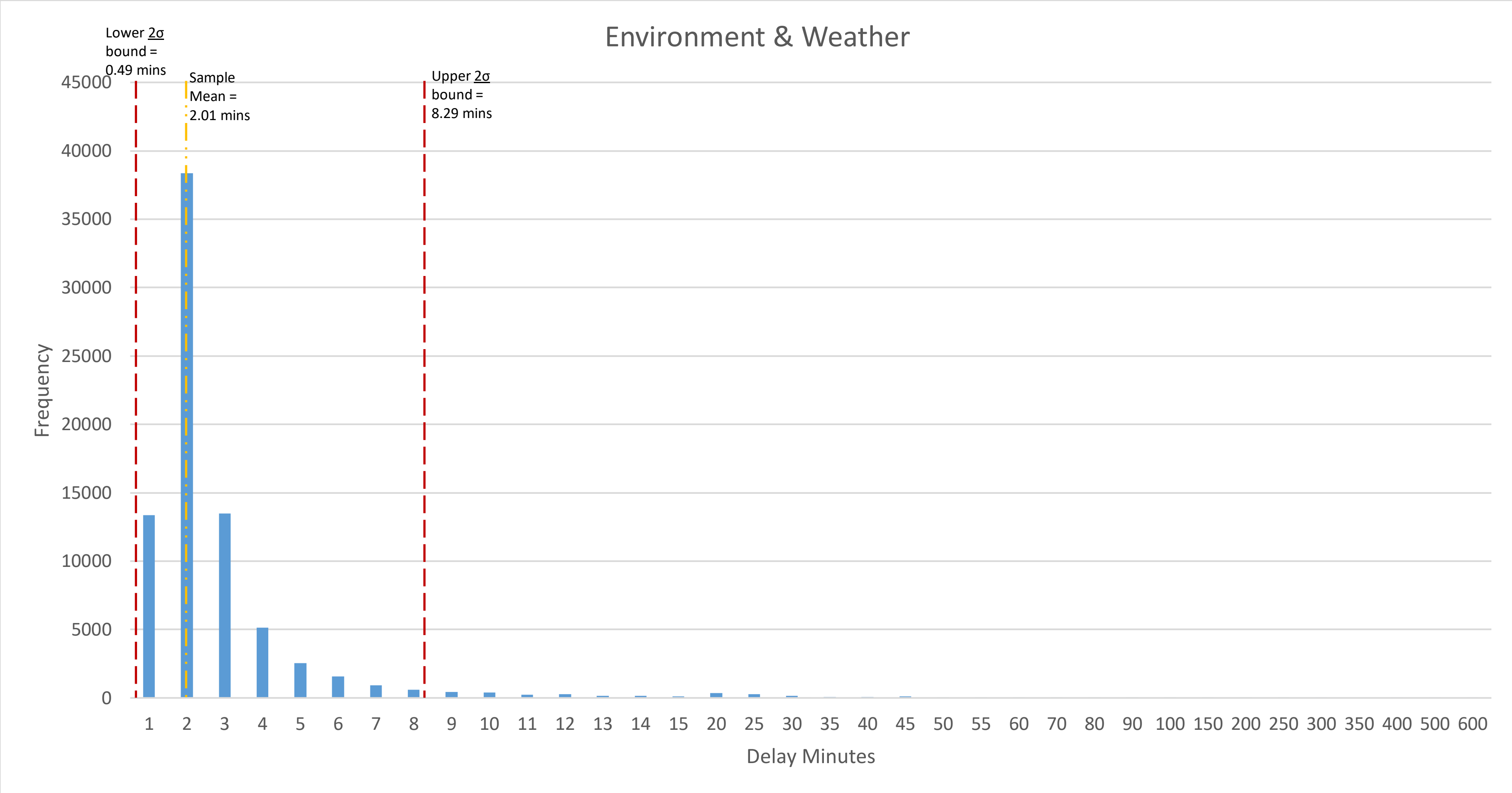
c) Passenger Train SPADs sample delay data distribution graph



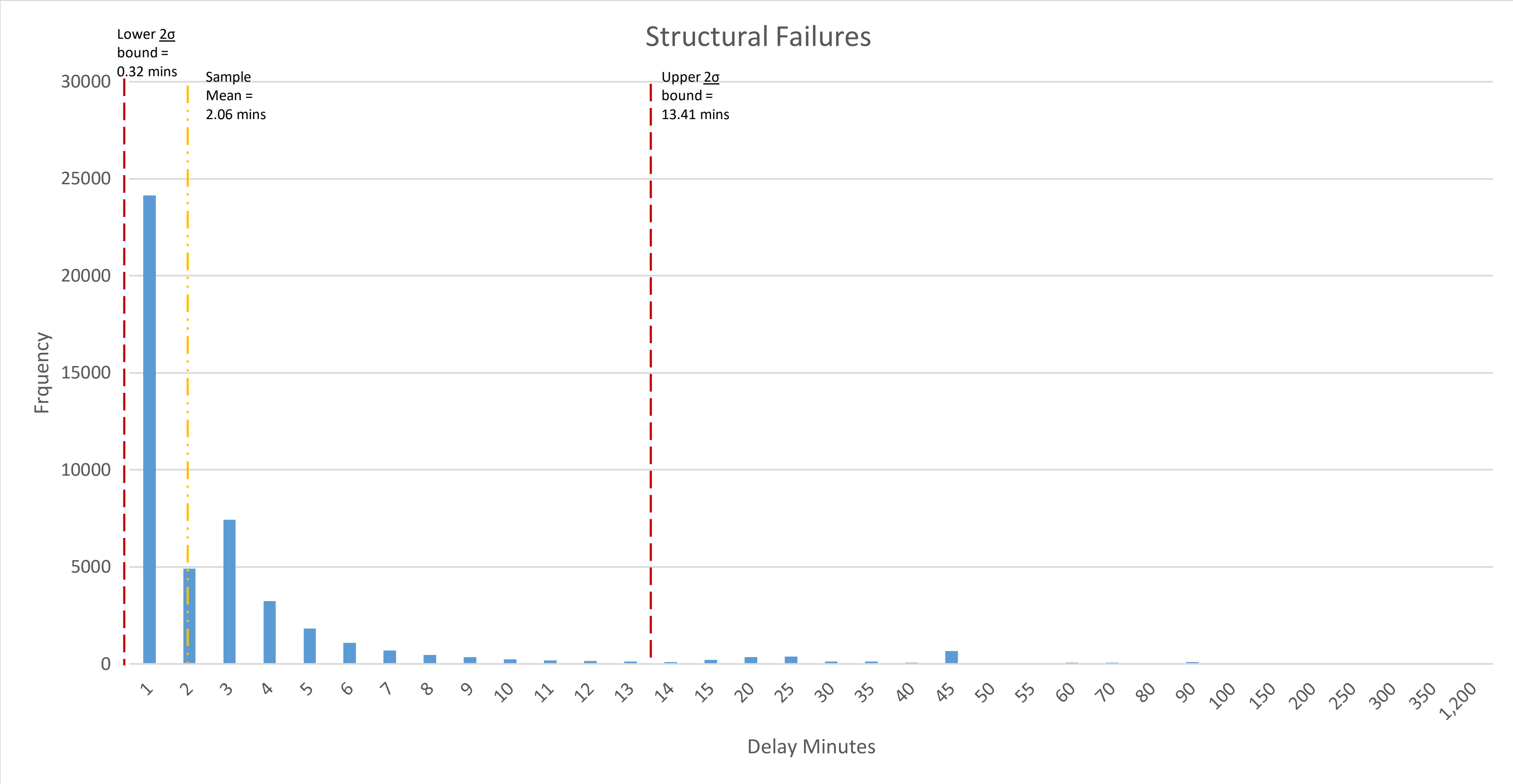
d) Signaller errors sample delay data distribution graph



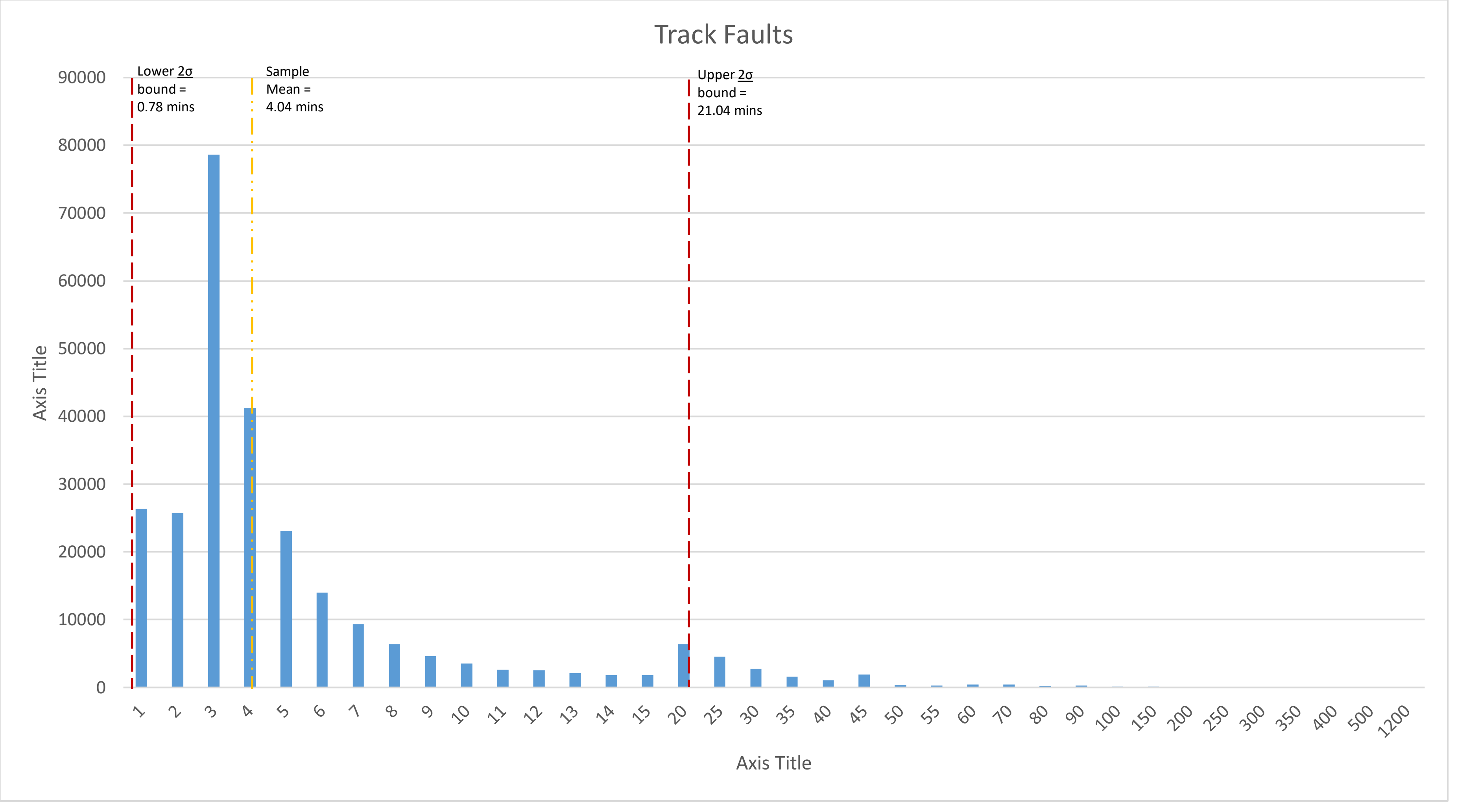
e) Environment & Weather sample delay data distribution graph



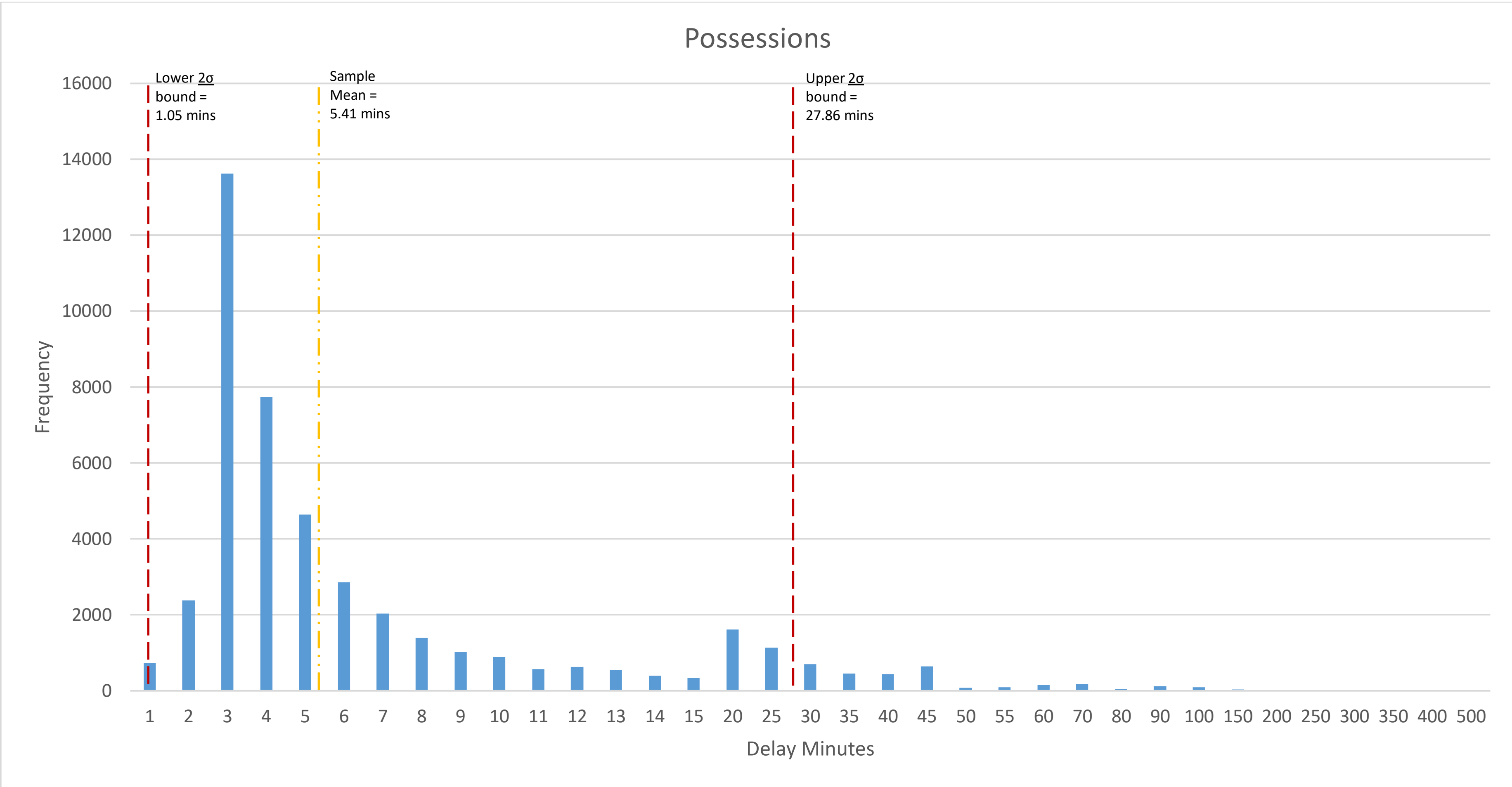
f) Structural failures sample delay data distribution graph



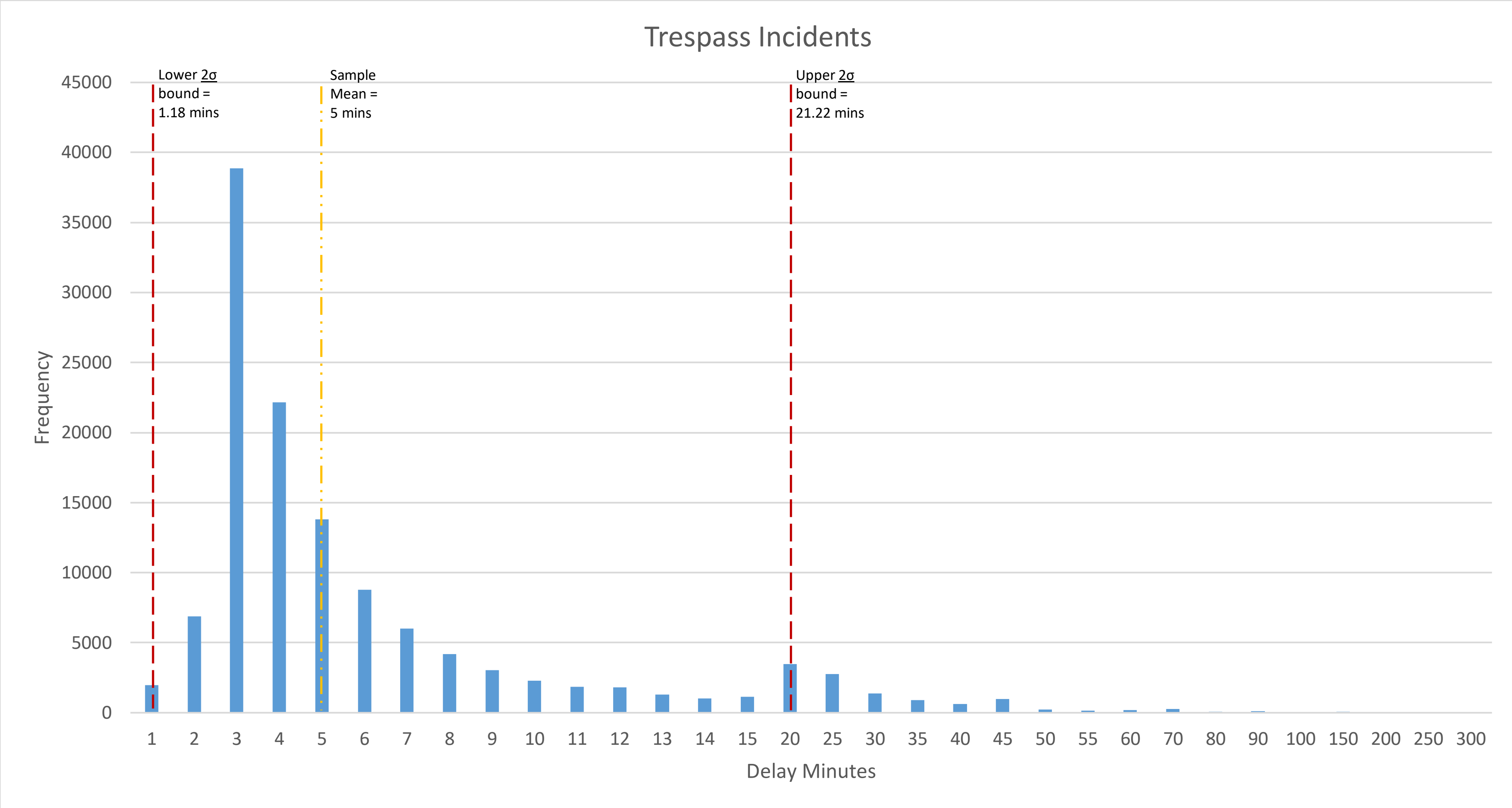
g) Track faults sample delay data distribution graph



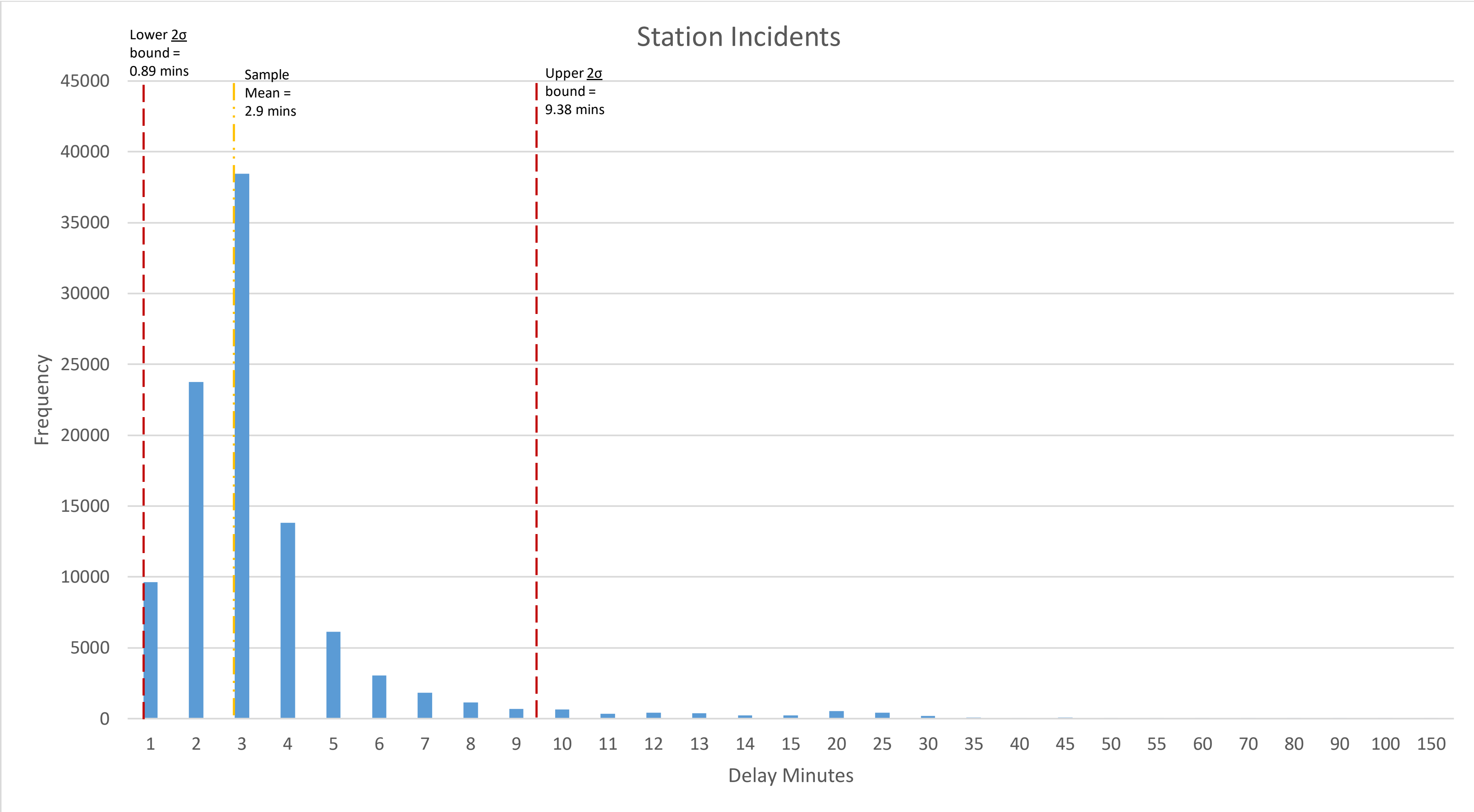
h) Possessions sample delay data distribution graph



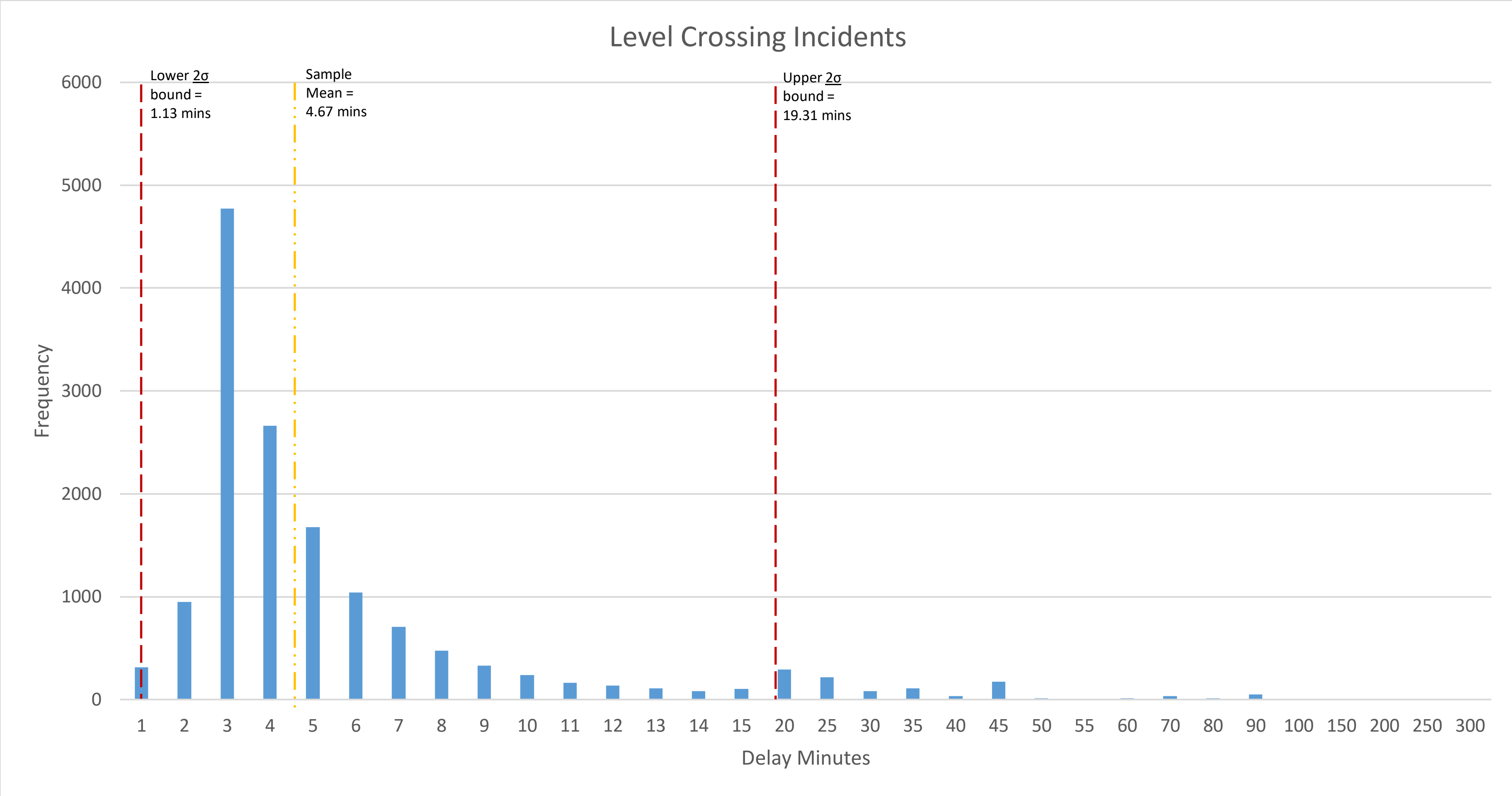
i) Trespass incidents sample delay data distribution graph



j) Station incidents sample delay data distribution graph



k) Level crossing incidents sample delay data distribution graph



l) Vandalism sample delay data distribution graph