Improving the Performance of Railway Track Switching through the Introduction of Fault Tolerance

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Declaration

This is to certify that I am responsible for the work submitted in this thesis, that the original work is my own except as specified in acknowledgements or in footnotes, and that neither the thesis nor the original work therein has been submitted to this or any other institution, in whole or in part, towards the award of any degree. I have exercised reasonable care to ensure that the work is original, and does not to the best of my knowledge break any UK law or infringe any third party's copyright or other Intellectual Property Right. I have read the University's guidance on third party copyright material in theses.

Samuel David Bemment
July, 2018

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Abstract

In the future, the performance of the railway system must be improved to accommodate increasing passenger volumes and service quality demands. Track switches are a vital part of the rail infrastructure, enabling traffic to take different routes. All modern switch designs have evolved from a design first patented in 1832. However, switches present single points of failure, require frequent and costly maintenance interventions, and restrict network capacity. Fault tolerance is the practice of preventing subsystem faults propagating to whole-system failures. Existing switches are not considered fault tolerant. This thesis describes the development and potential performance of fault-tolerant railway track switching solutions. The work first presents a requirements definition and evaluation framework which can be used to select candidate designs from a range of novel switching solutions. A candidate design with the potential to exceed the performance of existing designs is selected. This design is then modelled to ascertain its practical feasibility alongside potential reliability, availability, maintainability and capacity performance. The design and construction of a laboratory scale demonstrator of the design is described. The modelling results show that the performance of the fault tolerant design may exceed that of traditional switches. Reliability and availability performance increases significantly, whilst capacity gains are present but more marginal without the associated relaxation of rules regarding junction control. However, the work also identifies significant areas of future work before such an approach could be adopted in practice.

"If the modern railway industry is to be successful it must continuously improve the safety, reliability and whole life cost efficiency of its operations. The performance of switches and crossings is central to a high performing railway. The quality of switch and crossing installation and maintenance is therefore at the heart of our railway system. Nowhere can a permanent way engineer or skilled maintainer contribute more to the success of the railway industry than in these activities."

Prof. Andrew McNaughton. Former Chief Engineer, Railtrack.
Rob Boulger. Former President, Permanent Way Institution.
June, 2002
from 'British Railway Track, vol. 5' (Cope and Ellis, 2001).

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List of Abbreviations and Acronyms

A	Actuation
C	Control and Power
CBTC	Communication Based Train Control
CM	Condition Monitoring
CUI	Capacity Utilisation Index
D	Detection
EPE	Elastic Potential Energy
EPSRC	Engineering and Physical Scineces Research Council
ERTMS	European Rail Traffic Management System
ETCS	European Train Control System
FEA	Finite Element Analysis
FMECA	Failure Modes Effects and Criticality Analysis
FMS	Fault Management System
FPL	Facing Point Lock
FTA	Fault Tree Analysis
GPE	Gravitational Potential Energy
H	Humans
HS2	High-Speed 2

HSE	Health and Safety Executive
IBCL	In-Bearer ClampLock
II	Intelligent Infrastructure
IRSE	Instution of Railway Signal Engineers
KE	Kinetic Energy
L	Locking
LRU	Line Replaceable Unit
LU	London Underground
MA	Movement Authority
MBS	Multi-Body Simulation
MOM	Mobile Operations Manager
MTTFRI	Mean Time To Fault Requiring Intervention
MTTR	Mean Time To Repair
MTTSAF	Mean Time To Service Affecting Failure
NR	Network Rail
ORR	Office for Rail Regulatuon
OTPH	Operational Train Paths per Hour
P	Permanent Way
POE	Points Operating Equipment
P-way	Permanent Way
RBD	Reliability Block Diagram
RCM	Remote Condition Monitoring or Reliability Centred Maintenance
REPOINT	Redundantly Engineered Points
RHDR	Romney, Hythe and Dymchurch Railway

RMS	Root Mean Square
ROGS	Railways and Other Guided transport Systems
RSSB	Rail Safety and Standards Board
SIL	Safety Integrity Level
SMS	Signal Maintenance Specifications
SMTH	Signal Maintenance and Testing Handbook
SPAD	Signal Passed At Danger
STPH	Signalling Train Paths per Hour
TCT	Timetable Compression Technique
TDC	Top Dead-Centre
TOPS	Total Operations Processing System
TRUST	Trains Running Under System Tops
UIC	Union Internationale des Chemins de fer (International Union of Railways)

A note on terminology

There is some disagreement in literature as to the meanings of 'points', 'turnout', 'track switch' and 'junction'; compounded by terms having subtly different meanings in British and American English. Definitions as used in this thesis are clarified below.

Much terminology in the rail sphere is used with inconsistent meaning; especially between signalling and permanent way disciplines. For rail related terms with multiple meanings, signalling definitions have been used herein, as per the IRSE Glossary (IRSE, 2011). Track specific terms are defined in the Permanent Way Institution's 'Track Terminology' (Ellis, 2001), and fault tolerant terminology in IFAC SAFEPROCESS definitions (Blanke et al., 2006; Iserman and Balle, 1997). Most terms are defined within the work, but more detail is provided in Ellis' Encyclopaedia (Ellis, 2006). Regarding switches specifically:

Points Traditionally refers to the pair of movable rails themselves, hence its normal form is plural. The movable rails were traditionally controlled with a human-operated lever, with force transmission through rodding. With the addition of more modern automated drive arrangements, 'points' has sometimes been taken by extension to refer to the whole remote mechanical arrangement of movable rails, drive, closure panel and common crossing. It is sometimes accepted in everyday dialogue to mean this, yet some technical documents disagree. For these reasons, in this thesis, the use of the word 'points' is avoided.

Turnout almost exclusively refers to a diverging track arrangement, including switch rails, closure panel and common crossing. In essence, the term 'turnout' refers to track assets but not signalling assets. However, in some cases, the term is also taken to include the drive arrangement. Herein, 'turnout' relates to a whole arrangement of track elements - movable rails, closure panel, and common crossing - without consideration of the motive power arrangement.

Junction generally refers to a node at which two or more routes intersect. This may mean a single track switch, but could include any number.

Track switch often abbreviated 'switch', is the preferred term in American English, but unlike 'points', generally includes reference to the motive power as well as some or all track elements. The term has seen extensive usage in British English, albeit variously to refer to switch rails alone, all track components, or all track components *and* motive components. In this thesis, this term will be used to refer to the movable track elements (including their related supporting elements), and motive power elements, of a single track divergence - but not ancillary track components such as the common crossing. Hence the term ‘switches and crossings’ could be interchangeable with ‘turnouts’.

Chapter 1

Introduction

1.1 Evolution of the track switch

An early Victorian railway engineer would be simultaneously familiar and astonished if presented with a modern railway system. Elements such as tunnels, viaducts, traction, rolling stock, signalling and telecommunications all still play a role, yet all have changed over time to be almost unrecognisable from early days. Even the cross section of the rails themselves – usually now continuously welded - has evolved with much research and experience. However, the track switches would appear broadly similar. The mode of operation, in some cases, may have moved from human muscle and levers to remote electric or hydraulic machines, but a modern railway track switch takes a general form which is essentially unchanged since first patented by Charles Fox in 1832 (Fox, 1904), and illustrated in Figure 1.1.

In rail, development is driven by business and operational needs. The historical trend has been to run more frequent, faster, or higher-capacity services, whilst necessarily controlling costs, performance, and safety to societally acceptable levels. This is reflected in the parallel historical trend of the gradual evolution of components, with an occasional step-change as radical new technologies are introduced. An example of the former is the ever-evolving discipline of signalling and train control; and of the latter the move from steam to diesel then electric traction. Until now, as evidenced by the similarity of state-of-the-art switch designs to Victorian types, switches have generally followed the former pattern. Gradual improvements to switch design have seen axle loads and traffic speeds increase. Such changes are detailed in industry design and maintenance manuals (Morgan, 2009). Powered operation has allowed the number of switches which can be controlled from a single signal box – and the distance of those switches from the box – to be many times that of mechanical arrangements (Hadaway, 1950).

1.2 Problem statement

With the current trend towards communication-based train control, track switches and level crossings may soon represent the only remaining ‘active’ (i.e. requiring power and physical movement to perform function), ‘mission-critical’ (i.e. correct system function is required in order for the railway to operate successfully) fixed-assets on the rail infrastructure. Track switches, if unchanged from the present day, will then form the performance limiting elements of the railway network in most instances. A step change in their performance will be necessary in order that the switches do not prevent other assets - and therefore the network as a whole - reaching full performance potential.

Indeed, as of 2012, literature identifies locations on the British mainline network where switch and junction design is the limiting factor on train capacity (Ison et al., 2012; Network Rail, 2011a). However, performance limitation may be true whether the chosen measure of ‘performance’ is reliability, availability, maintainability, capacity, cost or quality of service. It is therefore both relevant and timely to investigate opportunities for the re-engineering of track switches; not only to bring about the same step changes in performance seen from other assets over the preceding two centuries, but also to prevent them limiting the performance of other elements of the modern rail transport system.

1.3 Railway track switching

1.3.1 Current practice

Rail transport networks operating more than a single line are dependent upon the ability to change routes for traffic. Switches serve this purpose, allowing the permanent way to merge and diverge. There have been various designs to achieve this aim through history. However, Fox’s design is now the worldwide industry standard, illustrated in Figure 2.1. Herein, this shall be referred to as the ‘traditional’ switch layout. This design consists of a ‘common crossing’, two ‘switch blades’ able to slide laterally between two ‘stock rails’; with all components resting upon a suitable supporting structure, typically ballast with sleepers and bearers, or concrete slab.

Motion of the blades is achieved by human-powered rods and levers, or by POE (Points Operating Equipment) of hydraulic, pneumatic or electric type. There are various designs of POE which are located either between the running rails, at the line side, or a combination of both. Switch blades are prevented from unwanted motion by a mechanical locking arrangement generally combined into the POE. In 2011 there were 21,602 track switches on the British Mainline network (Network Rail, 2016), and many more in depots and on metros.

Figure 1.1 A Switch Panel ready for installation as part of remodelling works on the Romney, Hythe and Dymchurch Railway, Kent, England. Though 381mm gauge, all essential components have been scaled down faithfully. Credit: Author

1.3.2 Design for safety considerations

Like most rail engineering, switch design and operation has evolved over time with safety as the priority. This is a societal necessity - many accidents and deaths have been caused by poor switch design, malfunction, and associated interlocking and signalling practices. L. T. C. Rolt's 'Red for Danger' (Rolt, 1982) provides a history of British railway disasters, explaining why many modern interlocking controls exist. Two primary historical switch safety developments were the FPL (Facing Point Lock) and interlocked protecting signal. FPL prevents the switch rails moving under a train, and the vehicle 'splitting the points' - different wheelsets of a train being guided down separate routes, usually with disastrous results. Splitting the points has occurred as recently as February 2007 at Greyrigg (RAIB, 2011), killing one; and in May 2002 at Potters Bar, killing seven and injuring 76 (RSSB,

Figure 1.2 The aftermath of the Greyrigg (Left) and Potters Bar (Right) derailments. Source: (Left) RAIB (RAIB, 2011, p. 6), (Right) BBC News.

2005). The aftermaths of these incidents are illustrated in Figure 1.2.

This safety risk is identified by governmental and regulatory bodies. In Britain, methods of switch control and operation are specified by the government through a group of documents referred to as the ‘ROGS’ (Railways and Other Guided Transport Systems (Safety) Regulations 2006) (ORR, 2006). These requirements are further cascaded through a series of Railway Group Standards covering design, operation and maintenance, latterly issued by the Office of Rail Regulation (Genner, 1997; Hayter, 2000, 2011).

1.3.3 Performance limitations

Prioritising safety has not *necessarily* been to the detriment of cost, reliability, maintainability, or capacity. However, it is the case that improving non-safety performance may have been side-lined. Existing designs do not feature fault tolerance. In Britain, it is only in the 21st century, as part of Network Rail’s ‘Intelligent Infrastructure’ programme (Section 2.2.5.2), that condition monitoring data is being collected. Signallers operating the network have no knowledge about these critical assets beyond whether they are ‘Normal’, ‘Reverse’, or ‘Somewhere in-between’.

When fully operational, switches limit network performance (Chapter 2). However, the impact upon network performance from switch failures is also detrimental. A switch which cannot correctly operate to set the route presents a potential derailment risk and cannot be traversed by a vehicle. The vehicle must wait at a danger signal until the switch is fixed or alternative arrangements are made. Alternative arrangements can involve staff flagging trains on at walking pace with the switches clamped in position. Diversionary routes are scarce, trains queue until the problem can be rectified. This leads to significant immediate delay, and further ‘knock-on’ delay or cancellations as the junction timetable becomes perturbed (Section 2.4.3.1).

Clearly, in this instance, a level of fault tolerance may be able to improve network performance. If subsystem faults did not directly cause system failures, then trains could continue to traverse the switch and service could continue, ideally in full operation but perhaps in a degraded mode. Emergency repair could be carried out in quieter periods, freeing up capacity and removing the necessity of having emergency maintenance teams on standby. If switch reliability achieved a much higher level, the safety margins surrounding junctions could perhaps be relaxed, allowing a higher fraction of plain line capacity to be utilised. An ultimate extension of this would be that the junction behaved as plain line, meaning minimal plain line headways could be carried through junctions, and equivalent plain line capacity achieved across the network.

1.4 Fault tolerance

A fault is a defect occurring in hardware or software, within a given system boundary. Faults can result in the undesirable or unexpected behaviour of the system. When a system is unable to complete an action or command as expected, it is said to have failed. Depending upon the purpose of the failed system, this failure may cascade to interfacing systems such that a wider system, or system of systems, is unable to complete a required task. The consequences of failures in engineering systems can include loss of revenue, further damage to the system itself, and ultimately, in safety-critical systems, loss of life.

A fault tolerant system is able to prevent faults developing into failures through design. Fault tolerance is important in safety-critical engineering, such as in trains, aircraft, bridges, cars and nuclear power (Isermann, 2006). Without fault tolerance, many designs could not function to the standard required by their regulatory environment. A prime example is aircraft flight control surfaces, which would typically have triplex or quadruplex actuation systems to retain control of the aircraft in the case of multiple faults.

Fault tolerance can also have benefits for non-safety critical systems. When correctly implemented, fault tolerance can increase operational availability and/or ease maintainability. For instance, plant in large power stations is typically over-specified when compared to rated generating capacity, such that one turbine/generator set can be taken offline for repairs without compromising output. Fault tolerance can reduce operational, maintenance and whole-life costs. Fault tolerance has been adopted by the rail industry in other areas (Section 2.3).

1.5 Project Background

The work in this thesis follows the author's work upon the REPOINT[1] and REPOINT II[2] Projects. This thesis forms a contribution to the projects at large, and does not aim to address all research questions posed by fault tolerant track switching.

REPOINT was an EPSRC (Engineering and Physical Sciences Research Council) and RSSB (Rail Safety and Standards Board) funded project which ran from March 2011 to May 2013, as one response to a call related to removing the constraints caused by nodes (stations and junctions) upon the GB rail network. The project was instigated by Prof. Roger Dixon (Principal Investigator) and Prof. Roger Goodall (Co-Investigator). The project was inspired by other industries, particularly aerospace and nuclear, to examine whether the redundancy concepts which are readily accepted in other safety critical environments could be applied to track switching. The literature review (Chapter 2) establishes that fault-tolerant railway track switching has not been investigated before. This work poses a number of research objectives, expanding upon the research question originally posed by the REPOINT Project:

> Could a fundamental re-think of railway track switching ease some of the current route-setting constraints to provide higher capacity, and provide a significant reduction in operational unreliability arising from points failures?

1.6 Aim and Objectives

The aim of this thesis is as follows:

> To investigate the opportunity to engineer fault tolerance into railway track switching, and its potential to improve performance.

Figure 1.3 presents a research map which identifies the key areas of work in the remainder of this thesis, and how they link together to meet each objective and therefore this aim, and the outputs related to each objective, whether paper or chapter.

The five objectives presented in Figure 1.3 follow from the aim, and broadly correspond to the work presented in Chapters 3-7, which are discussed in turn in the next section. Numbered tasks in the figure refer to individual and independent modelling tasks in Chapters 4 through 7.

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[1] REPOINT Project: United Kingdom EPSRC and the United Kingdom RSSB grant number EP/I010823/1, for the project titled 'REPOINT: Redundantly engineered points for enhanced reliability and capacity of railway track switching'

[2] EIT (Enabling Innovation Team) and RSSB grant number RSSB/12/EIT/1647 for construction of a laboratory demonstrator of REPOINT concepts.

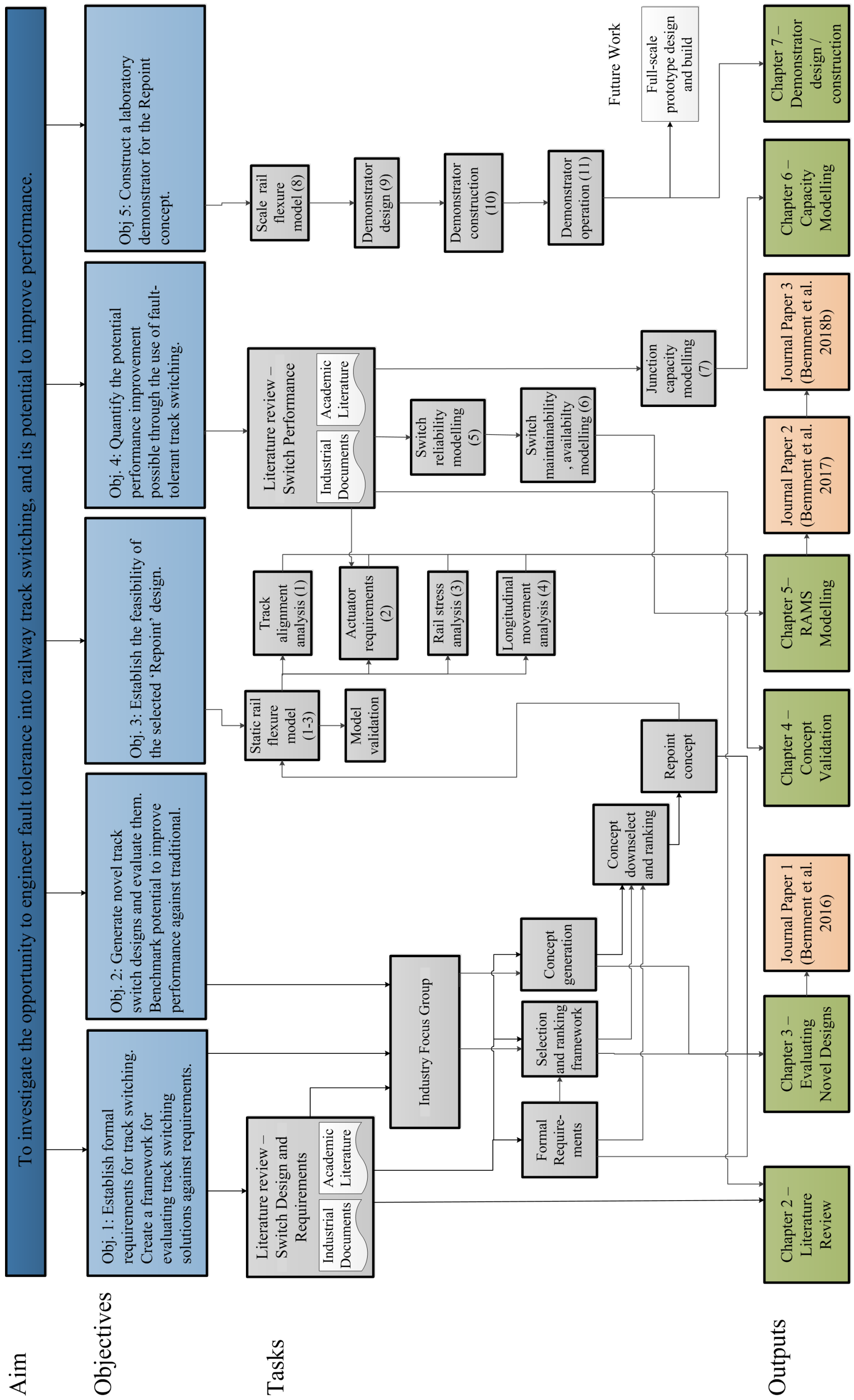


Figure 1.3 Research map showing research development overview, indicating thesis aim, objectives, tasks and outputs.

1.7 Thesis overview and outline methodology

The thesis aim and objectives identified in Section 1.6 are achieved in the following work and chapters:

1.7.1 Existing practice & literature survey

A survey of relevant literature and background information is provided in Chapter 2. The literature review is divided into three sections. The first section explores existing track switching practice, including operational and maintenance aspects, drawing heavily from industrial design and maintenance literature. The second section explores the concept of fault tolerance, including state-of-the-art practice in other fields, drawing more heavily upon academic literature. The third section explores how the performance of track switches can be measured and modelled, drawing from both industrial data sources and academic studies.

1.7.2 Evaluating novel track switch designs

Chapter 3 explores options for novel solutions to the track switching problem which may allow for fault tolerance. The chapter firstly establishes a set of functional and non-functional requirements for track switching solutions by analysing the system interfaces. The methodology adopted to generate a range of possible solutions is to assemble a cross-industry focus group. A selection of novel solutions are compared to the requirements, to establish which ideas may outperform traditional designs. Traditional switching solutions used as benchmarks in Chapters 5 and 6 are also compared to the requirement set.

1.7.3 The 'Repoint' switching concept

The top ranking idea from Chapter 3 is discussed in more detail in Chapter 4. This idea is termed the 'Repoint' solution. The functional elements of the design are described in detail, including how fault tolerance and maintainability could be designed in. This chapter includes modelling of rail behaviour to ensure the concept is practically feasible. The methodology used is to derive models from first principles and parametrise for a series of typical switch sizes.

1.7.4 Modelling reliability, maintainability and availability performance

Chapter 5 establishes Reliability, Maintainability and Availability performance. The performance of traditional switches is first benchmarked using field data. Relevant human factors issues are also examined. Performance is established through a combination of published literature, analysis of data provided by industry, interviews with rail industry professionals, and modelling based upon these sources. The modelling methodology adopted is to fit appropriate failure distributions to key subsystems of existing systems through analysing field data. These models are then extended using an RBD approach to make projections of the possible performance of fault-tolerant systems featuring multi-channel redundancy.

1.7.5 Modelling capacity performance

Chapter 6 establishes the network capacity performance of track switching. The performance of traditional switches is first benchmarked using established industry methods for capacity calculation. Fault-tolerant switches are then modelled in the same way to establish the potential capacity benefits.

1.7.6 Mechanical design and development of a concept demonstrator

Chapter 7 describes the modelling, development and construction of a Repoint concept demonstrator. Firstly, the concept is modelled dynamically to establish kinematics, dynamic and static loadings, and to size the actuator and motor drive. The architecture and detail design of the demonstrator is then described.

1.7.7 Conclusions and further work

The final chapter draws conclusions from the work presented in the preceding seven chapters. It also includes suggestions for work which can build upon the investigation and findings in this thesis.

1.8 Contributions

As the concept of fault-tolerant track switching has not been explored before, there is much originality in the research that is associated with it. Specific contributions are highlighted in the introduction to each chapter, but are summarised as follows:

Contribution to systems science. Contributions in identification and evaluation of the functional and non-functional requirements of track switching solutions. Primarily presented in Chapter 3, this thesis contains a decomposition of the fundamental requirements for track switching solutions. Also established is a framework for the evaluation of alternative track switching designs and performance, which could be utilised in other situations, e.g. metro or overseas.

Contributions to the risk and reliability field. Namely, contributions related to the understanding of the reliability of existing switch machines and the possible effects of embedding subsystem redundancy. Chapter 5 models the effects of various schemes using subsystem redundancy in order to improve the 'classic' reliability and availability of the switching system. This exercise is performed with data relating to real-world reliability of switch installations.

Contributions to rail network performance modelling. Namely, contributions in modelling the performance of fault tolerant track switching. As established in the literature review in Chapter 2, 'performance' is a wide ranging term, and herein capacity, reliability, availability and maintainability are considered the main indicators. This modelling is explored in Chapters 5 and 6.

Contributions to railway engineering. Including permanent-way design, signalling principles and maintenance principles. Namely, contributions in mechanisms enabling fault-tolerant approaches in railway track switching, and the modelling and model validation of such. Chapter 4 explores a novel design of track switch, but specifically the enabler, which is the 'passive locking' movement and associated mechanical arrangement. This contribution forms one patented element of the research.

1.8.1 Publications

1.8.1.1 Journal papers:

1. Bemment, SD, Ebinger, E, Goodall, RM, Ward, CP and Dixon, R (2016) 'Rethinking rail track switches for fault tolerance and enhanced performance', Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit.[3] (Bemment et al., 2016)
2. Bemment, SD, Goodall, RM, Dixon, R and Ward, CP (2017) 'Improving the reliability and availability of railway track switching by analysing historical failure data and introducing functionally redundant subsystems', Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit. (Bemment et al., 2018)

[3]This paper was awarded the 2018 William Alexander Agnew Meritorious Award/Clarence Noel Goodall Award by the Institution of Mechanical Engineers for a meritorious paper on the subject of Railway Engineering.

3. Bemment, SD, Harrison, T, Goodall, RM, Ward, CP and Dixon, R (2017) 'Extending emergency repair response times for railway track switches through multi-channel redundancy of functional subsystems', International Journal of Railway Technology (Bemment et al., 2017b)

Verbatim copies of journal papers are included in Appendix A.

1.8.1.2 Conference and proceedings papers:

1. Bemment, S, Dixon, R, and Goodall, R (2012). 'An evaluation of redundancy concepts for fault tolerant railway track switching' Proceedings of 8th IFAC SAFEPROCESS Symposium, IFAC Proceedings 2012, pp.763-769, DOI: 10.3182/20120829-3-MX-2028.00295. (Bemment et al., 2012b)
2. Bemment, S, Dixon, R, and Goodall, R (2012). 'Redundantly Engineered Points (REPOINT) for Enhanced Reliability and Capacity of Railway Track Switching', Proceedings of the 1st Annual RRUKA Conference, November 2012. (Bemment et al., 2012a)
3. Bemment, S, Dixon, R, Goodall, R, and Brown, S (2013). 'Redundantly engineered track switching for enhanced railway nodal capacity', Proceedings of ACATTA 2013 – Advances in Control and Automation Theory for Transportation Applications, in IFAC Proceedings Volumes (IFAC-PapersOnline), pp.25-30. Istanbul, Turkey, September 2013. (Bemment et al., 2013b)
4. Goodall, R, Bemment, S et al (2013). 'The Future of Train Control Systems', Proceedings of Institution of Railway Signal Engineers.(Goodall et al., 2013)
5. Bemment, S, Dixon, R, and Goodall, R (2013). 'REPOINT – Redundantly Engineered Points for Enhanced Reliability and Capacity of Railway Track Switching', Proceedings of the 10th World Congress on Railway Research, Sydney, Australia, November 2013. (Bemment et al., 2013a)
6. Wright, N, Bemment, S, Ward, CP, Dixon, R, and Goodall, RM (2014). 'The Performance and Control Requirements of a REPOINT Track Switch.' In Pombo, J (ed) Railways 2014: The Second International Conference on Railway Technology: Research, Development and Maintenance, Ajaccio, Corsica, France. DOI: 10.4203/ccp.104.215. April 2014.(Wright et al., 2014b)
7. Wright, N, Bemment, S, Ward, C and Dixon, R (2014). 'A Model of a REPOINT Track Switch for Control', In United-Kingdom-Automatic-Control-Council (UKACC) 10th International Conference on Control (CONTROL), Loughborough, UNITED KINGDOM, pp.549-554, June 2014. (Wright et al., 2014a)
8. Bemment, SD, Dixon, R, Goodall, RM, Ward, CP and Wright, N (2015). 'Design, Construction and Operation of a Repoint Laboratory Demonstrator', in the proceedings of the 1st IMechE Stephenson Conference, The Institution of Mechanical Engineers, London, April 2015. (Bemment et al., 2015a)
9. Bemment, S, Goodall, R, Ebinger, E, Ward, C, and Dixon, R (2015). 'Extending maintenance intervals of track switches utilising multi-channel redundancy of actuation and sensing', in proceedings of the International Symposium on Speed-up and Sustainable Technology for Railway and Maglev Systems, Chiba, Japan, November 2015. (Bemment et al., 2015b)
10. Bemment, S, Harrison, T, Goodall, R, Green, D and Soares, V (2017). 'The Repoint fault-tolerant switch', in Proceedings of the 2017 IRSE ASPECT Conference, Singapore, Singapore, November 2017. (Bemment et al., 2017a)

1.8.2 Patents

- Patent GB2516706A, 'Railway Points' (GB Patent: Loughborough University, 2013a)
- Patent GB2516707A, 'Railway Points Operating Apparatus' (GB Patent: Loughborough University, 2013b)
- Patent GB2516712A, 'Railway Track Crossing' (GB Patent: Loughborough University, 2013c)

The full text of the patents is included in Appendix B.

Chapter 2

Existing practice & literature survey

2.1 Introduction

The purpose of this chapter is threefold: to establish the state-of-the-art of the academic field(s) in question; to establish existing industry practice; and, by extension, to establish the academic originality of the work herein. From the title of this thesis, the work encompasses three major topics:

1. *Track Switching:* Existing practice, what are the different subsystem functions, and how does the system interact with other systems (including humans)? How does switching limit performance? What is the state of the art in track switch engineering?

2. *Fault Tolerance:* What is fault tolerance, how is it applied, what are the state of the art methods and techniques, and how have they been applied in rail or other industries?

3. *Performance:* What are the current metrics and methods used to evaluate network performance? What is the existing performance, and how can changes in performance be quantified? Why is it necessary to improve performance?

2.2 Existing track switching practice and technology

Though similar worldwide, some differences exist in switch design and operation, even within a single jurisdiction. British practice is referred to in this section, unless explicitly specified otherwise. 'General' practice is discussed, as there are exceptions throughout.

2.2.1 Division of responsibility

Rail transport is a complex system with many interactions and dependencies. The design, maintenance and operation of such a system is split between teams specialising in different disciplines. Switches fall at the interface of several disciplines. Most track elements are considered the realm of Permanent Way engineering. Most control and actuation elements are considered Signalling engineering; if distant from the controller/signaller there may also be Telecommunications engineering. The substructure is considered Civil engineering. If present, traction electrical elements are of Electric and Power engineering. Daily operation of the switch falls to the Signaller, a role distinct from the signalling engineer. The following description of existing practice will follow these divisions.

2.2.2 Permanent way elements

2.2.2.1 Single turnout arrangement

Figure 2.1 shows a single turnout panel: a structure composed of components, pre-fabricated off-site and transported in sections by road or rail. A turnout consists of 2 stock rails, 2 switch rails and a common crossing, fastened by clips, bolts and/or chairs to supporting bearers of wood, steel or concrete, themselves supported by a substructure of ballast or concrete. The stock rails are securely fixed, whilst the free ends of the switch rails can to slide upon supporting cast iron chairs, their movement limited by the attached stretcher bars and the lock and drive provided by the POE (Points Operating Equipment), described separately below. The switch rails are planed down along their length to mate up to the stock rails when closed. Figure 2.2 shows the detail of these permanent way elements. Further details of switch blade planing are provided in (Esveld, 2001, p. 334); general process and formulae used to specify the geometric layout of the rails is found in (Esveld, 2001, p. 344-347); and the GB-specific (Network Rail, 2010a). Designs are generally of infrastructure-operator standard specification.

Higher line speeds require shallower divergence angles, which in turn require longer switches. Designs therefore differ between a typical station throat and mainline installation - short, small clearances with many overlapping features in the former, and long, spaced out designs in the latter. Where the routes cross, a common crossing provides a gap for the flangeway of each wheelset to pass the inner running rail of the opposite route, and vice versa. The design of crossings is such that there is a region of wheelset travel where that wheelset is unguided laterally; this issue grows worse with faster crossings of shallower angles and correspondingly longer gaps. To keep the wheelset guided through this portion of track, a check rail is provided, which guides the wheelset by acting upon the flange-back of the wheel opposite the crossing.

Details of most GB designs are listed in industry manuals for switch design and maintenance, (Morgan, 2009) and (Cope and Ellis, 2001) respectively, published by the PWI (Permanent Way Institution). Standard British designs are detailed in a series of RE/PW (Railway Engineering Permanent Way) drawings (Simmons and Ventry, 2001) - RE/PW/800 to RE/PW/807 for UIC54B rail, RE/PW/600 to RE/PW/603 for BS113a rail and RE/PW/905 to RE/PW/912 for CEN60 rail section. The drawings are proprietary, but access was granted as part of this work. The RE/PW switches are identified by a letter, between A-H, which indicates the turnout speed and therefore length. There are 'vertical' (V) and 'inclined' (I) designs. V-designs have rails mounted vertically, with a rail twist on entry and exit, to simplify the machining of components. I-designs continue the 1 in 20 inboard inclination of the rails through the switch panel, improving ride dynamics at the expense of manufacturing complexity.

The sleepers and bearers are supported by the track substructure, which in Britain, is almost universally ballast and sub-ballast on layers of local soil or clay. The sleepers, ballast and substructure are designed as a whole-system to offer the correct stiffness and support to the vehicles. Consistent support is important; local irregularities can change the stress distribution leading to sub-optimal ride dynamics and stress concentrations. This often true at S&C, where mechanised maintenance can be more difficult, and track components such as extra rails and extended bearers on which to mount actuation elements can change the system stiffness and stability considerably.

2.2.2.2 Lesser utilised switch types

There are several other, lesser-utilised switch types. Literature does not provide any examples of these switches currently in use upon mainline networks, and only limited use in other situations (e.g. depots). **Turntables** can be used to switch between many tracks radiating from a central origin. They are able to rotate vehicles 180°, but can only switch short elements of a train (Raymond et al., 1937). **'2-Throw', '3-Throw'** switches, of use in confined spaces, are several (2- or 3-) switches overlaid upon each other such that the switch blades of each share the same slide plates, i.e. their moveable length covers the same length of track. They are generally low-speed solutions. **Track Substitution Switches** are common in non-standard track forms: funicular rail, monorails and roller coasters. They substitute an entire section of track with others, as in Figure 3.4. They are large and complex, but are the only viable solution for some track forms. **Loose-heel Short switches** have a hinge at the heel of the movable rail section, unlike most types where the switch rail itself bends, particularly used when the switch is very short, and described in (Morgan, 2009). **Trap and**

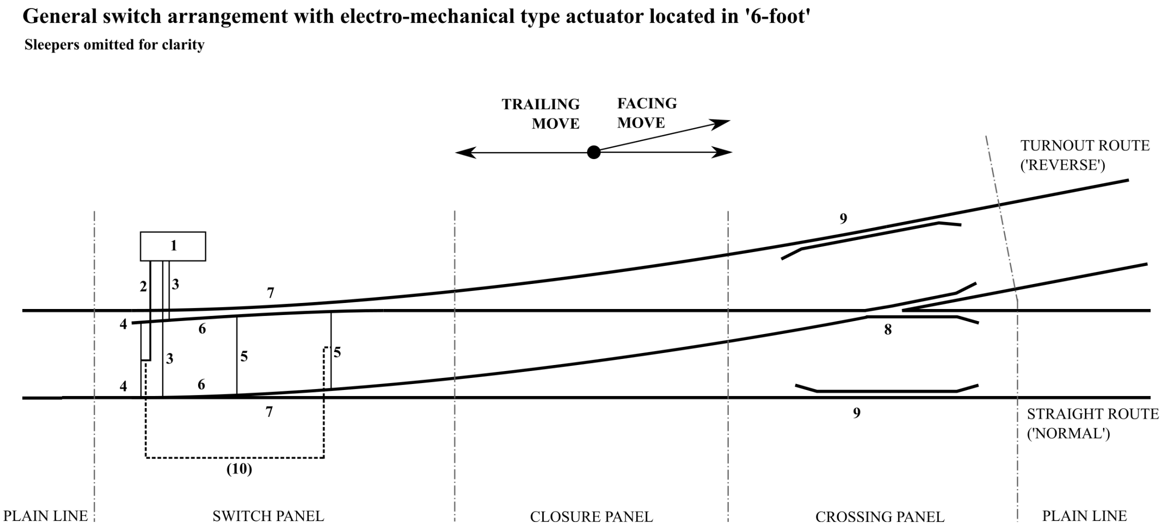


Figure 2.1 General arrangement of the permanent way elements of a track switch. This turnout is considered ‘Left-hand’ (diverging route to the left). Numbered elements as follows: (1) Lineside type POE; (2) Drive rod and drive stretcher; (3) Detection rods; (4) Switch rail toes; (5) Stretcher bars; (6) Switch rails ; (7) Stock rails ; (8) Common crossing (of given angle); (9) Check Rails; (10 - optional) Back Drive Arrangement.

Catch Points exist to derail vehicles in an emergency. They are generally found where a siding or stabling line joins a mainline - it is often safer to derail a runaway vehicle than let it encroach upon a running line. (IRSE, 2001).

2.2.2.3 Junction layouts

Junctions consist of one or more switches, the simplest being a single turnout in a single track route. A Crossover allows a vehicle on one running line to swap to an adjacent running line and consists of two switches. Crossovers can be facing and trailing, the direction selected for operational reasons. Trailing crossovers are inherently safer as they require a vehicle to stop and reverse before it is able to access the adjacent line (Pope, 1975). A scissors crossover consists of two crossovers superimposed. Crossovers on several lines arranged adjacent to each other are known as a ladder. These are sometimes fitted on running lines far from stations or junctions.

There are several other basic junction layouts, which can be seen in Figures 2.3 and 2.4, reproduced from (Esveld, 2001, p. 340-341). Crucially, any of these layouts will still be operated by the same designs of POE, with a single POE element for each pair of movable rails, referred to as an ‘end’.

A junction between two routes, each of multiple running lines, would typically consist of many switches allowing traffic to pass from any utilised route to any other. The traffic which will be using the routes needs to be known at the track design stage in order for this to be achieved (Pope, 1975). There is generally only a single signalled route through the junction from each arrival point to each destination, even if the permanent way is arranged to allow more. Conversely, even though the permanent way may be arranged to allow a route, the signalling system may not allow such.

2.2.2.4 Complex layouts

The most complex layouts occur at depots or terminal stations which serve several major routes. Provision will be such that vehicles from each route have enough platform space during normal operation. In practice this requires routes from most entry points to most platforms, necessitating complex layouts. Due to space restrictions, several solutions to provide additional switching flexibility exist, including single and double slips (Figure 2.3). Switches are often placed almost adjacent to each other; track layout is closely tied to the timetable; literature is rich with examples of optimisation of complex layouts, alongside timetable design, explored further in Section 2.4.1.

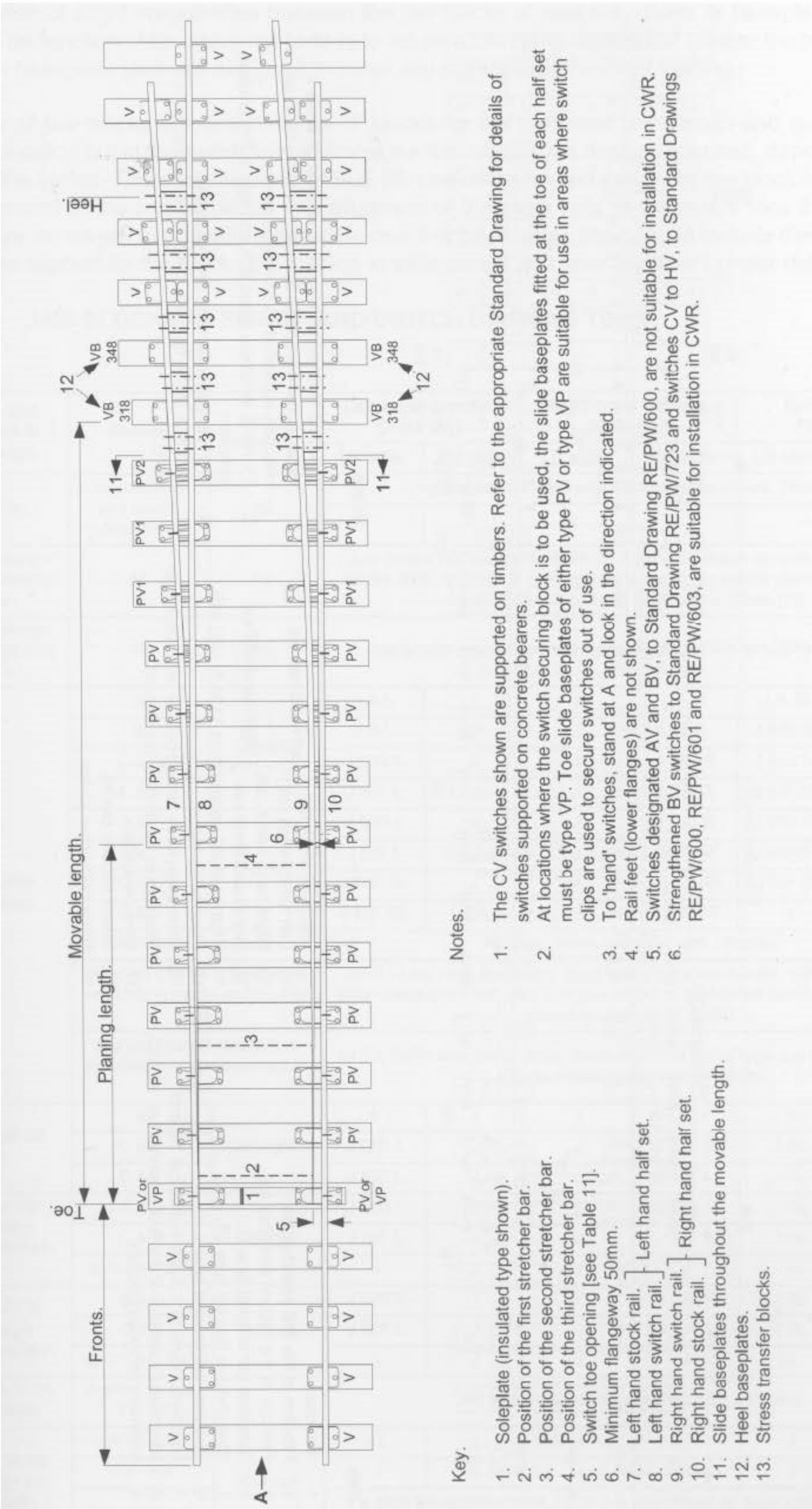


Figure 2.2 Permanent way component arrangement in an example layout - Flat-Bottom Vertical Design in 113A Rail, of length 'C'. Reproduced from 'Switch and Crossing Maintenance' (Cope and Ellis, 2001, p. 143)

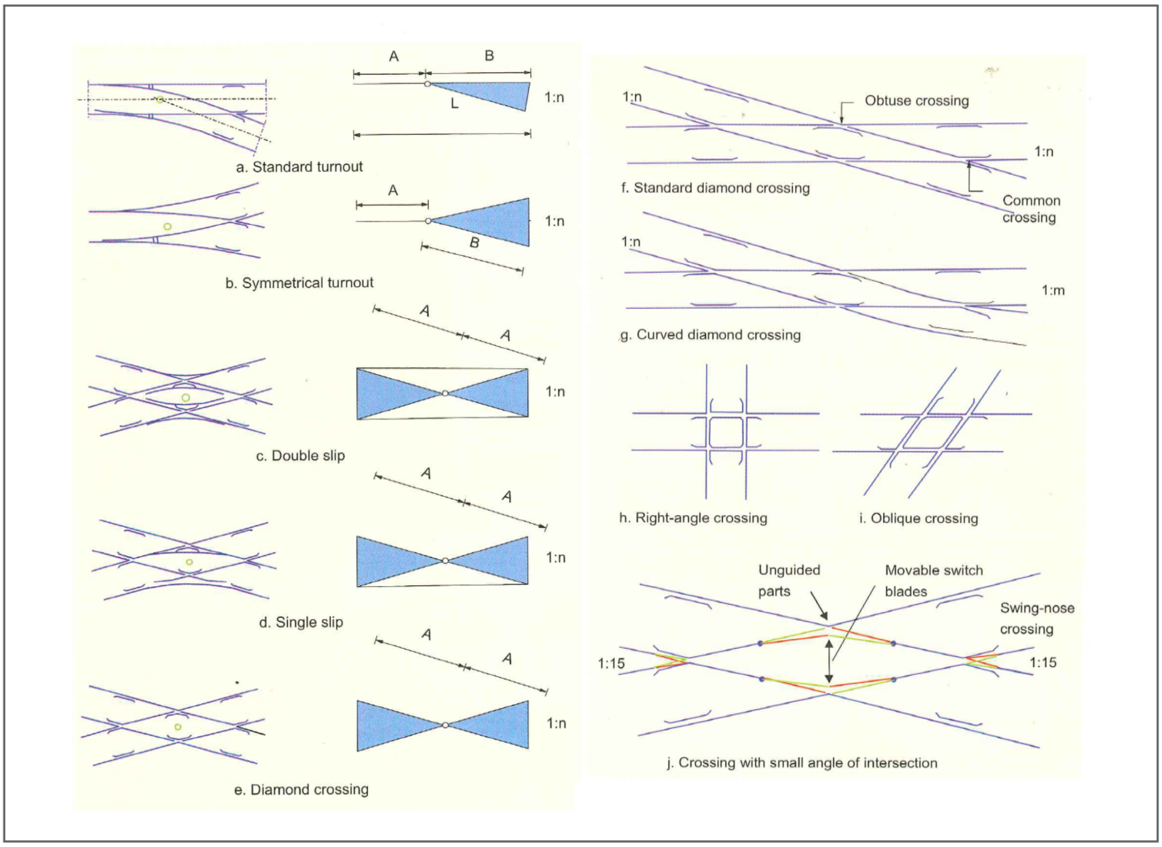


Figure 2.3 Commonly utilised junction types, reproduced from (Esveld, 2001, p. 340).

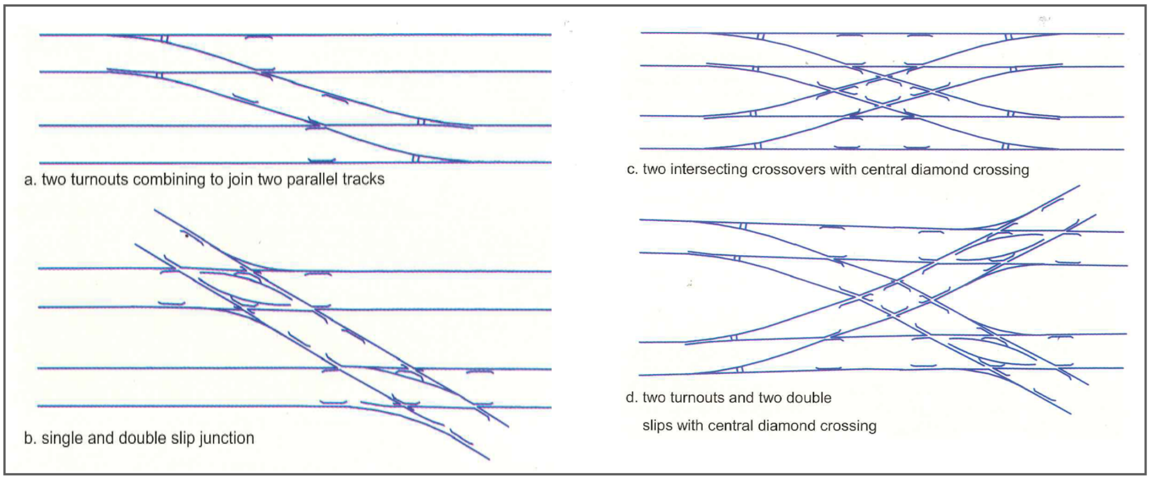


Figure 2.4 Commonly utilised Crossover types, reproduced from (Esveld, 2001, p. 342).

2.2.3 Interaction with rolling stock

2.2.3.1 Facing moves, trailing moves and 'Trailing the points'

There are two distinct vehicle moves through a switch, as labelled in Figure 2.1. A facing move is where the routes diverge, and a trailing move where they converge. Most switch designs allow both, though designs for a single move exist. These are distinct from'trailing the points', which is the act of making a trailing move through the switch when the switch blades are set for the opposite route. This can lead to damage to the POE, and/or blades, and possible derailment. To reduce the probability of derailment, most mechanisms are fitted with breakable links which allow the blades to unlock and move under a given load. For British mainline, this is detailed in a standard (Simmons and Ventry, 2001), which requires the POE to allow a run-through by yielding at a force of not less than 35kN, also requiring it to withstand a total lateral force of 88kN. Recent modelling work has established that 50kN may be a more suitable yield force for resilience (Colantuono et al., 2016).

2.2.3.2 Ride dynamics and vehicle-track interaction

The design of plain line - gradient, cant, and radius of turn - is, where possible, optimised for the traffic upon it (Esveld, 2001, p. 35-170). Modern railway track design keeps interruptions to the running rails to a minimum by using continuously welded rail, to minimise the dynamic disturbance, increased wear and maintenance at rail joints. However, at switches and crossings, these design priorities must be relaxed for three reasons:

1. Where a fixed crossing is employed, there is necessarily a disjoint in the track.
2. Switches present a divergence of routes; both routes cannot maintain optimum alignment throughout given geometric restrictions (e.g. crossing rails must be equal height).
3. It is not possible to machine an infinitely thin switch blade, therefore some aspect of the 'perfect' alignment for one or both routes must be sacrificed to ensure the switch can be manufactured.

The dynamics of rolling stock through switches and crossings is a busy area of academic study. (ORR, 2014, p. 8) establishes that the vehicle ride dynamics through S&C is not as consistent as the surrounding plain line - at the switch toes, because of the extended POE bearers, through the turnout portion, and due to wheel impacts at the common crossing. These elements are explored in a review paper (Bezin, 2016), which also states that over 20% of the planned GB maintenance and renewals budget for 2014-19 is taken by S&C despite the fact switches only represent around 3% of the network. Interactions in this area have been extensively modelled - throughout the entire switch, for instance, in (Nicklisch et al., 2010), which establishes that extreme gauge widening, alongside the use of more elastic rail mountings, can improve ride dynamics. (Andersson and Dahlberg, 1998; Coleman, 2014; Sun et al., 2010) provide different methodologies for modelling the discontinuity at the crossing, variously using multi-body simulation and finite element analysis. (Andersson and Dahlberg, 1998) in particular establishes a tripling of dynamic loads under high-speed scenarios due to crossing wheel impacts. (dos Santos and Barbosa, 2015) carries out a range of field tests to validate models of traffic flow through switches in order to establish optimum vehicle speeds.

Mechanised track maintenance through S&C is complicated by the additional rails and linkages, meaning tasks such as tamping must sometimes be completed manually. These factors lead to a higher degradation rate of track and ancillary elements, which further compounds maintenance and reliability issues. A direct link between the annual usage (in million gross tonnes) and degradation of the track alignment through the turnout has been established (Jönsson et al., 2014). A mathematical relationship (2-Parameter Weibull) is also established in (Rama and Andrews, 2013), however, this relates number of switch operations and component degradation; a link with track utilisation can only be inferred.

2.2.4 Signalling elements

Railway signalling is a wide-ranging discipline with much literature, and its own professional body, the IRSE (Institution of Railway Signal Engineers). Discussion herein is limited to general signalling principles at junctions. The purpose of a signalling system is twofold; to prevent vehicles from colliding, and to allow vehicles to take different paths as required. The first purpose - valid at junctions and plain line sections - is ultimately provided through the 'interlocking' (Marshall, 1961; Stratton, 1988; Such, 1956), which physically prevents the operating human or computer system issuing a command which could cause two vehicles to collide. The second purpose is achieved through the operation of switches. Signalling arrangements at nodes are, therefore, more complex than anywhere else upon a network. IRSE publications provide an excellent overview of the signalling system (IRSE, 2001; Leach, 1991).

2.2.4.1 Locking

Once the switch blades are in position, they are locked in place to prevent unauthorised movement. This is achieved with a mechanical linkage. In Britain, locking is required by law for passenger trains making facing moves (Genner, 1997). However, locking is almost universally applied; most POE designs have an integrated locking function. There is a force requirement to overcome the lock for reasons described in Section 2.2.3.1.

2.2.4.2 Operation Cycle

The principles of powered point operation were established in the early 20th century (Hadaway, 1950). The principles have more recently been combined into a industry standards, notably *GKRT0062* (Genner, 1997), and those listed in 2.2.6. The turnout is commanded to be in a position - labelled ‘normal’ or ‘reverse’ - at all times by the interlocking. Should the required position change, the command signal from the interlocking will change. This triggers a sequence of events in the line-side control circuitry and POE, no matter which motive power source is utilised:

1. The signalling system breaks detection of the current position, allowing the actuator to move.
2. The actuator firstly unlocks the switch blades, allowing them to move freely.
3. The actuator moves both switch blades to their commanded position.
4. The blades reach their commanded position, and the actuator ceases to move them.
5. The actuator re-engages the locking mechanism.
6. Detection is made for both switch blades and the lock, the actuator is isolated.

A timing element built into the control system isolates the POE if detection is not made after around 8 seconds, to prevent damage to the machine. Should detection be lost, the POE will immediately try to move the blades and lock to the commanded position once more. Typically, all relays and control equipment for a switch will be arranged together in an apparatus case at line-side. The turnout is considered unsafe without full detection, even though both switch rails may be locked in the correct position (Hadaway, 1950). Most points operation machines offer combined actuation, locking and detection through single combined motion mechanisms.

2.2.4.3 Detection

Detection proves that the elements of the turnout are in the commanded position. The position of 3 individual components is detected (Hadaway, 1950): the closed switch rail against the stock rail; the open switch rail open far enough to allow a wheel flange to pass through; and the lock in place. When the detected position of all elements is as the commanded position the switch is said to be ‘in correspondence’, otherwise, it is ‘out of correspondence’. There is a short period of ‘out of correspondence’ when the move command is issued as the blades are in a different position to that requested. Without full detection, the interlocking will prevent the signaller setting a route through the turnout (Genner, 1997; Such, 1956).

As well as detection as defined above, the signalling system is also responsible for detecting the position of trains; 'train detection'. This is provided variously by track circuits or axle counters. As a general rule, if a train is detected on approach to a switch, or indeed if a route is set over the switch, then a mechanism in the interlocking prevents that switch moving until the train is seen clear. i.e. the system prevents the Signaller from inadvertently moving the points in front of, or under, a train.

2.2.4.4 Actuation evolution

Historically, most switches were located near signal boxes. Levers in the box operated rodding, transmitting motion to the switch blades. This type still exist on the British mainline (see Table 2.1), mostly on quieter rural lines or depot entrances (Such, 1956). The advent of power signalling, allowed location of turnouts much further from signal boxes (IRSE, 2001; Leach, 1991), necessitating remotely operated systems to provide actuation, locking and detection. Several designs of POE have been developed, utilising either electrical, hydraulic or pneumatic mechanisms (Marshall, 1961). POE is fed from signalling power supplies of various specifications - AC, DC and pneumatic. At large junctions, power supplies are designed to accommodate many POE installations drawing current at once, even though this is rarely the case (Mitchell, 1958).

2.2.4.5 Powered actuator types

Information in this section is taken from (IAD Rail Systems, 2001; Leach, 1991; Morgan, 2009; Network Rail, 2016).

Pneumatic Not dealt with further herein, the mainline has a small count of pneumatic POE; they are considered obsolete with all scheduled to be replaced (Network Rail, 2015).

Classic electro-mechanical Typically the HW1000/HW2000 and M63 shown in Figure 2.5. Developed in the 1920s-1970s, with incremental improvement since. All consist of a large, brushed motor and a custom gearbox driving a linkage bar to transmit linear drive to the switch rails. The HW types use a crank and pin arrangement to translate rotational movement into linear; the M63 a ballscrew. Locking is provided by a separate mechanism, a pin sliding into a locking rod. Drive and detection rods prevent mechanised track maintenance.

Classic electro-hydraulic The clamplock-type actuator is a 1960's British Rail design. The arrangement consists of a pair of actuating rams between the rails, linked to clamps which pass up and around each stock rail in the closed position, positively locking the rail in place (Figure 2.5). A power pack, located up to 10m from the actuators, provides hydraulic drive and a manual pumping facility. POE is located between sleepers, fully exposed to the railway environment and preventing mechanised track maintenance.

Modern electro-mechanical In the 1990s - 2000s, Railtrack/Network Rail helped develop next-generation POE, the High-Performance Switch Actuator (Figure 2.6) (IAD Rail Systems, 2001). Drive is provided by a brushless DC motor and sealed gearbox with electromechanical lock. Detection is through a pair of LVDTs. The design is an in-bearer solution, allowing mechanised maintenance (see Section 2.2.3.2). However, in 2005, mainline installations were put on hold due to significant reliability issues, which is still the case in 2017 (Network Rail, 2015, 2016). Other manufacturers offer similar products not currently in GB mainline use.

Modern electro-hydraulic In the 1980s and 1990s, the Clamplock design was developed to be mounted inside a bearer as the in-bearer clamplock (IBCL), and further to have a hydraulic backdrive arrangement (Hy-drive Mk1 and Mk2). These designs share the clamplock mechanism, but allow mechanised track maintenance, (see Section 2.2.3.2). They are the current preferred installations for new build and renewals upon GB mainline (Network Rail, 2015).

Route	Electro-Hydraul.		Electro-Mech.				Mech.	Other	Total
	Clamplock	Hy-Drive	M63	HW	Other	HPSS			
Anglia	826	3	0	696	0	0	207	0	1732
South East	673	8	0	1520	43	27	446	79	2796
Wessex	336	10	31	725	22	61	206	2	1393
London North East, Midlands	2062	4	115	1679	30	101	403	60	4454
London North West (South)	620	6	0	898	1	203	214	38	1980
London North West (North)	1040	5	549	344	102	28	470	21	2559
Scotland	769	7	0	645	21	95	338	176	2051
Wales	322	9	0	364	8	25	384	4	1116
Western	597	11	318	514	40	42	525	2	2049
National	7245	63	1013	7385	267	582	3193	382	20130
Proportion	36.0%	0.3%	5.0%	36.7%	1.3%	2.9%	15.9%	1.9%	

Table 2.1 Population of POE types in administrative regions of the GB rail network. 'Clamplock' includes ICBL. Variations are due to devolved purchasing. Sources: (Network Rail, 2015, 2016).

2.2.4.6 Signalling for train control

Signalling prevents trains coming into collision through allocating 'blocks', each block can only be occupied by one train at any time (Pope, 1975). In fixed block signalling, semaphore or colour-light signals convey to the driver how far ahead the line is clear. Semaphores are

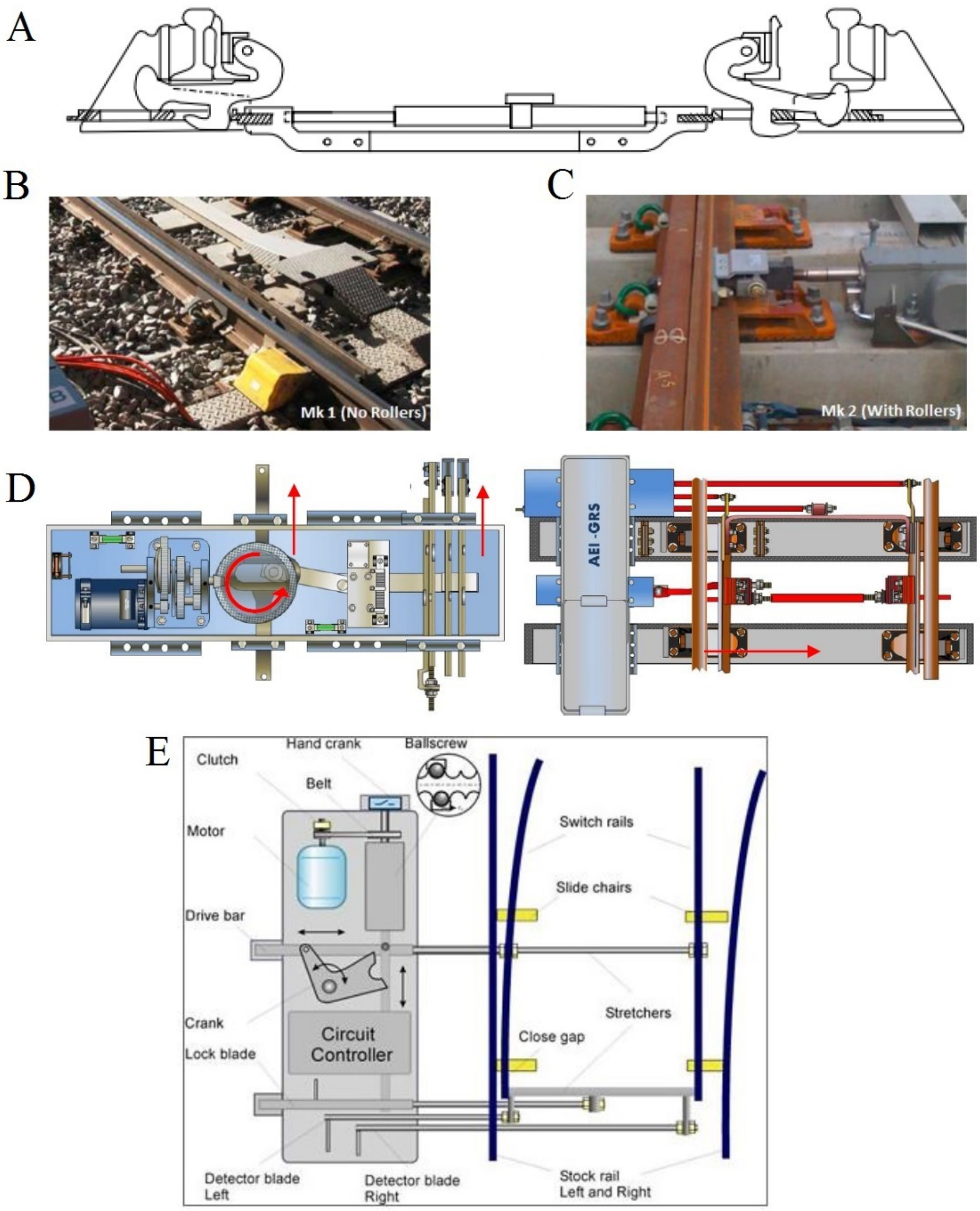


Figure 2.5 (A) Mk2 Clamplock cross-section. (B) Mk1 and (C) Mk2 Hydrive installations. (D, left) Cross-section and (D, right) fitted arrangement of the HW1000/2000 machine. (E) General arrangement of M63 machine. Source (All) Network Rail (Network Rail, 2016).

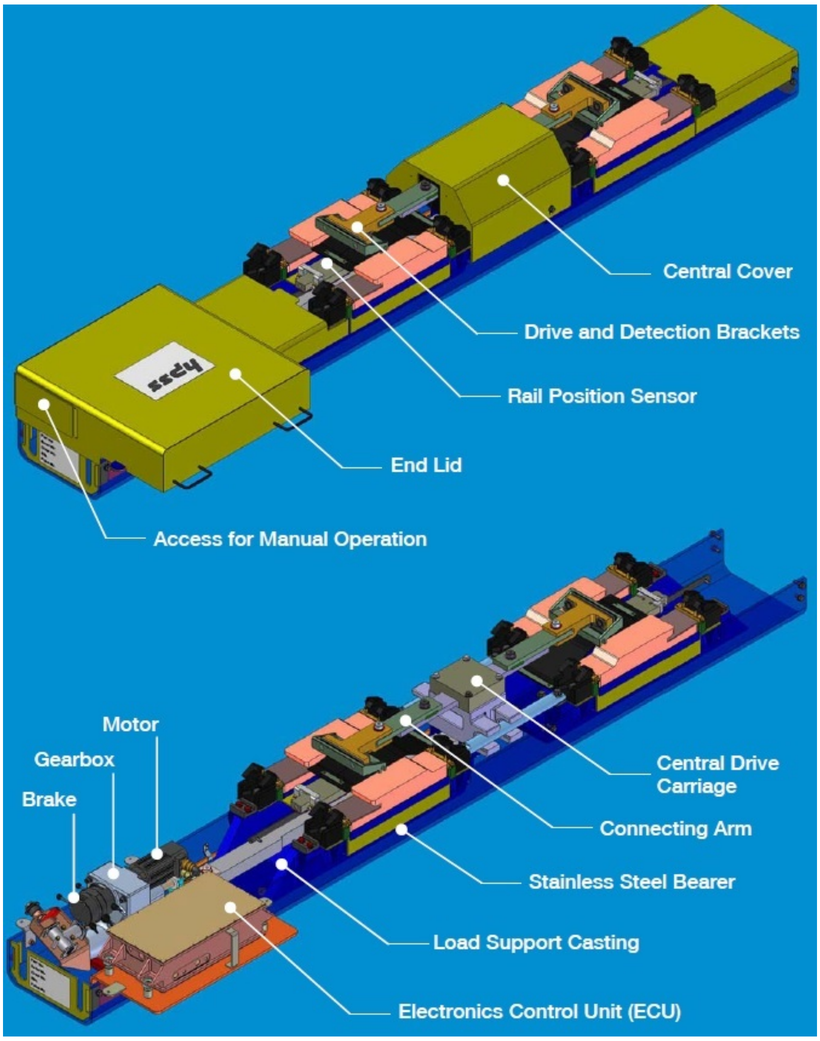


Figure 2.6 Internal arrangement of the 'HPSA' in-bearer switch machine. Source: IAD (IAD Rail Systems, 2001).

not dealt with further herein, the principles involved are equivalent to colour light signalling (Champion, 1957). More modern systems such as ETCS (European Train Control System) allow blocks to either be virtual, or move along the track with the vehicle (Stanley, 2011). In some moving-block and colour-light systems retrofitted with 'DAS' (Driver Advisory System), an allowable or recommended speed is also conveyed directly to the driver. Through junctions, implementation becomes more complex. The signalling system must convey that the line is clear, and also set and lock out a route to ensure no conflicting moves. Junction signals have further purpose: to protect trains converging; and to provide diverging directional indications. Additional safety provisions are also stipulated in design rules, e.g. 'flank protection' - setting adjacent switches to divert SPADs (Signals Passed At Danger) (Marks, 2000). This applies equally to all types of signalling. Moving block signalling systems revert to fixed block systems through junctions, albeit generally with a higher granularity than traditional fixed block signalling.

Fixed-block signalling practice As moving the switch places it in an 'out of correspondence' state, signals to an approaching train must be at danger. Stop signals protecting junctions have repeaters on approach to enable fast traffic to come to a halt clear of the junction (Marshall, 1961). In normal operation it is not permitted to have a signal reverting to a more restrictive aspect in front of a driver, hence moving a switch requires restrictive aspects well ahead of a train. The action of setting a route therefore represents a significant capacity constraint (see Section 2.4.1). Published work explores changing signal operation at junctions to a form of fault tolerant control to relax these restrictions and increase capacity (Liu et al., 2013).

ERTMS, ETCS and CBTC ERTMS (European Rail Traffic Management System) is the specification for a single Europe-wide rail traffic control system. ETCS is a component of ERTMS for the individual control of trains, with information presented to the driver in-cab. It is envisaged that all GB traffc will be controlled under ERTMS in future. The ETCS specification allowing full moving block operation through junctions is under development as of 2017. ETCS up to level 2(d) utilises fixed blocks through junctions, though blocks can be small enough to approximate the ideal of moving block operation (Stanley, 2011). Crucially, the same limitations established in colour light signalling will apply to ERTMS. CBTC (Communication Based Train Control), defined in IEEE1474.1 (IEEE, 2004) is akin to ERTMS, but is utilised upon metro systems with homogeneous traffic.

2.2.5 Maintenance and operations

2.2.5.1 Fixed-interval interventions

POE maintenance is achieved by fixed-interval interventions. The SMS (Signal Maintenance Specifications) state maintenance requirements at a high level, proscribing general procedures to be followed to ensure assets are maintained to a functional standard (Network Rail, 2013b). Actions range from remote visual inspection to full disassembly or replacement under possession. Interventions are recorded in the 'Ellipse' database, with entries made line-side on hand-held consoles. However, Ellipse is not linked to other databases covered in Section 2.2.5.3. The SMS cites other documents which together define all periodic maintenance:

- **Implementation of Signalling Maintenance Specifications** mandates the use of the SMS, and provides a guide to doing this in practice (Network Rail, 2011b).
- The **Signal Maintenance and Testing Handbook (SMTH)** specifies procedures which must be undertaken including task breakdowns specific to POE type (Network Rail, 2013c).
- **Signalling Responsibilities for S&C Maintenance** defines the additional procedures for S&C inspection and maintenance over and above that detailed in the SMS (Network Rail, 2010b).
- The **Signalling Maintenance Task Intervals** standard defines maximum and normal intervals currently applicable to signalling maintenance tasks (Network Rail, 2013a).

2.2.5.2 Reliability-centred maintenance and condition monitoring

Literature explores moving to RCM (Reliability-Centred Maintenance), however, this has not yet been adopted in the GB. Indeed, POE is used as a textbook candidate for such an approach, with the caveat that knowledge of asset use and condition is a prerequisite for a successful RCM programme (Rausand and Vatn, 2008). GB knowledge is either lacking, or exists in disparate data sources. Condition monitoring of railway assets, in particular switches, is an area of intense academic activity. Literature recognises switch unreliability and offers potential fault detection and diagnosis methods - as early as 2003 (Garcia et al., 2003), later extended to prognosis (wear prediction) in 2007 (Marquez et al., 2007). However, the solutions require full instrumentation of the POE which would be complex and expensive in practice. The monetary cost of RCM is explored by the same authors in (Marquez et al., 2008), establishing that whilst RCM can reduce delays, it will reduce cost only under a given, optimistic set of circumstances when in parallel with a time-based maintenance regime. Notable further academic contributions to condition monitoring algorithms are made in (Silmon and Roberts, 2010) and later (Asada and Roberts, 2013). Applicability of methods from different fields is explored in a review paper (Marquez et al., 2010); however, this paper also notes that there is a very limited subset of published methods which have been applied in the field. Post 2007, Network Rail have rolled out II (‘Intelligent Infrastructure’) RCM, using data-loggers and current sensors to collect basic data about most POE on the network (McNaughton, 2007). Threshold analysis is used to identify potential incipient faults. Table 2.3 shows a downward trend in switch failures over the period between II rollout and present, however this was a period of political change and no causal link is established in literature.

2.2.5.3 Fault and failure logging and response

There is a set procedure on mainline when a switch fault or failure occurs (Bannister, 2016):

- The fault is reported to control - typically by operations or maintenance staff.
- The fault, and severity, is logged in the FMS (Fault Management System) database.
- If the fault will prevent scheduled train movements, a MOM (Mobile Operations Manager) is dispatched. Sometimes a fault team is dispatched concurrently.
- The MOM manually operates the points, enabling train movements, and can fix certain simple faults - e.g. blockages - but cannot access the POE mechanism (Fleming, 2015).
- If the fault is still present, a fault team (3- or 4- person) is dispatched to site.
- The fault team fix the fault (if possible).
- The fault team enter further details of the fault and cause into FMS using a handheld computer, and leave site.
- An off-site team acts to divide responsibility for the fault, associated delay minutes (see 2.4.3.1), using a database called TRUST (Train Running Under System TOPS (Total Operations Processing System)).

Network Rail keeps records of all known fault and failure events in the FMS database, identifying the two with a ‘criticality index’ between 1 and 4. Indices 1 to 3 represent failures requiring immediate rectification; 4 is a known fault, not developed to a system failure, which will need rectifying when possible. FMS data is entered by human operators, often in difficult conditions, and as such there are a significant number of records which may be incomplete or considered corrupt. Data accuracy improves after 2009 when free-text entry was replaced by option selection (Network Rail, 2015). There are no formal links between FMS, the II database (Section 2.2.5.2), TRUST (Network Rail, 2008, p. 23), and Ellipse. Cross-referencing failures to corresponding incurred delay minutes is therefore prohibitively time consuming.

2.2.6 System requirements and standards

All equipment fitted to the GB infrastructure is covered by standards, which cascade safety and functional requirements. Table 2.2 lists the main standards which apply to Switches. Top-level Railway Group Standards are maintained by the ORR or RSSB; lower-level standards are proprietary to each rail operator. Standards are generally written with knowledge of existing technological solutions and their potential performance and behaviour. Literature does not present a set of the basic functional requirements of a track switch.

Standard	Owner	Description
'ROGS'	ORR	The Railways and Other Guided Transport Systems (Safety) Regulations 2006 (ORR, 2006)
	ORR and HSE	HMRI:- Railway Safety Principles and Guidance part 2 section D: Guidance on Signalling (HSE, 2005)
RGS-GK-RT0062	RSSB	Control Of Points (Genner, 1997)
RGS-GI-RT7004	RSSB	Requirements for the Design, Operation and Maintenance of Points (Hayter, 2000)
RGS-GC-RT5021	RSSB	Track System Requirements (Hayter, 2011)
RGS-RT-0064	RSSB	Provision of Overlaps, Flank Protection and Trapping (Marks, 2000)
RGS-GK-RT0210	RSSB	Asset Management for the Safety of Signalling and Operational Telecommunications Systems (Fleming, 2000)
GE-RT8000	RSSB	Rule Book (Master Manual) (Fleming, 2015)
RT-SRS-2001	Network Rail	Requirements for Powered Point Operating Equipment (Simmons and Ventry, 2001)
NR-L2-TRK-2049	Network Rail	Track Design Handbook (Network Rail, 2010a)

Table 2.2 List of Railway standards directly applicable to track switching (See also Section 2.2.5.1)

2.2.7 Conclusions

This section has presented current practice related to track switches. Switches fall at the interface of many traditional railway engineering disciplines. The literature is rich with information; much is held in industrial documents. There is also much academic literature, but published work is concentrated upon several relatively small areas of the system - notably dynamic interaction with rolling stock and condition monitoring of existing designs. Literature does not present a set of the basic functional requirements of a track switch. There is no academic literature regarding fault tolerant switches, indicating the research area is novel.

2.3 Fault tolerance

2.3.1 Faults, failures and fault tolerance

A fault is a defect in a system. This could be in hardware or software, located in the physical plant itself, or in the controlling elements, power supplies, actuators, sensors or mechanisms. For systems including humans, the fault could be in the human element. Faults result in unexpected, and often undesirable, system behaviour. If a fault renders the system unable to complete an expected action, the system is said to have failed (Isermann, 2006; White and Miles, 1996). This is illustrated in Figure 2.7. Nominal system behaviour, b_n, is central in a region of acceptable system behaviour; surrounded by a bound representing uncertainties which may occur in the operation of the system, plant, or controller. Faults, b_f, may change system behaviour. A range of faulty system behaviours lie within an acceptable operation region, the system is tolerant to these particular faults. However, if a faulty system behaviour lies outside this region, the system has failed. A fault tolerant system is able to achieve adequate system behaviour in the presence of faults. Fault tolerance is important in safety-critical systems such as aircraft, trains and road vehicles, but also in non safety-critical systems - e.g. machine tools and production robots - where increased reliability and availability can increase operation times, reduce maintenance and life-cycle costs (Davies, 2009). The ability to maintain functionality when portions of a system are faulty is referred to as 'graceful degradation'; or 'degraded mode' operation, if the system remains functional with reduced capacity (Davies et al., 2014).

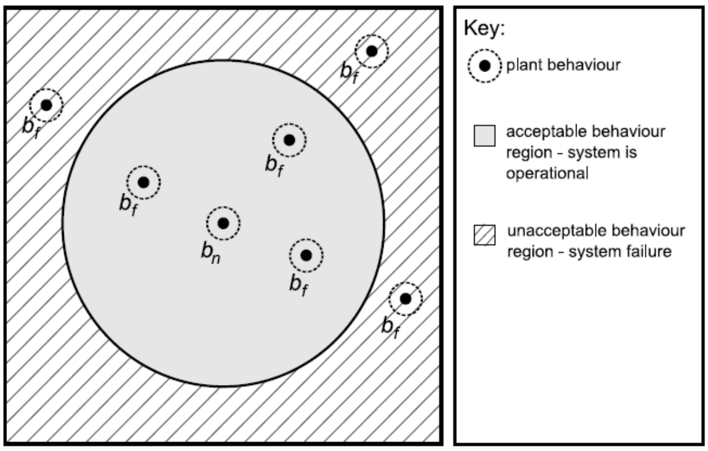


Figure 2.7 Behaviour of nominal, faulty and failed systems. Source: (Davies, 2009, p. 12).

2.3.2 Fault tolerant system design

The most effective means of achieving fault tolerance is through systematic analysis and integrated design - most easily achieved with new designs, however, retro-fitting fault tolerant elements to existing designs is possible (NASA, 1995). An understanding of the system's structure and function, and the reliability of its components, should be developed and analysed to determine vulnerable areas, and how fault tolerance could be provided. Figure 2.8 illustrates the fault tolerant design process.

Processes used to identify failure modes include 'bottom-up' approaches - FMECA (Failure Modes Effects and Criticality Analysis) and/or FTA (Fault Tree Analysis). The techniques are complementary methods, applied retrospectively or at the design phase, which enable all possible failure modes of a system to be established, and to establish the combinatorial range of faults which can lead to each failure (Andrews and Moss, 2002). Alternatively, if systems are in service, in the 'top-down' approach data is collected and reliability modelled to identify failure modes and, through further analysis, possible causes or design issues (Rausand and Hoyland, 2004) (Section 2.4.3). Both processes can be iterative - over time as new faults are discovered, or through components, subsystems and whole systems. Information from these processes can be used to inform actions to reduce the probability of individual subsystem/component faults developing to failures. There are several ways in which the reliability of a system can be improved, each with an associated set of penalties, benefits and prerequisites. Some are classified as fault-tolerant approaches. Not all methods can be applied in every situation, but some can be applied simultaneously and are complementary. The most common recognised methods, documented in (Blanke et al., 2006; Hecht, 2004; Isermann, 2006; Modarres et al., 2009; NASA, 1995), are listed here and detailed in context.

1. Increasing individual subsystem/component reliability
2. Condition monitoring for failure prevention
3. The introduction of redundancy
4. The introduction of fail-safe mechanisms
5. Incorporation of fault-tolerant control strategies

2.3.3 Increasing individual subsystem or component reliability

This is often the lowest cost and simplest method. Whilst not fault tolerance, this is a critical aspect of fault tolerant design. Improving single component or subsystem reliability can improve system reliability, especially if an element is identified as under-performing. It should

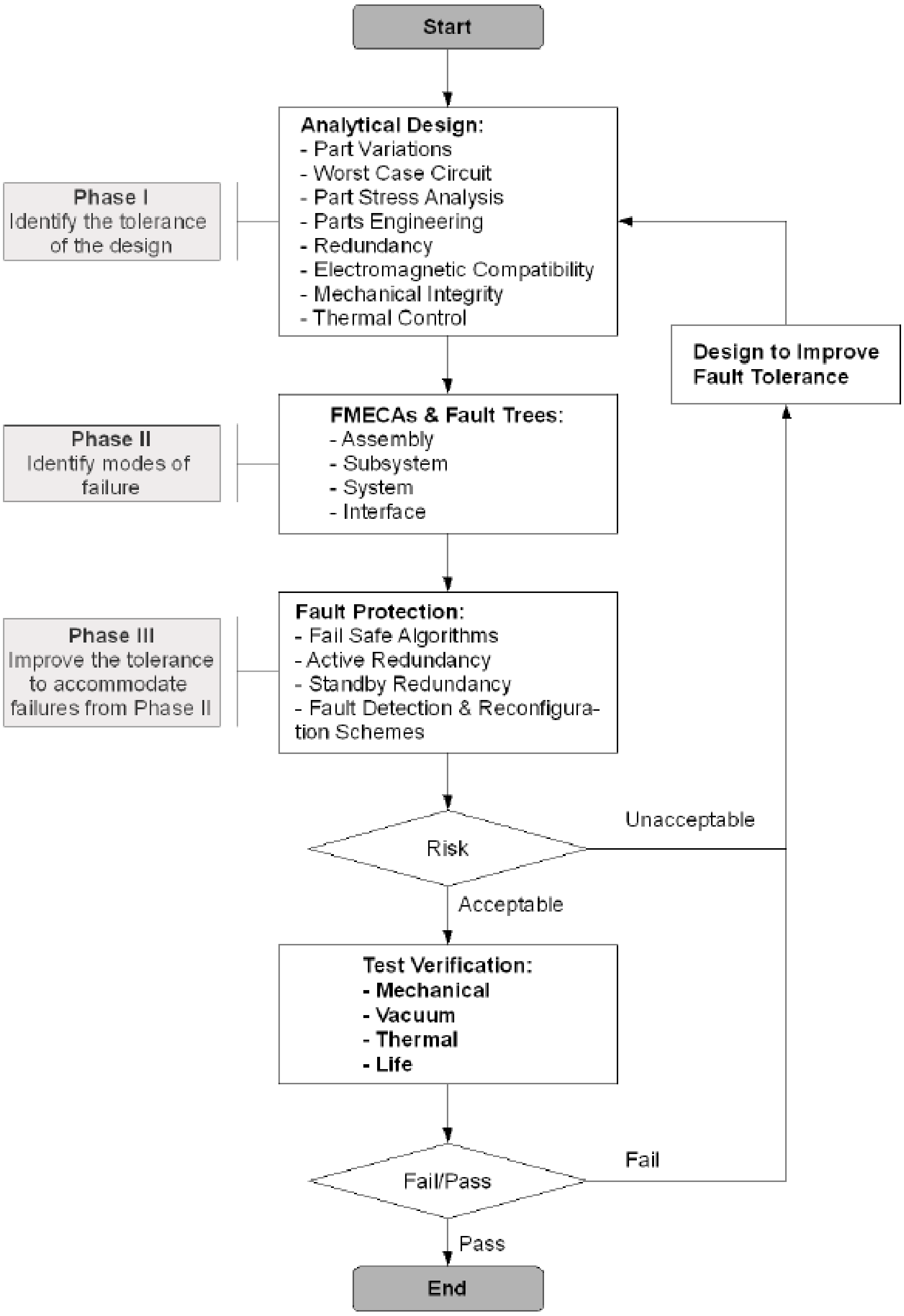


Figure 2.8 Flow diagram for fault tolerant design process Source: (NASA, 1995).

be applied to any remaining SPOF (Single Points of Failure). Sometimes, a component is found to be operating outside original design parameters. It is rare, but not impossible with modern engineering design techniques, for components to be unfit for purpose. Potential causes and models for premature component failure have been established (Proschan, 1996). Reliability analysis can reveal which subsystems contribute the greatest level of unreliability, and may also determine whether components tend towards early-life or late-life failures. This can indicate incorrect fitment/out-of-specification components or increased load or wear respectively (Section 2.4.3). In Figure 2.7, this technique reduces the incidence of b_n becoming b_f. Some literature regards this process as 'Fault prevention', as in Figure 2.9 (Lee and Anderson, 2012). POE examples include the Clamplock (Section 2.2.4.5) design, which has gone through Mk1, Mk2, IBCL and Hydrive generations, each one engineering out unreliability; and the stretcher bar - originally 'swan-neck', evolving to the 'adjustable' design then tubular.

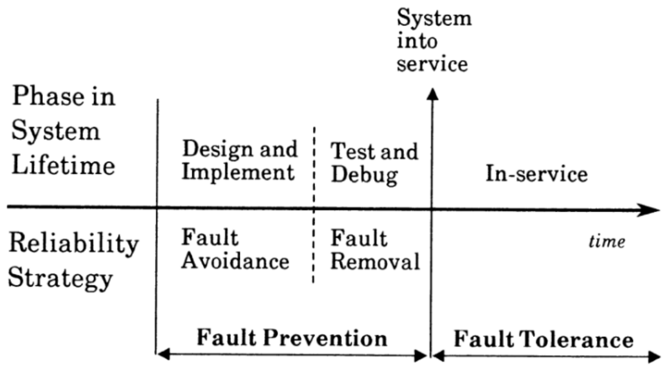


Figure 2.9 Reliability improvement techniques vs product lifecycle. Source:(Lee and Anderson, 2012).

2.3.4 Condition monitoring for failure prevention

Whilst not a fault-tolerant approach, CM (Condition Monitoring) can form part of a fault tolerance strategy, especially if combined with active redundancy. CM required data collection and processing for fault detection, diagnosis, and prognosis (Isermann, 2006). Advance knowledge of incipient faults allows interventions before faults become failures, reducing system failure rates. However, the method requires an understanding of plant behaviour, appropriate sensors and processors, which carry a cost, weight, maintenance and/or complexity penalty.

CM in a single-channel system has a false-positive rate, increasing maintenance workload, or reducing availability through excessive interventions. In a system with redundancy, it allows isolation of faulty channels before fault propagation, thus facilitating maintenance. CM can ease maintenance tasks through allowing better preparation - what spares to transport to site, and at what time (Rao, 1996). There is much literature in the CM field, several review papers describe state of the art (Ding, 2008; Isermann and Ballé, 1997). There is a divergence between model-based and signal-based techniques. Signal-based methods (including statistical methods) monitor sensor output signals or derivatives for unexpected deviations, and have some overlap with Statistical Process Control in literature (Mason and Young, 2002). Model-based methods compare sensor signals to expected values generated by a mathematical plant model to derive condition (Chen and Patton, 2012; Isermann, 2005). Both have been successfully applied in a range of situations. Much literature exists examining CM applications to switches, (Section 2.2.5.2).

2.3.5 The introduction of redundancy

Redundancy is defined as the multiplication of system components in order to increase overall system reliability or safety (Modarres et al., 2009). It is applied in safety critical systems, such as nuclear process control and aircraft fly-by-wire or hydraulic systems. If the probability of single module failure is small, the combined probability of all redundant systems failing is diminishingly so. The technique is generally only applied in instances where the penalty (monetary, weight, complexity, maintenance, and/or design difficulty) is offset by subsequent improvement in system performance. The goal of redundancy is to eliminate SPOF elements. A review of early work is presented in literature (Yearout et al., 1986). Redundant subsystems can be represented through the use of RBD's (Reliability Block Diagrams), as in Figure 2.10. RBDs define a system by components or subsystems for which reliability data is available (Modarres et al., 2009, p. 198). Each RBD block has a given (constant or time-variant) failure distribution. If a path exists through the diagram from start to end, through functional blocks only, the system is regarded as functional. RBDs do not necessarily mimic the physical design of a system. For time-variant failure rates, the RBD is evaluated over a given 'mission time'.

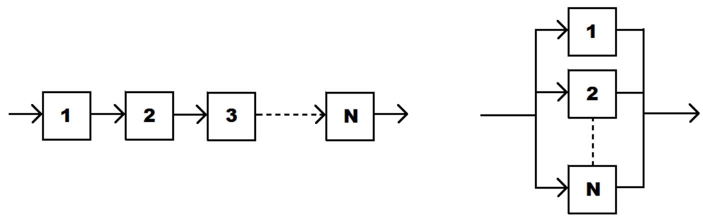


Figure 2.10 (Left) Series and (Right) parallel RBDs. Source: (Modarres et al., 2009).

2.3.5.1 Passive redundancy

Passive redundancy does not require the intervention of an agent. An example is the multiplicity of structural members in a steel skyscraper or aircraft; should one member fail, load is redistributed. It may be the case that the remaining elements sustain a higher load, their failure rate may then increase. With design, passive redundancy can allow a system to remain functional whilst the repairs are effected. By definition, passive redundancy requires that extra capacity is built into the system, which carries design penalties which may be minimised through optimal design (Murthy and Hussain, 1995). Passive redundancy includes redundancy with consolidated outputs, not requiring reconfiguration because the faulty channel is over-driven by the fault-free ones. A rail example is BR specification colour light signalling lamps. The lamps have 2 filaments of different resistances, connected in parallel. In early-life, the lower resistance filament has a higher current flow and thus greater load. If it burns out, the higher resistance filament is still bright enough to meet specification. The reduction in current flow is sensed to indicate the need for a replacement (Cardani, 1958; Loosemore, 1958). GB switches have several stretcher bars for passive redundancy, though as several are necessary to accurately restrain the whole switch rail, this is not pure passive redundancy (Morgan, 2009).

2.3.5.2 Active redundancy

Methods of making reliable computers from unreliable elements is first established in literature in 1956 (Von Neumann, 1956). Active redundancy relies upon an agent (human or automated) to sense faults and reconfigure to distribute load to parallel elements. This may be upon failure of the subsystem or ahead of this, if CM is also employed. Reliability of switching elements must be taken into account when calculating whole-system performance, unless the ‘perfect switching’ model is used (Murthy and Hussain, 1995). In some examples, load is shared between parallel channels (Dixon et al., 2009). With design, it can be possible to change out subsystems whilst the system is operational. By definition, active redundancy requires that extra capacity is built into the system, alongside a controller, which together carry design penalties. A successful and widely adopted rail example is SSI (Solid State Interlocking) (Cribbens, 1987; Stratton et al., 1988), illustrated in Figure 2.11. To quote (Cribbens, 1987): *To achieve acceptably small probabilities of unsafe failure, there is no alternative to the use of redundancy techniques*. SSI uses a majority (2-out-of-3) voting system, an approach since used to much success in Aeronautical and Nuclear industries. Three identical microcomputers, each known as an MPM (interlocking MultiProcessor Module) receive identical inputs, and run identical programmes. Each

MPM checks its own outputs against those of the other two. Each module has a 'Security Fuse', which, when activated, permanently disconnects the module. Each unit can blow its own fuse; any two modules can co-operate to trigger the fuse of the third. Each MPM is designed as a hot-swappable, line replaceable unit to maintain high availability.

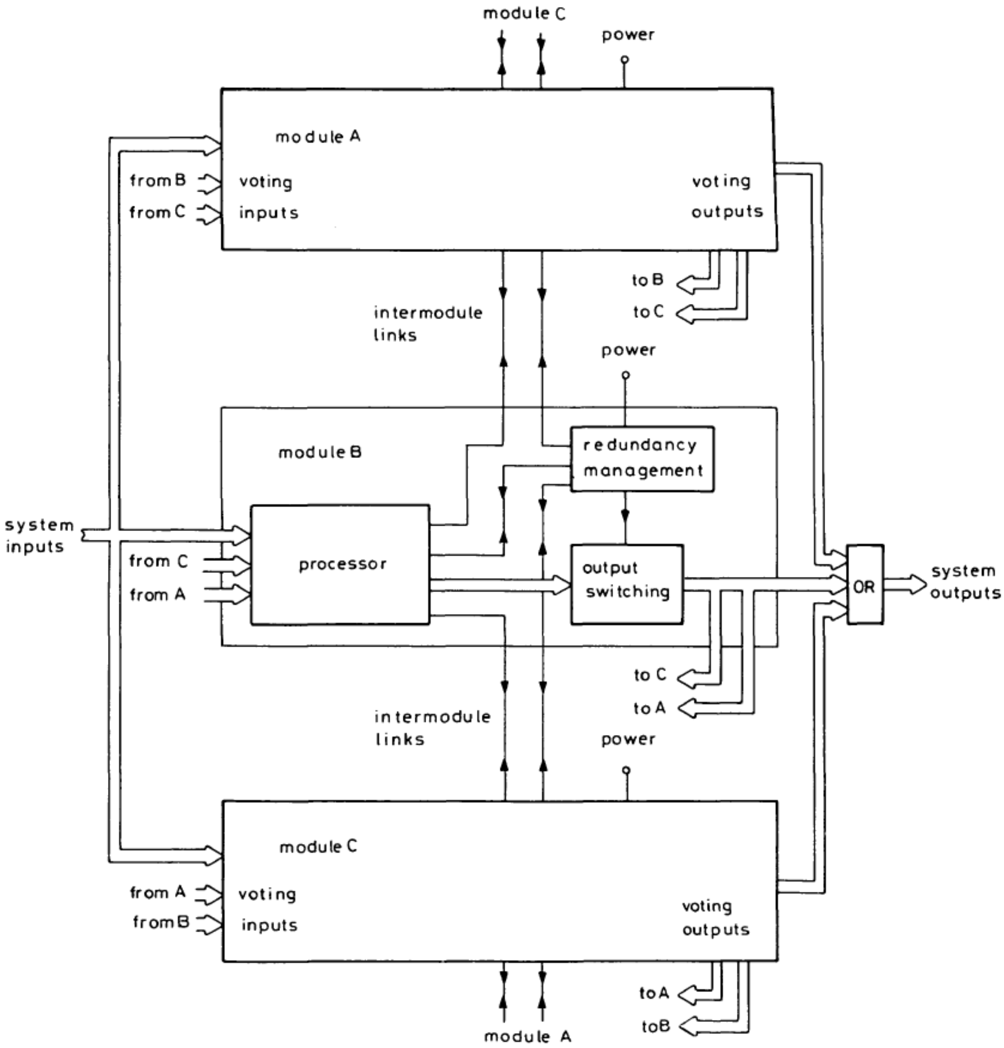


Figure 2.11 Architecture of Solid State Interlocking. Source: (Cribbens, 1987).

2.3.6 The introduction of fail-safe mechanisms

A system is 'fail-safe' when failures cannot render the system unsafe. Alone, it is not a fault-tolerant method - faults may still lead to a failure. Alongside redundancy it can ensure the safe performance of a system, by ensuring any single channel failure does not render a system unsafe (Steffen et al., 2013). Generally, this is an important consideration in high SIL (Safety Integrity Level) systems - see section 2.4.3.2. SIL Levels and fail-safe concepts are explored in the rail-specific RAMS (Reliability, Availability, Maintainability, Safety) standards (EN50126, 1999; EN61508, 2002). An example of fail-safe design is coolant valves in nuclear power stations defaulting to full flow in the event of actuator failure. Whilst plant output may reduce, a dangerous core meltdown has been avoided. The railway signalling field makes extensive use of fail-safe principles. Track switches remain safe if power or communications are lost. Relays default to a safe state in the event of a mechanical fault. Signalling uses the terms 'right-side' and 'wrong-side' failure. The system is designed to fail in a certain, safe way; when this occurs it is 'right-side'. When the system fails in a way it was not designed to, it is a 'wrong-side' failure; the failure can be safe or dangerous (Palmer, 2012).

2.3.7 Incorporation of fault-tolerant control strategies

FTC (Fault Tolerant Control) describes a control strategy able to perform as required in the presence of a system fault. This is an active area of research; a number of survey papers exist (Blanke et al., 2001; Zhang and Jiang, 2003). FTC can actively and automatically reconfigure to allow for sensor, actuator and processor faults, a form of fault tolerant design. It is distinct from condition monitoring in that the controller compensates for the fault, rather than the fault merely being identified. FTC can be combined with CM to provide combined benefits. FTC is generally less onerous to implement than full active redundancy as it can make better use of available resources; for example lowering load on a faulty actuator rather than isolating it. However, it has associated design penalties. FTC may be applied to POE, however, no examples exist.

2.3.8 Conclusions

This section has presented an overview of state of the art with regards fault tolerant principles. Fault tolerance is the technique of preventing component faults developing into system failures. Academic literature is rich with information on various strategies and modelling methods, especially in the areas of condition monitoring (including of existing switches) and fault-tolerant control. Examples of fault tolerant design exist in the rail sphere, showing the industry is open to the technique. However, to date it has not been used in switches.

2.4 Performance

This section explores how the performance of track switches and networks can be modelled and quantified. This will focus on five areas; the latter three part of RAMS Performance (EN50126, 1999):

- **Capacity**: The measure of volume of traffic the network can handle.
- **Switching time and energy use**: Time to move the switch between positions and power required to do so.
- **Reliability**: A system's probability of performing a specific function, at a specific time.
- **Availability**: The portion of time a system is in a functioning state.
- **Maintainability**: The ease by which a product or system can be repaired/maintained.

2.4.1 Capacity

2.4.1.1 Network utilisation

The capacity metric is variably the number of passengers, quantity or mass ('weight lifted') of freight, or number of vehicles able to pass a given section of network in a given time.

The British rail industry has been undergoing sustained growth since privatisation. Statistics illustrated in Figure 2.12 show passenger numbers have more than doubled since FY (Financial Year) 1993-1994 (ORR, 2013). Since FY 1985-1986, the number of passenger stations has grown by 7% to 2550. Freight measures have marginally increased in the period for which data is available, FY 2003-2004 on. However, over the same period, the route kilometres[1] open to traffic has fallen by 6%. The increasing utilisation over a shortening route length suggests greater capacity is required of each route mile. This demand will not be spread evenly, literature (Ison et al., 2012), and government (Network Rail, 2011a; Rail, 2009) documents define routes at maximum capacity.

2.4.1.2 Vehicular, signalling and operational capacity

The measure of capacity used in the signalling and operations fields is that of vehicular capacity, having a direct influence upon the passenger/freight capacity in Figure 2.12. Vehicular capacity is a measure of how many vehicles a given line, route or node can handle in a given time, in TPH (Train Paths per Hour). Signalling capacity, in STPH (Signalling

[1] A measure of the length of open rail corridor, not how many parallel tracks are available along that route.

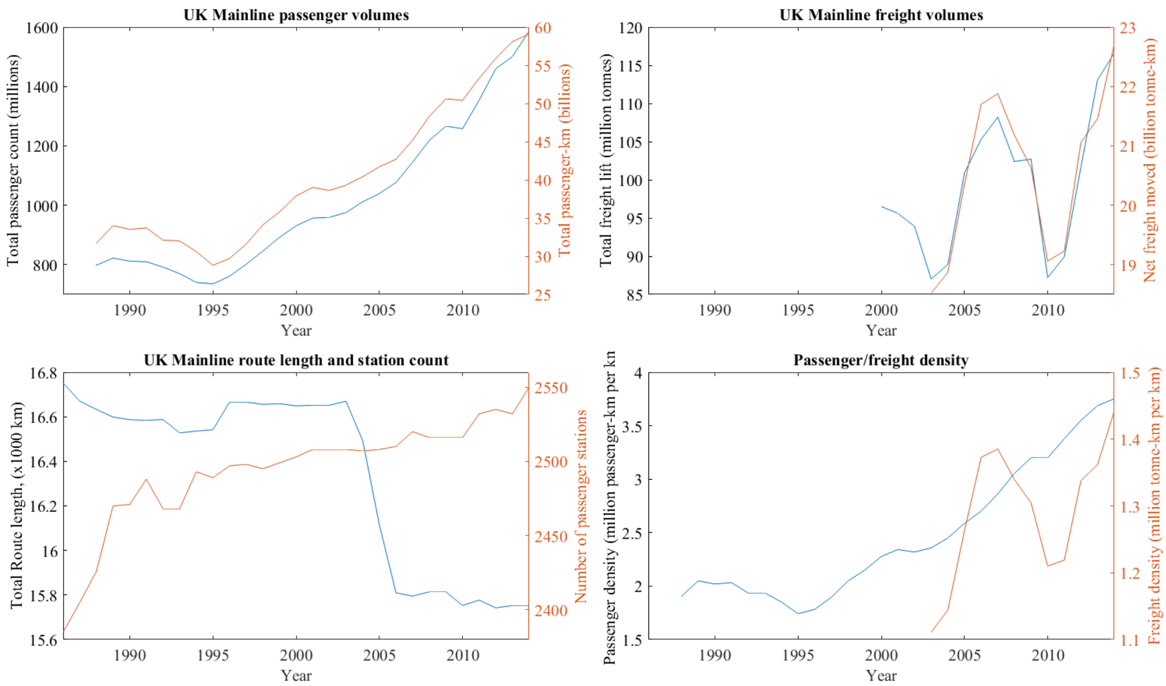


Figure 2.12 Increasing demand, declining route-km, and therefore increasing density upon the GB mainline network. Source: ORR (ORR, 2013)

Train Paths per Hour), defines the theoretical maximum limit if all systems perform perfectly. OTPH (Operational Train Paths per Hour) is specified as a fraction (the Capacity Utilisation Index or CUI) of the STPH, to allow a margin for variability in driving style, train dispatch times, or adhesion conditions (McNaughton, 2011). The fraction used depends upon the type of railway operations, the highest fractions being 0.85 for a dedicated suburban metro-type operation, and 0.75 for a high-speed line. The method is specified in (UIC406, 2004).

2.4.1.3 Calculation of capacity

The TCT (Timetable Compression Technique) in UIC406 is the industry standard for calculating vehicular capacity. Capacity is a function of the signalling system, track gradient, speed restrictions, mix and pattern of traffic. Capacity is dependent upon rolling stock specifications, thus a given section of infrastructure can have different capacity values for different traffic mixes. To evaluate the performance of a single asset, it is therefore necessary to keep all other infrastructure and rolling stock parameters equal; a homogeneous traffic mix may also provide a more meaningful comparison. To quote (UIC406, 2004):

> "Capacity as such does not exist. Railway infrastructure capacity depends on the way it is utilised. The basic parameters underpinning capacity are the infrastructure characteristics themselves and these include the signalling system, the transport schedule and the imposed punctuality (...) it is not possible to determine a theoretical capacity within the framework of a generally-valid definition and method of calculation."

TCT involves plotting train trajectories for a planned timetable, including the track blocks occupied by MA's (Movement Authority) for each train. The timetable is then compressed in time until all 'unoccupied time' is removed, and a resultant STPH figure established. Literature is rich with application examples (Landex, 2009; Landex et al., 2006a,b). At complex junctions, hand calculation is time consuming, thus specialist software such as Railsys (Bendfeldt et al., 2000) has been developed. Railsys is widely regarded as state-of-the-art (Armstrong et al., 2011), though a range of capacity simulation tools - macroscopic and microscopic - are available (Barber et al., 2007).

2.4.1.4 Capacity consumption, service reliability and timetable design

'Capacity consumption' is the ratio between scheduled trains per hour and the STPH. Capacity consumption defines how close to being 'full' a particular route or node is. There is a negative correlation between capacity consumption and service quality (Goodall et al., 2013). As capacity is consumed, deviations from planned operations have a larger impact upon other services until, at 100% consumption, no trains are able to run. This justifies the use of the OTPH value when service planning. Figure 2.13, qualitatively illustrates this relationship. The ability of a particular timetable to prevent perturbations affecting service quality, or operational robustness, is referred to as its 'resilience'. Resilient timetables may minimise conflicting moves, and have a large amount of spare capacity (i.e. a low CUI), as per Figure 2.13. However, under-utilisation of capacity is clearly expensive in terms of infrastructure. Optimisation of the infrastructure and timetable design is a multi-variate and multi-objective problem beyond the scope of this thesis, but to note that any increase in capacity brought about by revised track switching practice could lead to a more resilient timetable and therefore more robust service through this relationship (Goverde and Hansen, 2013).

2.4.1.5 Capacity of nodes upon the network

As nodes (stations, junctions) introduce four capacity restrictions beyond plain line signalling, they govern the vehicular capacity of a railway system:

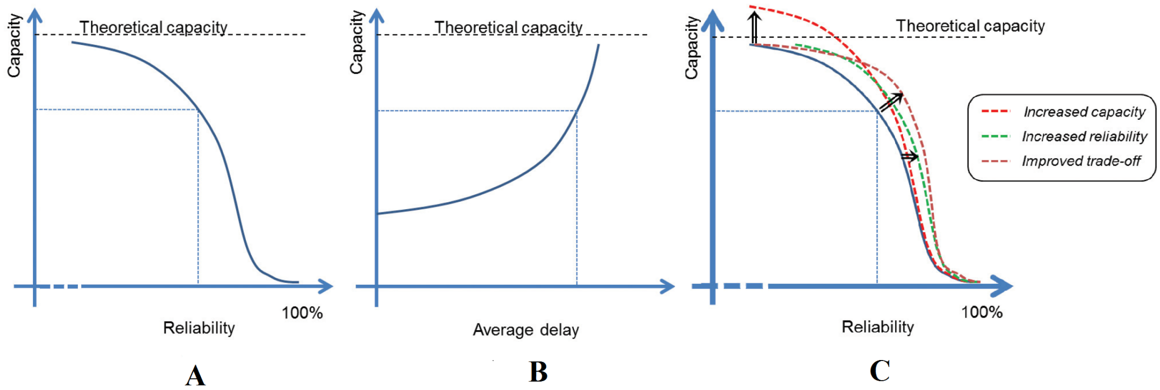


Figure 2.13 The relationship between capacity consumption and service reliability. (A) As capacity consumption approaches the theoretical limit, service reliability drops to negligible levels, essentially creating a 'gridlock' situation. (B) As capacity consumption approaches the theoretical limit, average service delay increases in a non-linear fashion. (C) Improving reliability could improve capacity or a trade-off adopted. Source: (Goodall et al., 2013).

Mainline braking / acceleration allowance:- Turnout routes are generally rated for a lower speed than mainline (see 2.2.2.1), therefore diverging trains must brake on the mainline (Pope, 1975). Similarly, converging routes require trains to accelerate upon the mainline. Changing speeds require longer track occupation times than constant, leading to longer headways and lower capacity. A turnout route rated for mainline speeds eliminates this restriction.

Switch actuation time:- Switches require time to operate (Sections 2.2.4.2 and 2.4.2), which is added to the headway of each train, reducing capacity. To eliminate this restriction, switches must move instantaneously or remain safe throughout their move - neither is possible in existing designs. A reduced switching time can directly result in a reduced headway and therefore improved capacity.

Conflicting moves:- A conflicting move is where a train crosses the path of another (IRSE, 2001; Leach, 1991). They are common in space-limited metro operations and at station throats. Conflicting moves can be eliminated by fully grade separating junctions, which is expensive and not always practical. The impact of conflicting moves can be reduced with intelligent timetabling and track layout, and there is much ongoing research in this field, (Goodall et al., 2013; Liu et al., 2013).

Junction margins:- Additional timetable margins which accommodate perturbations (Section 2.4.1.2); namely variations in the arrival time of trains. Networks with many conflicting moves and changes in speed require greater junction margins. They can be prescribed at timetable design time, either as additional mandated time between trains or deliberate gaps - 'firebreaks' - in the timetable, or by the selection of a lower CUI.

Capacity losses from switch actuation time and mainline braking and acceleration allowances are directly influenced by track switch performance. Junction margins are influenced by the reliability of the infrastructure and rolling stock. Conflicting moves can be minimised at timetable design time, but are a trade-off with other infrastructure limitations. Co-optimisation of track layout, signalling, and timetabling around stations is an area of much academic study. Markov chain methods to ensure station layouts robustness with regards timetable perturbation have been demonstrated (Odijk, 1999), but the problem of scheduling in large stations is too complex to solve by standard combinatorial or integer programming methods (Carey and Carville, 2003), with solution time exponential in the number of trains (Kroon et al., 1997). Modelling software, therefore, normally takes a Monte-Carlo approach (Bendfeldt et al., 2000).

2.4.1.6 Case studies

Section 2.4.1.3 establishes there is no universal definition of capacity. The approach commonly taken in literature is to select case study locations to establish the capacity change possible from defined infrastructure changes. Examples include work on fault tolerant signalling (Liu et al., 2013), and work defining both route (Landex, 2009) and nodal (Armstrong and Preston, 2011; Armstrong et al., 2015) capacity. This study will adopt the same strategy, selecting a range of case study nodes.

2.4.2 Switching time and energy use

Actuation time is a trade-off against power supply requirements. Supplies are sized at design time for the population of powered equipment. Standards specify 1000W steady state and 1500W inrush for POE - the joint highest power consumption alongside level crossing actuators (Network Rail, 2006; Simmons, 2001). Power supply is a large contributor to monetary cost, more so if train-based signalling solutions (Section 2.2.4.6) render other line-side assets superfluous. ‘Type D’ circuit breakers are used, allowing 4 seconds inrush; sustained over-current will lead to a points failure (BS EN 60947, 1996; Network Rail, 2006). Data from II (Section 2.2.5.2) indicates that whilst the inrush current specification is often exceeded, steady state is rarely so (McNaughton, 2007).

Whilst it may be possible to upgrade power supplies for novel designs, work herein assumes that the supply is fixed to to enable a fair performance comparison. Two performance metrics need calculating to establish design feasibility: that a concept can operate from the given supply; and how quickly the concept can switch. Both may be established by modelling from first principles, making necessary assumptions. Minimising actuation time is of importance due to the direct link between actuation time and capacity (Section 2.4.1.5).

2.4.3 Reliability, availability and maintainability

Reliability is the ability of a system/component to perform required functions under stated conditions for a specified period. Availability is a portion of time for which an asset is available for use. Maintainability contributes to availability by influencing scheduled downtime (Rausand and Hoyland, 2004). Service reliability is influenced by asset reliability, though measures differ.

2.4.3.1 Service reliability

Service reliability is published in two measures, PPM (Public Performance Measure), and DMs (Delay Minutes). PPM is a non-technical figure for the public, specified for a whole network. It provides insufficient detail compared to direct incident analysis; PPM is not be used herein. One DM is incurred for each minute each train affected by an incident arrives late *at its final destination only*, if it arrives over ten minutes late (five, for commuter and south-east services). It is therefore possible that two identical infrastructure failures result in different DM totals, or that DM are negated if delayed trains catch-up with the timetable. DMs are open to manipulation, and whilst widely used, are not considered a scientific measure - values are indicative only (ORR, 2015). ORR has published asset failure and DM figures since 2008, shown in Table 2.3 (ORR, 2013). In every published year apart from 2013-2014, points failures contribute the highest portion of delay incidents. However, points failures have fallen significantly over the same period. This may be due, in part, to Network Rail's II programme (Section 2.2.5.2).

2.4.3.2 Operational reliability

It is necessary to distinguish mean time between unsafe failures (i.e. system in an unsafe state), and mean time between operational failures. Literature represents either by the term 'MTBF' or 'MTTF' (Meant Time Between/To Failure). Herein, MTBF refers to mean time between unsafe failures, and MTTSAF (Mean Time To Service Affecting Failure), to failures which interrupt operations. MTTSAF reflects the service quality that the system provides, and is expected to be significantly lower than MTBF (Dwyer et al., 2012; Goodall et al., 2006). To make this distinction for track switching specifically, the MTBF is required to be of SIL-4 standard (10^8 to 10^9 hours between failure) – i.e. so high that one would not normally expect to encounter a failure within the working life of a network population.

	Incident count							Delay minutes ('000s)						*Mean mins*
	08-09	09-10	10-11	11-12	12-13	13-14	*Mean*	08-09	09-10	10-11	11-12	12-13	13-14	*/incident*
Track	**7750**	**6665**	**5879**	**5519**	**5346**	**5997**	***6193***	**957**	**764**	**763**	**804**	**855**	**931**	***137***
Speed Restrictions	1428	1278	932	717	685	747	*965*	204	147	107	78	71	100	*122*
Track Faults	6322	5387	4947	4802	4661	5250	*5228*	753	617	655	726	784	831	*139*
Non-Track	**32001**	**30109**	**27157**	**25767**	**25121**	**25491**	***27608***	**2829**	**2596**	**2612**	**2609**	**2673**	**2700**	***97***
Points	8022	7118	5803	5162	5021	4376	*5917*	752	663	646	597	577	514	*106*
Level Crossings	2261	2162	2003	1932	1857	1936	*2025*	101	96	101	93	100	104	*49*
OLE/Third Rail	1458	1241	1281	1276	1265	1259	*1297*	238	245	251	227	325	309	*205*
Signals	6559	6202	5116	5018	4449	4278	*5270*	313	256	216	240	235	258	*48*
Track Circuits	5381	5145	4567	4243	3902	3729	*4495*	585	517	550	605	534	515	*123*
Axle Counters	1096	913	648	683	706	799	*808*	122	107	67	72	86	114	*117*
Signalling/Power	3750	4016	4422	4202	4494	4684	*4261*	442	419	517	486	517	545	*114*
Other Signalling	1495	1430	1513	1505	1300	1338	*1430*	64	56	60	60	53	60	*41*
Telecoms	1406	1352	1252	1176	1513	2406	*1518*	70	70	53	56	73	95	*46*
Cables	573	530	552	570	614	686	*588*	142	167	150	172	173	187	*281*
Other	**12633**	**9303**	**9084**	**9212**	**9289**	**10753**	***10046***	**779**	**601**	**639**	**654**	**795**	**977**	***74***
Structures	397	436	385	279	444	574	*419*	80	79	62	60	161	194	*253*
Other Infra.	5478	3772	3455	3774	3612	4739	*4138*	251	204	213	253	297	318	*62*
Track Patrols	3362	2565	2269	1949	2213	2075	*2406*	68	34	33	30	34	34	*16*
Mishaps	1839	1183	1493	1838	1836	2009	*1700*	191	108	133	145	147	228	*93*
Fires	197	221	250	257	116	218	*210*	17	32	34	22	13	64	*145*
Bridge Strikes	1360	1126	1232	1115	1068	1138	*1173*	172	144	163	144	144	139	*129*
Total	*52384*	*46077*	*42120*	*40498*	*39756*	*42241*	43846	*4565*	*3961*	*4013*	*4066*	*4323*	*4608*	*97*

Table 2.3 Failure count and delay minutes (thousands) incurred for GB mainline infrastructure assets between 2007-2012, for top 18 incident categories by total count. Source: ORR (ORR, 2013)

(EN61508, 2002) describes SIL levels and their calculation . However, the MTTSAF is much lower, of the order of $10^4 - 10^5$ hours (Chapter 5) (Rama and Andrews, 2013). This is further described in (EN50126, 1999), and illustrated in Figure 2.14.

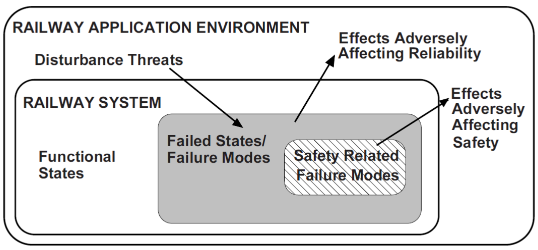


Figure 2.14 Effects of failures within a railway system. Source: (EN50126, 1999, p. 14)

2.4.3.3 Metrics

The most relevant metrics used by industry are:

- **MTTSAF** - Mean Time To Service Affecting Failure, describes how often the system can be expected to suffer a failure which is service affecting (operational reliability).
- **MTTFRI** - Mean Time To Fault Requiring Intervention, describes the frequency that maintenance crews must visit the asset to rectify faults *and* failures.

- **MTTR** - Mean Time To Repair - the mean time from reporting of a failed asset (or subsystem thereof) to returning that asset or subsystem to an as-good-as-new state.

MTTSAF and MTTFRI are useful measures for constant failure rate systems, but if failure rate is heavily skewed to early-life (infant mortality) or late-life (wear-out), arithmetic means provide skewed impressions of the data. MTTSAF is the de-facto industry standard, however for skewed distributions the 50% survivor function, or B_{50}, provides a better indicator. B_{50} indicates the time at which half the population is expected to have failed (the median). Highly skewed distributions have been observed in switches, and the 2P-Weibull model is established as the most appropriate for modelling switch failures (Rama and Andrews, 2013); equations for calculating MTTSAF and B_{50} from this distribution are published (Hecht, 2004). Alongside population statistics, expected lifetimes and failure distributions of individual subsystems can provide useful comparators. For 2P-Weibull models, these are represented by β (the shape parameter) describing skew to early or late life failures, and η, the characteristic life. One drawback of the Weibull function is that it is not capable of exhibiting non-monotonic shapes in the hazard function. This means the bathtub curve, typically observed over a whole population lifetime, cannot be replicated. However, this drawback can be offset by the sample period being across a range of component ages, and the use of confidence intervals to give an indication of goodness-of-fit of the distributions identified. MTTR is covered in Section 2.4.3.4.

2.4.3.4 Availability

Availability metrics (EN50126, 1999) specifies availability for railway systems as *'the ability of a product to be in a state to perform a required function under given conditions at a given instant of time or over a given time interval assuming that the required external resources are provided'*. Availability is the ratio of system uptime to system downtime. Calculation of availability, therefore, requires knowledge of all aspects of downtime - due to failures (i.e. reliability) and maintenance interventions. To an infrastructure custodian, availability may be considered a more useful metric than reliability, as it describes total asset downtime. EN50126 also specifies the knowledge required to make an informed calculation of availability; expressed in diagrammatic form on (EN50126, 1999, p. 17) and as a simple list (EN50126, 1999, p. 13), reproduced here:

a) reliability in terms of:
- all possible system failure modes in the specified application and environment;

- the probability of occurrence of each failure or alternatively, the rate of occurrence of each failure;

-the effect of the failure on the functionality of the system.

b) maintainability in terms of:

- time for the performance of planned maintenance
- time for detection, identification and location of the faults;
- time for the restoration of the failed system (unplanned maintenance).

c) operation and maintenance in terms of:

- all possible operation modes and required maintenance, over the system life-cycle;
- the human factor issues

At very high availabilities, unavailability, rather than availability, is usually expressed, due to the relative scale of the numbers involved. If very high availabilities are expressed, it is usually as a percentage approaching 100%, this having led to the adoption of 'nines' as an informal unit . A system with 99.9% uptime can be referred to as 'three nines' or 3N. Relevant availability calculations are presented in (EN50126, 1999, p. 59) and referenced as used.

Differing impact of unavailability It is worth noting that unavailability may have different consequences at different times; for example a railway operating 12 hours per day could achieve a perfect service with only 50% availability so long as the two time periods intersect. The required availability will change depending upon network and location. Section 2.4.1 establishes that the general GB trend is towards an ever higher capacity utilisation, including traffic encroaching traditional maintenance windows. This indicates that high availability is, or will soon become, key to both maintenance flexibility and service reliability. There will be a different monetary cost between scheduled and unscheduled elements of unavailability; unscheduled typically being much higher.

Emergency response time, MTTR and τ MTTR is difficult to quantify through research as the time the switch is unavailable following a failure is not recorded by the infrastructure operator; nor are staff transit-to-site times, a constant is therefore adopted for the work in Chapter 5. Traditional reliability modelling of a system may deliver results which are somewhat abstracted from the realities of the day-to-day operation of a railway. Some modelling herein takes a railway asset management perspective, in that the primary controlled variable is one which can be directly affected by the asset manager to bring about the level of availability required of the asset. This variable is τ, which describes the target time period in which a failed (or isolated as identified faulty) unit must be replaced by a maintenance team to deliver a given system MTBSAF:- a target MTTR. The variable has been used in this way in reliability modelling literature (Dwyer et al., 2012; Goodall et al., 2006)

2.5 Institutional and industry body recommendations

An IRSE report explores how fault-tolerant principles (Section 2.3) can be implemented in rail control systems(IRSE, 1993). The importance of reliability engineering, including RBDs, is noted, as is the necessity of fault-tolerance in order to provide required availability. The report falls short of specifying fault tolerance be applied to track switching.

> “When designing a new railway control system, the signal engineer should constantly bear in mind the great importance of overall reliability and maintainability of new systems. The required availability level shall therefore be an essential part of the specification and its achievement shall be checked at every stage of the design and development process.” (IRSE, 1993, p. 28)

The RTS (Rail Technical Strategy) (Yianni, 2012) sets out the future vision of the British rail industry, its strengths and areas requiring further research and development. Switch designs are listed as one of the main infrastructure development objectives; specifically:

> “New designs of switches and crossings reduce failures to negligible levels and reduce costs and disruptions associated with maintenance interventions. (...) Detailed modelling work has shown that the existing railway could double its capacity and still provide the current levels of public performance measures if (...) some key infrastructure, such as points, underwent a step change in performance.” (Yianni, 2012, p. 37)

Switches are also recognised in influencing other development objectives and enablers, notably 2.56, 2.57, 2.63, 2.68-2.70 and 2.80. In 2014, the academic community published a response to the RTS highlighting active areas of research towards it’s objectives. The work in this thesis is cited on two occasions (Iwnicki, 2014, p. 10, p. 21).

2.6 Conclusions

The background and literature review has been presented in three sections; track switching, fault tolerance and performance metrics.

The design and operation of traditional track switch installations has been explored. Switches operate in harsh conditions, often remote from the operator and maintainer, and adhere to minimal fault tolerant design principles. There are a variety of switch actuation methods, but each acts to bend the switch rails to position before locking in place. Switch operation is a fundamental part of the rail safety architecture; for this reason the position of the rails and lock is interlocked with signals to minimise derailment risk. Most faults are undetected until failure occurs, and some faults/failures are only detected by human inspection. Switches are therefore subject to intensive inspection and preventative maintenance.

Fault tolerance is of importance to systems which need to provide safe and cost effective operation without sacrificing availability. One of the most effective means of achieving fault tolerance is through systematic analysis of system fault modes, and integration of fault tolerant principles at the design stage. There are several methods to achieve fault tolerance: re-design of systems; inclusion of redundant channels; fault tolerant control systems; or a combination. Fault tolerant actuation in high integrity systems is often achieved through redundancy. Redundant channels can also have benefits for maintainability. Much research exists in the parallel fields of fault detection/diagnosis/prognosis and fault tolerant control.

There are many ways to measure performance, with a dichotomy between the numeric methods in literature and industrial metrics. Some industrial measures are not scientific in their derivation, so results should be treated carefully. It will require a mixture of approaches to ascertain the theoretical and practical implications of fault tolerant track switching.

The literature review indicates fault tolerant track switching has not yet been explored. Therefore, the opportunity is presented for novel work to investigate engineering fault tolerance into railway track switching. If switch systems can be engineered for fault tolerance, then the performance characteristics of the system need to be modelled to ascertain whether further development would be justified. A lack of literature in the area indicates novelty in the work presented in this thesis; specific novelties are listed in each chapter introduction.

Chapter 3

Evaluating novel track switch designs

3.1 Introduction

This chapter evaluates novel railway track switching solutions. Alternative designs of track switch may offer better performance, however, any novel design must meet track switching requirements to be feasible. As Chapter 2 established that there is no formally defined requirement set for a track switch, requirements are firstly established herein in Section 3.2. Each requirement is decomposed to its fundamental parts to understand how it can be satisfied; requirements are functional and non-functional. Candidate solutions, identified from a series of industry workshops in Section 3.4, are compared to the requirements set in Section 3.4.2, and ranked using the weighted average decision matrix technique. The traditional track switching solution is found not to satisfy all requirements, and could be considered unfit for purpose. The highest ranking novel solution is termed the 'Repoint' concept, which is described in further detail in Chapter 4.

The novel contributions of this chapter are threefold. Firstly, to formally establish a set of functional requirements for track switches. Secondly, to identify that traditional track switching solutions do not meet the functional requirement set, and are therefore unsuitable, in their current form, for a modern, high-performance rail transport network. Thirdly, to identify that several novel solutions have the potential to fulfil all functional requirements with the potential to outperform traditional solutions in non-functional areas. Work presented in this chapter led to a journal paper by the thesis author and supervisors, titled *'Rethinking Rail Track Switches for Fault Tolerance and Enhanced Performance'* (Bemment et al., 2016).

3.2 Requirements analysis

3.2.1 Overview

Switches fulfil a given purpose within a wider rail transport system - to allow different vehicles to follow different routes through the network. Switches can simultaneously be considered subsystems of a rail infrastructure system, or systems within a transport/railway SoSE (System of Systems Engineering) framework. SoSE is a branch of systems engineering which considers the interrelationships between distinct systems within a larger system environment (Boardman and Sauser, 2006; Jamshidi, 2011). SoSE is recognised in the transport domain (DeLaurentis, 2005). Switch systems interact with the surrounding environment, placing a set of requirements upon the switch to perform in a certain manner. These requirements can be functional or non-functional (Young, 2001). Functional requirements specify what the switch must and must not do - i.e. specific behaviour of the switch. Non-functional requirements specify criteria that can be used to judge the operation of a system when compared to other solutions. A systemic review of requirements engineering is available in literature (Neill and Laplante, 2003). One method to formally capture requirements is to examine all interactions with neighbouring systems and 'actors' (or stakeholders), to establish the way the system must behave in each case (Sharp et al., 1999). This method is suitable for track switches, as though technical solutions may change, interactions and actors remain equivalent between locations and networks. A key tool for understanding these interactions is the System Context Diagram (SCD), which defines the boundary between a system and its environment, identifying all external entities that may interact with the system (Kossiakoff et al., 2011). Figure 3.1 shows the SCD for a track switch.

Requirements placed upon a switch are a combination of requirements for a track system, those for a safety-critical asset, and those for a mission-critical asset. As a broad definition, functional requirements are those placed upon the switch in day-to-day operation - i.e. how the switch *must* function. Non-functional requirements, referred to as 'desirable properties' in some literature (Neill and Laplante, 2003; Young, 2001), are generally related to 'one-off' considerations, such as the purchase price of the system - business and economic considerations (Pohl, 1994). Functional requirements are placed upon the switch by the rail vehicles, the signalling system and the operations management system. These requirements are shown in Figure 3.1 as arrows. Arrows pointing towards the switch system indicate an action performed upon it, whereas arrows pointing away represent an action performed by the switch.

Let us consider that any switch design will most likely consist of three elements, namely 'track elements', 'actuator elements' and 'feedback elements'. The track elements have

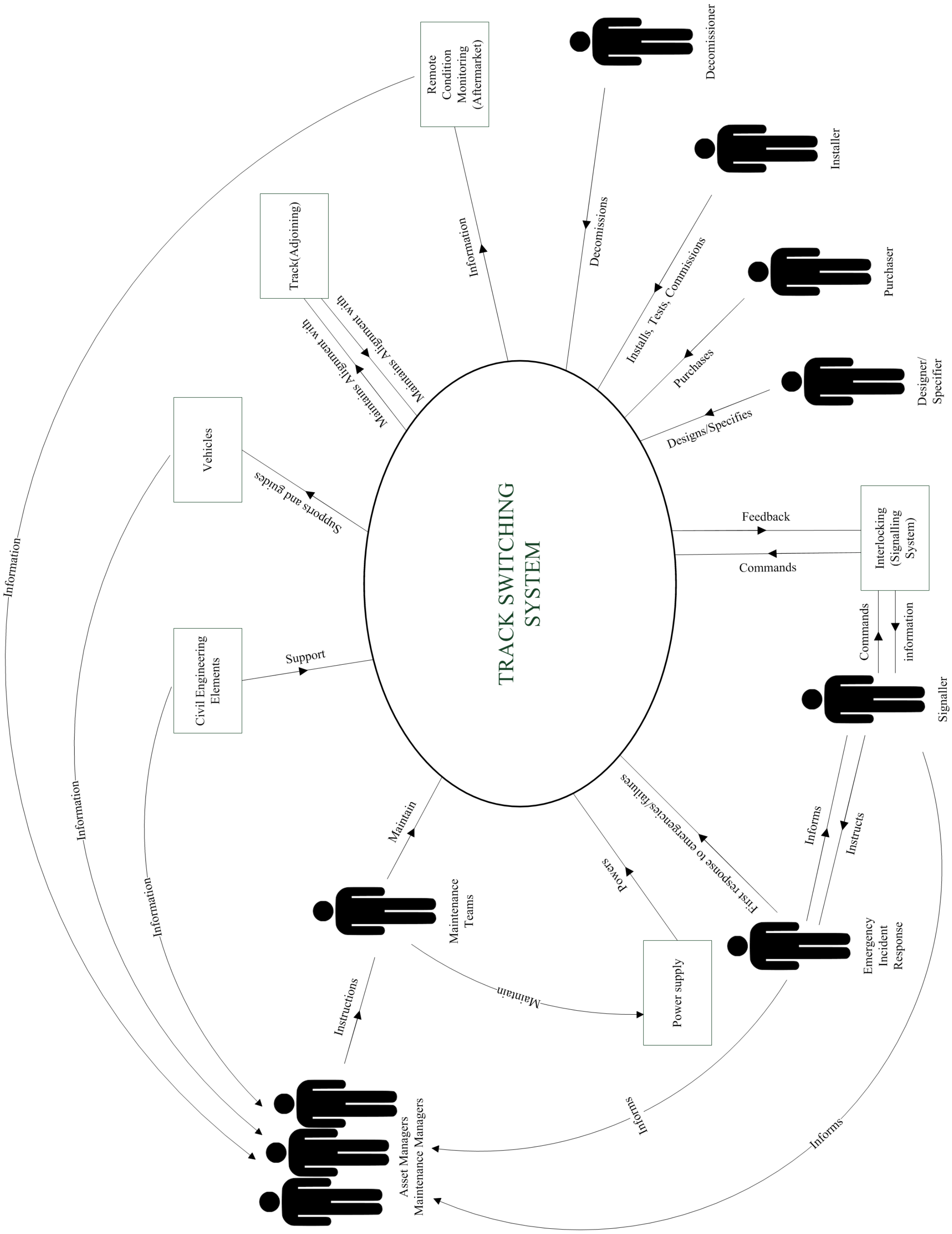


Figure 3.1 SCD for a generic track switching system, with external condition monitoring.

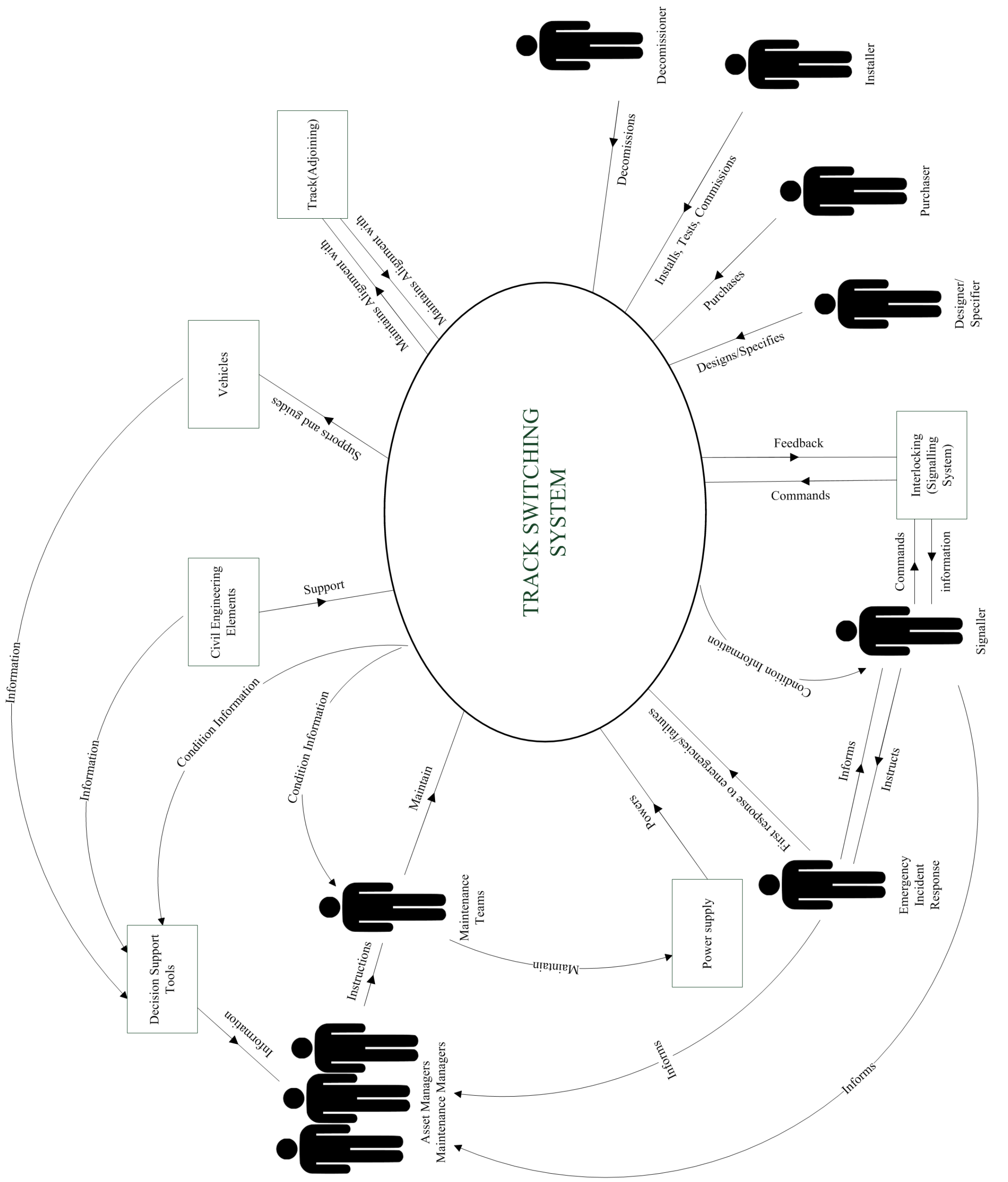


Figure 3.2 SCD for a railway track switching system with internal condition monitoring.

requirements equivalent to corresponding plain line, namely support and guide vehicles adequately. The actuator elements are required to direct vehicles along the correct path. The feedback elements are required to confirm the path the vehicles will be directed along to the interlocking, alongside information which confirms that the switch is safe/unsafe. In

ID	Sub-ID	Description
1		**The switch shall adequately support and guide all passing vehicles (as in (Network Rail, 2010a), for the GB case).**
	a	It shall support vertically and laterally the specified static loading.
	b	It shall support vertically and laterally the specified dynamic loading.
	c	It shall guide the wheel sets with maximum deviations as specified for the given track quality.
	d	It shall manage the wear and degradation of support and guidance elements to allowable levels.
2		**The switch shall direct vehicles along the path specified by the interlocking ((Genner, 1997; Hadaway, 1950)).**
	a	When commanded to, and not otherwise, it shall align any movable elements as to direct the wheelset of a vehicle along the specified route.
	b	When commanded to, it shall align any movable elements for the requested route within a specified maximum time-frame.
	c	It shall ensure all wheel sets of a vehicle are directed along the same route.
3		**The switch shall confirm to the interlocking the route vehicles will be directed along, and that all active elements are safe for the vehicle to pass ((Genner, 1997; Hadaway, 1950)).**
	a	It shall provide feedback to the interlocking that the requested route is set.
	b	It shall provide feedback to the interlocking if the requested route is unable to be set.
4		**The switch shall provide information to maintenance organisations regarding the future projected ability to perform requirements (2) and (3).**
	a	It shall monitor wear of wear-susceptible parts and adjustment of adjustable parts.
	b	It shall communicate current state of wear and adjustment to maintenance organisations.
	c	It shall calculate and communicate the remaining time of useful operation of the asset without maintenance intervention.
	d	It shall achieve a given minimum level of availability commensurate with the operations at the node.
	e	The design shall minimise maintenance downtime, and personnel track-side, to a level commensurate with the operations at the node.

Table 3.1 Top level functional requirements of track switching solutions.

the past, these have been the only requirements of a switching solution. However, given the high performance standards of a modern railway and the criticality of switch availability established in Chapter 2, another functional requirement could be included; namely to communicate the current and predicted ability of the switch to meet the other requirements to operators. This may involve communicating the state of switch subsystems to the maintenance managers. This set of requirements is what would normally be met by the use of a condition monitoring system. It is possible that a condition monitoring system may now be a functional requirement, rather than a desirable. This arrangement (and subsequent additional requirement) is shown in the revised system context diagram in Figure 3.2.

3.2.2 Functional requirements

Using the SCDs, 3.1 and 3.2, a top-level list of functional requirements can be compiled. Each requirement can then be further decomposed into functional elements as in (Neill and Laplante, 2003). These requirements are listed alongside a requirement identification number in Table 3.1. However, there are weaknesses in this definition and decomposition method. Firstly, the system boundary has been set through a combination of research, interview, and engineering judgement. However, it would be both possible and reasonable to set the boundary elsewhere using a different set of assumptions and/or constraints, which could lead to a wildly different conclusion. An example of a different but valid system boundary is that track switching could be achieved by a steerable vehicle with static track elements, which would place the 'vehicle' element inside the boundary. Secondly, whilst every effort has been made to correctly establish the system interactions, it is possible that the some interactions may have been excluded, which would then lead to missing functional requirements. The risk of this has been minimised through the use of peer review (Bemment et al., 2016).

3.2.3 Non-functional requirements

Alongside the functional requirements are further requirements that need to be established, collectively termed 'non-functional' requirements (colloquially 'desirables'). Whilst solutions should satisfy all functional requirements, non-functional requirements form a set of trade-offs whereby the relevance of each will vary in every given scenario. For instance, there is pressure in Europe to reduce track-side working for safety reasons. There is political pressure to reduce the cost of infrastructure (McNulty, 2011). In some retrofit locations (depots, city centres), space is at a premium; the alignment of the track, or capacity, is sacrificed as there is insufficient room for a switch of the ideal specification (Ison et al., 2012), not as often the case in new build. A non-exhaustive list of the most relevant non-functional requirements was established with the aid of the focus group (Section 3.4). It must be acknowledged that as the list of desirables is representative of the views of the group, that list and subsequent rankings may be inherently biased towards those views. A different focus group with alternative views or experience may have generated or ranked the list differently.

Limitations of focus group methods with small sampling frames are described, for instance, by (Collis and Hussey, 2013, pp130). The limitations introduce a potential weakness in the method whereby the ranking and selection process is unable to be fully validated. Unfortunately, due to constraints of time and resource, more appropriate methods such as a poll with wider population, or the use of several, independent focus groups to cross-check results, perhaps through a fixed questionnaire (Collis and Hussey, 2013, pp143), were unavailable to the thesis author. Additionally, the sampling (in this case the selection of the focus group members) was completed before the thesis work began, meaning that the focus group may be judgementally sampled, perhaps further aggravating the weaknesses above.

1. Degree of Fault Tolerance: *How long/well can the switch tolerate faults, remaining in a usable state until such a time as repair can be performed?*
2. Design Adaptability: *Switches must handle many types of traffic at many speeds. Whilst many different designs could fulfil these different purposes, a single, adaptable design is preferable.*
3. Unit Cost: *Monetary cost of the solution, estimated using engineering judgement.*
4. Space Utilisation: *Physical footprint of the solution.*
5. Energy Requirements: *Lower energy requirements are more desirable due to the difficulty of supplying power line-side (Section 2.4.2).*
6. Ease of Manufacture: *Able to be mass-manufactured using existing techniques and processes.*
7. Likelihood of Acceptance: *The rail industry has processes and standards regarding the design of products for use upon the network. Is the concept likely to be certified?*
8. Switching Speed: *Whilst there is a functional requirement to meet a given maximum switching time; the faster the switch can change positions, the better (Chapter 2.4.1).*
9. Maintainability: *Does the design help to ease maintenance, and reduce the amount of time personnel spend performing maintenance tasks track-side?*
10. Standardisation:*Can the design be built from COTS (Commercial Off-The-Shelf) components, or are many custom components necessary?*
11. Human Factors: *Maintenance teams (and trespassers) may be exposed to movable elements of the switch. How big is the risk posed?*

3.2.4 Concept ranking and selection technique

Having established a set of requirements, the next step is to develop an approach for ranking and selection of candidate solutions. As stated earlier, functional requirements must be met without exception in order that the solution be suitable. Several solutions may meet this set, therefore a method is required to discern which one(s) may offer the best available solution. Literature explores various methods of selecting one of a number of options based upon a set of goals; in business and operations management literature as well as engineering design literature. (Cross and Roy, 1989, p. 140-161) in particular lists several methods of selecting the best solution, from a mechanical design evaluation perspective. In this case, the 'Weighted Objectives' technique will be used. The weighted average decision matrix technique was used for this down-selection process due to its speed and suitability for decision making across a smaller sample size of varying opinions. It is acknowledged that with greater resource or time, other processes such as the Delphi approach to disruptive innovation, or other methods listed in (Collis and Hussey, 2013; Cross and Roy, 1989) including cross-checking individual, smaller focus-groups, may have offered more academically rigorous results.

The weighted-objectives technique requires a matrix to be created specifying the relative importance of each requirement. Requirements are ranked, by combining pairs; each requirement is then assigned a weighting. Calculation is simplified if the weightings sum to one. Each design option is then scored, in this case out of 10, against how well it satisfies each non-functional requirement, and this score is multiplied by the weighing representing the relative importance of that requirement. The resulting weighted scores are summed to give each option a total score. Thus, it follows that a concept which scores highly in many areas is may not be identified as the best option if the weighting of those requirements is low.

Table 3.2 shows a comparative ranking between each of the established non-functional requirements listed in section 3.2.3, for the GB mainline scenario. The results of each pair comparison have been generated through discussion with a panel of British stakeholders in track switching (Section 3.4.1). Reference was made to earlier sections of this thesis, particularly relevant sources cited in Chapter 2. It is important to note that the rankings are subjective; a different judging panel, or consideration of a different railway jurisdiction may lead to different weightings and therefore a different final solution ranking.

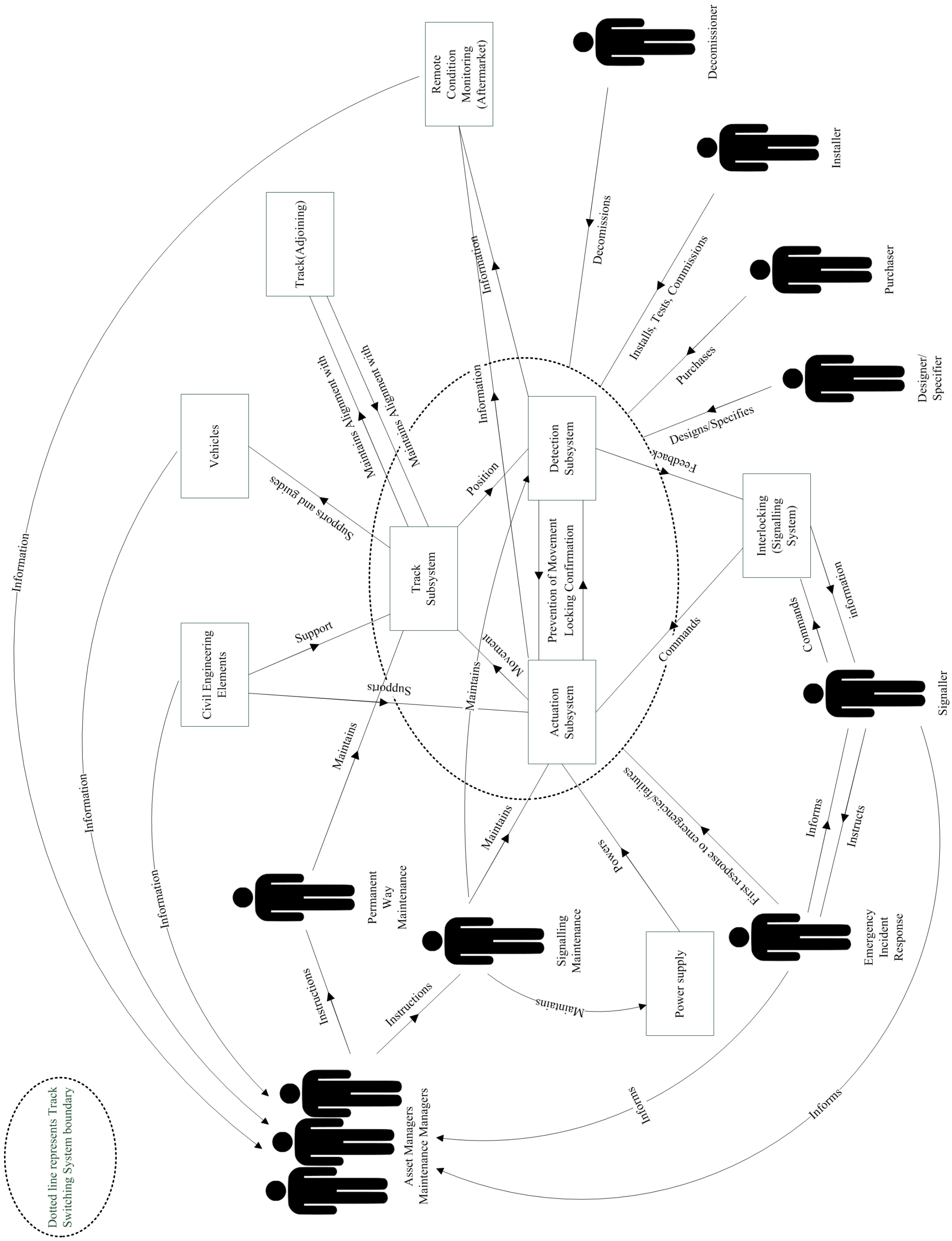


Figure 3.3 Systems Context Diagram for traditional railway track switching systems. Requirements are met through the use of three subsystems - track, actuation and detection. Interactions between the switching system and external systems are shown alongside some relevant interactions entirely outside the system boundary.

Table 3.2 Non-functional requirements ranking and weighting matrix. If Row is more important than Column, then value is 1; of equal importance, 0.5; of lesser importance, 0 (Standard practice).

	Degree of Fault Tolerance	*Design Adaptability*	*Unit Cost*	*Space Utilisation*	*Energy Requirements*	*Ease of Manufacture*	*Likelihood of Acceptance*	*Switching Speed*	*Maintainability*	*Standardisation*	*Human Factors*	*Total*	*Weighting (w)*
Degree of Fault Tolerance	-	0	0.5	1	1	0.5	0	1	1	1	0.5	*6.5*	*0.12*
Design Adaptability	1	-	0	1	1	0.5	0	1	0	0.5	1	*6*	*0.11*
Unit Cost	0.5	1	-	0	1	0.5	0	1	0.5	0	0.5	*5*	*0.09*
Space Utilisation	0	0	1	-	0.5	1	0	1	0.5	1	0.5	*5.5*	*0.10*
Energy Requirements	0	0	0	0.5	-	1	0	0	0	0	0	*1.5*	*0.03*
Ease of Manufacture	0.5	0.5	0.5	0	0	-	0	0	1	0.5	0	*3*	*0.05*
Likelihood of Acceptance	1	1	1	1	1	1	-	1	1	1	1	*10*	*0.18*
Switching Speed	0	0	0	0	1	1	0	-	0	0	0.5	*2.5*	*0.05*
Maintainability	0	1	0.5	0.5	1	0	0	1	-	0.5	0.5	*5*	*0.09*
Standardisation	0	0.5	1	0	1	0.5	0	1	0.5	-	1	*5.5*	*0.10*
Human Factors	0.5	0	0.5	0.5	1	1	0	0.5	0.5	0	-	*4.5*	*0.08*

3.3 Comparing traditional switches to the requirements

3.3.1 Identifying satisfied requirements

Referring to the numbered requirements in Table 3.1, and to Figures 2.1 and 2.2, each requirement can be mapped to a functional element of existing switches. The subsystems used to achieve this, and their interactions, are shown in the systems context diagram in Figure 3.3.

Requirements (1a,b,c) are achieved by designing the track elements of the switch to be of equivalent rating to the surrounding plain line and traffic requirements. However, in order to meet (1c), in some cases this has meant relaxing the standards, notably around the switch toes, in order to prevent having infinitely thin blades at the point of intersection of routes (Section 2.2.3.2). Requirement (1d) is achieved through a regular programme of inspection with wear gauges, followed by corrective action such as grinding or packing, as laid down in industry maintenance handbooks (Cope and Ellis, 2001; Network Rail, 2013c).

For requirements (2a,b,c), routing of vehicles is currently achieved by the combination of an actuator and two moveable switch rails (Section 2.2.2.1). The actuator acts to close one switch rail against the corresponding stock rail, and open the opposite to create a flangeway. The same actuator, by means of a mechanical arrangement, then provides locking to prevent un-commanded movement of the rails. However, the use of a single actuator means that component failures may easily prevent the actuation elements meeting this requirement, even with appropriate maintenance as per requirement (4).

Requirements (3a,b) are provided through the detection elements. Limit switches indicate that the two movable switch rails are in the correct position, and that the lock preventing movement (for requirement 2c) is engaged. A signal is then transmitted to the interlocking. If the switch is unable to be set for a particular route, then not all of the limit switches can be engaged, thus no detection signal is transmitted, and after a given time-frame as in (2b), the signaller would deduce there was a failure. Switches do not, in the signal to the interlocking, differentiate between ‘currently moving to desired position’ and ‘unable to move to desired position’; both states appear equivalent to the limit switches.

3.3.2 Identifying unsatisfied requirements

Some existing designs - specifically the classic electro-mechanical - (Section 2.2.4.5) fail to meet requirements (1b,c), (2c) and (3a) due to issues with the design of stretcher bars. Stretcher bars are responsible for holding the open switch rail in place; their failure allows the switch rail to close, uncommanded, against the corresponding stock rail, almost inevitably leading to derailment. Traditional designs have several stretcher bars, partially to counter this possibility. Regular inspection and maintenance is used to mitigate against the risk, at as high a frequency as once per week. Derailment and loss of life has happened twice in recent history - at Potters Bar and Greyrigg (Figure 1.2). Despite mitigations, short-cuts taken in the inspection and maintenance processes contributed to these disasters (RAIB, 2011; RSSB, 2005). Switch designs based around the use of the bolted stretcher bar, and without a mechanical backup or monitoring system, fail to meet the functional requirements laid out above, on the grounds that a programme of regular, frequent additional inspection has necessarily been adopted to provide mechanical integrity. Traditional switches do not meet requirements (4a,b,c) for this reason.

Existing switch designs are least compliant with the requirements in group (4), perhaps as these requirements have only evolved with the enhanced performance of a modern railway system. Network Rail has recently retro-fitted condition monitoring equipment to better meet (4a) and (4b) (Section 2.2.5.2) (McNaughton, 2007). As a retro-fit, this is shown external to the switch system in Figure 3.3. However, safety-critical , and wear part monitoring is still achieved by regular human inspections, clashing with requirement (4e). Requirement (4c) is currently not catered for, however work in the prognostic field seeks to improve this (Marquez et al., 2010; Silmon and Roberts, 2010).

3.3.3 Performance against non-functional requirements

Despite some POE failing to meet some of the functional requirements, it is a useful exercise to compare existing switches to the non-functional requirements in order to benchmark. Using the scoring system presented in Table 3.2 (Section 3.5), traditional switches were ranked. The results of this exercise are presented in the first two columns of Table 3.4. The first column, 'As is', indicates switches as currently deployed - scoring 5 for each category as per Table 3.3, giving a weighted non-functional score of 5.90. The second column lists mean scores for an 'Ultimate evolution' switch; the ultimate performance evolution of the traditional track switch design, scoring 6.37 overall.

3.4 Novel concepts

3.4.1 Industry focus groups and idea generation

An industrial focus group was assembled on four occasions through 2011-2013, to generate and rank candidate track switching solutions. Further to these sessions, a series of remote and face-to-face meetings was conducted with other stakeholders within Network Rail and London Underground (Bemment et al., 2016).

Sessions were structured around questions related to existing and novel track switching solutions before providing an open forum. Questions were structured to include system (and human) interactions of the track switching system as well as the engineering elements. The sessions resulted in over 100 individual ideas related to improvements to switches and crossings, covering their physical design, signalling and operation, associated maintenance activities, and routes to market. Specific questions were as follows:

1. What alternate means of directing and supporting traffic may be adopted?
2. What alternate means of actuating any moveable elements may be adopted?
3. How might we avoid ‘failures’ due to obstruction of the mechanism?
4. The other main failures could be grouped under: Friction, Adjustment, Mechanical, Control and Feedback, Other. How might we go about reducing the probability of other failure modes?
5. How might we go about removing the indeterminate (OOC) state from the normal operation of the switch?
6. What are the rules that might change as a result of the implementation of points incorporating redundancy to provide very high reliability and integrity?
7. Who should we be involving during the concept evaluation and development phases to ensure industry buy-in?
8. What areas of the network could provide good case studies as to the potential benefits of such a concept?
9. What are the factors which may prevent successful deployment of any novel concept upon the network?

3.4.2 Idea filtering and down-selection

The first filter for down-selection was to exclude any ideas which were mechanically implausible; it is the nature of a brainstorming-type approach that construction and operation of some ideas will not be possible, these ideas must be rejected at an early stage. Secondly, any ideas which would require wholesale modification of the entire rolling stock fleet were excluded, including the removal of all wheel flanges, or steerable bogies. These options can broadly be defined as 'Vehicle-Based Switching' (VBS). Whilst it is accepted that VBS may ultimately deliver higher levels of performance than track based switching (Ward et al., 2014), this is out of scope for this work. Thirdly, any ideas which would require more than 20 years estimated 'time to market' were excluded. For example, novel vehicle control solutions which required European Rail Traffic Management System ERTMS Level 4 or higher (Stanley, 2011). In some cases this would also have ruled out VBS solutions. These solutions also fall outside the scope of this work - regulatory body panel members noted industry would be unlikely to adopt such solutions due to the cyclic nature of development funding in the sector and the need to deliver benefits early. Thirty novel options remained to be investigated and ranked. These solutions ranged from detail changes to traditional switches (towards the 'Ultimate Evolution') to completely novel designs, which are now listed.

3.4.3 Novel concepts

This subsection presents the novel designs remaining after idea filtering; ranked in Section 3.5.

3.4.3.1 Concept A: 'The track substitution switch'

Shown in Figure 3.4. Not used on the GB mainline, but can be seen at amusement parks with tracks of large cross-section, or where the bogie wraps entirely around the rails, such as monorails. Track for either exit route is entirely separate, and substituted into the available space when required. This substitution can be by way of sliding, rotating, or lifting.

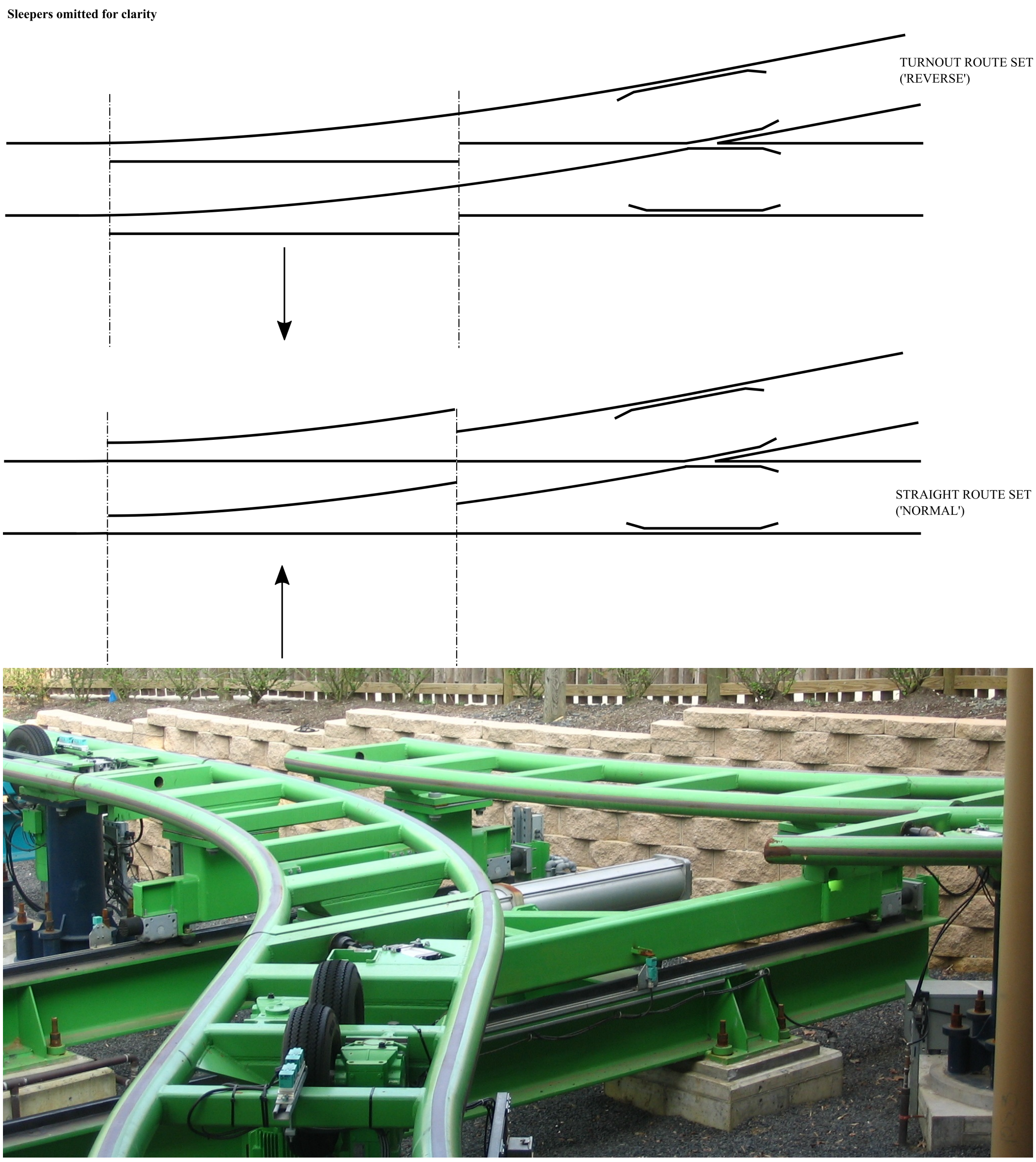


Figure 3.4 Concept A: (Top) General arrangement of a track substitution switch, and (Bottom) a roller coaster implementation, 'Kingda ka', Six Flags, USA (Credit: Dusso Janladde, wikimedia)

3.4.3.2 Concept B: 'The single flange controlled switch'

Traditional switches provide a flangeway for each wheel to pass through the switch, with one or both flanges contacting the switch rails to set a direction. It may be possible to do away with one moving switch rail, instead providing a fixed flangeway one one side and selecting direction with a single moveable switch rail on the opposite side, as a moveable check rail as in Figure 3.5 On longer switches designed for faster traffic, this may mean some distance where the wheelset is running upon the tip of the flange, with the resulting implications on the ride dynamics. This may restrict maximum traffic speed, but its advantage is to halve the moving parts of traditional layouts.

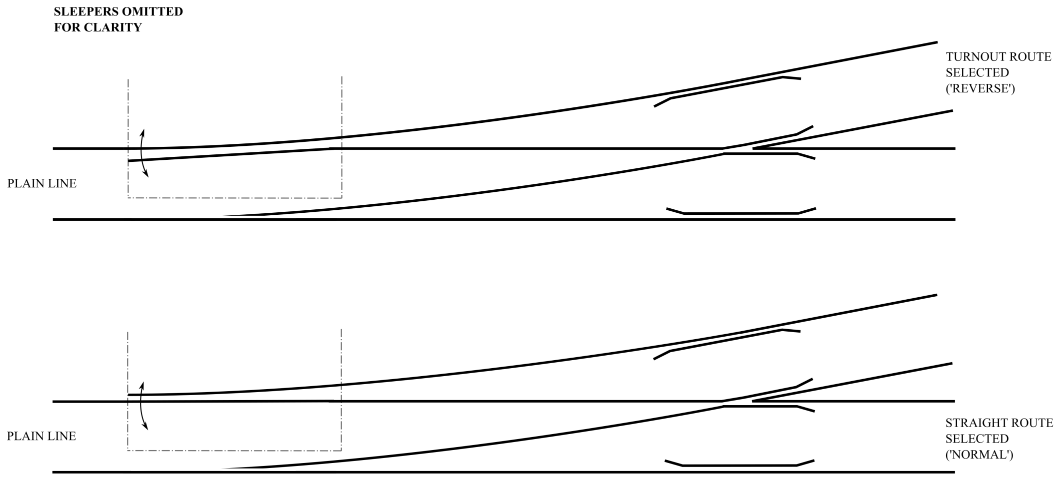


Figure 3.5 Concept B: General arrangement of the single flange controlled switch

3.4.3.3 Concept C: 'The wheel-face switch'

This switch has fixed track elements, with flange-ways built in, as in Figure 3.6. An element higher than the running rails contacts the wheel faces and acts to direct the vehicle along either route. Multiple elements could be provided to enable redundancy. Contact elements would need to be locked in place as in a traditional switch, to prevent splitting the switch. These arrangements would eliminate the opening and closing gap between the switch and stock rails upon existing designs which can lead to blockages of the mechanism. They may also simplify the provision of multi-channel actuation and locking elements as several wheel face contact elements could be utilised together. One drawback is simultaneous failure of both wheel face contact elements would leave switch in an undefined state.

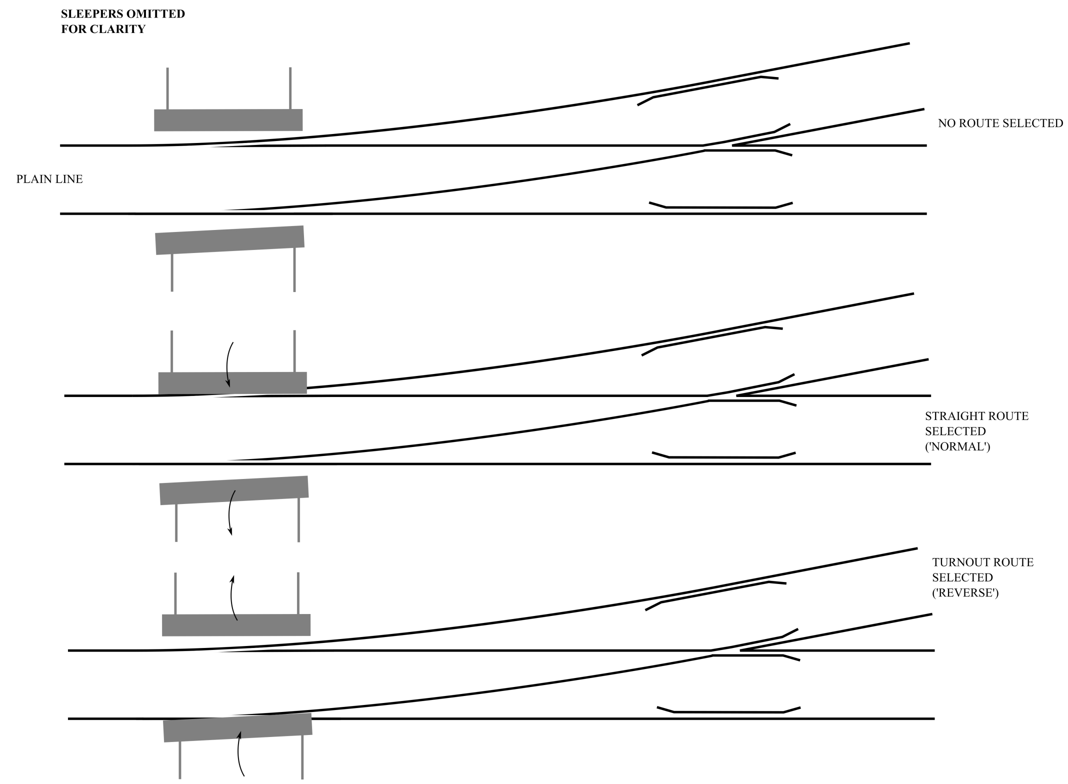


Figure 3.6 Concept C: General arrangement of the the wheel-face switch

3.4.3.4 Concept D: ‘Interlocking rails’

This concept (Figure 3.7) provides the locking function through the shape of the rails themselves, rather than through an additional mechanism. The rails are locked in place by virtue of being lowered into cut-outs, but when raised are free to move laterally between positions. The rails would need to be unlocked by an actuation element which would need an element of vertical motion. This could assist in enabling multi-channel actuation; each actuator may be capable of unlocking the switch rails individually. Unlike existing designs which rely upon the stretcher bar to restrain the open rail, this concept could positively lock both rails in position in multiple places. However, because of its similarity to existing designs it may have similar disadvantages - much machining of switch rails and possible blockages.

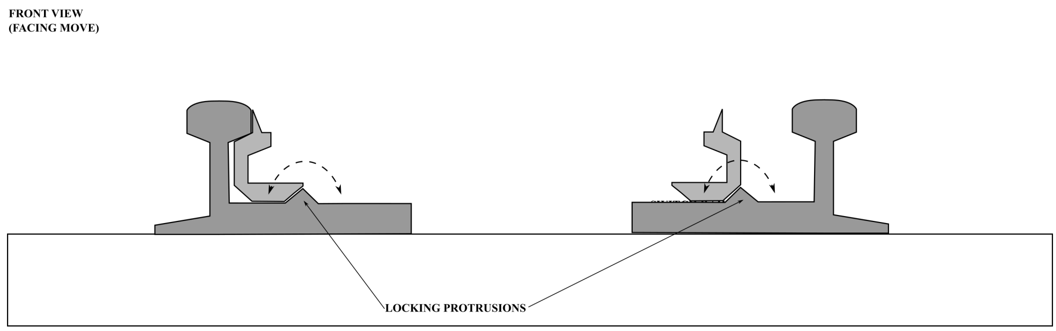


Figure 3.7 Concept D: Interlocking rails - general arrangement

3.4.3.5 Concept E: 'The stub switch'

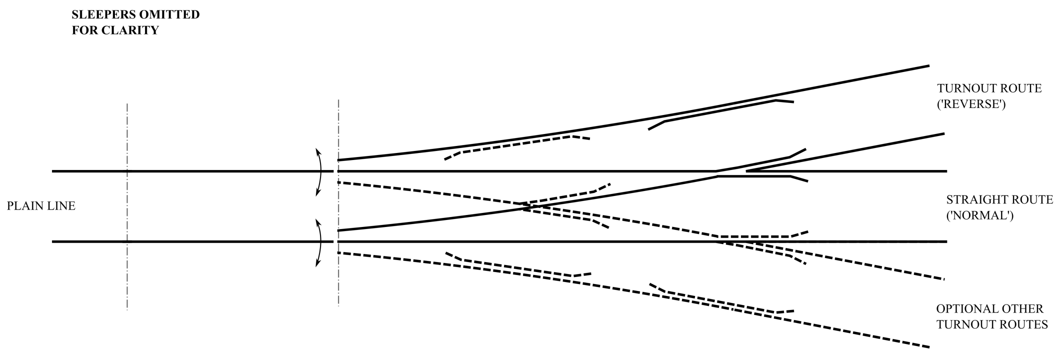


Figure 3.8 Concept E: General arrangement of a stub switch, showing bending full-section rails to select route. Additional routes are possible, a third is shown in dashed lines.

The stub switch, in Figure 3.8 reverses elements of a traditional switch, using full-section rail throughout. The route is selected by bending or hinging the approach rails to position. There is no opening/closing gap between switch and stock rails. This has the benefit of allowing more than two routes from a single switch, and reduces the probability of blockages. There is, however, a discontinuity at the rail ends. In practice it may be difficult to control the track alignment at this discontinuity. Actuators may be required along the moveable length of the rail to ensure it follows the correct alignment.

3.4.3.6 Concept F: 'The over running rail switch'

The concept in Figure 3.9 takes a fixed set of diverging rails and places a specially shaped ramp over the left or right rail in order to direct the vehicle along one of the two (or three) potential routes. One side of the wheelset is lifted over the running rail; no flangeway is provided. Devices like this are in use as temporary turnouts in work sites to direct on-track plant onto temporary track, and also as derailers. The ramps could be actuated using multi-channel parallel actuation for fault tolerance, and be self-locking by underside shape.

Figure 3.9 Concept F: A temporary over running rail switch. (Credit: Martinus Rail Australia)

3.4.3.7 Concept G: 'Raising and lowering the switch rails'

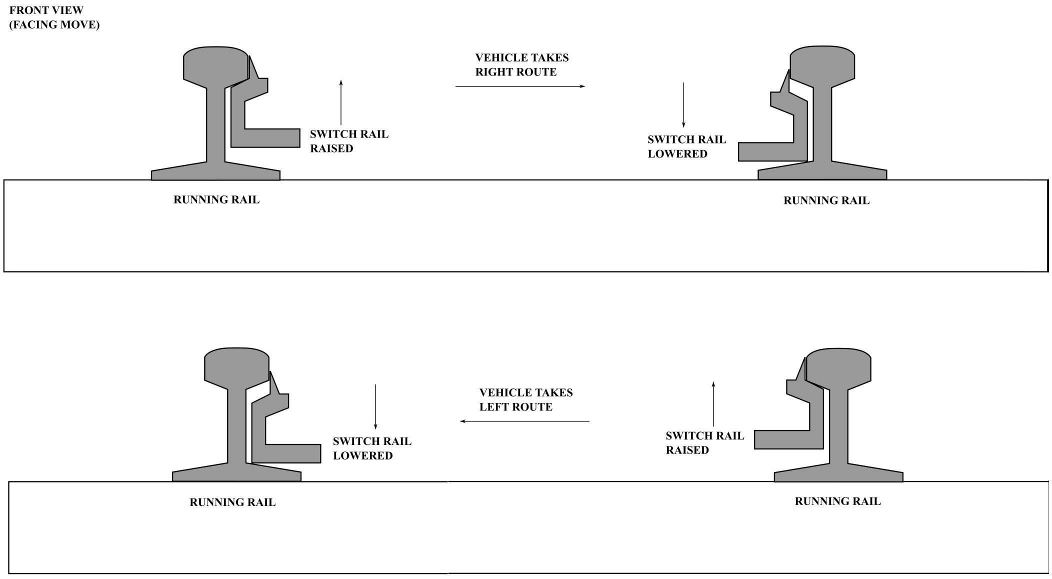


Figure 3.10 Concept G: Raising and lowering the switch rails.

It may be possible to raise and lower the switch rails instead of the traditional lateral motion (Figure 3.10). The raised switch rail would need supporting adequately for the static and dynamic loading from rail vehicles, and the lowered rail would need to be locked in a lowered position. It may be easier to provide multi-channel actuation and locking with this arrangement when compared to a traditional switch. The switch rails still need to support the mass of a vehicle, perhaps through actuating the rails by driving shaped wedges underneath.

3.4.3.8 Concept H: 'The swing-nose switch'

The swing-nose crossing exists as a method to support the wheelset at the common crossing; a similar concept is applicable to the switching elements as in Figure 3.11. A flangeway is created by flexing a pair of rails. The rails can be held a certain distance apart. The drawback is the additional energy required to bend/pivot two pairs of moving rails, though if the bearing surfaces were contained under the spacing elements, friction could be controlled. Accurate alignment of the rail ends could be achieved by limiting elements; rails would have to be closely controlled and aligned. It may be possible to have more than two routes out of the switch, as per concept E. This arrangement has a lower likelihood of blockages, as the variable gap between switch and stock rail is eliminated.

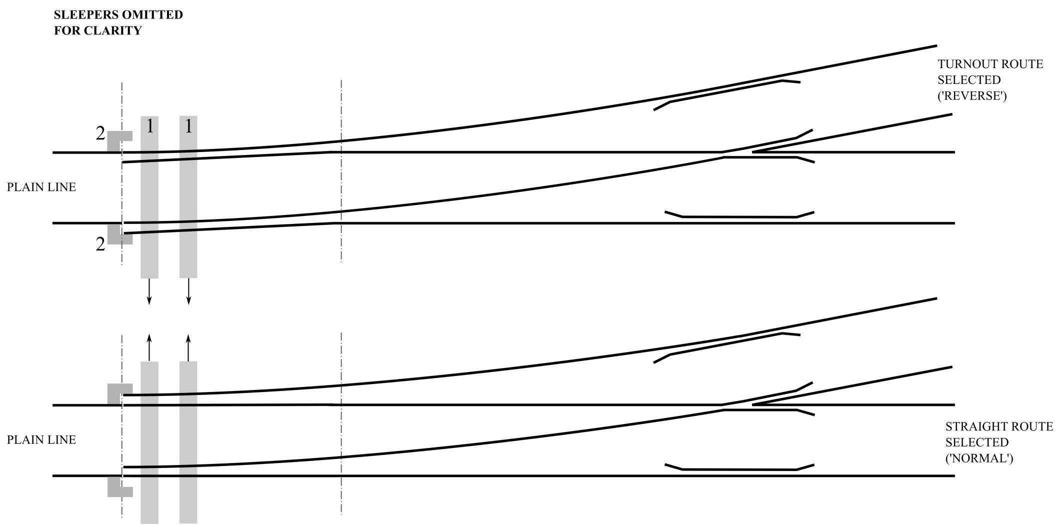


Figure 3.11 Concept H: General arrangement of a swing-nose switch, showing pivoting/flexing pairs of full-section rails to select route. Plates maintain gauge (1) and limit blocks (2) maintain accurate track alignment .

3.4.3.9 Concept I: 'The hopping switch'

Also known as the bunny switch, and illustrated in Figure 3.12. In this arrangement, the switching rails hop between fixed, locked positions. The rails could either hinge or bend. A switch of this design which uses a track substitution arrangement is patented (Winter, 2006). The rails are lifted out of position and dropped in an adjacent position.

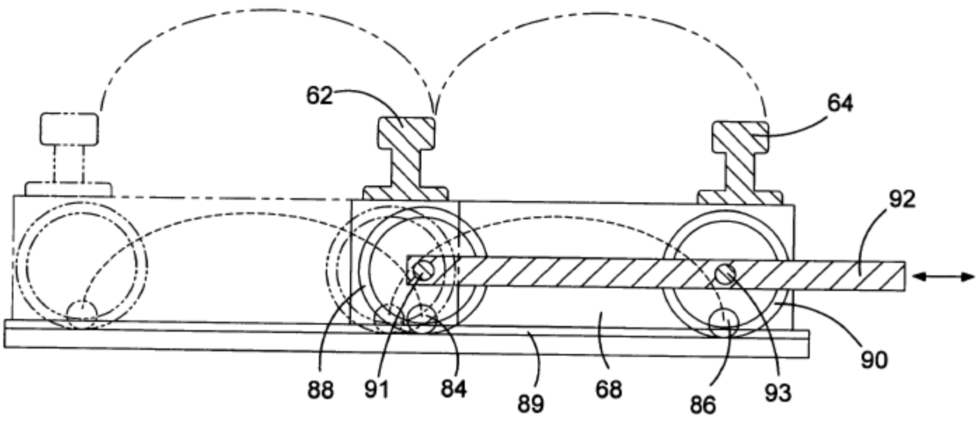


Figure 3.12 Concept I: Hopping switch general arrangement. (Source: (Winter, 2006))

3.4.3.10 Concept J: 'The Spring Switch'

Some switches of the traditional type exist without actuators, typically used at remote passing loops , to always direct traffic in a given direction for a facing move, but allow trailing moves from either direction (Morgan, 2009). Many switches are used for trailing moves only, the primary example being exiting directional platforms at stations. It may be possible to have an entirely passive solution for select locations, including at higher speed.

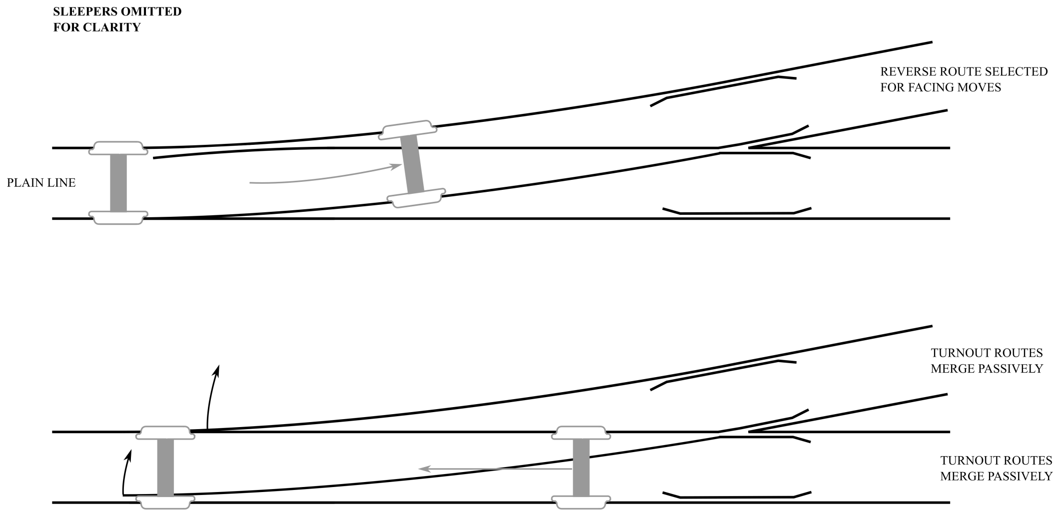


Figure 3.13 Concept J: General arrangement of a spring switch. All vehicles making a trailing move are directed passively; facing moves along the turnout route.

3.4.3.11 Concept K: 'Hopping Stub Switch' (D, E and I Combined)

During the idea downselection process, the panel noted that ideas D, E and I were not mutually exclusive and could be combined into a single concept which may deliver the combined benefits of each, which is included here as an additional concept, K. The concept is a stub switch arrangement, which hops between positions, using interlocking rail ends to provide a positive lock when in position.

3.5 Ranking novel concepts

Each concept was then ranked against the weighted non-functional requirements in Table 3.2, with scoring guidelines in Table 3.3. This was carried out with input from the industrial panel. Each member of the judging panel was independently asked to score each concept against each category. Also included in the ranking were traditional switches in two forms; 'As is' and 'Ultimate evolution' (Ult. Evol.) (Section 3.3.3). Note Concept J scores 10 in the Product Acceptance category; this design is already deployed. The mean scores, totals and concept ranks from this exercise are shown in Table 3.4.

Score	Description
0	Impossible to fulfil this requirement
1	Very minimal ability to fulfil this requirement
2	Minimal ability to fulfil this requirement
3	Some ability to fulfil this requirement
4	Good abbility to fulfil this requirement
5	Matches the capability of existing solutions
6	Marginally exceeds the capabilty of existing solutions
7	Fulfils this requirement better than existing solutions
8	Fulfils this requirement significantly than existing solutions
9	Fulfils this requirement very significantly better than existing solutions
10	Perfectly fulfils this requirement

Table 3.3 Scoring used for judging the performance of each novel solution.

Table 3.4 Results of the weighted scoring exercise - mean scores from the judging panel, including rankings.

		Traditional		Concept										
Requirement	w	As is	Ult. Evol.	A	B	C	D	E	F	G	H	I	J	K
Degree of Fault Tolerance	0.12	5.0	5.3	3.4	3.0	5.8	4.7	3.3	8.1	5.2	3.1	8.5	9.3	9.2
Design Adaptability	0.11	5.0	4.9	2.8	5.0	6.6	7.0	9.2	3.3	4.7	5.2	7.3	0.9	9.2
Unit Cost	0.09	5.0	6.9	1.9	7.8	6.9	8.3	5.4	6.7	7.3	8.6	5.0	6.2	5.8
Space Utilisation	0.10	5.0	5.0	0.5	6.9	5.0	7.5	9.5	4.5	4.7	6.5	5.2	4.7	9.9
Energy Requirements	0.03	5.0	5.9	2.1	6.8	7.3	7.0	3.8	7.5	4.8	7.7	2.9	10.0	7.1
Ease of Manufacture	0.05	5.0	7.0	2.0	6.6	6.2	5.0	8.1	4.5	4.6	6.4	5.6	8.0	6.4
Likelihood of Prod. Accept.	0.18	10.0	10.0	8.2	8.3	5.2	8.0	7.1	2.1	2.9	5.0	7.6	10.0	7.8
Switching Speed	0.05	5.0	6.2	3.4	6.3	7.0	6.6	4.8	3.7	4.2	7.9	4.4	10.0	8.1
Maintainability	0.09	5.0	5.0	2.1	6.0	8.0	5.1	8.0	5.6	3.4	3.3	4.7	7.8	6.5
Standardisation	0.10	5.0	5.9	4.9	4.8	5.4	8.1	5.1	2.8	5.1	8.0	8.0	5.7	6.9
Human Factors	0.08	5.0	5.0	2.8	5.2	2.6	7.5	6.8	3.4	5.1	9.2	2.9	8.4	3.2
Weighted Sum		5.90	6.37	3.65	6.08	5.83	6.93	6.64	4.45	4.59	6.05	6.21	7.18	7.51
Rank				11	6	8	3	4	10	9	7	5	2	1

3.6 Analysis of rankings

3.6.1 Relevance of score weightings

Section 3.2.4 explains the methodology for assigning weightings to non-functional requirements. It upon the opinions of the panel. In this case, the panel were told to consider the GB mainline and significant metro networks only. It is possible that for other situations different weightings would have been assigned. This may mean that, in a different situation, a different switch design may have ranked top in non-functional requirements. Examples of this may include new build city systems, where switching speed and space utilisation may be of higher weighting; and long distance routes through remote, difficult to reach locations where energy requirements may be of more importance. Crucially, this may mean that whilst the industry has standardised around a single solution, there may be a range of solutions with unique advantages which decide particular suitability. It is therefore important not to eliminate any solution based upon a marginally lower weighted score in Table 3.4. Further work may be carried out to establish different versions of Table 3.4 for given locations or scenarios. This is, however, beyond the scope of this thesis.

3.6.2 Comparison to benchmark

The traditional track switch achieved a score of 5.9, and the ultimate evolution 6.37. Seven novel concepts ranked higher than the 'as-is' switch, and four ranked higher than the ultimate evolution. Of the four concepts outscoring the ultimate evolution:

- Concept K scores the highest of all options with 7.51. This concept is a combination of concepts D, E and I, and could therefore be expected to score more highly than each of these concepts ranked alone. The concept scores very highly in degree of fault tolerance, adaptability and space utilisation. The design scores low in human factors due to the likelihood of harm to trespassers with the novel motion. However, the weighting matrix places more emphasis on the former three factors.
- Concept J, scored second highest at 7.18. The design scores 10/10 for likelihood of product acceptance as examples already exist. The design also scores full points in energy requirements and switching speed, being entirely passive. However, because of the passivity of the concept, it scores very low (0.9) in design adaptability - it could not be used in every location. As the second highest scoring concept, and with higher scores in other areas, the opportunity could be explored for further roll out of the spring switch across the network in locations which have trailing moves only, or facing moves of a single direction.

- Concept D scores 6.93, with particular strengths in unit cost and likelihood of product acceptance, but with weaknesses in the degree of fault tolerance (due to heightened blockage likelihood) and maintainability (due to the complex stock rail arrangement). Concept K eliminates some of these concerns and therefore scores more highly.
- Concept E, the stub switch, scores 6.64. It has particular strengths in space utilisation and adaptability, by allowing multiple routes from a single switch. Alone, the design scores low in the degree of fault tolerance, and the energy requirements of bending and holding full-section rail between positions.

Concepts I, B and H score between the as-is and ultimate evolution benchmarks. This means that with the given requirements weighting matrix they may, or may not , outperform traditional solutions. Concepts A, C, F G score less than the ‘as is’ benchmark. All other concepts evaluated as part of this process (Section 3.4) scored less than concept A (3.65), the lowest scoring concept in Table 3.4.

Concept K is the highest ranking option, with a score significantly higher than the ultimate evolution of traditional designs. It allows a degree of fault tolerance through a redundancy of actuation and locking not possible with traditional designs, and will thus be explored further in this thesis. The proposed function of this concept, alongside modelling of its operation, is described fully in Chapter 4. Development of the concept into a laboratory demonstrator is the subject of Chapter 7.

3.7 Summary and conclusions

This chapter firstly developed a set of functional and non-functional requirements for track switching. The traditional track switching solution is found not to satisfy all requirements, and thus it could be considered unfit for purpose; different designs fail to meet different requirements. Any novel design must meet the functional requirements to be suitable, and exceed the performance of the traditional design in its non-functional properties (desirables) in order to offer a preferable solution. Several novel designs of switch, generated during workshops with an industry panel, were evaluated against the desirable properties using the weighted average decision matrix technique. Several concepts rank highly, though it is noted that for a different weighting of non-functional requirements, a different concept may have ranked first. The highest ranking novel solution for the GB mainline requirements weighting will be described in functional and mechanical detail in the following chapter. It is termed the ‘Repoint’ switching concept.

Chapter 4

The ‘Repoint’ switching concept

4.1 Introduction

Chapter 3 detailed a set of requirements for track switching before identifying a concept based upon interlocking rail ends with a hopping motion on a stub switch arrangement, termed the ‘Repoint’ concept, as highest ranked for further development. This chapter explores this concept in further detail, in two halves. In the first half, the general design is described, including it’s enabling of multi-channel actuation and locking. In the second half, the concept is modelled from first principles to establish that it has feasible, practical characteristics; fundamental formulae governing the design of stub switches are derived. Novel contributions of this chapter are the introduction of the concept of ‘Passive Locking’, a practical solution to engineering multi-channel actuation and locking of railway track switches for the first time; the arrangement to put this into practice, and the first principles modelling of these elements to ensure feasibility. In this chapter, Section 4.2 introduces the new concept for multichannel passive locking, before describing the overall Repoint concept in Section 4.3. In Section 4.4, it is shown how the concepts meet the functional requirements from Chapter 3. In Sections 4.5, the proposed layout and actuators are modelled. Concepts described in this chapter have been extensively published (Bemment et al., 2012a, 2013a,b, 2015a, 2016), and form granted UK patents (GB Patent: Loughborough University, 2013a,b). Further detail is provided in Chapter 7, which explores the design and development of a laboratory scale demonstrator.

4.2 Providing multi-channel locking - 'Passive locking'

Chapters 2 and 3 established the requirement to lock the track elements in place to prevent trains splitting the points. Chapter 5, however, identifies that the locking system is a significant source of unreliability in existing designs. It is relatively simple to provide, for example, multiple actuators or detectors with existing designs. However, the locking requiremen introduces a design choice if providing full multi-channel redundancy; any failed lock may prevent any switch movement, causing an operational failure. There are several design options:

1. Remove the requirement for locking.
2. Provide 'soft locking' through a software, control or 'energised' solution.
3. Provide multi-channel locking, and an arrangement in which each actuator is able to unlock all other channels to allow movement.
4. Provide single channel locking only.

It is unlikely that options 1 or 2 would be acceptable to the regulatory bodies, given the history of locking-related accidents (RAIB, 2011; Rolt, 1982; RSSB, 2005) and the consequent requirement for FPL written into British law (ORR, 2006). Option 4 would significantly restrict the performance improvement available as a single point of failure would still be present (See Chapter 5). Option 3 is not possible with locking designs in existing POE arrangements (Section 2.2.4.5). However, the novel design of actuator described herein - using the hopping actuation motion described in Concept I of Chapter 3 - can allow this.

The passive locking concept follows a lift-move-drop action to move the switch rails between adjacent positions. When the rails are lowered, they sit in grooves which prevent lateral movement at each bearer. When raised, they are free to move laterally. Each actuator unit is therefore capable of unlocking the locking elements of all other actuator units purely by lifting the rails. When the rail is in one of its stationary, lowered positions, it is unable to move in any direction apart from directly upwards. Compared to other axes, there are no significant uplift forces present, and a significant net downward force when the mass of a train is present. This fundamentally differs from all existing designs, which have active mechanisms or linkages specifically to lock the rails. If an actuator unit is isolated, it still provides a positive lock when the rails are lowered - illustrated in Figure 4.2. This principle is novel, and has been termed 'passive locking' as no external mechanism is required to lock the rails - they are locked whenever at rest.

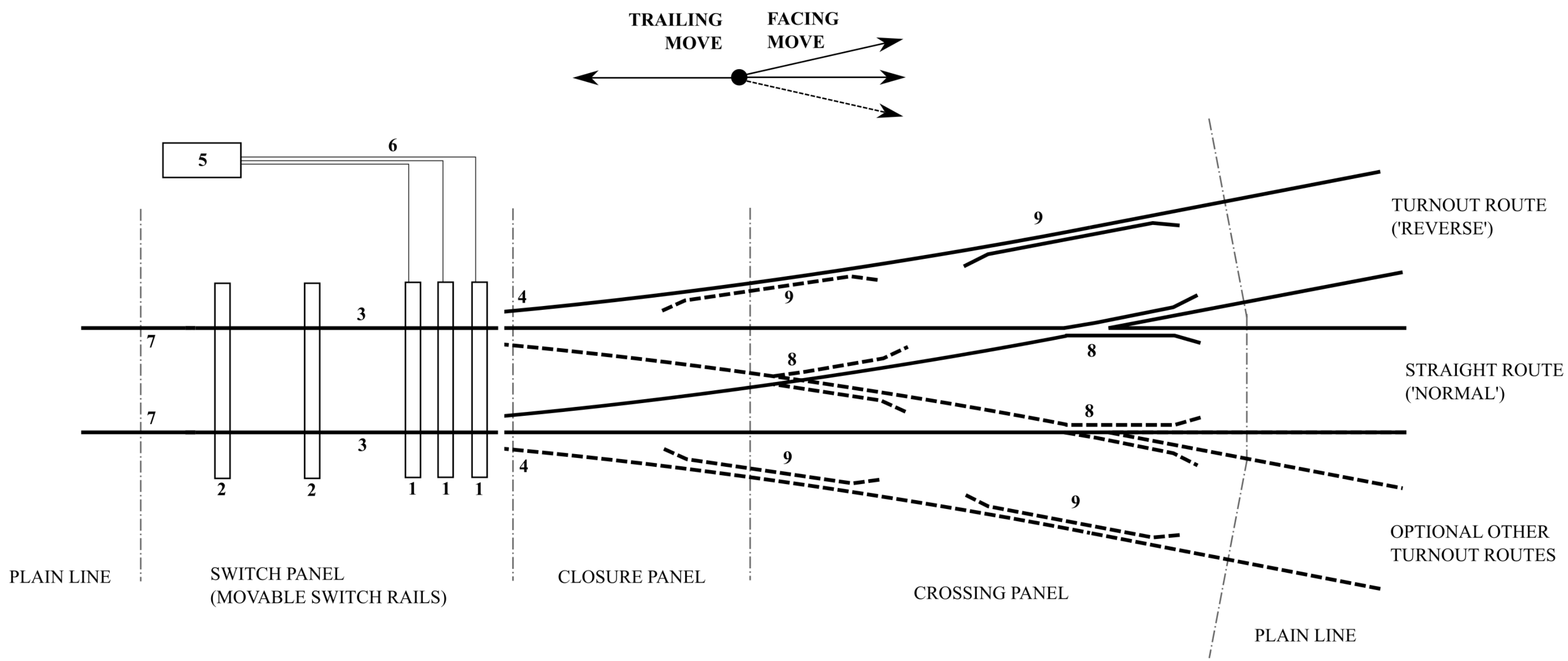


Figure 4.1 Repoint stub switch general arrangement with electro-mechanical in-bearer type actuators, with most sleepers/bearers omitted for clarity. Numbered elements: (1) In-bearer type electo-mechanical actuators featuring integral passive locking elements with detection system; (2) Bearer featuring integral passive locking elements; (3) Bendable, full-section switch rails; (4) Interlocking rail ends; (5) Lineside processing and condition monitoring cabinet; (6) Power, position and monitoring signal cables; (7) Last static point of curve (i.e. location at which rail bending starts); (8) Common crossings (of given angles); (9) Check Rails.

4.3 Design overview

This section makes reference to the numbered elements in Figures 4.1 and 4.2. The design is based around a stub switch arrangement. The stub switch reverses the elements in a traditional switch, replacing long, planed down switch rails in Figures 2.1 and 2.2 with short, stub-ends formed of full section rail, able to move between positions (3). Figure 4.1 shows the general arrangement of a 'Repoint' stub switch, with an optional second turnout route shown. A bank of actuators (1) is responsible for moving the full-section switch rails between each position. The actuators bend the rail from a stationary point (7), beyond which the track is plain line. There is no hinge. To ensure the correct bending profile, it may be necessary to alter the cross section of the rail around the stationary point and an established method such as flange relief could be applied to achieve this. If the rail position requires further lateral restraint between the stationary point (7) and actuator bearers (1), this may be achieved with passive locking bearers (2) which feature the locking elements of Figure 4.2 only.

4.3.1 Actuation and locking

Actuation is provided by a multi-channel actuation bank (1), with actuation elements within bearers near the movable rail ends. 'Actuator-bearers' are each capable of moving the switch independently, giving triplex redundancy. However, the number of actuation channels could be tailored to particular RAMS requirements. The moveable rail is supported upon the actuator-bearers, which transmit the static and dynamic loading from vehicles to the track substructure. These bearers have a movable top surface, a 'shuttle' (15), to which the rails are attached. The lower casing of the actuator-bearer is embedded in ballast or affixed to slab track. Vehicle load is transmitted from the rails, through the shuttle and then locking blocks (16, 17) to the bearer casing, where it is distributed to and through the substructure as normal. When the rails are lifted, they are free to move laterally, but restrained longitudinally. The rail moves in an semi-circular path between adjacent positions. If an actuator is isolated, adjacent unit(s) can still actuate the switch, as the lifting action will unlock the isolated unit. There are many ways to provide drive inside the actuator units, this work proposes utilising a motor (10) and gearbox (11), linked to a rack (12), two cams (13) and followers (14) as per the figure. Ultimately, the actuators would be enclosed in sealed, line-replaceable units. The motor and gearbox arrangement needs to be back-driveable, in order that, if a failure occurs between positions, the mass and spring force of the elevated rail will cause the switch to drop back into one of the safe, lowered and locked positions. The system can be considered 'bistable'.

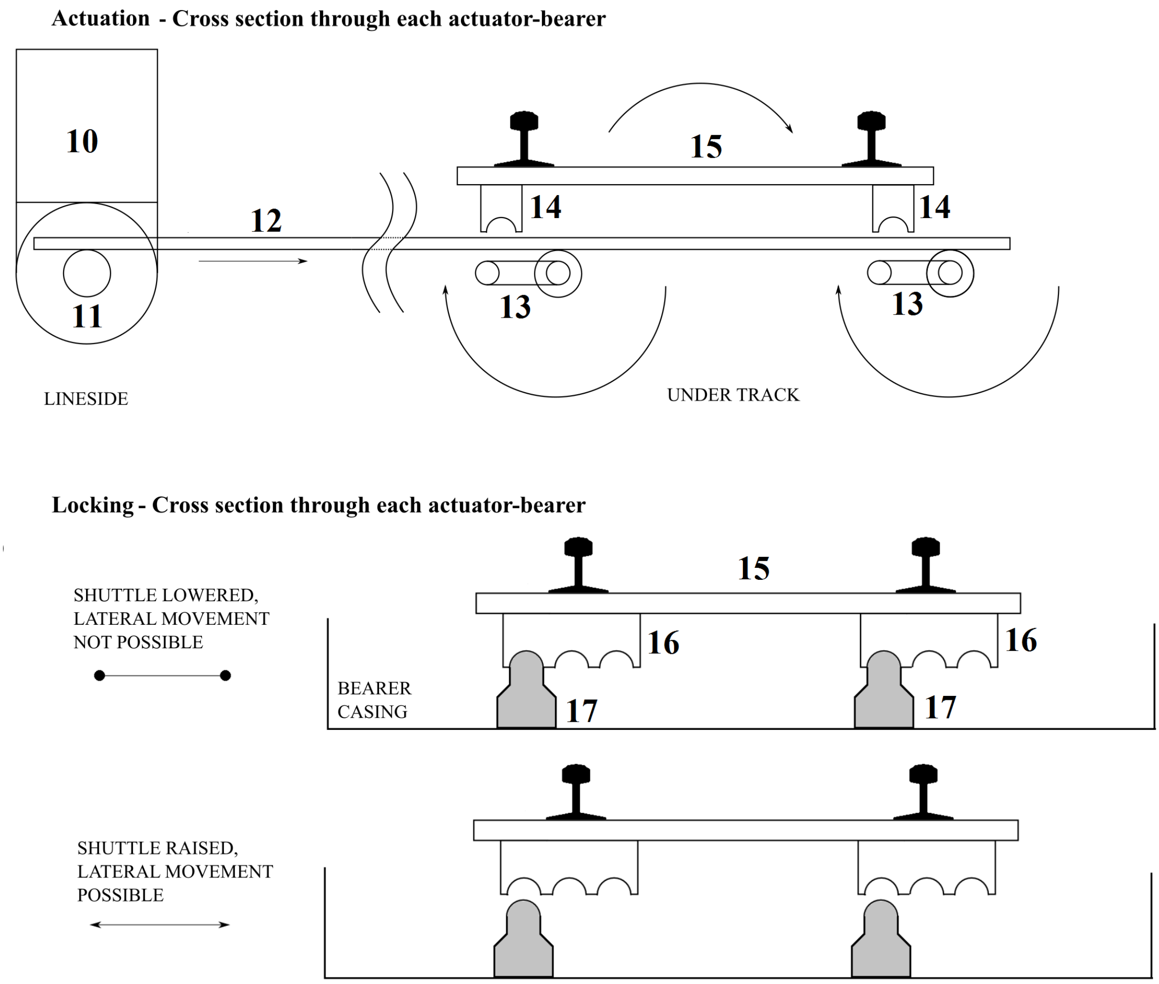


Figure 4.2 Actuation (top) and locking (bottom) elements within each actuator bearer. Numbered elements: (10) Motor; (11) Gearbox; (12) Toothed actuation rod; (13) Cam; (14) Cam follower; (15) Shuttle; (16) Upper locking block; (17) Lower locking block.

4.3.2 Control, detection and condition monitoring

A line-side control cabinet (5) interfaces with the signalling, commanding each actuator bearer when a movement is requested (6). Each bearer transmits back the shuttle (and therefore rail) position, even if the actuation elements are isolated. The line-side controller can then deduce switch position using voting logic as per SSI (Cribbens, 1987) - 2-out-of-3 voting, with 2-out-of-2 fall-back. Detection would need to establish the vertical and lateral rail position; though it may be sufficient to detect vertical position only, given the locking arrangement. The line-side controller is also responsible for condition monitoring in each actuator-bearer. If a fault is suspected, the bearer can be immediately isolated, and the maintenance organisation informed.

4.3.3 Rail ends

The interaction of the moving rail ends with the static rails (4) in the track panel needs to be managed. Stub switches have historically used butt joints. Butt joints are an undesirable solution due to rail-creep, temperature variations and alignment issues. It is unlikely that a butt-joint would provide the support and guidance necessary across the full operating range - i.e. requirement 1 in Table 3.1. A novel rail end solution was therefore required. This solution was in the form of chamfered mating rail ends.

4.3.3.1 Diagonal chamfer mating rail ends

The first version of the chamfered rail ends (Figure 4.3) used a single chamfer in a diagonal plane, such that the movable female element would self-align and self-lock upon the male element when lowered. The fixed half is shaped such that foreign objects would be shed, minimising blockages. The rail end is relatively short and (ideally) standardised such that spares can be held which is different to replacing existing long, planed-down switch rails (Section 2.2.2.1). During development it was noted that excessive rail creep or thermal expansion may lead to a vertical step in the railhead or a gap in the running rails;. It would therefore fail to meet Requirement 1 in Table 3.1.

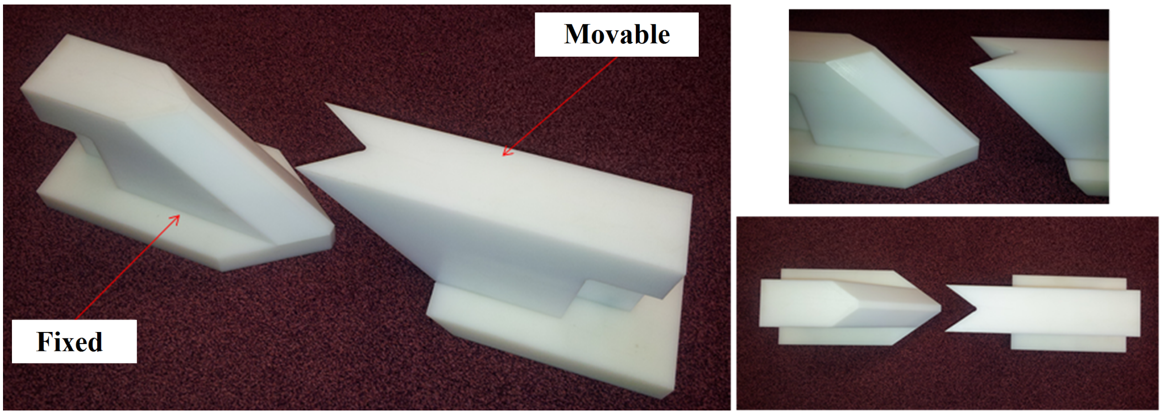


Figure 4.3 Diagonal chamfer mating rail ends - photograph of prototyped mock-up.

4.3.3.2 Double chamfer mating rail ends

This refined design combines chamfers in two planes, as per Figures 4.4 and 4.5. The longitudinal chamfer locks and locates the rails, allowing an amount of expansion or contraction of the switch rails without introducing a vertical step. The chamfer in the vertical plane allows a gradual load transfer from one element to the other as each wheelset passes, as in an expansion switch (British Railways, 1962, 1965). These refinements overcome earlier functional deficiencies in order to meet requirements. It is noted that additional support/strengthening may be required at the rail ends; support conditions and vehicle dynamics are the subject of further study (Sarmiento-Carnevali et al., 2017a). This support could consist of full section rails connected to the bearers outboard of the moveable ends to ensure stability and consistency of deflection under load.

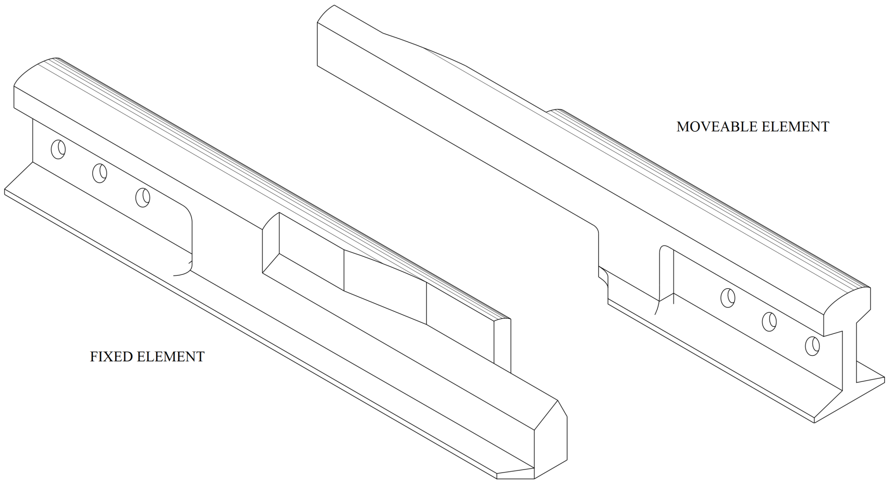


Figure 4.4 Double chamfer interlocking rail ends. Holes are shown for bolted mounting though units could be welded.

Figure 4.5 Double chamfer interlocking rail end mock-ups as fitted to laboratory demonstrator.

4.3.4 Maintenance considerations

With design, redundant systems can continue to function until repair is effected. Conceptually, it is proposed that the functional elements take the form of LRUs (Line Replaceable Units). LRUs, rather than being repaired, maintained or adjusted track-side, can simply be replaced with a known-good unit. The removed unit may subsequently be maintained or repaired in the background. For examples explored in Chapter 5, the LRUs may either be at the subsystem level, or at the POE level, depending upon the redundancy architecture chosen. The maintenance organisation would then have the choice of when to intervene, based upon a target reliability, availability or service pattern (Section 2.4.3.4). This concept has important implications in Section 5.6 in particular, as LRU replacement time becomes an important variable in availability modelling. A value of 2 minutes scheduled unavailability has been suggested as a target for this action; this value was suggested by Network Rail as being a typical service 'firebreak' (Section 2.4.1.5) meaning that maintenance actions could occur without disruption to the timetable.

4.3.5 Other considerations

The novel motion has other potential benefits. In existing switches, slide chairs provide a low-friction surface for the movable switch rails, in addition to providing vertical support for the switch rail vehicle load. However, these plates are exposed to the elements and friction related failures are a significant source of unreliability (Chapter 5). The Repoint actuation path enables the separation of bearing surfaces required for switch movement and vehicle support, meaning the movement bearings can be sealed and properly lubricated. The design also makes stretcher bars obsolete; rail gauge is maintained by standard sleeper tops, plates, and rail clips. Stretchers are a one reason some traditional designs do not meet all functional requirements, (Section 3.3.2) and a significant source of unreliability. The upper locking element can have unique cut-outs for each route through the switch, enabling the track to adopt a differential cant for each route, allowing a higher traffic speed (Section 4.5.2).

4.4 Fulfilling the functional requirements

4.4.1 Systems context diagram and primary use case

Figure 4.6 shows subsystem interactions within the Repoint concept. Compared to those presented in Chapter 3, the locking system is no longer separate; it is passive and part of the Actuation subsystems. The Actuation and Detection systems are multi-channel redundant. Figure 4.7 illustrates the subset of the subsystem interaction diagram which forms the primary use case, that of the signaller operating the switch and receiving feedback of its position; the switch subsequently supporting and guiding vehicles.

4.4.2 Comparison to functional requirements

Referring to the functional requirements (Section 3.2.2), it is postulated that the Repoint solution can meet *all* requirements, exceeding the extent to which existing systems meet requirements, as follows:

1. Adequately support and guide all passing vehicles:
   (a) The solution is constructed of the same rail as surrounding plain line.
   (b) Dynamic loading should be reduced due to the track alignment through the switch being of full-section rails.
   (c) The solution has full-section rail throughout, accurately aligned at each sleeper/bearer, exactly as for plain-line, including cant.
   (d) (1b) means that wear could be reduced. The wear element is now the interchangeable and standardised chamfered rail end, rather than long switch rails. Wear can be managed as the rail ends are replaceable as a short pair.
2. Direct vehicles along the path specified by the interlocking:
   (a) The switch can move to a new route when commanded, however it can always form a route when commanded due to the multiplicity of actuators.
   (b) The concept can switch at an acceptable rate as actuators do not have to be sized to overcome variable friction; energy is stored in the rails, which may be used to assist in the motion for the second half of the throw. (Section 4.5)
   (c) The locking elements of each bearer ensure the switch remains locked on a single route for traffic until commanded otherwise. The switch is not able to move under the mass of a train, as the mass acts downwards and thus further locks the switch. It eradicates the ambiguous failure state between routes.
3. Confirm to the interlocking the route vehicles will be directed along, and that all active elements are safe for the vehicle to pass:
   (a) Limit switches can provide confirmation to the interlocking that each bearer is in a given lowered position, and therefore which route is set.

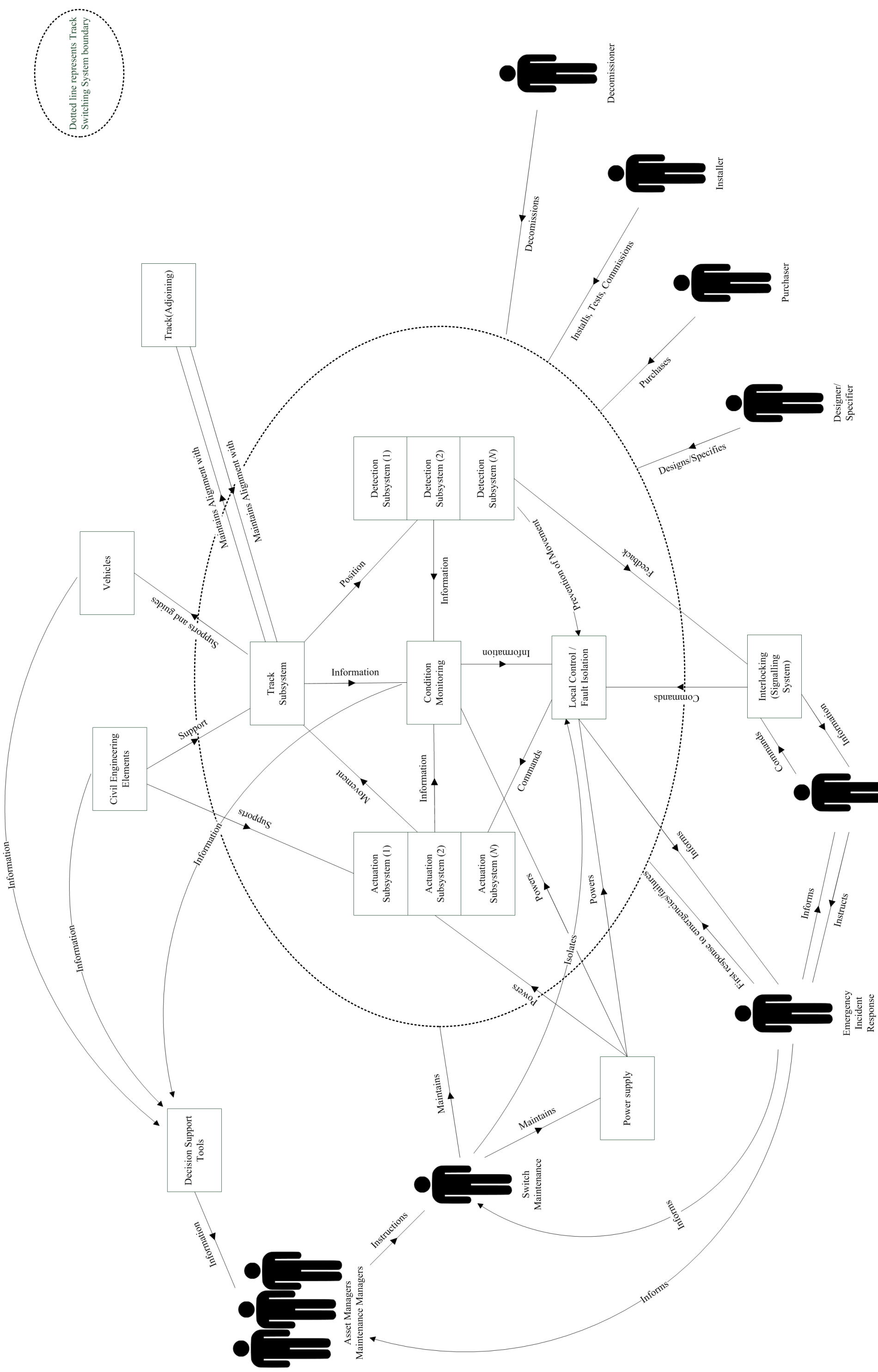


Figure 4.6 Systems context diagram for ‘Repoint’. Note multiple, redundant systems performing the same task internally. Condition monitoring is integral.

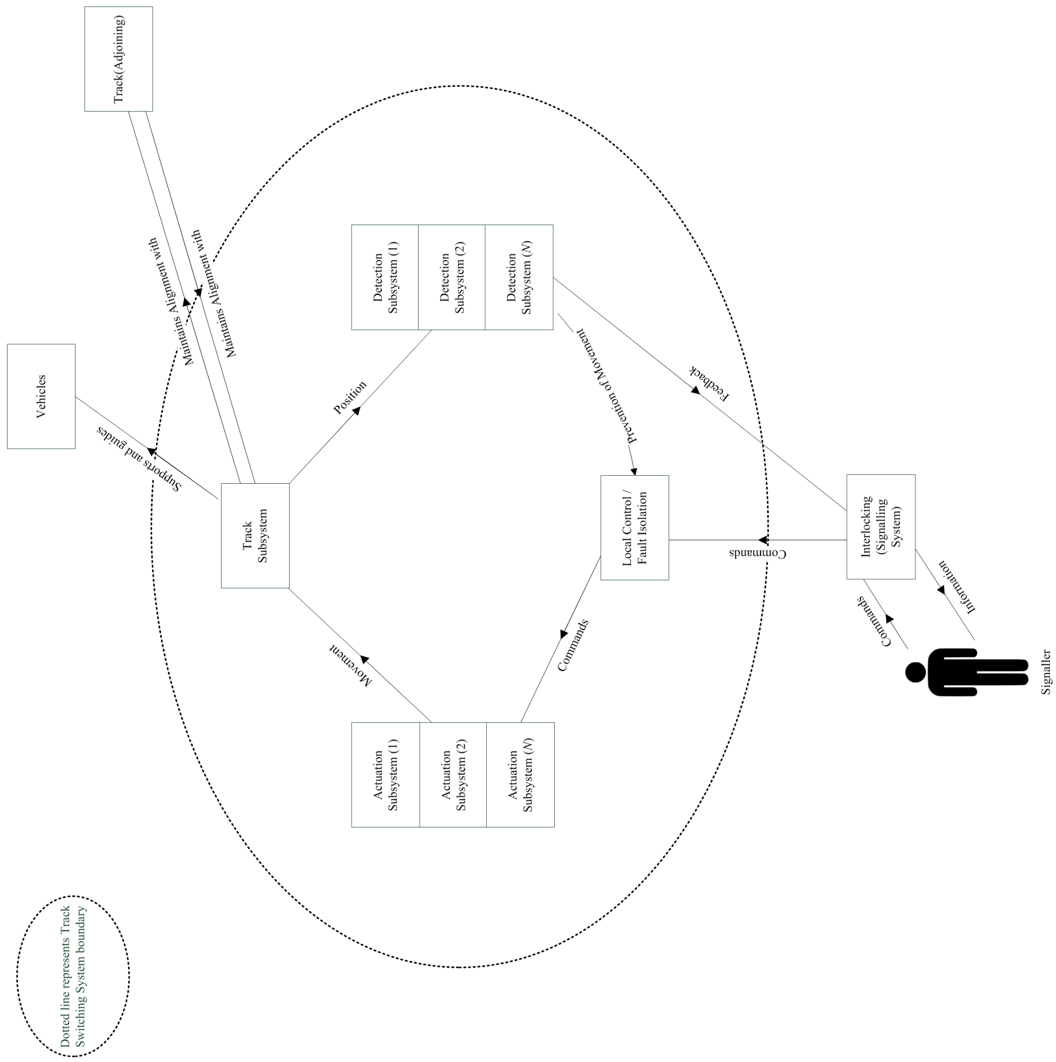


Figure 4.7 Primary use case for ‘Repoint’ system - subsystems directly providing the ability for the primary actor to direct a train and receive confirmation.

   (b) The local condition monitoring processor can determine if there is an issue preventing a route being set through comparing signals, and indicate such to the operator. The incidence of ‘unable to set’ is likely to be reduced due to the parallel-channel actuation and reduced chance of blockages (Chapter 5).

4. Provide information to maintenance organisations regarding the future projected ability to perform requirements (2) and (3):

   (a) Condition monitoring, for the function of the multiply-redundant actuation, could monitor wear. A high false positive rate can be of lesser significance with a multi-channel system, easing the task of condition monitoring (Hecht, 2004).
   (b) Lineside processing could communicate switch prognosis.

(c) As above.
(d) Redundant elements enable a higher level of operational reliability and availability to be achieved.
(e) Redundant channels mean the active elements of the switch are fault tolerant, providing the opportunity for maintenance to be carried out in existing downtime. LRU's mean that maintenance tasks performed track-side are reduced in time.

4.5 Modelling concept feasibility

Before any further development work, it is important to establish the mechanical feasibility of the concept, which is the purpose of the remainder of this chapter. The work herein does not seek to create a fully developed model of the Repoint concept. Its purpose is purely to establish that there are no serious flaws with the concept with regards the areas modelled. Further modelling work, including dynamic simulation and stresses due to traffic, would be required at a later stage in development. Four key factors which may prevent feasibility were identified (numbering corresponds to the research map in Figure 1.3) and are addressed in turn:

1. Static rail shape in the horizontal plane being unsuitable for the passage of traffic.
2. Bending the rails in the vertical plane requiring an actuator size, power consumption or time greater than practicable.
3. Bending the rails in the vertical plane placing too great a stress upon the rails.
4. Long-term longitudinal movement of the free rail being too large to be accommodated by the proposed rail end interface.

It is important to note that whilst these factors view the switch in isolation, clearly the interaction of the switch and vehicle, and behaviour of the switch under the vehicle, is also of prime concern to concept feasibility. Modelling interaction with vehicles was carried out as part of the wider research work (Sarmiento-Carnevali et al., 2017b), but was not wholly the work of the author and is therefore excluded from this thesis.

4.5.1 Modelling rail flexure

Central to establishing (1-3) is the modelling of rail flexure; described in this section. The rail bending model is validated against a switch model created using commercial FEA software.

4.5.1.1 Modelling approach

The modelling of switch rail flexure across all switch types is complicated by many factors. Typically, commercial FEA (Finite Element Analysis) software is used to model a rail as a solid before applying forces to discern relative displacements along the rail length - or vice-versa. Such software includes Nastran, NX and CATIA. However, this necessitates a labour-intensive process of model definition, performing the task at each rail position in the actuation path for the desired granularity, repeated for each switch length and rail cross-section. A basic FEM would also not simulate any of the dynamic effects present in the system – e.g. acceleration of the rail. Another approach is to use MBS (Multi-Body Simulation) software, e.g. SIMPACK. MBS packages can simulate interacting flexible bodies under the influence of external forces. However, model set up times are even longer than FEM, MBS relying upon an FEM mesh. As the goal of this modelling is to rapidly establish forces, shapes and power requirements across a range of design options, a more rapid and easily user-adjustable approach was required; a relatively simple beam bending model was therefore created from first principles using MATLAB.

4.5.1.2 Variable-section rail flexure model

Figure 4.8 shows the nomenclature and co-ordinate system for this section. The MATLAB model is based around an iterative, two-dimensional finite element solver. The solver requires a single proscribed x,z or y,z position, through which the rail, treated as a beam, must pass. The solver then iterates to find the x or y forces which must be applied at a given z position to bring about this rail position. Outputs can be specified, and can include arrays defining the x or y displacement, slope, curvature etc of all beam elements in z. The resolution of the solver and granularity of the elements (dz) in the beam can be user-specified. Rails are described through discrete arrays of element length dz which describe masses, including point masses (e.g shuttles) ($M_e(z)$), second moment of intertia $I_{xx}(z)$, $I_{yy}(z)$, and any other external forces, e.g. back-drives ($F_e(z)$).

The solver assumes small bending angles only (i.e. constant beam span), and has several limitations. Firstly, the beam is not prevented from bending into the negative y direction at any point other than the proscribed x,y,z position, therefore vertical results (y) must be manually checked to ensure beam position is positive throughout; additional 'back-drive' actuators being required if this is not the case. Friction in the interaction of rails and shuttles is not simulated, nor is that upon slide chairs for beam elements remaining at $y=0$; however as the goal is to lift the rail throughout, this is only a limitation when using the model for traditional switches. The solver can be wrapped in a range of scripts, described in each

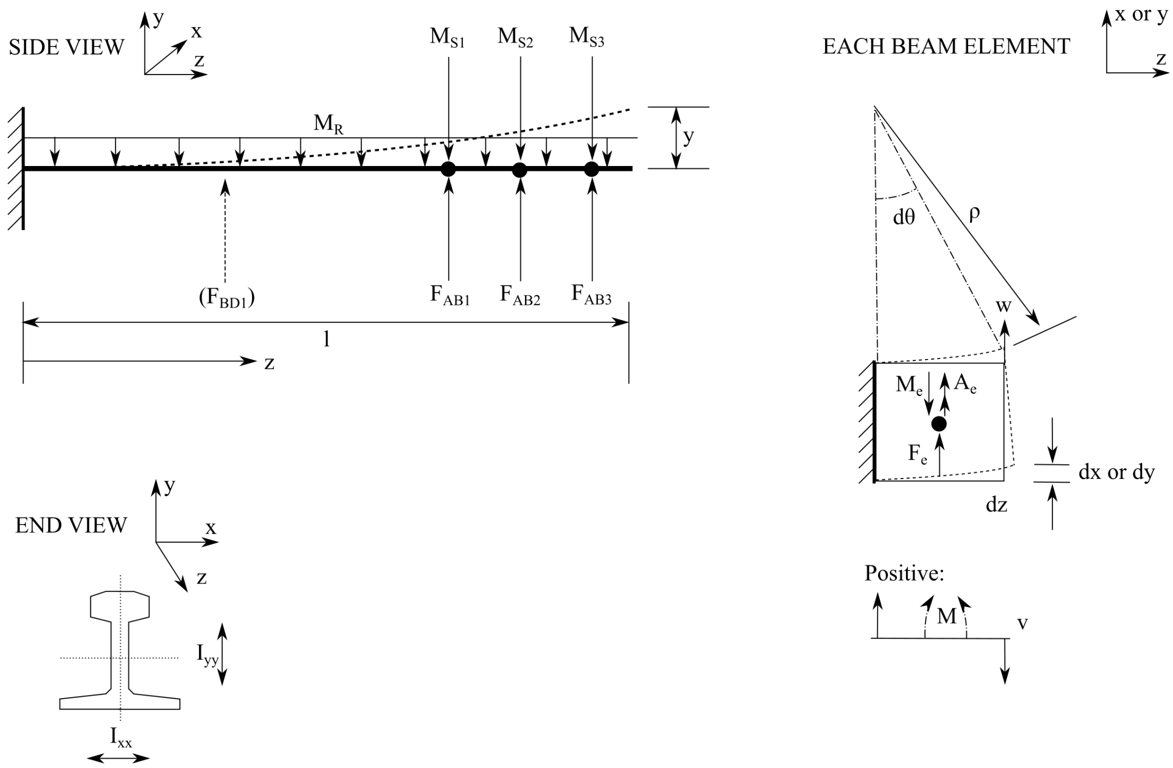


Figure 4.8 Beam bending model - elements and nomenclature.

relevant section below. Further scripts were developed for traditional switch geometries for comparative assessments, but are only used for model validation herein.

$$w(z) = \left(\left(-M_e(z) \times A_e(z)\right) + F_e(z)\right) \times \frac{l}{dz} \tag{4.1}$$

$$v(z) = \int_0^l w(z)dz \tag{4.2}$$

$$M(z) = \int_0^l v(z)dz \tag{4.3}$$

$$\theta_x(z) = \int_0^l \frac{M(z)}{EI_{xx}(z)}dz \tag{4.4}$$

$$\theta_y(z) = \int_0^l \frac{M(z)}{EI_{yy}(z)}dz \tag{4.5}$$

$$x(z) = \int_0^l \theta_x(z)dz \tag{4.6}$$

$$y(z) = \int_0^l \theta_y(z)dz \tag{4.7}$$

The solver makes use of the direct integration method of the Euler beam bending equations (Hibbeler, 2005) using discrete beam elements of a single, fixed cantilever, illustrated in Figure 4.8. The direct integration method takes, for each element, a force w expressed in kN/m, as per equation 4.1. Equation 4.2 integrates w in z, to give the internal shear force present in the beam at a given element, v, in N. The integration constant is the variable force to be calculated to give a target displacement, F. Integrating again in Equation 4.3 gives the internal moment, M; the constant of integration is 0 as there is no externally applied moment. Dividing by beam stiffness, $EI(z)$ and integrating again, as in Equations 4.4 and 4.5 for x and y respectively, gives the angle of rotation of the beam (θ), expressed as a slope (i.e length per length, and therefore unity); the constant of integration is initial slope at $z = 0$:- 0. A final, further integration in Equations 4.6 and 4.7 gives displacement in x or y respectively; the constant of integration is displacement at $z = 0$ and therefore also 0. For variable section rails (e.g. traditional switches), I_{xx} and I_{yy} need to be calculated from beam cross sections, provided in, for example, RE/PW/807 (Section 2.2.2.1), with interpolation along z where necessary. For constant section elements, rail manufacturers provide I_{xx} and I_{yy} values which can simply be doubled to allow for 2 rails.

4.5.1.3 Model validation

Description	Symbol	Value	Unit	Source / notes
Young's modulus, mild steel	E	210×10^9	N/m^2	(Vitaly et al., 2016)
Density, mild steel	ρ	7820	kg/m^3	(Vitaly et al., 2016)
Shuttle Masses	M_{Sx}	0	kg	Assumed 0 to verify rail model in isolation
Cam Radius	r	57.5	mm	Resultant toe opening of 115mm
Switch moveable length	l	8.9	m	RE/PW/807 (CVS Specification)
Rail neutral offset	N	0	mm	i.e. 'Y-switch'
Actuator location in z (F_{AB3})		8.9	m	i.e. actuator at toes
Second moment of inertia (Horizontal)	I_{xx}	Variable	cm^4	Linear interpolation of sections in RE/PW/807
Second moment of inertia (Vertical)	I_{yy}	Variable	cm^4	Linear interpolation of sections in RE/PW/807
Rail Mass	M_R	Variable	kg/m	Linear interpolation of sections in RE/PW/807

Table 4.1 Parameters used in the validation of the variable-section rail flexure model.

The model was validated against a CATIA model produced by an appointed third party with FEA capability (Corbin, 2016), as in Figure 4.9 for static forces and resultant torque for a single actuator force (F_{AB1}). Comparative results are listed in Table 4.2 and illustrated in Figure 4.10.

Results show residual error between the two models is small. Due to the smaller magnitude of forces in x, this translates to a larger percentage error, but the resolution to a torque value negates this with residual torque error between the two models being a maximum of

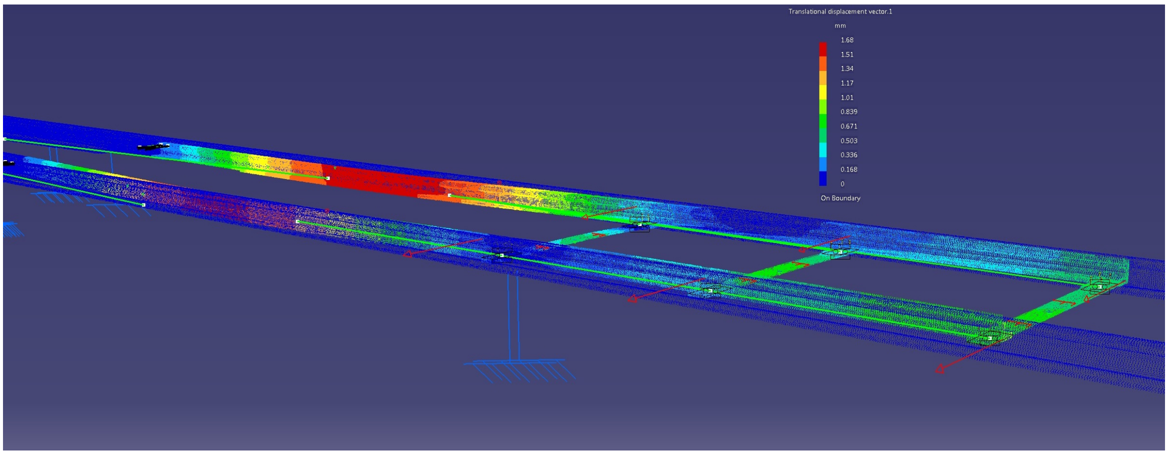


Figure 4.9 Screenshot from CATIA FEA analysis provided by Motion Concepts Ltd. Source: (Corbin, 2016)

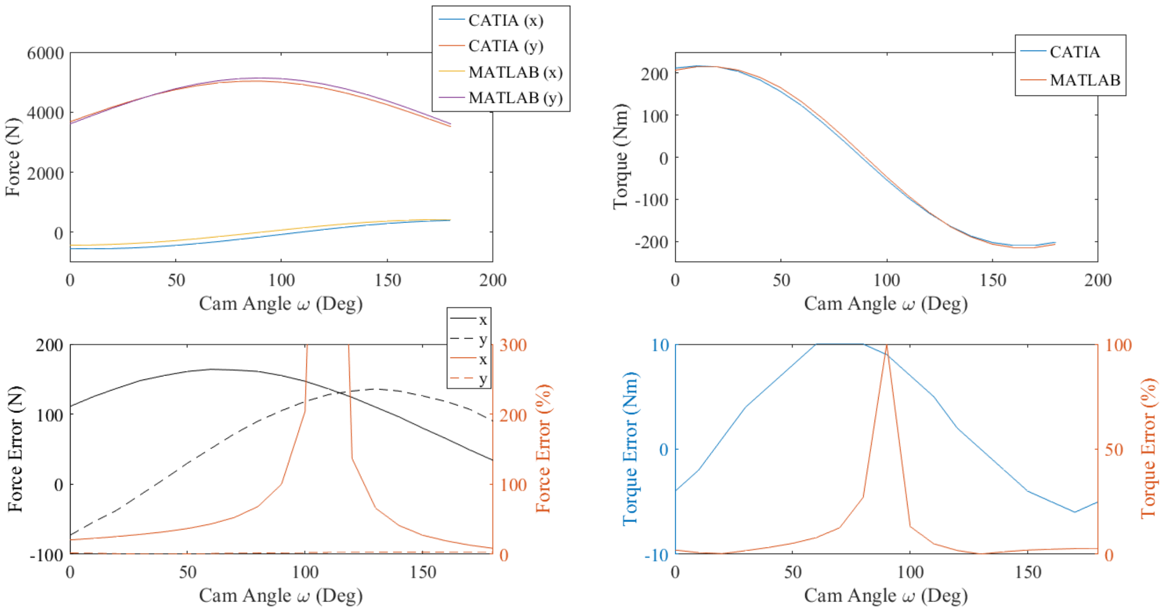


Figure 4.10 Plots of rail flexure model validation data from Table 4.2. Top left: force in x and y; Bottom left: force error in x and y. Top right: torque; Bottom right: torque error.

10Nm on a peak torque of 215Nm. Possible error causes are different meshing methods; CATIA selects a variable element size, and also interpolates on cross section to ascertain an accurate I_{xx} and I_{yy} value, whereas the MATLAB model assumes linear interpolation. Peak error is small with regards to maximum values and proportional error large only at very small force values, which are not the values which will define performance of the switch.

Cam Angle	MATLAB			CATIA			Error (Abs)			Error (Proportional)		
	$F_{AB1}(x)$	$F_{AB1}(y)$	Torque	$F_{AB1}(x)$	$F_{AB1}(y)$	Torque	$F_{AB1}(x)$	$F_{AB1}(y)$	Torque	$F_{AB1}(x)$	$F_{AB1}(y)$	Torque
Deg	N	N	Nm	N	N	Nm	N	N	Nm	%	%	%
0	-431	3607	207	-542	3680	212	111	-73	-4	20.5	2.0	2.0
10	-424	3873	215	-549	3927	217	125	-54	-2	22.7	1.4	0.8
20	-405	4131	215	-542	4168	215	137	-37	1	25.3	0.9	0.3
30	-373	4373	207	-521	4388	204	148	-15	4	28.4	0.3	1.7
40	-330	4592	190	-485	4585	184	155	7	6	32.0	0.2	3.3
50	-277	4781	165	-438	4751	156	161	30	8	36.7	0.6	5.2
60	-215	4934	131	-379	4883	122	164	51	10	43.2	1.1	7.9
70	-147	5047	91	-311	4975	81	163	72	10	52.6	1.5	12.6
80	-75	5117	47	-235	5027	37	161	90	10	68.2	1.8	27.1
90	0	5140	0	-155	5035	-9	155	105	9	100.0	2.1	100
100	75	5117	-47	-72	4999	-54	147	118	7	203.9	2.4	13.2
110	147	5047	-91	11	4919	-96	136	128	5	1239	2.6	5.0
120	215	4934	-131	91	4801	-133	124	133	2	136.7	2.8	1.8
130	277	4781	-165	167	4645	-164	110	136	0	65.8	2.9	0.1
140	330	4592	-190	234	4459	-188	96	133	-2	41.0	3.0	1.2
150	373	4373	-207	293	4247	-203	80	126	-4	27.2	3.0	2.0
160	405	4131	-215	340	4013	-210	65	118	-5	19.1	2.9	2.4
170	424	3873	-215	375	3766	-210	49	107	-6	13.0	2.8	2.7
180	431	3607	-207	397	3517	-202	34	90	-5	8.5	2.6	2.6

Table 4.2 Variable section rail flexure model validation results

4.5.2 Static turnout rail profiles

This section establishes that the running rail geometry for the turnout route is generally comparable to existing turnout geometries. It does not seek to optimise the turnout profile; an entire research field in itself (Section 2.2.3.2). The work in this section corresponds to item 1 in Figure 1.3.

4.5.2.1 Toe offset, cam radius and switch lengths

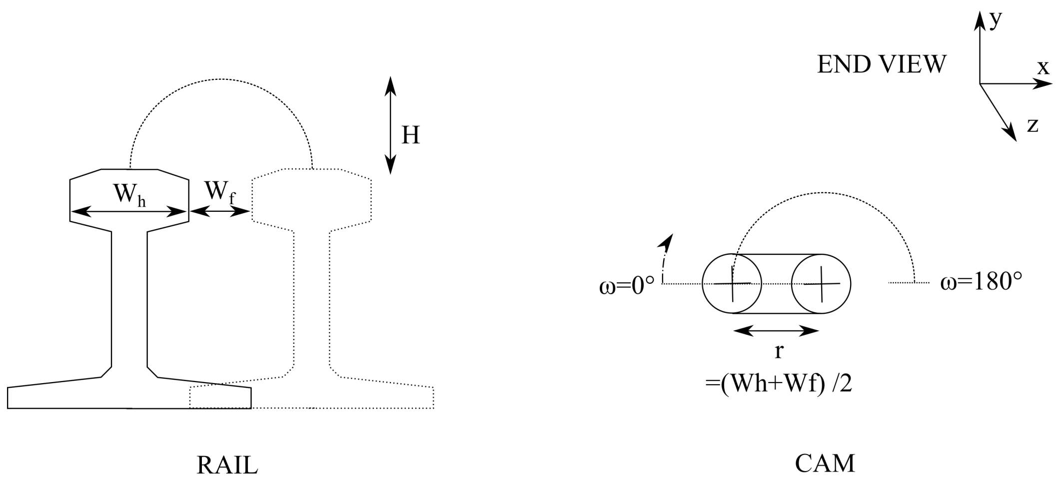


Figure 4.11 Rail end toe offset and cams nomenclature.

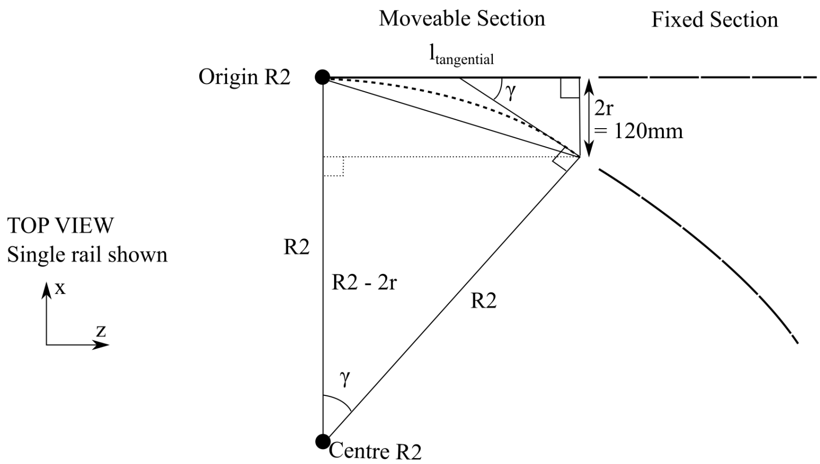


Figure 4.12 Calculation of slope at given offset for a given curve radius. Not to scale.

Figure 4.11 shows the nomenclature of the toe offset and cam radius calculations. As the passive locking concept requires vertical movement at the beginning and end of the stroke, the cam must move the rail through a 180°motion, defining offset as $2r$ (Equation 4.8), and peak rail lift during motion H as r, (Equation 4.9). Assuming a railhead width W_h of 69.85mm (BS113a rail (Steel, 2014)), and a required clear flangeway of W_f as 50mm (as per RE/PW/807), rail end offset is 119.85mm; r is therefore approximated as 60mm.

To establish whether it is possible to flex a full section rail within the approximate envelope of existing designs, the length of rail where the curve intersects with a traditional switch rail at the 120mm offset point, with equal slope γ, needs to be established. Flexure only needs considering to this point. Beyond this, in the fixed section, rails can be positively constrained by sole plates. Analysis is performed for each switch size in RE/PW 807 (B-H), from which the diagram of switch curvature is reproduced in Figure 4.13. In all cases, γ, the slope at the 120mm offset, falls in the 'R2' constant radius section, simplifying calculation of γ and $l_{tangential}$ to trigonometry as in Figure 4.12 and Equations 4.10 and 4.11. In order to calculate the Repoint 'natural' beam length, equations derived from the integrals presented in Equations 4.1 to 4.7 can be used, valid under the assumption of constant section only. Equations 4.12 and 4.13 describe displacement and slope at the beam tip, for a given applied point force P at that tip. These can be combined, the force terms cancelling out, to give Equation 4.14, which expresses the natural beam length $l_{repoint}$ in terms of cam radius r and desired intersection slope γ. Results are presented in Table 4.3, and the relative lengths of the different designs in Figure 4.14.

Switch	Design Speed		Switch Radii		120mm offset:			Moveable Length		
			R1	R2	γ	γ	$l_{tangential}$	NR V	NR I	$l_{repoint}$
	mph	m/s	m	m	°	m per m	m	m	m	m
B	20	8.94	230.725	184.012	2.069	0.0361	6.644	7.480	n/a [1]	4.982
C	25	11.18	287.251	245.767	1.791	0.0313	7.679	8.900	10.580	5.758
D	30	13.41	367.038	331.687	1.541	0.0269	8.921	9.610	11.230	6.690
E	40	17.88	739.696	645.116	1.105	0.0193	12.442	12.480	14.480	9.331
F	50	22.35	1137.067	980.92	0.896	0.0156	15.343	13.900	17.080	11.507
SG	60	26.82	1398.518	1263.74	0.790	0.0138	17.415	16.740	20.330	13.061
G	70	31.29	1826.293	1650.38	0.691	0.0121	19.902	19.580	22.280	14.926
H	90	40.23	3000.716	3000.716	0.512	0.0089	26.836	25.545	30.080	20.126

Table 4.3 Comparison of existing and Repoint 'Natural' switch rail lengths. [1] 'B' switch deprecated for NR Inclined series switches.

$$2r = W_h + W_f \tag{4.8}$$

$$r = \frac{W_h + W_f}{2} \tag{4.9}$$

$$L_{tangential} = \sqrt{R^2 - (R - 2r)^2} \tag{4.10}$$

$$\gamma = Cos^{-1}\left(\frac{R - 2r}{R}\right) \tag{4.11}$$

$$2r = \frac{Pl_{repoint}^3}{3EI_{xx}} \tag{4.12}$$

$$\gamma = \frac{Pl_{repoint}^2}{2EI_{xx}} \tag{4.13}$$

$$l_{repoint} = \frac{3r}{\gamma} \tag{4.14}$$

It can be seen from Table 4.3 and Figure 4.14 that in each case, the Repoint natural flexing length is shorter than the equivalent NR-V or NR-I design, indicating the approach is feasible from a moveable length perspective. However, it is also important to establish that the deviation of the switch rails from the 'ideal' curve required by traffic is acceptable.

4.5.2.2 Stub rail profile vs traditional switches

This section compares typical deviations from 'perfect' shown by traditional switches and potential stub layouts to establish that the stub approach is within reasonable bounds. Section 2.2.3.2 established that geometry through traditional switches is compromised. For tangential switches, geometry is illustrated in Figure 4.13, which shows a disjointed switch

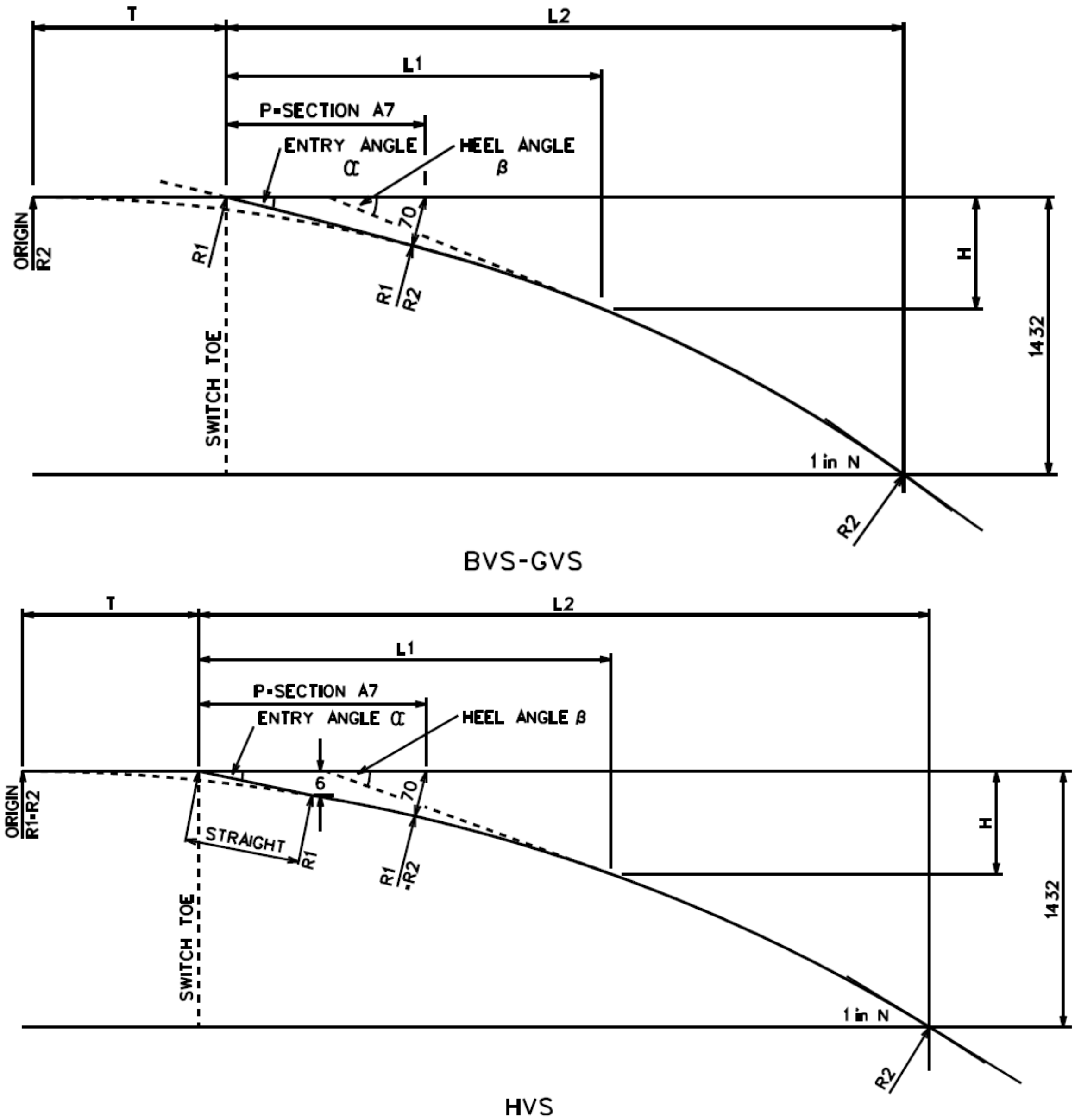


Figure 4.13 Tangential switch geometry for BVS-GVS (top) and HVS (bottom) switch designs. Not to scale. Reproduced from RE/PW/807 (Network Rail).

entry angle α. Despite known negative effects of this disjoint upon vehicle dynamics, it is accepted to enable manufacture. Tangential geometry in NR-V series switches is defined by several abutted radii ($R1$, $R2$), presented in Table 4.3. NR-I series switches use an approximated transition curve on switch entry, necessitating longer switch rails, but still apply 'switch toe tangent' for manufacturing reasons. In a stub switch, there can be no entry angle; flexing full-section rails does not allow instantaneous changes in curvature or slope, leading to deviations from both the curvature of traditional switches and 'ideal' plain-line curves.

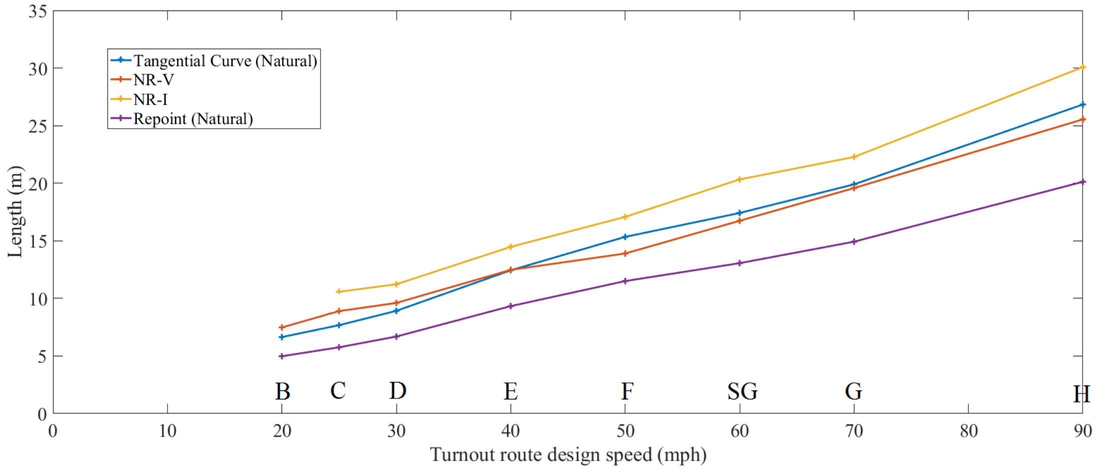


Figure 4.14 Moveable rail lengths vs switch design speed for NR-V and NR-I switches; including tangential natural length and Repoint natural length for $r = 60mm$, from Table 4.3.

The variable section bending model was used with full section rail of lengths specified in Table 4.3. The required outputs were displacement and slope at peak bend in x, and tip displacement of 120mm. These profiles were then plotted with the 'ideal' and as-designed NR-V tangential switches. The output of this comparison, for B, F and H switches only (for space reasons), is shown in Figure 4.15. Figures 4.16 and 4.17 illustrate relative error from the perfect curve for displacement and slope for all GB switch sizes.

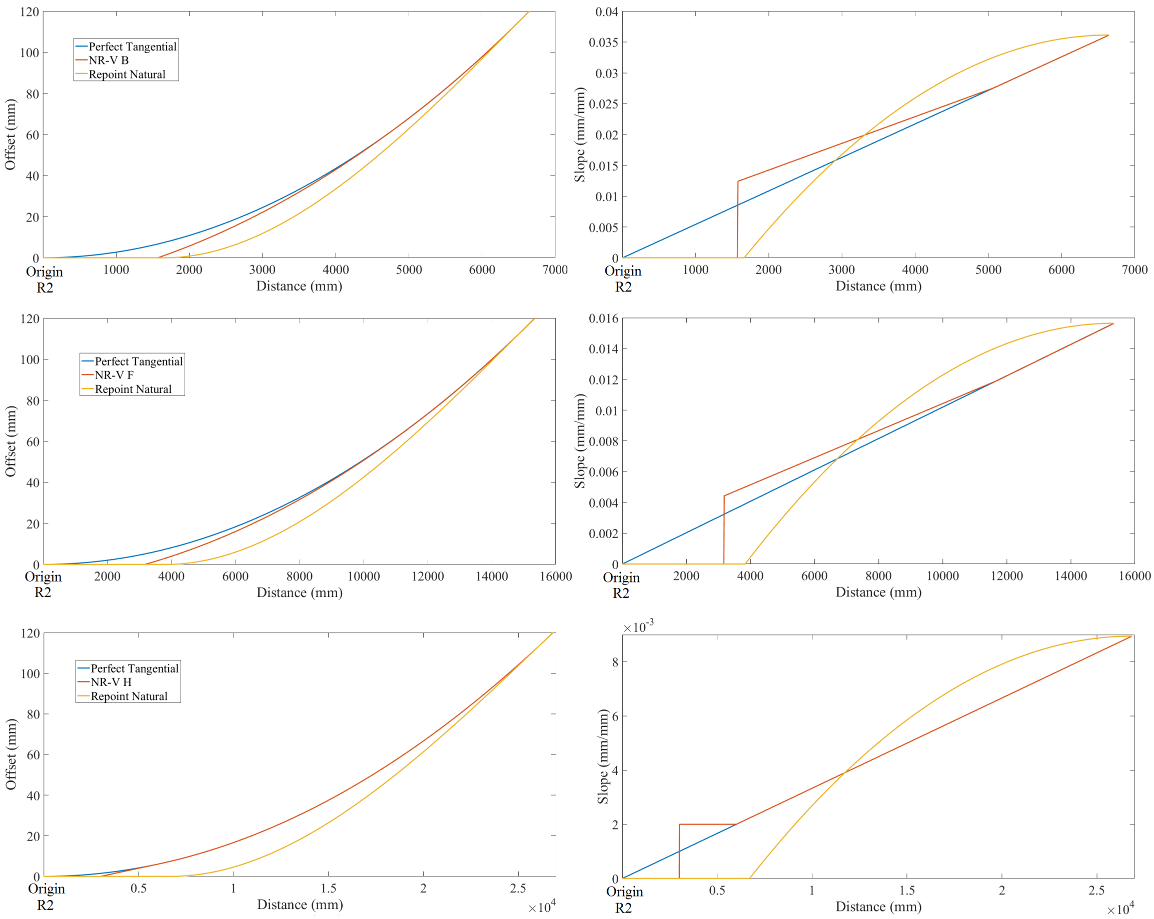


Figure 4.15 Offset and slope of perfect tangential, NR-V and Repoint 'natural' stub switch layouts for B (20mph), F (50mph) and H (90mph) switches.

4.5.2.3 Analysis

- It can be observed from Figure 4.15 that the natural curves obviate the need for a defined switch entry angle, providing smoother entry. However, there is instead an instantaneous change in curvature (rate of change of slope) at the root of the flexible beam, to a curve with smaller radius, this curvature reducing to infinite radius at the tip. This change is the opposite to an ideal entry transition curve, where radius reduces with distance from entry.
- Whilst removal of the entry angle may improve ride dynamics at that point, the effects of the curve remain unknown as is is not a geometry currently found on the infrastructure. Whilst ride quality is strongly influenced by jerk, there are many other contributory variables in the wheel rail interface which would need significant further modelling to understand. Further analysis is therefore necessary.

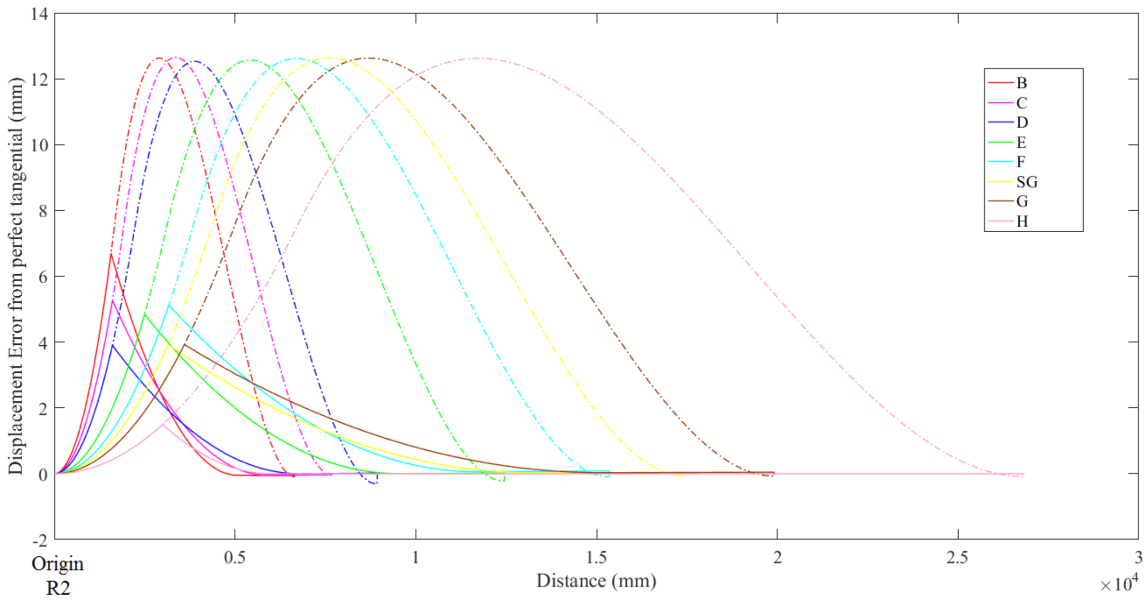


Figure 4.16 Displacement error vs length for NR-V (Solid) and Repoint (Dot-dash) natural switches from B-H sizes. Error is considered linear offset difference from 'perfect tangential curve'.

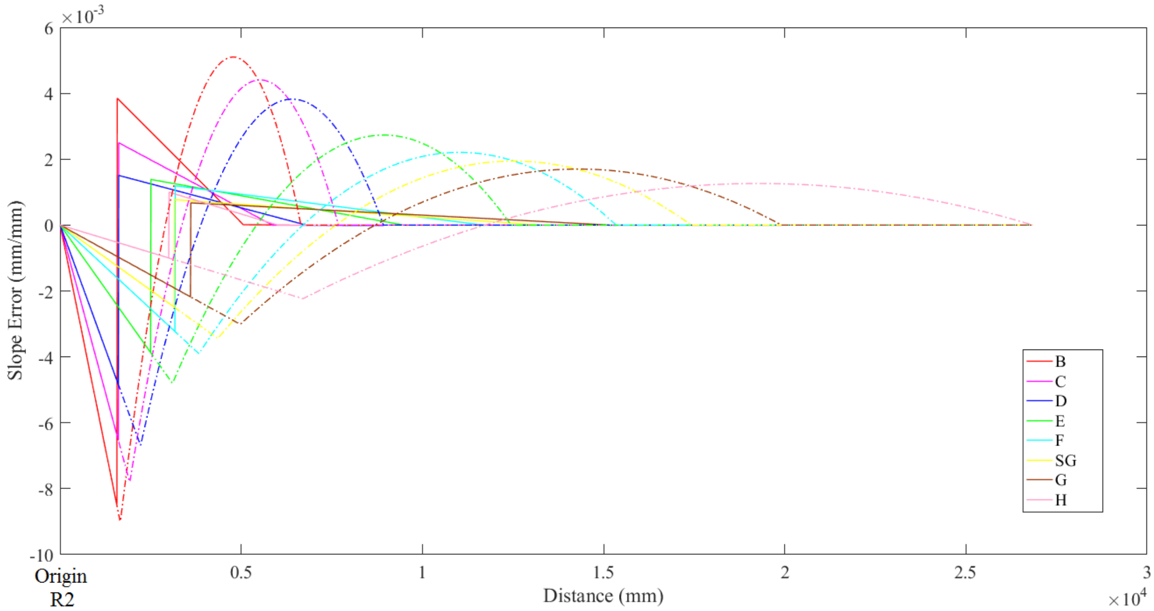


Figure 4.17 Slope error vs length for NR-V (Solid) and Repoint (Dot-dash) natural switches from B-H sizes.

- It should be noted that this 'reverse transition' curve may be more suited to some situations; often switches turn onto straight track, the natural curve in this instance providing an approximated curve exit transition.
- A pattern emerges in the displacement error in Figure 4.16 in that Repoint error is limited in all cases to around 12mm. NR-V error reaches a peak of around 6.7mm in the 'B' switch, and smaller for increasing switch size, Repoint 'natural' error is therefore twice traditional; though this in itself is not significant as dynamics are governed by a number of factors including rate of change of cant deficiency and lateral acceleration.
- Repoint slope error is of the same magnitude as traditional throughout, though there is a greater spread of error in positive/negative which may have a detrimental effect.
- From a feasibility perspective, this analysis shows that deviations when bending full-section rail stubs are within reasonable approximation of traditional switches. Some unknowns remain regarding particular rail geometries. If future analysis reveals that the profile of the turnout route needs to be modified, this could be achieved by stiffening (i.e. adding material or an alternate rail profile) or encouraging bending (e.g. flange relief) in key locations. The variable section rail bending model described in Section 4.5.1 is ideal for rapidly iterating designs in future work.

4.5.2.4 Increased traffic speeds

One conclusion from the geometry study above is that a shorter natural curve, removal of the switch entry angle and the ability to apply cant throughout the turnout may allow traffic speeds to be increased. This was later confirmed by a third party report, commissioned to examine geometry in Repoint switches compared with traditional (Foan, 2014), quantifications from which are replicated in Table 4.4. This forms an important input to the capacity modelling exercise in Chapter 6. Further modelling work on ride dynamics, based upon (Foan, 2014), is the subject of later collaborative publication (Sarmiento-Carnevali et al., 2017b).

4.5.3 Actuation time and energy use requirements

This section explores the actuation time and energy use of the Repoint switch. Switch sizes from previous sections will be used with the moveable length assumed as the natural length (Table 4.3). The energy use is defined as that required by the moveable elements, with the actuator-bearer treated as a 'black box'.

Size	Traditional design		Repoint (clothoidal)		Improvement
	mph	m/s	mph	m/s	%
B	20.00	8.89	25.86	11.50	29.3
C	25.00	11.11	29.89	13.29	19.6
D	30.00	13.33	34.72	15.43	15.7
E	40.00	17.78	48.43	21.52	21.1
F	50.00	22.22	59.72	26.54	19.4
SG	60.00	26.67	67.78	30.12	13.0
G	70.00	31.11	77.46	34.43	10.7
H	90.00	40.00	104.44	46.42	16.0

Table 4.4 Increased turnout road speeds through use of clothoidal transitions and cant through stub layouts, compared to range of standard switch sizes, excerpt from (Foan, 2014).

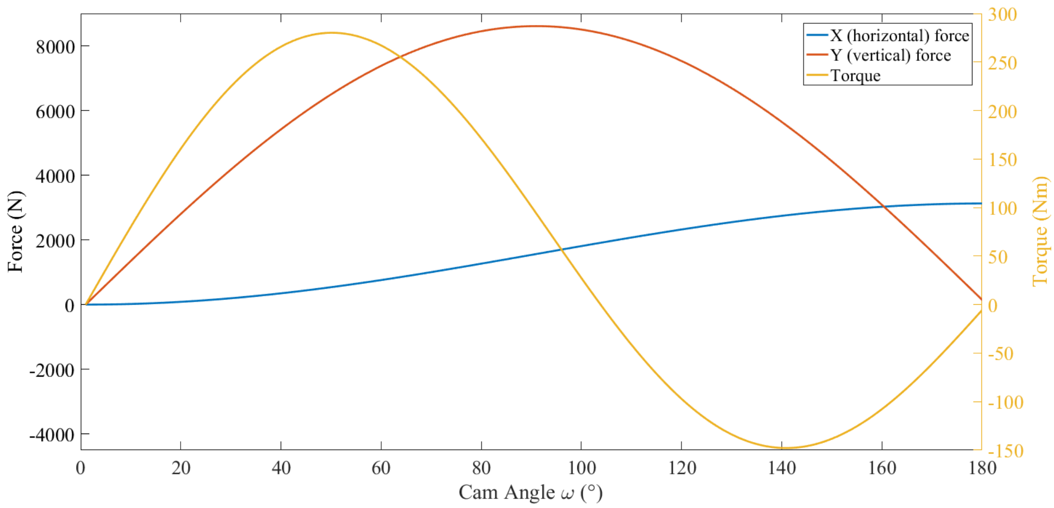


Figure 4.18 Equilibrium horizontal and vertical forces, resolved to a torque, for a Repoint stub C-switch natural length, with single actuator at tip of moveable length.

Figure 4.18, generated from the MATLAB model, shows equilibrium forces in x and y, resolved to cam torque (Figure 4.11), for a Repoint C-Switch. Forces vary linearly with beam displacement in x and y, as expected. When resolved to a torque upon the actuator cam, two distinct phases occur. In the first phase, the torque required is positive, indicating a net energy input to the system, as energy is being stored in the rail as gravitational potential energy and as spring energy. For the second phase, torque becomes negative, as the stored energy is released. When the cam is at, or near, top-dead-centre, there is comparatively little torque required, and a point where all forces in the system balance at around 105°. This has several implications:

- Energy input required for actuation is concentrated in the first half of the stroke.
- In the second phase, there is an opportunity for regenerative braking to recover energy. The actuator may be required to function as a brake so as to prevent heavy impacts. This means an element of active control is necessary.
- Assuming regenerative braking, net energy use for a single operation is small, and recoverable from the opposing swing (by also recovering the stored horizontal spring energy over an N-R R-N cycle).
- The above is also true of traditional switches under a zero friction assumption. However, in the Repoint case, friction is managed in sealed bearings in the mechanism, specified for the motion, rather than on open-to-elements slide chairs.
- Peak torque in Figure 4.18 is not indicative of peak or mean power - this plot does not account for dynamic load. The opportunity exists to optimise the power profile to remove potential peaks - but in order to establish feasibility, it is instead important to calculate mean power.
- When establishing mean power, the two phases of the motion need to be considered in isolation.

4.5.3.1 Energy transfers during switch actuation

Total energy transferred in each phase can be calculated using knowledge of the beam shape and classic mechanics formulae. Considering the flexing switch rail as a closed system, in the first phase, there are three energy transfers (Equation 4.15):

- *GPE (Gravitational potential energy)*:- Energy is required to lift the mass of the rails, shuttles and fixings to top-dead-centre.
- *EPE (Elastic potential energy)*:- Energy is input to bend the rail in the vertical. If the switch is moving from straight to turnout, then energy is also required to bend the rail in the horizontal. Otherwise, energy is released from the straightening horizontal.
- *KE (Kinetic energy)*:- Energy is required to accelerate the switch rails to a velocity at which they are able to complete the move in the specified time.

And in the second phase:

- *GPE*:- Energy is released from the falling mass of rails, shuttles and fixings.
- *EPE*:- Energy is released from the bend in the vertical. If the switch is moving from straight to turnout, energy is required to bend the rail in the horizontal. Otherwise, energy is released from the straightening horizontal.

- *KE*:- Energy is released in decelerating the switch rails to a stop - ideally a dead stop at opposite register to prevent damage[2].

$$E_{total} = GPE + EPE + KE \tag{4.15}$$

$$GPE = mgh \tag{4.16}$$

$$k = \frac{F}{x} \tag{4.17}$$

$$EPE = \frac{kx^2}{2} \tag{4.18}$$

$$KE = \frac{mv^2}{2} \tag{4.19}$$

$$v = \frac{2\pi \times 0.0586}{t} \tag{4.20}$$

GPE Energy required to raise a mass m to given height h is given in Equation 4.16, where g is acceleration due to gravity (9.81m/s^2). As this is a linear relationship, and the rail follows a curved profile, mean rail height can be used. Vertical beam profile is an output provided by the beam flexure model which indicates mean lift is 0.0226m for a B switch; this figure will be assumed throughout to remove complications from longer back-driven switches. Additional masses needs to be added to allow for the shuttle elements.

EPE Energy stored in a spring is a function of spring constant k, which can be calculated from force and displacement as in Equation 4.17; the spring constant is unique to each beam length. Force and displacement are obtained from the MATLAB model in both x and y. Equation 4.18 defines the energy required to bend a spring of given spring constant k a given distance x. In this instance the figures used for k and x are tip flexure, though equivalents could be taken from any point on the beam length.

KE Energy required to accelerate/decelerate a mass m to/from a given speed v is given in Equation 4.19. To estimate beam velocity, it is assumed that for the first phase, the beam is linearly accelerated to peak angular velocity at top-dead-centre, (where velocity is entirely in x), and linearly decelerated to a stop in the second phase. Peak velocity for each point on the length of the beam is therefore twice mean velocity. Though mean lift is 0.0226m, due to the squared term in the KE function an RMS value of beam shape must instead be used, obtained from the MATLAB model as 0.0586m, giving mean beam travel over the 180 °arc

Switch	Length	Mass	Peak forces		Spring Constants		First Phase						Second Phase					
	l	m	F_x	F_y	k_x	k_y	EPE_x	EPE_y	GPE	KE	Total	Power	EPE_x	EPE_y	GPE	KE	Total	Power
	m	kg	N	N	N/m	N/m	J	J	J	J	J	w	J	J	J	J	J	w
B	4.982	558.0	4886	13449	40718	224157	73.3	403.5	256.1	0.6	733.5	489.0	73.3	-403.5	-256.1	-0.6	-586.9	-391.3
C	5.758	644.9	3128	8609	26064	143488	46.9	258.3	275.4	0.7	581.3	387.5	46.9	-258.3	-275.4	-0.7	-487.4	-325.0
D	6.690	749.3	2028	5581	16897	93020	30.4	167.4	298.6	0.7	497.1	331.4	30.4	-167.4	-298.6	-0.7	-436.3	-290.9
E	9.331	1045.1	757	2084	6310	34738	11.4	62.5	364.1	1.0	439.0	292.7	11.4	-62.5	-364.1	-1.0	-416.3	-277.5
F	11.507	1288.8	400	1102	3335	18361	6.0	33.0	418.2	1.2	458.4	305.6	6.0	-33.0	-418.2	-1.2	-446.4	-297.6
SG	13.061	1462.8	273	752	2276	12532	4.1	22.6	456.8	1.3	484.7	323.1	4.1	-22.6	-456.8	-1.3	-476.5	-317.7
G	14.926	1671.7	184	506	1533	8437	2.8	15.2	503.1	1.4	522.5	348.3	2.8	-15.2	-503.1	-1.4	-516.9	-344.6
H	20.126	2254.1	75	206	624	3435	1.1	6.2	632.2	1.9	641.4	427.6	1.1	-6.2	-632.2	-1.9	-639.1	-426.1

Table 4.5 Energy transfers in 3 second Repoint actuation by switch length, from straight to curved route. Results include 75kg allowance per shuttle. Positive energy transfer indicates work done on the switch.

Switch	B	C	D	E	F	SG	G	H
Actuation Time, t (s)	0.404	0.341	0.312	0.304	0.322	0.339	0.361	0.427

Table 4.6 Minimum Repoint actuation times for a 1000W power supply.

as 0.184m, and peak speed at top-dead centre defined by Equation 4.20 (where t is switch actuation time).

4.5.3.2 Concept feasibility results

Selected results from calculations are presented in Table 4.5 and Figure 4.19, which assume a 3 second switch actuation time. Power available track-side is established in Section 2.4.2 as 1000W continuous (Network Rail, 2006; Simmons, 2001). In shorter switches, EPE is the dominant contributor, whereas in longer designs GPE becomes dominant. KE has a negligible influence throughout due to the relatively low velocity. The highest power requirement in the range is the B-size switch, at 489W, falling to just 293W for the E-size. It can be observed in all cases that mean power is below the typical amount provided trackside. All switch lengths are therefore deemed feasible at a comparable switching time as existing, using existing power supplies, even allowing for losses of up to 50%.

4.5.3.3 Improved switching time

Sections 2.4.1.5 and 2.4.2 identify the time taken to actuate the switch as a key contributor to capacity loss at junctions. Section 4.5.3.1 identifies an opportunity to provide regeneration in the second part of the motion. With regeneration, it is surmised that a line-side energy store could provide for the first phase of actuation, to be partially replenished by the negative transfer in the second. In this case, mean power use becomes the energy lost by the system in a full actuation cycle. To estimate losses, knowledge of the particular actuator

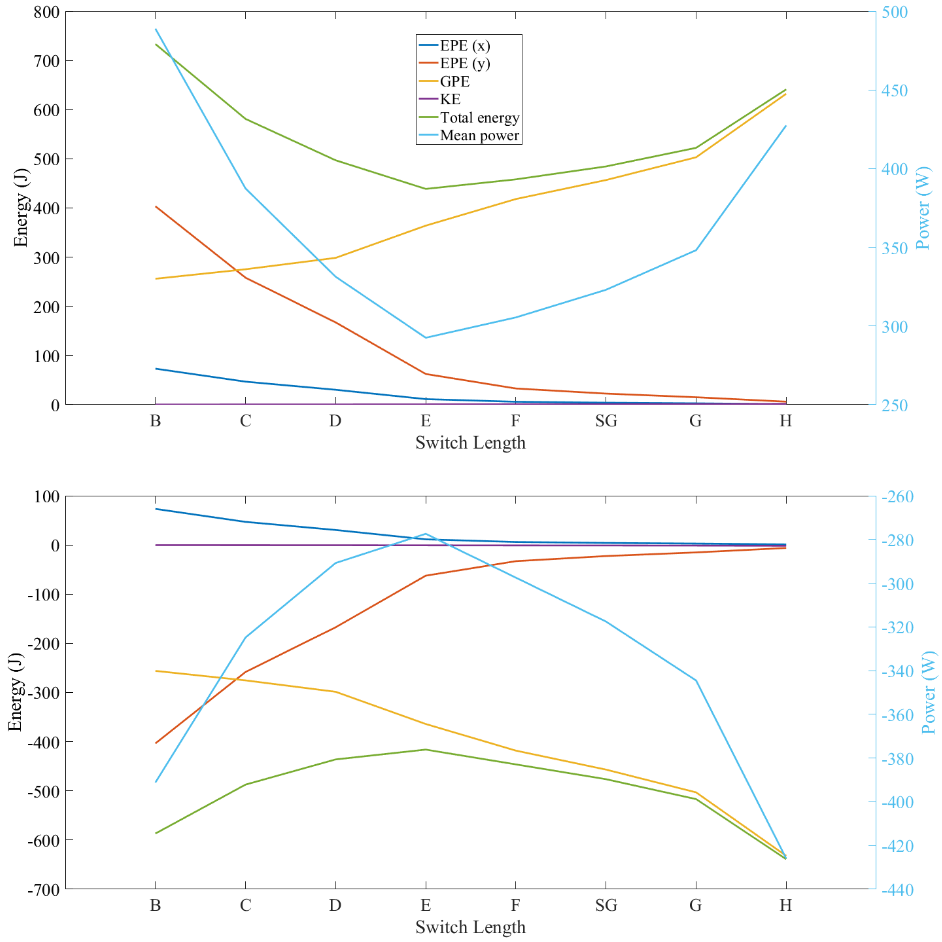


Figure 4.19 Energy transfers in 3 second Repoint actuation by switch length, from straight to curved route, from results in Table 4.5. Top: First (rising) phase. Bottom: Second (falling) phase.

and transmission efficiency is required; the transmission efficieny from the Repoint laboratory demonstrator (Section 7.4.4) will be used as a basis for this, approximated here as 0.75. Figure 4.20 is a contour plot of external power requirement for each switch length and switching time. At much reduced actuation times (i.e. under 0.5s), KE quickly becomes the dominant and limiting factor due to the v^2 term. Table 4.6 indicates actuation time achievable assuming a 1000W supply limit (Network Rail, 2006; Simmons, 2001). These figures do not consider whether an actuator/transmission to provide such an energy transfer is a practical proposition; actuator sizing is explored in Chapter 7. Table 4.6 forms an important input to capacity calculations in Chapter 6.

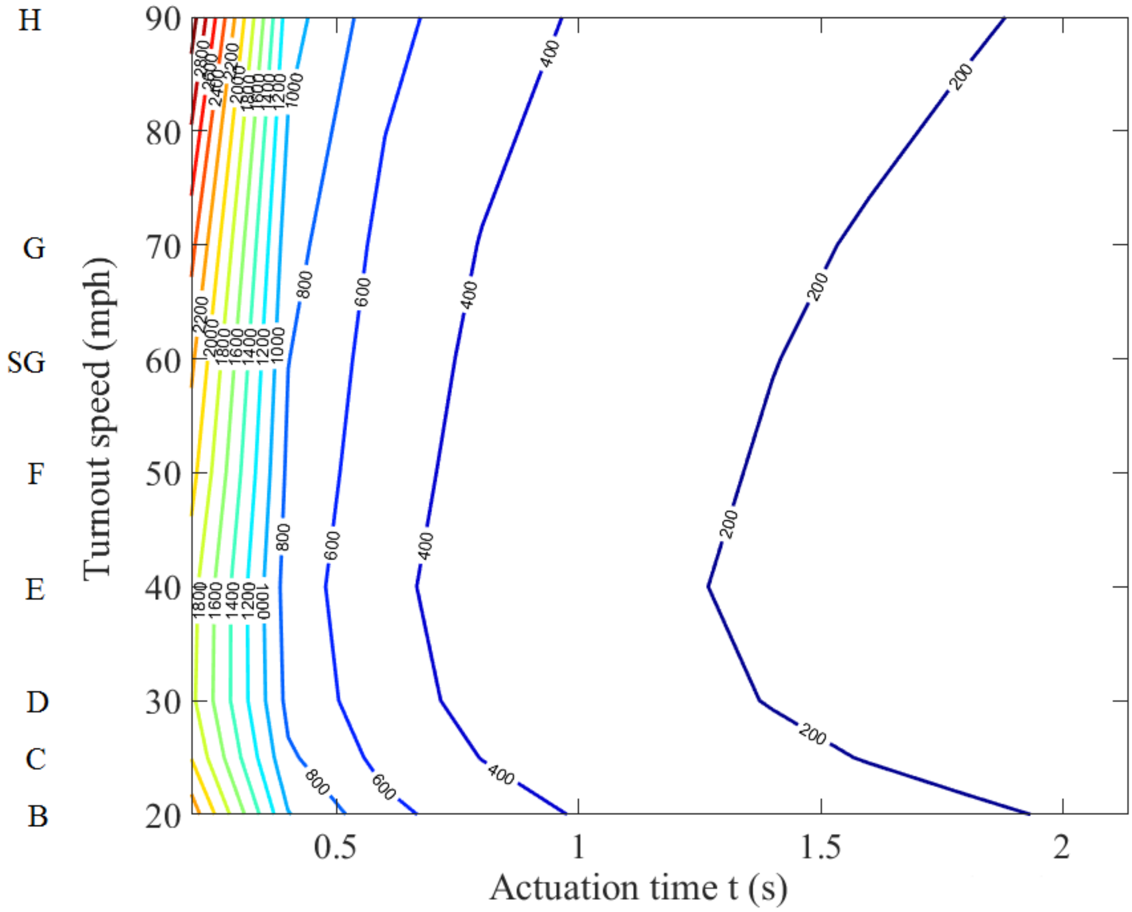


Figure 4.20 Contour plot showing power input required (Watts) for a given actuation time upon a given turnout route speed.

4.5.4 Stress and fatigue in rails during vertical flexure

Stress is a function of beam curvature and material properties. The shorter the switch, the greater the curvature, therefore the greater the stress. The 'B' size switch will therefore be evaluated, assuming a natural bending length of 4.982m from Table 4.3, that the beam is full-section 56lb rail, and that material is linear-elastic (i.e. Hooke's law applies). Material furthest from the neutral axis undergoes greatest stress as it has the greatest extension/compression per unit length (Equation 4.22). The equation relating stress and strain is given in 4.21. Stress is defined as the force per unit area of material; in order to avoid permanent disfigurement, stress imposed on the rail should be significantly less than the compressive/tensile yield strength of 540MPa (Vitaly et al., 2016). The neutral axis of the rail is identified as 82.17mm from the crown of the rail (Cornish, 2014). Fatigue failure, which is the structural failure of the material after repeated loading cycles, is another con-

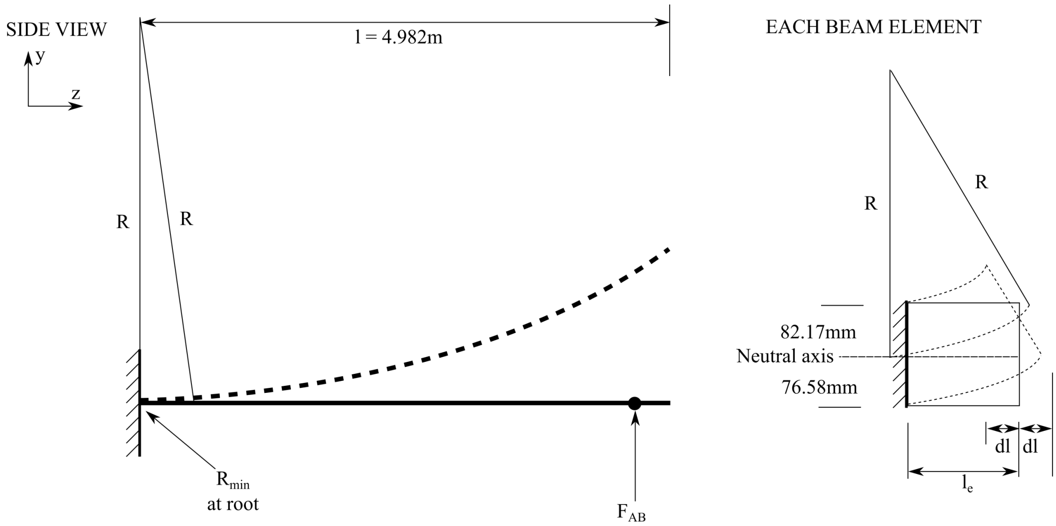


Figure 4.21 Stress and strain in rail from vertical flexure (not to scale).

sideration. In order to prevent fatigue failure over an infinite number of cycles, the stress must not exceed the material's S_e value, which for undamaged steel is equal to 290MPa - half the ultimate tensile strength (Beer et al., 1992).

$$E = \frac{\sigma}{\varepsilon} \tag{4.21}$$

$$\varepsilon = \frac{dl_e}{l_e} \tag{4.22}$$

$$\therefore \sigma = \frac{dl_e E}{l_e} \tag{4.23}$$

For this calculation, the beam bending model was used to define the curvature of the 'B' size switch in the vertical plane at maximum lift - i.e. $\omega = 90$ (Figure 4.21). Peak curvature in this case occurs at the beam root, a conclusion confirmed by the B-switch slope plot (curvature is gradient of slope) in Figure 4.15. The curvature at this location has a vertical radius of 138168m, equating to a strain ε in compression of (rail head) and elongation (rail foot) of -5.947×10^{-7} and 5.543×10^{-7} respectively. This in turn equates to a **peak compressive stress of 124.9 MPa**, and **peak tensile stress of 116.4 MPa**. It can be observed that the peak stress from the Repoint vertical bending occurs in the rail head, and is circa 23% of the yield strength. It should be reiterated that this is an absolute worst-case scenario, with the smallest bending radius in the family of standard switch sizes, and full-section rail throughout. Performing the same calculations for a 'C' switch, for example, shows peak compressive stress in the rail head as reducing to 93.5 MPa, and for an ‘E’, 35.6 MPa. From a feasibility perspective, stress in the rail is therefore considered manageable. From a fatigue perspective, all stress values are significantly less than the S_e value of 290MPa, and fatigue in the rail is therefore considered manageable. However, the quoted S_e value is for undamaged material, and damaged material may have an S_e value significantly lower (Beer et al., 1992). It may therefore be necessary to regularly inspect the stub switch rails. This is not considered onerous, as it is already standard practice for all plain-line rails.

4.5.5 Longitudinal rail movement calculation

Rail temperature fluctuates with the environmental temperature. In continuously-welded rail this variation is unable to expand/contract the rail due to pre-stress (Network Rail, 2012b). However, pre-stress cannot be applied to switch rails as they are longitudinally unrestrained at the toes. The same applies at the the movable section of a stub switch, though the effect is more critical; difficulty managing movement is one factor preventing the widespread use of stub switches. An additional complication is long-term rail creep, managed in traditional switches by a ‘ball and claw’ arrangement (Ciobanu and Nogy, 2017; Morgan, 2009). Conceptually, the double chamfer rail end (Figure 4.4) can accommodate longitudinal movement. With a practical upper limit on movement set by the pitch of bearers, typically at 0.65m centres (Esveld, 2001; Network Rail, 2010a), it is unlikely expanding/contracting rail would be able to remove or refit itself from/to a second bearer. If both sides of the switch are unstressed (Figure 4.22), the practical upper limit is half this.

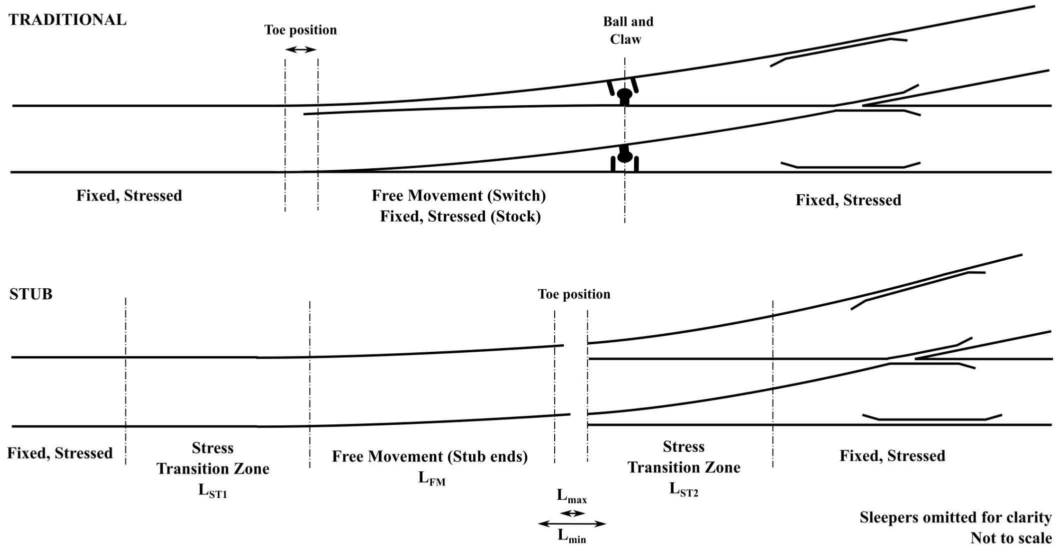


Figure 4.22 Longitudinal stress and expansion zones of traditional switch and stub switch.

Variable	Symbol	Value	Unit	Source
Rail Stress-free temperature	T_{SF}	24	°C	21 °C - 27 °C allowable (Network Rail, 2012b)
Rail Minimum temperature	T_{min}	-20	°C	Approximated
Rail Maximum temperature	T_{max}	50	°C	Approximated (Max. ambient + 10 °C)
Thermal expansion coefficient (mild steel)	α	1.25×10^{-05}	m/m C	(Network Rail, 2012b)
Ball and Claw fixed tolerance (+/-)	L_{BC}	7×10^{-03}	m	(Ciobanu and Nogy, 2017)
Stress Transition Length (max)	L_{ST}	90	m	(Ciobanu and Nogy, 2017)
Free Movement Length	L_{FM}	Various	m	Table 4.3

Table 4.7 Variables used to calculate rail longitudinal movement and thermal expansion.

To establish feasibility, it is necessary to ensure that the maximum longitudinal variation (ΔL) is below this upper limit. It is assumed creep (L_{BC}) is managed as in traditional designs in each fixed half. Temperature will influence rail length over the free stub ends (L_{FM}) and over the stress transition zones (L_{ST}) (Ciobanu and Nogy, 2017). Using the formulae in Equations 4.24, 4.25 and 4.26, with parameters in Table 4.7, expansion from stress-free (ΔL_{Tmax}), contraction from stress-free (ΔL_{Tmin}) and total size change (ΔL) are tabulated for each common switch size in Table 4.8. ΔL is below the ceiling in each worst-case; switch size has minimal influence as the fixed stress transition zones are dominant. This indicates a single rail end design may be suitable for the entire range of switch sizes. Results are of the order of that which expansion switches accommodate - 100-150mm (British Railways, 1962, 1965).

$$\Delta L = \Delta L_{Tmax} - \Delta L_{Tmin} \tag{4.24}$$

$$\Delta L_{Tmax} = \alpha(T_{max} - T_{SF})(2L_{ST} + L_{FM}) + 2L_{BC} \tag{4.25}$$

$$\Delta L_{Tmin} = -\alpha(T_{SF} - T_{min})(2L_{ST} + L_{FM}) - 2L_{BC} \tag{4.26}$$

Switch Type	Free Movement Length	Expansion	Contraction	Length change
RE/PW/ 800-806	L_{FM} m	ΔL_{Tmax} mm	ΔL_{Tmin} mm	ΔL mm
B	4.982	67.2	-122.7	189.9
C	5.758	67.4	-123.1	190.5
D	6.690	67.7	-123.7	191.4
E	9.331	68.4	-125.2	193.7
F	11.507	69.1	-126.5	195.6
SG	13.061	69.5	-127.4	196.9
G	14.926	70.0	-128.5	198.6
H	20.126	71.5	-131.6	203.1

Table 4.8 Longitudinal rail movement calculation results

4.6 Summary and conclusions

The previous chapter described the idea generation and subsequent selection of a concept for railway track switching which may better meet the established set of desirable properties. This chapter has made two important contributions. The first describes the operational concept of the 'Repoint' track switch, which was the highest scoring design from the previous chapter. The core of the concept is the passive locking philosophy, which enables, for the first time, parallel locking functionality, and separates out the actuation and locking mechanisms. The actuation elements are contained in hollow bearers, and the rails are actuated in an arcuate motion, lifting them out of the passive locking recesses and placing them into corresponding recesses for the corresponding route. This section also describes how the design meets, or could meet, the functional requirements for track switches established in Chapter 3. The second contribution models the concept from first principles to establish that the design has both feasible and practical characteristics. Significant further potential benefits in actuation time and turnout route traffic speeds are identified. However, also identified are significant areas of required further understanding, related to the ride dynamics through revised geometries and potential loads at the rail discontinuity. The following chapter concentrates on modelling the potential reliability, availability and maintainability performance of this design.

Chapter 5

Modelling reliability, maintainability and availability performance

5.1 Introduction

This chapter establishes the performance of existing and fault tolerant track switching solutions with respect to reliability, maintainability and availability. The analysis begins in Section 5.2.1 by acquiring field data to establish reliability performance of existing switches, alongside a review of literature to establish maintainability (Section 5.3) and availability (Section 5.4). The reliability data is used in Section 5.5 to create 2P-Weibull models of the expected failure rates of each switch subsystem, across each common POE type. These failure rates are then used as an input to modelling the potential reliability and availability of a range of possible fault-tolerant switch architectures in Section 5.5. Section 5.6 concludes the chapter by examining maintainability of fault tolerant designs. The work described in this Chapter corresponds to items (5) and (6) in the research map in Figure 1.3. The conclusions to the modelling indicate that a significant performance improvement is possible across reliability, availability and maintenance flexibility by the adoption of fault-tolerant architectures. Work detailed in this chapter directly resulted in two journal publications (Bemment et al., 2018, 2017b). The novel contribution of this Chapter includes:

- The operational reliability of existing designs and their constituent subsystems is quantified through study of historical failure data. 2P-Weibull failure distributions and confidence intervals for each subsystem are calculated.
- A range of potential fault-tolerant architectures is established for the first time. The reliability, availability and maintenance flexibility of those architectures is quantified, with the potential performance improvement established as significant.

5.2 Existing switch reliability

To quantify any improvement in switch reliability through the introduction of fault tolerance, it is first necessary to establish the performance of existing designs. Existing performance will be used both as a basis for comparison, and as an input to later fault-tolerant reliability modelling. The literature review (Chapter 2) established that whilst improving switch reliability (e.g. through RCM) is an active area of academic study, there is limited literature on field reliability performance beyond top-level MTTSAF figures.

5.2.1 Assumptions and limitations of the study

The first step in analysing reliability is to establish exactly what data are required and/or available. Switches present both continuous and discrete use cases, therefore reliability could variously be expressed in terms of time, number of actuations, or tonnage of traffic. Whilst any could be used as a measure, reliability will be related to all three, requiring extensive data for a 'perfect' study:

1. The number of actuations each switch performs within the time period, and the time-stamp of those actuations.
2. The tonnage of traffic which passes each switch, along each route, of what type and at what speed, and the time-stamp of each occurrence.
3. Environmental conditions at each switch for the time window in question.
4. Maintenance interventions at each switch, including actions performed, and the time stamp of these interventions.
5. The failures of each switch, the components/subsystems which failed, the time to response and repair, and the time-stamp of each occurrence.

This study is limited by the available data. (1), (2) and (3) are not logged by the infrastructure owner. Some general statistics regarding (2) were provided (Section 5.2.4). (3) may be inferred from historical weather reports with limited precision due to sun heating effects, micro-wetting etc. Some of (4) is logged, but relatively inaccurately, and the database cannot be manually interrogated. FMS (Section 2.2.5.3) gives accurate and accessible data regarding (5), but digital recording only began in 2006, in limited form, thus limiting the study time window. The ideal window is infinite - clearly not possible - though a window at least the order of expected MTTSAF should be adopted to limit confidence bands. Whilst limited, the available data is enough to perform a reliability study, if the limits of that study and its results are understood and acknowledged:

- The limited data mandates the use of time as the measure of expected reliability, as traffic volume and actuations remain unknown, even though it is accepted that other measures may be more suitable.
- The limited time window for which data was available will result in a wider confidence band (Section 5.2.2). This will have the biggest impact on relatively rare failures with few data points.
- Models and results apply to the whole studied population only; this does not necessarily transfer to an individual switch - i.e. one cannot say that an individual switch with an MTTSAF of 3 years will fail after exactly 3 years, only that this is the population mean. It should be understood that individual units will show a range of performance according to local conditions.
- Without knowledge of maintenance interventions, maintenance is assumed part of the system and perfect - i.e. performed on time and to specification. The exception is where data explicitly cites humans as a cause of failure; to accommodate this instance, 'Humans' are considered a functional element of the system (Section 5.2.3)
- One must be careful making comparisons between the reliability of different switch classes due to differing use cases (Section 5.2.4)
- If extending models or results to future cases (i.e. the fault tolerant case), the assumption is made that unknown variables (actuation count, tonnage) remain time invariant.
- Often, parts used for repair are reconditioned units rather than new. Their quality is known to be lower than brand new in some way. However, as no information is available on the fraction of reconditioned vs new parts, it is assumed all parts are of equal quality.

5.2.2 Obtained dataset and cleansing process

Network Rail provided a dataset extracted directly from FMS (Section 2.2.5.3), a database query for all entries pertaining to switches for dates between 1 April 2008 and 17 September 2011, supplied in CSV format. 1 April 2008 was the earliest date the database became 'stable'; the query was performed on the 22nd September 2011, these dates thus limiting the available study window. The population of switches on the GB mainline was 21602 in 2011 (Network Rail, 2012a), and has stayed broadly constant during the period, so populations will be considered constant throughout this analysis. The data corresponds to a cumulative operating time of 74,800 years. Since the data were directly extracted from the database, extensive processing was required before use. Of the fields supplied, several contain duplicate information, and not every field was populated for every record. Identifying duplicates was

Total Records Obtained/Analysed:	39339
Minus:	
Blank/insufficient data/corrupted/irrelevant:	966
Pneumatic machines:	1519
GRS Type 5 Machines:	253
Remaining Useable Data Records:	36601
Of which:	
Criticality 1-3 (Service Affecting Failure):	17603
Criticality 4 (Non-service Affecting):	18998
Within The Useable Data:	
Unique Switch assets identified:	12042
(from an analysed population of:)	19915
Switches without a failure event in the period:	9560
Showing only a single failure event:	4756
Showing two failure events:	2516
Showing three failure events:	1567
Showing four or more failure events:	3203

Table 5.1 General properties of pre- and post- cleansing dataset obtained from Network Rail for period 1 April 2008 and 17 September 2011.

therefore important for data cleansing. Firstly, a script was created which back-populated missing fields based upon the contents of populated entries. Secondly, selected switch types were then excluded from the usable data, for example, those with very small populations, obsolete technology already being phased out (e.g. pneumatic machines), and hydraulic derailers. Table 5.1 identifies the number of records discounted for each reason.

5.2.3 Subsystem identification and event assignment

POE types were classified as in Section 2.2.4.5; classic and modern electro-hydraulic were pooled as the data did not discern between Hydrive and Clamplock Mk1/2/In-bearer. Understanding the design and operation of each POE design allows decomposition of components into a number of functional subsystems. The division of functionality into subsystems is however, in some cases, an exercise of engineering judgement, as some components can cross functional boundaries. The subsystem divisions used for the modelling are presented below. A shorthand letter for each subsystem has been adopted. The relationship between these subsystems is shown in Figure 5.1.

		All Recorded Fault/Failure Incidents (FRI)							Service Affecting Failures Only (SAF)						
POE Class	(Pop)	A	C	D	H	L P	Total	A	C	D	H	L	P	Total	
Elec.-hydraulic	6852	5412	1780	2358	256	5129	885	15821	2494	921	1120	115	2235	346	7231
Modern elec.-mechanical	599	345	548	872	32	n/a	20	1817	175	328	601	17	n/a	13	1134
Classic elec.-mechanical	9153	5799	2607	2681	349	1483	1687	14606	2874	1466	1327	178	778	655	7278
Mechanical	3311	2102	52	1251	50	837	66	4357	656	23	494	21	320	18	1533
Total	19915	13658	4987	7162	687	7449	2658	36601	6200	2738	3542	331	3332	1033	17176

Table 5.2 Switch populations and fault/failure incidence count for each subsystem type within each switch class, for sampled period

- (A) *Actuation:* Elements for moving the track between positions and actuating the locking mechanism; actuator/gearing, transfer of power/motion, including backdrive arrangements
- (C) *Control / Power:* Elements which locally control the other subsystems, and provide power. Signalling relays, transformers, back-up supplies.
- (D) *Detection:* Elements which sense and transmit the position of the switch rails and lock back to the control system. Microswitches, contacts, LVDTs.
- (H) *Human:* Humans responsible for the design, maintenance and operation of the switch; including maintenacne, fault finding and repairs.
- (L) *Locking:* Elements which prevent the un-commanded movement of one or both switch blades. Lock bodies, lock dogs, associated mechanisms
- (P) *Permanent Way:* Elements which support and guide vehicles, maintain the gauge and alignment of the track. Stretcher bars, track clips, slide chairs, but NOT stock rails or sleepers/bearers, whose failures are considered those of plain line and logged independently.

Traditional switches can be represented in RBD form (Section 2.3.5). Figure 5.2 illustrates this case, with a single subsystem of each type connected in series, meaning any failure of a single subsystem directly causes a whole system failure.

By comparing the switch type, assembly type and component type identified in each dataset record, each failure event can be assigned to a particular subsystem, for a given POE class. The total number of records in each assignment is shown in Table 5.2. It is not possible to separate the locking and actuation functions in the HPSS machine, as the locking is carried out by the screw jack mechanism within the actuation element (Section 2.2.4.5); all failures have thus been grouped in the Actuation category. Failure counts for 'Control/Power' upon mechanical switches is comparatively low. This does not indicate a much higher reliability; not every mechanical switch is fitted with electronic interlocking

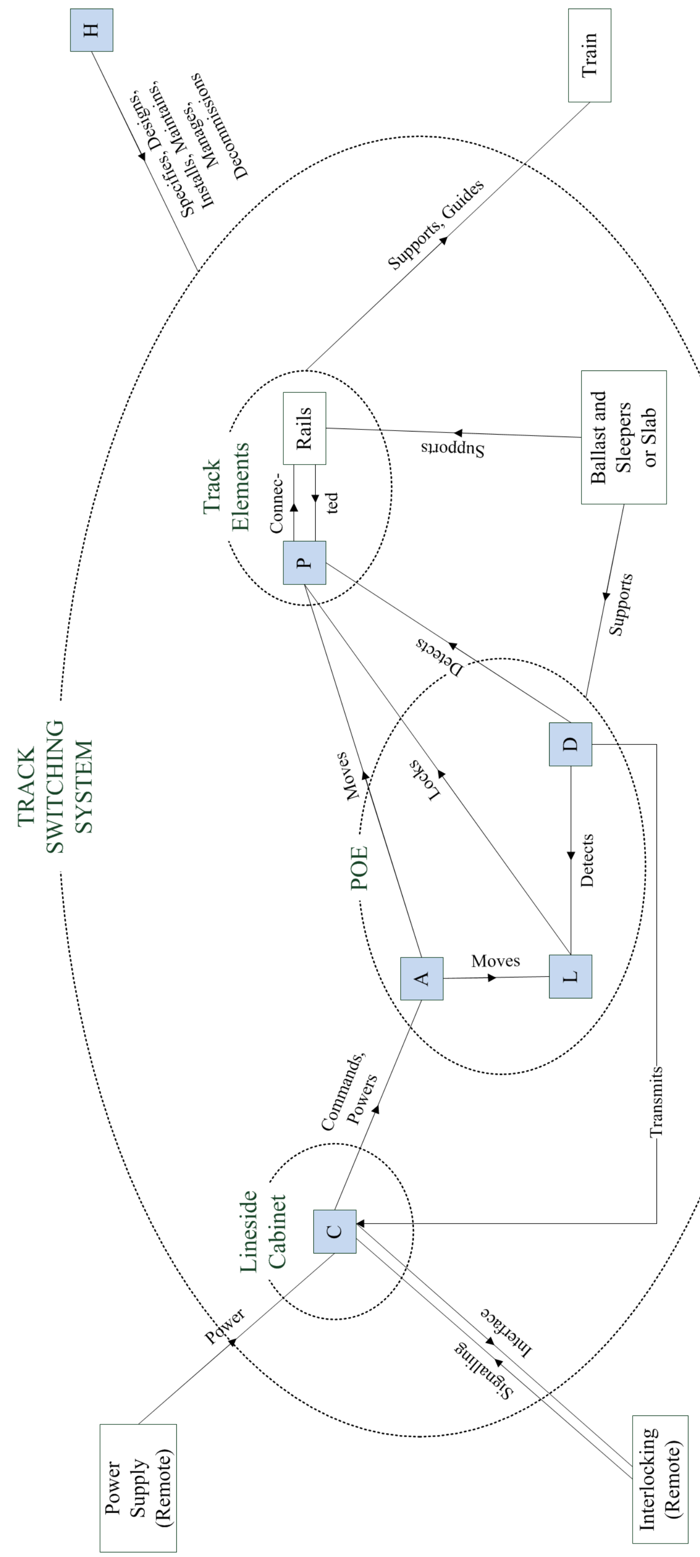


Figure 5.1 System Context diagram showing relationship between functional subsystems, and where appropriate, their relationship with the wider railway environment.

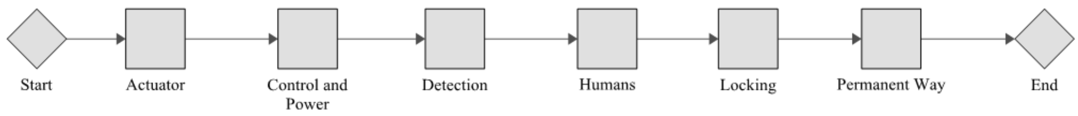


Figure 5.2 Reliability Block Diagram illustrating traditional switch architecture, with a single subsystem of each category connected in series.

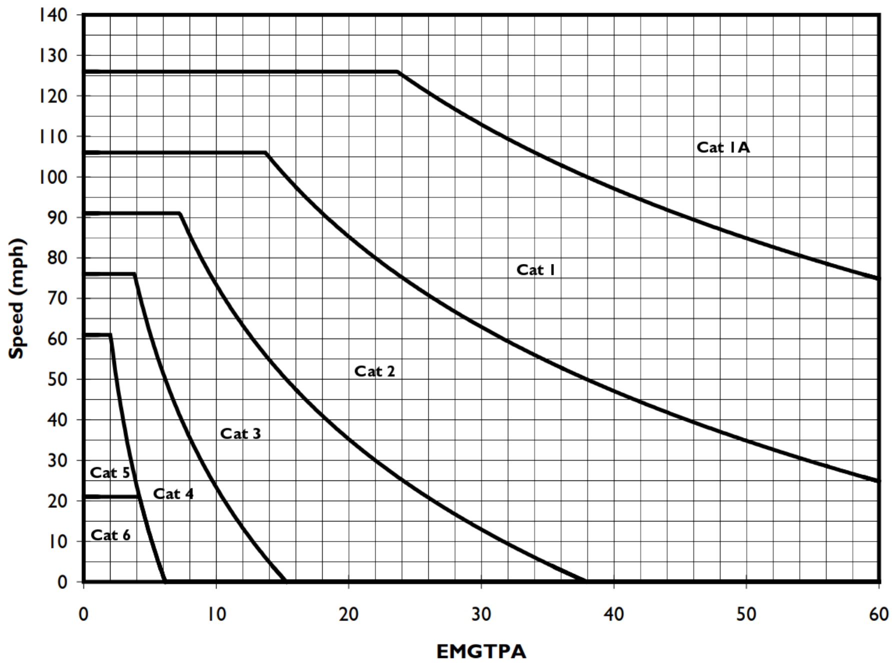


Figure 5.3 Network Rail track categories based upon speed and tonnage. EMGTA = Equivalent million gross tonnes per annum. Source: GC/RT5023 (Fargher, 1999).

and at the time of analysis, data was not available on the portion of the population with or without this feature.

5.2.4 POE use cases

Devolved purchasing decisions have allowed a range of POE populations in different geographical locations (Table 2.1). Engineering policy, however, dictates some POE types as recommended fitment. The criticality of fitment locations is decided by categorisation of track, where category 1/1A track is very high speed and/or high tonnage, and category 6 very low speed and/or low tonnage, as per Figure 5.3. More details on track categories is provided in standard GC/RT5023 (Fargher, 1999). This differing usage intensity presented to each POE class in the failure data prevents direct comparison between POE classes in

	Track category							
	1a	1	2	3	4	5	6	Unlogged
Electro-hydraulic	152	809	1047	1292	1236	881	927	964
Modern electro-mechanical	119	183	104	64	36	15	13	48
Classic electro-mechanical	393	1142	1979	1640	1323	919	951	318
Mechanical	3	65	143	384	375	414	409	1400
Total	667	2199	3273	3380	2970	2229	2300	2730

Table 5.3 POE population by track category on NR infrastructure. Source: (Network Rail, 2012a)

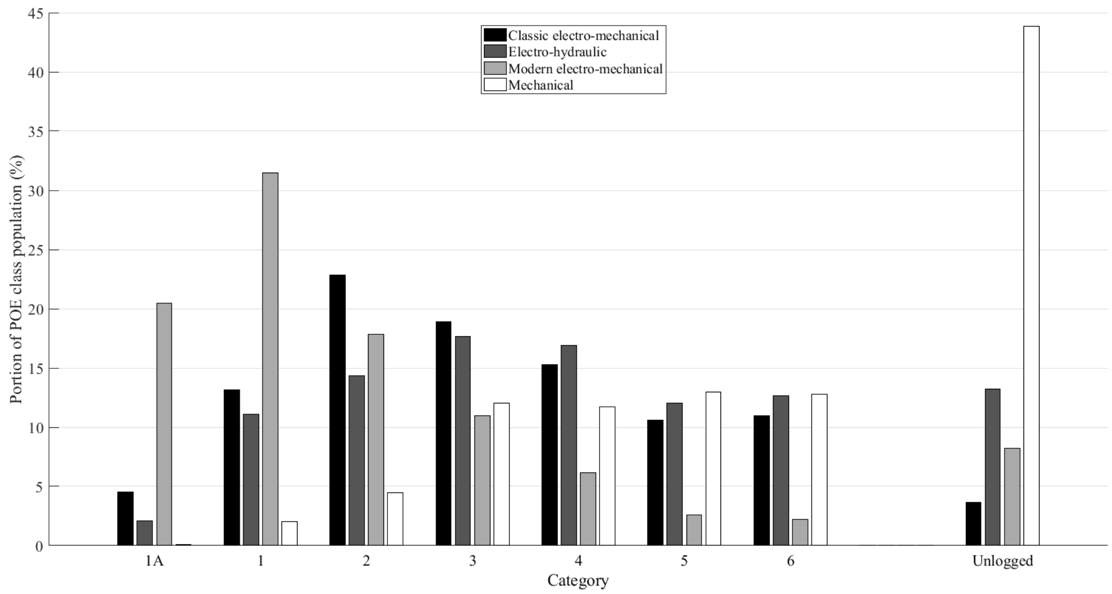


Figure 5.4 Relative proportion of POE population by track category on NR infrastructure.

the results of this study. Network Rail provided population counts of POE class per track category for this study, but were unable to link individual machines identified in the failure data in Section 5.2.2 to a particular track category. Table 5.3 shows POE populations by track category; Figure 5.4 illustrates this as the portion of total POE class population which falls into each track category. There is a clear trend for the modern electro-mechanical class to be fitted in higher category locations, and mechanical in lower category locations, with the remaining electro-hydraulic and classic electro-mechanical classes appearing most often in middle category track.

5.2.5 Establishing failure rates and distributions

5.2.5.1 Constant failure rate assumption

Industry standard practice is to assume a constant failure rate, in which case well known equations presented by, e.g. (Hecht, 2004), can be used to calculate MTTSAF and MTTFRI figures for each subsystem using data in Table 5.2. Equation 5.1 expresses the sum of the operational time between events (TTF) and observational suspensions (TTS) for each failure event (NFT) in the total (N_{SAF} or N_{FRI}) and observational suspension event (NST), divided by the number of observed failure events (N_F). An observational suspension (also known as a censored lifetime) is a subsystem reaching the end of the observation window in a functional or repaired state; the asset is known not to have failed in that period but its exact point of failure subsequent to the window is unknown. In the case of a fixed observation window across all assets, as here, this can be simplified to equations 5.2 and 5.3, including the known population (P) and observation time window (T). For a constant failure rate, the rate can be expressed as the reciprocal of the mean, as in equations 5.4 and 5.5.

	MTTFRI (Years)							MTTSAF (Years)						
	A	C	D	H	L	P	All	A	C	D	H	L	P	All
Elec.-hydraulic	4.4	13.3	10.1	92.7	4.6	26.8	1.5	9.5	25.8	21.2	206.1	10.6	68.5	3.3
Modern Elec.-mechanical	6.0	3.8	2.4	65.0	n/a	102.2	1.1	11.8	6.3	3.5	121.1	n/a	157.4	1.8
Classic Elec.-mechanical	5.5	12.1	11.8	90.6	21.4	18.8	2.2	11.0	21.6	23.9	178.4	40.7	48.3	4.4
Mechanical	5.5	219.9	9.2	230.9	13.7	174.3	2.6	17.5	490.6	23.2	548.3	35.8	621.4	7.5
All	5.0	13.8	9.6	100.3	9.3	25.9	1.9	11.1	25.2	19.5	208.4	20.7	66.7	4.0

Table 5.4 MTTFRI and MTTSAF figures for functional subsystems of common POE classes, assuming a constant failure rate.

$$MTTF = \frac{\sum_{i=1}^{NFT} TTF_i + \sum_{j=1}^{NST} TTS_j}{N_F} \tag{5.1}$$

$$MTTSAF = \frac{P \times T}{N_{SAF}} \tag{5.2}$$

$$MTTFRI = \frac{P \times T}{N_{FRI}} \tag{5.3}$$

$$\lambda_{SAF} = \frac{1}{MTTSAF} \tag{5.4}$$

$$\lambda_{FRI} = \frac{1}{MTTFRI} \tag{5.5}$$

$$B_{50SAF} = \frac{\ln 2}{\lambda_{SAF}} \tag{5.6}$$

$$B_{50FRI} = \frac{\ln 2}{\lambda_{FRI}} \tag{5.7}$$

The results of this calculation are tabulated in Table 5.4. Mean times calculated in this way are indicative of the relative unreliability contribution of each subsystem to the whole system, and of the reliability of each POE class in-service. One must be careful, however, in comparing classes (Section 5.2.1). To provide baseline values for comparison with variable-failure rate analysis later in the thesis, the B_{50} values of the same assets are shown in Table 5.5. The B_{50} values in Table 5.5 have been derived from Equations 5.6 and 5.7, which are valid under the assumption of constant failure rates only.

5.2.5.2 Variable failure rate modelling

Constant failure rate models do not require failure timestamps as the time of failure within the window is irrelevant to their calculation. However, as the FMS data includes timestamps of each failure, it is possible to parametrise variable failure rate models. A range of suitable variable failure rate models were evaluated using the data, including 2P- and 3P-

	$FRIB_{50}$ (Years)							$SAFB_{50}$ (Years)						
	A	C	D	H	L	P	All	A	C	D	H	L	P	All
Elec.-hydraulic	3.0	9.2	7.0	64.3	3.2	18.6	1.0	6.6	17.9	14.7	142.8	7.4	47.4	2.3
Modern Elec.-mechanical	4.2	2.6	1.6	45.1	n/a	70.8	0.8	8.2	4.4	2.4	83.9	n/a	109.1	1.3
Classic Elec.-mechanical	3.8	8.4	8.2	62.8	14.8	13.0	1.5	7.6	15.0	16.5	123.6	28.2	33.5	3.0
Mechanical	3.8	152.4	6.4	160.0	9.5	120.8	1.8	12.1	340.0	16.1	380.0	24.8	430.7	5.2
All	3.5	9.6	6.7	69.6	6.4	18.0	1.3	7.7	17.4	13.5	144.5	14.3	46.2	2.8

Table 5.5 B_{50} figures corresponding to the MTTSAF and MTTFRI figures presented in Table 5.4, assuming a constant failure rate.

Weibull, Gamma, Normal and 1P- and 2P- Exponential, using a correlation coefficient test and the MLE approach described below. For each subset of data, the 2P- or 3P- Weibull distribution proved the best fit for the data. In the analysed cases where the 3P-Weibull distribution proved most suitable, it did so with an offset parameter which was insignificantly small; the 2P- Weibull was therefore selected as the most suitable distribution for this exercise. Published work obtains a similar though more targeted dataset from the same source and fits distributions to the grouped data (Rama and Andrews, 2013). The work also establishes that the Weibull distribution is the most appropriate distribution to model switch component lifetimes, and selects the 2-Parameter model over the 3-Parameter model for the same reasons. (Rama and Andrews, 2013) lists a number of assumptions which are equally applicable here:

1. Each failure is rectified by repairing or replacing the failed component
2. Equipment can either be in a good (operational) or bad (failed) state
3. Repair/replacement returns components to the as-good-as-new state
4. Times to failure of individual components are independent of each other
5. Time duration of the component in the failed state is insignificant in comparison to the functioning period

$$f(t) = \frac{\beta}{\eta}(\frac{t}{\eta})^{\beta-1}e^{-(\frac{t}{\eta})\beta} \tag{5.8}$$

$$\lambda(t) = \frac{\beta}{\eta}\,\frac{t}{\eta}^{\beta-1} \tag{5.9}$$

$$B_{50} = \eta(\ln(2))^{\frac{1}{\beta}} \tag{5.10}$$

$$MTTSAF_{weibull} = \eta_{SAF}\Gamma(1+(\frac{1}{\beta_{SAF}})) \tag{5.11}$$

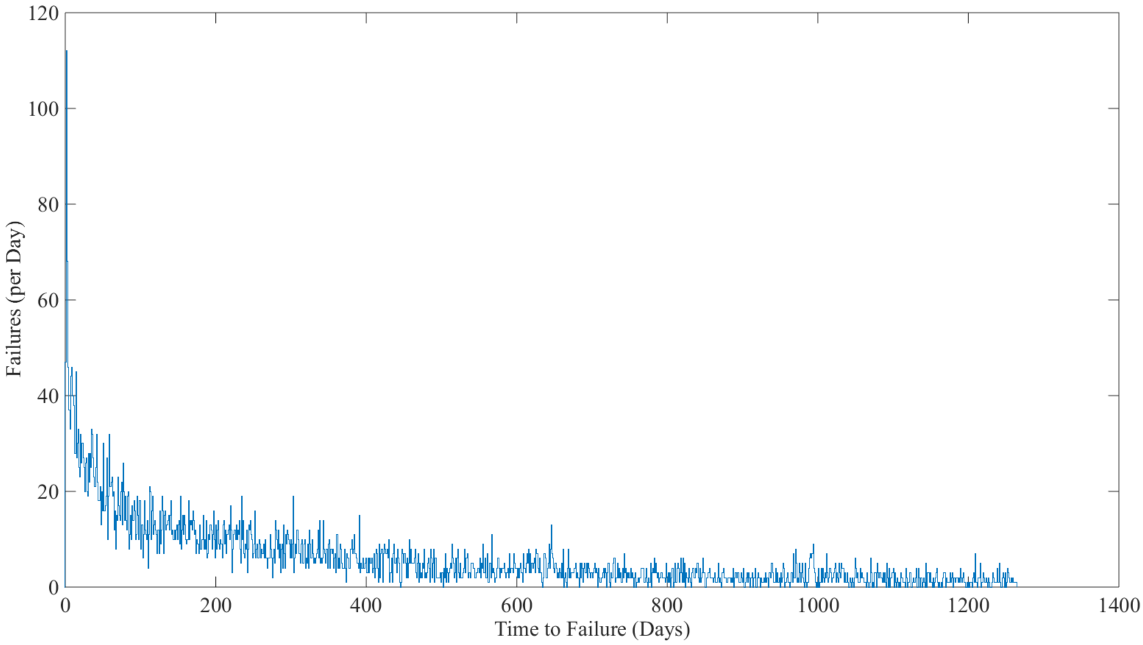


Figure 5.5 Electro-hydraulic failure interval histogram, indicating tendency to early-life.

5.2.5.3 Distribution fitting process

Records are grouped by each unique asset, and placed upon failure event time-lines. The output from this process is, for each subsystem/switch type, an array of 'time to event' figures, where the event is either a failure or suspension of test. This process was automated using an iterative script, however due to historical changes in data entry methods (Section 2.2.5.3), significant manual intervention was also required. Figure 5.5 is a histogram of time-to-failure data for all electro-hydraulic failures analysed, generated from the failure event time-lines. Figure 5.6 shows the cumulative proportion of observed failures over time for each POE class. As the gradient is shallower with time across all plots, it indicates that the failure pattern tends towards infant mortality for all POE classes.

The output data arrays are used as the input to a Maximum Likelihood Estimation (MLE) algorithm. MLE is an estimator technique suitable for data which has a relatively high portion of observational suspensions; the proportion of observational suspensions in this data prevents the use of other techniques, e.g. Rank Regression. MLE develops a likelihood function based upon sampling the data, and finding the values of parameter estimates that maximize this likelihood function. It is an iterative method. The process is well established and documented (Scholz, 2004). β and η values were established (for service affecting failures only) in each of the subsystems in each switch classification, and the computed values are tabulated in Table 5.6. Values of the parameters at the extremes of a 90% confidence

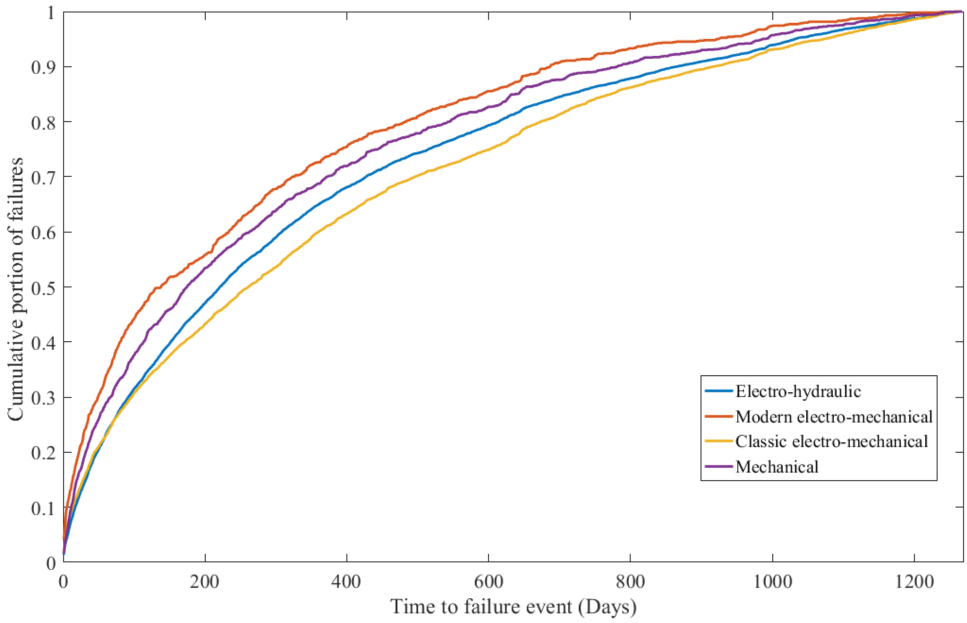


Figure 5.6 Cumulative portion of all failure events over time by POE Class.

interval are also provided to indicate the confidence of fit. Table 5.6 also lists the computed B_{50} values for each subsystem, and (for the sake of compatibility with existing practice only) the computed MTTSAF values, also with 90% confidence intervals. The calculation of these values for a given 2P-Weibull distribution uses eqns. 5.10 and 5.11, (where Γ represents the Gamma function).

An example of a fitted exponential model (i.e. constant failure rate) for failure distributions, for the Actuation subsystem of a Classic electro-mechanical POE type, is plotted in Figure 5.7. Figure 5.8 is a plot of the same failure data, instead fitted to 2P-Weibull distribution. These two plots illustrate the relative unsuitability of the constant failure rate model.

5.2.6 Analysis

- The distributions reveal modern electro-mechanical solutions (HPSS) to achieve the lowest reliability in the field, and mechanical points, the oldest approach, the most reliable. The low reliability of HPSS may be due to the observation window coinciding with the roll-out of HPSS, and the subsequent final development and testing period with live traffic. However, this result is also subject to the limitations stated in Section 5.2.1, in that different machines will see very different use cases.

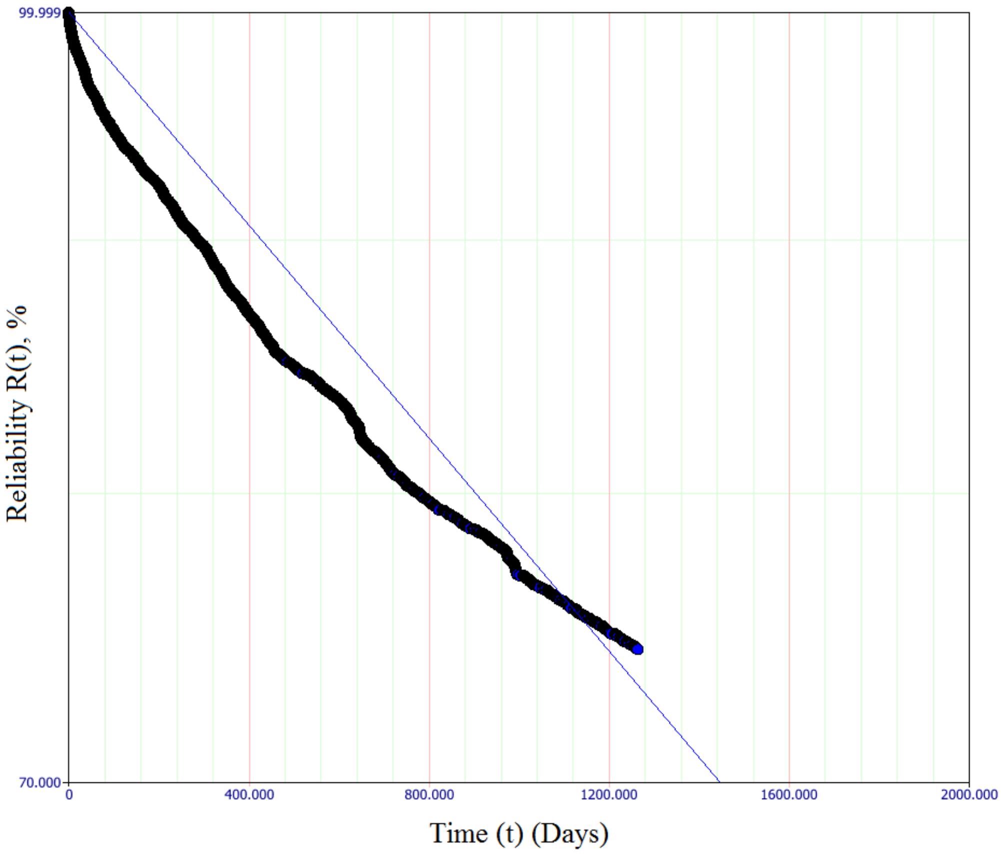


Figure 5.7 Best-fit line for exponential failure distribution (i.e. constant failure rate) of Actuation subsystem of Classic Electro-mechanical class, showing deviation from observed data.

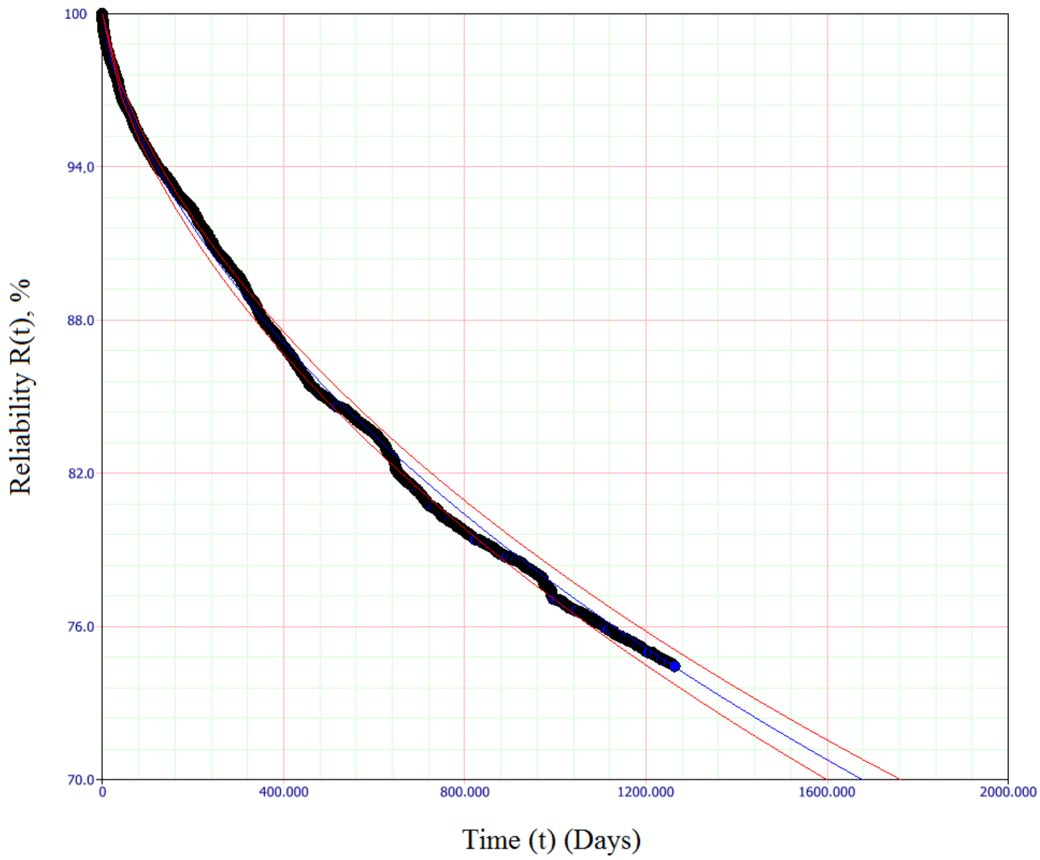


Figure 5.8 2-P Weibull failure distribution ($\beta = 0.662, \eta = 7953$) and 90% confidence interval of Actuation subsystem of Classic Electro-mechanical class, showing a closer correlation to the observed data than Figure 5.7

		SAF						
		A	C	D	H	L	P	All
Elec.Hydraulic	β_{lower}	0.716	0.750	0.674	1.268	0.709	0.809	0.636
	β	0.738	0.789	0.707	1.477	0.732	0.882	0.647
	β_{upper}	0.760	0.829	0.740	1.707	0.755	0.959	0.658
	η_{lower}	4639	12822	13920	13267	5329	26688	1332
	η (Days)	4940	14739	15941	19418	5713	35548	1374
	η_{upper}	5276	17104	18434	30914	6144	49022	1417
	$B_{50,lower}$	7.8	22.5	23.2	29.3	8.9	49.8	2.1
	B_{50} (Years)	8.2	25.4	26.0	41.5	9.5	64.3	2.1
	$B_{50,upper}$	8.7	28.8	29.4	63.5	10.1	85.6	2.2
	$MTTSAF_{lower}$	15.3	40.0	47.4	33.3	17.7	77.5	5.0
	$MTTSAF$ (Years)	16.3	46.2	54.8	48.1	19.0	103.7	5.2
	$MTTSAF_{upper}$	17.5	54.0	64.0	75.4	20.6	143.7	5.3
Modern Elec.-Mechanical	β_{lower}	0.594	0.519	0.599	0.641	n/a	0.809	0.545
	β	0.671	0.564	0.637	0.967	n/a	1.253	0.569
	β_{upper}	0.754	0.612	0.676	1.389	n/a	1.836	0.593
	η_{lower}	6481	3496	1492	15058	n/a	8756	644
	η (Days)	8641	4243	1671	47391	n/a	22730	701
	η_{upper}	12130	5267	1887	326420	n/a	119097	766
	$B_{50,lower}$	22.9	5.1	2.3	31.5	n/a	19.6	0.9
	B_{50} (Years)	31.2	6.1	2.6	88.9	n/a	46.5	1.0
	$B_{50,upper}$	45.2	7.3	2.9	509.1	n/a	208.7	1.1
	$MTTSAF_{lower}$	10.8	15.3	5.7	41.7	n/a	22.8	2.8
	$MTTSAF$ (Years)	13.7	19.1	6.4	131.7	n/a	58.0	3.1
	$MTTSAF_{upper}$	18.2	24.4	7.3	914.0	n/a	292.4	3.4
Classic Elec.-Mechanical	β_{lower}	0.643	0.771	0.622	1.454	0.594	1.199	0.600
	β	0.662	0.804	0.650	1.652	0.629	1.275	0.611
	β_{upper}	0.682	0.838	0.679	1.866	0.667	1.354	0.622
	η_{lower}	7388	11327	22576	10515	51175	8277	2211
	η (Days)	7953	12645	26253	13991	65123	9405	2293
	η_{upper}	8592	14207	30800	19611	84455	10805	2378
	$B_{50,lower}$	11.8	20.0	35.9	23.7	80.7	17.3	3.3
	B_{50} (Years)	12.5	22.0	40.9	30.7	99.7	19.3	3.4
	$B_{50,upper}$	13.4	24.3	46.9	41.8	125.2	21.8	3.6
	$MTTSAF_{lower}$	26.9	34.9	83.5	26.1	195.2	21.1	8.9
	$MTTSAF$ (Years)	29.2	39.1	98.3	34.3	252.9	23.9	9.2
	$MTTSAF_{upper}$	31.7	44.1	116.8	47.3	334.5	27.3	9.6
Mechanical	β_{lower}	0.512	0.690	0.649	1.151	0.554	0.910	0.474
	β	0.544	1.011	0.698	1.641	0.608	1.360	0.494
	β_{upper}	0.578	1.417	0.751	2.253	0.665	1.938	0.513
	η_{lower}	20682	43684	16604	11066	43218	17734	6706
	η (Days)	25687	188915	20797	25454	62510	56200	7531
	η_{upper}	32496	2022138	26696	93985	94833	381088	8505
	$B_{50,lower}$	29.9	92.2	27.8	25.7	67.9	40.2	8.9
	B_{50} (Years)	35.9	360.2	33.7	55.8	93.7	117.6	9.8
	$B_{50,upper}$	43.8	3269.6	41.8	187.6	134.9	699.8	10.9
	$MTTSAF_{lower}$	95.3	119.3	56.9	27.9	169.7	45.7	36.9
	$MTTSAF$ (Years)	121.8	515.3	72.3	62.4	253.3	141.0	42.3
	$MTTSAF_{upper}$	158.9	5504.0	94.3	219.9	398.0	916.2	48.8
All	β_{lower}	0.641	0.729	0.626	1.443	0.661	1.021	0.595
	β	0.654	0.751	0.643	1.576	0.679	1.073	0.601
	β_{upper}	0.667	0.774	0.660	1.717	0.698	1.127	0.608
	η_{lower}	11035	16225	17562	13109	15862	16625	1962
	η (Days)	11675	17767	19115	16281	17225	19090	2008
	η_{upper}	12364	19520	20882	20770	18770	22139	2055
	$B_{50,lower}$	17.4	27.6	27.5	29.0	25.6	32.9	2.9
	B_{50} (Years)	18.3	29.9	29.6	35.3	27.5	37.2	3.0
	$B_{50,upper}$	19.2	32.4	31.9	44.2	29.6	42.4	3.1
	$MTTSAF_{lower}$	40.8	52.6	66.1	32.5	56.3	44.4	8.0
	$MTTSAF$ (Years)	43.4	57.9	72.4	40.0	61.5	50.9	8.3
	$MTTSAF_{upper}$	46.2	63.9	79.8	50.6	67.5	58.9	8.5

Table 5.6 Calculated values of β, η, B_{50} and MTTSAF, including 90% confidence intervals, tabulated by POE class and subsystem type.

- The models established in Table 5.6 are comparable to those independently established (Rama and Andrews, 2013). Notably the shape parameter $\beta < 1$ indicates a high infant mortality rate. There are some differences between the B_{50} values in the constant and variable failure rate models.
- Comparing the MTTSAF and B_{50} presented in Tables 5.4 and 5.5 with those in Table 5.6 indicates that assuming a constant failure rate when modelling switch failures is not an ideal approach, as in all cases whole-system β values are significantly less than 1 - a conclusion which further agrees with (Rama and Andrews, 2013). The accuracy of many predict-and-prevent models used by industry may be significantly improved with the use of variable failure rates.
- Comparing the values presented in Table 5.4 with those in Table 5.6 further highlights the weakness of the industry-standard MTTSAF measure - the MTTSAF for mechanical switches at almost 50 years, for instance, is a misleading value for an asset manager, considering the B_{50} is nearer to 10 years.
- Most elements show a tendency towards $\beta < 1$, indicating a higher incidence of early life failures. This is not what is expected of an electromechanical device, which would typically be seen to wear out in use. Permanent way elements, with β approximately 1, have a broadly constant failure rate.
- An electro-mechanical or electro-hydraulic element showing high infant mortality is an indication of three main possible failure contributors. Firstly, that insufficient burn-in testing is being completed. Secondly, that there are negative human factors with regards to installation and adjustment, which lead to the components operating outside a design envelope. Thirdly, that the components have not been designed for the correct operating environment (Section 2.3.3). Further analysis would be required to establish which particular cause (or combination thereof) was prevalent.
- 'Human error' failures - that is, failures directly attributable to human error rather than those manifesting themselves through the failure of a component - have a relatively high beta. However, the confidence bands of these values are very wide, as there are relatively few failures attributable to this cause. As there is no obvious reason the likelihood of human error should increase with time, a constant failure rate model may be adopted for this element.
- Note that values in the 'all' column are calculated using all data points for a given machine to construct a distribution, which because of the mix of β values discovered is not considered an accurate approach, a better method being the mixed-Weibull, considered in section 5.5.

ID	Intervention Type	Event Frequency f_m (per Year)	Intervention Time t_m *minutes*	Team Size S (People)	Possession Requirement	Intervention Class
1	Track Visual Inspection	52	2	1	No	Inspection
2	Track Gauging/Component Inspection	13	30	4	Yes	Inspection
3	Track Element Renewals	0.1	600	12	Yes	Maintenance
4	Signalling A Service	13	15	4	Yes	Inspection
5	Signalling B service	4	30	4	Yes	Maintenance
6	Signalling C Service	1	120	4	Yes	Maintenance
7	Location Case Inspection	4	5	4	No	Inspection

Table 5.7 Typical scheduled interventions for GB switch installations. Labour time does not include travel to site.

5.3 Existing switch maintenance and maintainability

5.3.1 Calculating maintenance unavailability

The data in Table 5.7 were collated from interviews with staff of Network Rail (Bannister, 2015) and study of the SMS (Network Rail, 2013b), SMTH (Network Rail, 2013c) and related documents listed in Section 2.2.5.1. This table lists all maintenance interventions, the labour time required, and whether or not a possession of the track is required. Of note is the number of operations which take longer than typical timetabled fire-break periods during the daytime, meaning that the line has to be closed to traffic for the intervention to occur, and also the team size for most simple interventions. The interventions are the same across all POE classes (with the exception of mechanical), however different switch lengths may lead to different intervention times due to component counts.

In addition to scheduled interventions, additional visits are made from alerts in the II system (Section 2.2.5.2). Network Rail indicates there were 14000 alerts between 1 April 2008 and 17 September 2011 (Network Rail , 2012; Network Rail, 2012a), the majority towards the end of this period as the system became more widely adopted. However, no record is kept of which alerts were acted upon outside of the normal maintenance schedule, nor how long teams attended for. Figures in Table 5.7 must therefore be taken as minima. Minimum annual maintenance unavailability $U_{planned}$ and minimum annual on-site maintenance effort M_{effort} (in person-minutes) can then be calculated using equations 5.12 and 5.13 respectively, and the values in Table 5.7.

$$U_{planned} = \sum_{ID=2}^{6} f_{m(ID)} \times t_{m(ID)} \qquad = \mathbf{885} \text{ mins/annum} \tag{5.12}$$

$$M_{effort} = \sum_{ID=1}^{7} f_{m(ID)} \times t_{m(ID)} \times S_{(ID)} \qquad = \mathbf{4204} \text{ mins/annum} \tag{5.13}$$

5.3.2 Maintainability

Maintainability represents more than just the parameters specified in BS/EN 50126 (EN50126, 1999) (Section 2.4.3.4), also encompassing considerations such as access arrangements, component commonality, spares availability, manual adjustment requirements etc. It is beyond the scope of this work to investigate every possible maintenance action in every existing POE design. It is, however, worth noting some general observations on the maintainability considerations of existing designs, including those obtained through an interview with the maintenance organisation (Bannister, 2015):

- Most periodic maintenance is performed by visiting site, opening the POE and adjusting/replacing individual components. However, any maintenance performed trackside requires closing the line to traffic, impacting capacity (Chapter 6), and exposing staff to the dangers of the operational railway. There are minimal dangers in disassembling and repairing back at the depot, but this approach is not adopted as it relies on easy removal and replacement of equipment.
- Maintenance of POE is performed by removing protective covers line-side, which can lead to foreign object ingress into sensitive mechanical and electrical equipment. Lubricated surfaces are often exposed (especially slide chairs, and those in uncovered designs such as clamp-lock types) meaning they collect foreign objects, and must be time-interval cleaned and have lubricant renewed.
- For reasons above, gaining access and isolation can be relatively slow during heavy traffic hours as signallers are unwilling to hand over a critical asset to the maintenance organisation with a distant, and often uncertain, hand-back time.
- Regular inspection and adjustment is necessary due to the load case, and the number of connections and adjustment points which can drift over time. This is especially true of machines located outside the 4-foot (nearly all electro-mechanical POE in the GB), with extra linkages to the switch rails.
- Most designs have a high unique component count, with a large range of fastener types employed, complicating spares and supply chain. This is also true of permanent

way components, where traditional switches require, e.g. distance blocks unique to switch and bearer, leading to multiple of versions of the same component.

- POE itself is not man-portable, being of the order of 100-250kg in weight. Individual components are, however, nearly all man-portable.

5.4 Existing switch availability

5.4.1 Modelling availability

Knowledge of the failure rates and planned unavailability from Sections 5.2.5 and 5.3 respectively allows the modelling of benchmark availability figures for each switch type. The remaining variable is MTTR. MTTR is difficult to quantify through research as the time the switch is unavailable following a failure is not recorded by the infrastructure operator; nor are staff transit-to-site times. Values provided in Table 2.3 are used to provide a first estimate of MTTR of the correct order of magnitude - the mean number of 'delay minutes' per incident will be used - 106 minutes. More accurate knowledge of the distribution of MTTR figures would be of significant benefit to the study, especially in the case of different subsystem repair times. However, the influence of this figure upon the results has been mitigated by assuming a constant.

MTTSAF figures in Section 5.2 assume that the system is non-repairable. In order to establish unscheduled unavailability, a dynamic simulation including repairs is required. This can be performed using an RBD (Section 2.3.5) and Monte-Carlo approach. An RBD of each switch arrangement is first created, representing the series arrangement as in Figure 5.2. Each block in the RBD has a 2P-Weibull model describing its failure rate, obtained from Table 5.6. If a block fails, the unavailable time is recorded, and after the prescribed MTTR the block is repaired as-good-as-new, and the system functional again. In this way, failure and repair of individual subsystems do not affect other subsystems. Blocks cannot fail when the system is down for maintenance, which is scheduled as in Table 5.7. The simulation was executed over a 25 year window with a random seed, and the total unscheduled unavailability noted, for 5,000 iterations for each POE class. A mean was then taken to establish the unscheduled availability of that system over the 25 year period $\bar{U}_{25yr}$, from which annual mean unplanned unavailability $\bar{U}_{unplanned}$ is calculated by simple division as per Equation 5.14.

Mean unavailability $\bar{U}$, in minutes per annum, is then calculated from total unavailability as in Equation 5.15. Mean availability $\bar{A}$ is simply the mean fraction of minutes in a year (525,600) the system is available, as in Equation 5.16, normally expressed as a percentage.

For 25-year Window	Symbol	Unit	Classic Electro-mech.	Electro-hydraul.	Modern Electro-mech.	Mechanical
Planned unavailability	$\bar{U}_{planned}$	mins/annum	885	885	885	885
		%	0.16826	0.16826	0.16826	0.16826
Unplanned unavailability	$\bar{U}_{25yr}$	mins, lifetime total	433.95	246.5	383.5	76.75
	$\bar{U}_{unplanned}$	mean mins/annum	17.358	23.670	36.816	7.662
		%	0.0033	0.0045	0.0070	0.0014
Mean unavailability	$\bar{U}$	mins/annum	902.358	908.67	921.816	892.662
Availability	$\bar{A}$	%	99.8284	99.8272	99.8247	99.8303

Table 5.8 Unavailability contributions, and availability of each POE class over 25 year lifetime, using failure rates from Table 5.6 and maintenance actions from Table 5.7.

Table 5.8 tabulates these figures for the range of switch classes in Section 5.2.5.

$$\bar{U}_{unplanned} = \frac{\bar{U}_{25yr}}{25} \qquad \text{mins} \tag{5.14}$$

$$\bar{U} = \bar{U}_{planned} + \bar{U}_{unplanned} \qquad \text{mins/annum} \tag{5.15}$$

$$\bar{A} = \frac{525600 - \bar{U}}{525600} \times 100 \qquad \% \tag{5.16}$$

5.4.2 Analysis

- Unplanned unavailability is a relatively low contributor to overall unavailability, however its impact can be much higher due to the unpredictable timing. This differential impact is not accounted for in a pure availability figure.
- There is a range of unplanned unavailability figures. However, as these figures are based on the same field data as Section 5.2, the same limitations apply, particularly that the figures should not be used to judge relative performance due to differing use cases.
- In all cases, availability falls within the 'two-nines' range, i.e. 99.xxx.
- Depending upon the network, planned unavailability may be of little importance compared to unplanned unavailability. Metro scenarios may have an excess of overnight maintenance access time, but a failure which took 106 mins to rectify could prevent use of the whole node for a rush hour period. A power station freight railway may have traffic 24 hours per day, severely limiting maintenance access, however a failure which took 106 mins to rectify would not affect the operation of the plant.
- Further work developing these availability models could include assigning impact

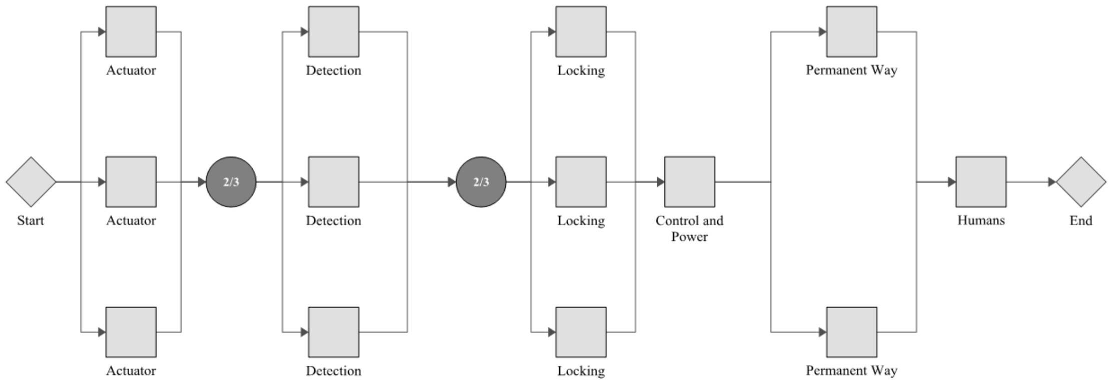


Figure 5.9 An example RBD showing parallel replication of individual subsystems, with 2-out-of-3 voting (for Actuation and Detection), Triplication (Locking) and Duplication (Permanent Way). Shorthand: 2/3A 2/3D 1/3L C 1/2P H.

values to planned vs unplanned unavailability for particular networks, which may give a better idea of total impact to the network operator.

- If availability performance is of the highest importance, for instance at capacity-limited nodes, (Section 2.4.1) then maintenance and maintainability must be targeted in addition to reliability; in all classes, over 96% of unavailability is for scheduled interventions.
- All figures in these sections relate to individual switches, but it should be noted that the impact of unavailability may be larger at larger junctions, as limited resources mean switches must be maintained or repaired sequentially, keeping the line closed for longer periods.

5.5 Fault tolerant switch reliability and availability

5.5.1 Modelling approach

With the β and η values established in the previous section, conceptual designs featuring subsystem redundancy can now be modelled, also through use of RBDs. In this section, it is again assumed that no repair of failed subsystems takes place. Three examples of RBDs are provided graphically in this chapter, other combinations are represented in shorthand only. The shorthand notation is adopted for brevity, whereby a fraction (representing x-out-of-y redundancy) is followed by the abbreviation adopted for each subsystem as used in the source data analysis. Figure 5.2 shows the baseline example used previously. This has a single instance of each subsystem, and would be termed $A\ C\ D\ H\ L\ P$ in shorthand. Other

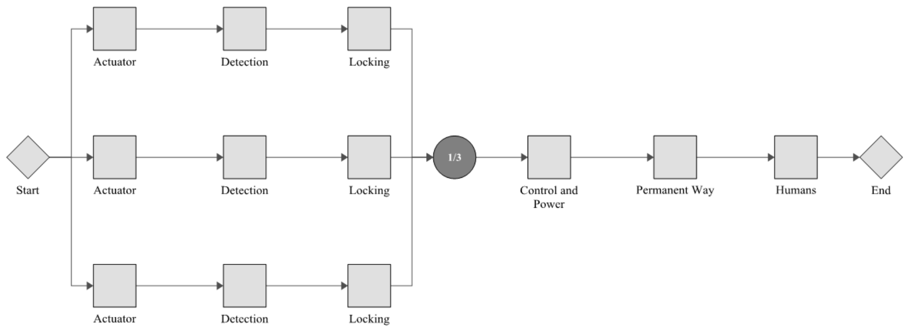


Figure 5.10 An example RBD showing parallel replication of whole POE units, wherein each unit has Actuation, Locking and Detection elements. Shorthand: 1/3(ADL) C P H.

example arrangements are shown in Figure 5.9, which has duplicate, triplicate and 2-out-of-3 elements (shorthand *2/3A 2/3D 1/3L C 1/2P H*), and 5.10, which features parallel POE (shorthand *1/3(ADL) C P H*).

5.5.2 Modelling scenarios and strategy

- *Actuation* elements can be combined in parallel-channel redundancy. A range of actuation options can be examined. Singular (i.e. current practice), Duplicate, Triplicate (including 2-out-of-3) are considered here. Actuators are relatively expensive. Cost is not calculated herein, but 2-out-of-3 may enable smaller/cheaper units to be utilised.
- *Control/Power* elements could be paralleled in a number of ways, however it is anticipated that x-out-of-y approaches would not be suitable due to the complexity of the control signalling. Therefore the options examined are singular, duplicate and triplicate.
- *Detection* elements can easily be paralleled. However, the sole purpose of detection is to sense the system state, so a problem exists in that a duplicate system showing two differing positions would likely still be regarded as a failure. Options considered are therefore singular, and the voting systems 2-out-of-3, and 3-out-of-4. The processing element is considered perfect.
- *Humans* Failures caused by human error must necessarily form part of the system analysis. However, a full analysis of the human factors elements of track switch design, operation, maintenance and repair is out of scope; the human element is therefore considered consistent with existing practice.
- *Locking* elements can be paralleled. As the fundamental purpose of the lock means a failure could lead to it preventing movement of the switch, it could be deduced that

multiplying this subsystem may in fact reduce overall system reliability; however it is assumed that the passive locking described in Section 4.2 negates this.

- *Permanent Way* elements could be duplicated or triplicated; no voting approaches could apply as these elements are entirely passive. For clarity, in the multi-channel design concepts, a duplication of P elements does not mean extra rails, but extra stretchers, clips chairs and associated fittings.

Another approach to be considered (for power operated points only) is the duplication, triplication or 2-out-of-3 voting for several identical point machines fitted to a single switch. This would require parallel detection, actuation and locking channels grouped together, in a larger framework of voting and processing, again considered perfect. An example of this approach is shown in Figure 5.10, the shorthand for which is *3(ADL) C P H* . These grouped elements would each have an associated permanent way, control/power and human elements, which could take the form of the strategies above. It is also not possible to apply each of these strategies to all POE classes because:

- *Actuation* upon the mechanical points type consists of rodding and cable runs from a lever frame to the points. Therefore a redundancy of actuators would not be practical.
- *Control/Power* elements upon mechanical points type are rare, yet the failure distribution listed is very low as it is for the whole population analysed. This has therefore been left as a Singular item.
- *Locking* elements upon modern electro-mechanical points type are combined with actuation as established earlier.

When all possible approaches listed above are combined there are approximately 350 permutations per POE class. For brevity, therefore, this thesis will present a baseline machine and a key selection of concepts for each machine type. The process for creating the distributions is again based upon the Monte-Carlo approach from Section 5.4.1. RBDs represented by each shorthand are used, with random seed, to predict first failure times of the system; a process repeated until a dataset of 500 simulated failure points is created, for each combination. This dataset can then be subject to the same iterative MLE process detailed earlier, in order to calculate the β and η parameters and B_{50} values of the combined system. For completeness, $MTTSAF$ figures are also calculated. This mixed-Weibull approach is different to that used to calculate the 'All' column in Table 5.6, which was to fit a single 2P-Weibull distribution to a dataset which was known to be a mix of different distributions. Though the results of the two processes are expected to be marginally different, magnitudes in Table 5.4 can be used to validate the approach.

5.5.3 Availability

One of the benefits of a multi-channel approach is that the system continues to function until such a time as a repair has been effected, unless all channels fail simultaneously. Whilst a static analysis can reveal the expected system reliability, a more relevant measure can be obtained from a dynamic simulation - using the same RBD and Monte-Carlo approach method as Section 5.4.1 - to establish unscheduled unavailability. The dynamic simulations are again run over an observation window of 25 years, and the mean unscheduled unavailability per annum, in minutes, taken as a measure for comparison. The results of the static modelling are presented in Table 5.9, dynamic results are presented in the right-hand column of the same table.

5.5.4 Analysis

Results in Table 5.9 show that redundancy can provide a considerable improvement over baseline for every POE class. The mean annual downtime for each redundantly engineered solution is an order of magnitude lower than the baseline scenario. The following points are of note:

- In all cases, parallel redundancy of functional subsystems acts to improve overall system reliability.
- For the modern electro-mechanical class, fitting 3 machines in a parallel configuration results in a five-fold improvement B_{50} value.
- For the classic electro-mechanical class, up to 12.5 year B_{50} values are achievable, a five-fold improvement.
- For electro-hydraulic types, B_{50} can also exceed 10 years, also five-fold improvement.
- As expected, different architectures have different effects upon whole system reliability. To select a suitable architecture for a given situation, cost constraints must also be taken into account, alongside the maintenance and repair policy in Section 5.6.
- Figure 5.11 shows the relative reliability importance of each subsystem type, for the classic electro-mechanical baseline example. Reliability importance is subsystem reliability divided by system reliability, and gives an indication of how likely a failure of that subsystem is to cause a system failure. It can be seen that for the series case, the failure of any block is of similar likelihood to cause a system failure at any point in the observation window. This result is to be expected for a series system.
- Figure 5.12 shows the relative reliability importance for a sample case, *1/3A 1/3C 2/3D H 1/3L 1/2P* of the classic electro-mechanical class. The importance of all

POE Class	Concept Architecture	Reliability (Static) β	η (days)	$MTTSAF$ (years)	B_{50} (years)	Unavailability $\bar{U}_{unplanned}$ (mins/annum)
Electro-hydraulic	A C D H L P (Baseline)	0.750	1136	3.7	1.9	24.1
	2/3A 1/3C 2/3D H 1/2L 1/2P	1.253	2587	6.7	5.1	1.3
	2/3A 1/3C 2/3D H 1/3L 1/2P	1.276	2861	7.4	5.7	1.3
	2/3A 1/3C 3/4D H 1/2L 1/2P	1.252	2345	6.1	4.7	1.3
	2/3A 1/3C 3/4D H 1/3L 1/2P	1.270	2572	6.6	5.2	1.3
	1/3A 1/3C 2/3D H 1/2L 1/2P	1.353	4181	10.6	8.6	1.3
	1/3A 1/3C 2/3D H 1/3L 1/2P	1.468	4802	12.1	10.0	1.3
	1/3A 1/3C 3/4D H 1/2L 1/2P	1.319	3603	9.2	7.3	1.3
	1/3A 1/3C 3/4D H 1/3L 1/2P	1.393	4088	10.3	8.5	1.3
	2/3(ADL) 1/3C H 1/2P	1.152	1319	3.6	2.5	1.3
	1/3(ADL) 1/3C H 1/2P	1.431	3610	7.3	9.3	1.3
Classic Electro-mechanical	A C D H L P (Baseline)	0.716	1568	5.0	2.7	18.9
	2/3A 1/3C 2/3D H 1/2L 1/2P	1.036	3618	9.5	7.1	1.8
	2/3A 1/3C 2/3D H 1/3L 1/2P	1.035	3682	9.7	7.3	1.8
	2/3A 1/3C 3/4D H 1/2L 1/2P	1.037	3251	8.6	6.4	1.9
	2/3A 1/3C 3/4D H 1/3L 1/2P	1.036	3303	8.8	6.5	1.9
	1/3A 1/3C 2/3D H 1/2L 1/2P	1.114	5845	14.7	12.2	1.7
	1/3A 1/3C 2/3D H 1/3L 1/2P	1.119	5995	15.0	12.5	1.7
	1/3A 1/3C 3/4D H 1/2L 1/3P	1.086	5025	12.8	10.3	1.9
	1/3A 1/3C 3/4D H 1/3L 1/2P	1.078	5143	13.1	10.6	1.8
	2/3(ADL) 1/3C H 1/2P	0.989	2398	6.6	4.5	1.9
	1/3(ADL) 1/3C H 1/2P	1.155	5603	14.1	11.6	1.8
Modern Electro-mechanical	A C D H P (Baseline)	0.623	555	2.1	0.9	36.2
	2/3A 1/3C 2/3D H 1/2P	1.055	1104	2.1	3.1	0.9
	2/3A 1/3C 3/4D H 1/2P	1.037	710	2.0	1.3	0.9
	1/3A 1/3C 2/3D H 1/2P	1.033	1261	3.5	2.3	0.8
	1/3A 1/3C 3/4D H 1/3P	1.020	770	2.2	1.4	0.9
	2/3(AD) 3C H 1/2P	1.026	863	2.5	1.6	0.9
	1/3(AD) 3C H 1/2P	1.256	2531	6.7	4.9	0.9
Mechanical	A C D H L P (Baseline)	0.621	3357	12.5	5.3	8.1
	A C 2/3D H 1/2L 1/2P	0.685	5193	16.6	9.0	3.7
	A C 2/3D H 1/3L 1/2P	0.680	5412	17.3	9.4	3.6
	A C 3/4D H 1/2L 1/2P	0.716	4148	12.8	7.3	3.9
	A C 3/4D H 1/3L 1/2P	0.713	4282	13.3	7.5	3.7
	A 2/3(DL) C H 1/2P	0.713	3967	12.5	6.9	3.8
	A 1/3(DL) 1/3C H 1/2P	0.648	7090	23.1	12.4	3.8

Table 5.9 β, η, $MTTSAF$ and B_{50} and $\bar{U}_{unplanned}$ values for a selection of redundantly engineered switch solutions based upon existing POE actuation classes.

physical subsystems has been considerably reduced, indicating a good fault tolerance. However, the human element is now dominant throughout. The same is true for *all* evaluated architectures - is not possible to add redundancy to the human element in the same way. Adding additional redundancy beyond that explored herein does not significantly improve system reliability further; the Human element is the limiting factor. This result is important in indicating that when implementing functionally redundant track switching solutions, human factors elements are important in gaining full reliability benefits.

- The results of the availability modelling show that an order of magnitude reduction in unscheduled downtime is possible across all asset types.
- The dynamic modelling shows that the particular architecture has a relatively insignificant effect upon the unscheduled unavailability for each switch type when compared with the act of multiplying subsystems.
- The main contributor to the unscheduled unavailability in each scenario is errors directly attributable to humans. This is further highlighted in Figure 5.12. The modern electro-mechanical class performs better than the other drive types in the mean unavailability per annum due to the fact the η value for human-induced failures is much higher - there is less likelihood of error as the machine has built-in monitoring and diagnostics.
- As the MTTR is insignificantly small when compared with the MTTSAF, there may be some scope in a multi-channel architecture to respond to subsystem failures in a much longer time frame - perhaps weeks or months - without having a significant detrimental effect upon availability, a property which is explored in Section 5.6.

5.6 Fault tolerant switch maintainability and availability relationship

5.6.1 Modelling approach and target repair time

Until now, this modelling has assumed that the MTTR is constant. One of the benefits of a fault tolerant switch with redundancy is that it continues to function until repair is effected. Conceptually, it is proposed that the functional elements in the Repoint track switching system are LRUs (Section 4.3.4), which will not be repaired; maintenance technicians can simply replace the faulty or failed unit with known-good. The unit may subsequently be repaired in the background. The opportunity therefore exists to relax the MTTR in order to

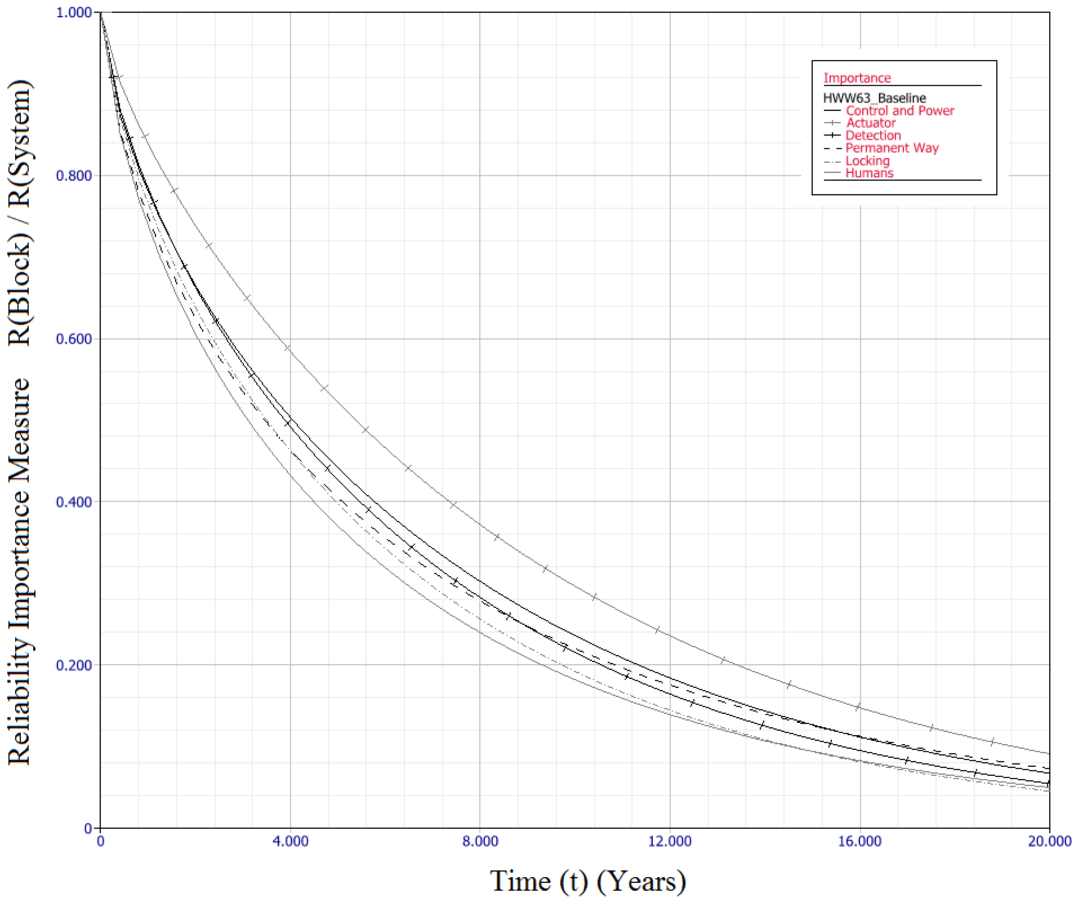


Figure 5.11 Reliability importance of each subsystem type for baseline case of the classic electro-mechanical class, over 20 years of operation. All elements contribute similar levels of unreliability at each point in time.

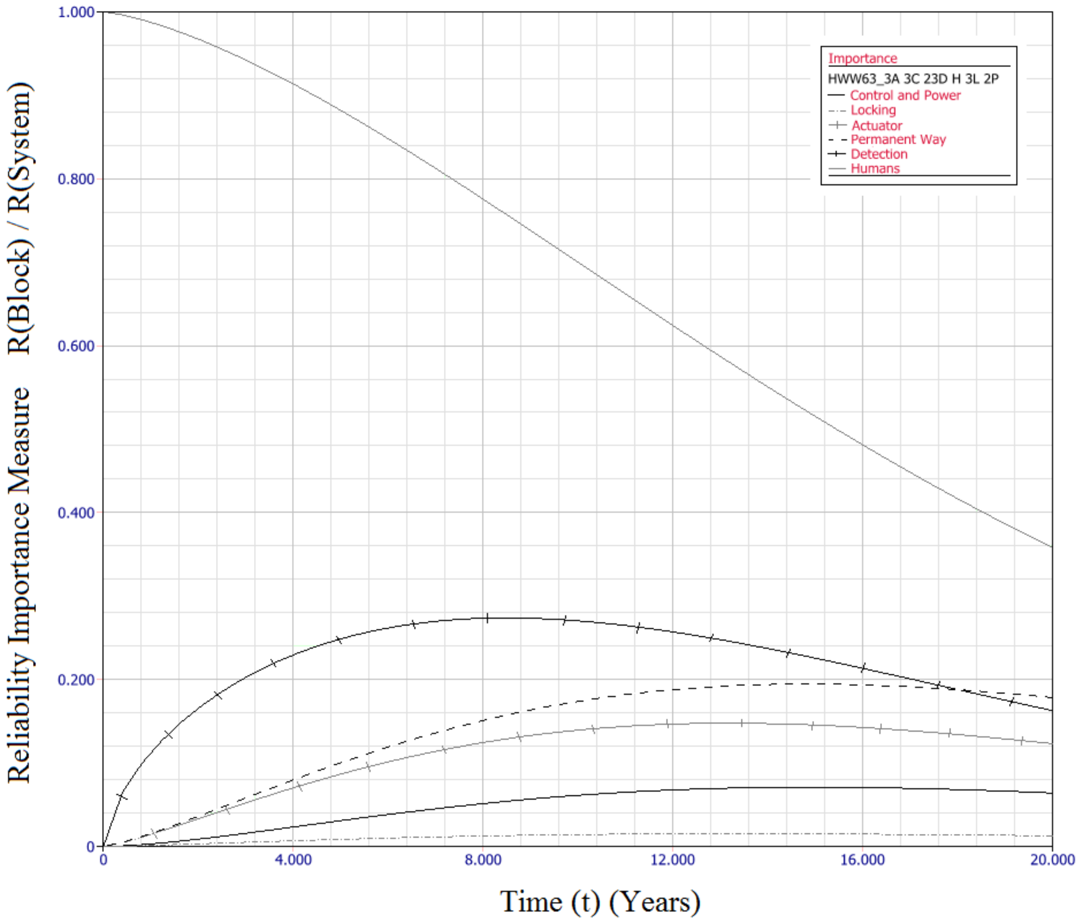


Figure 5.12 Reliability Importance of each subsystem type for example *1/3A 1/3C 2/3D H 1/3L 1/2P* case of classic electro-mechanical POE class, over 20 years of operation. System reliability is dominated by human error.

improve flexibility or reduce costs for the infrastructure owner. For this section, the fixed MTTR is replaced with a variable τ, which represents the target time in which faulty or isolated subsystems must be replaced; i.e. a target MTTR (Section 2.4.3.4). There is also the opportunity to adapt maintenance practices to take advantage of the LRU concept; Repoint could be adopted under existing maintenance regimes or alongside condition-based maintenance to better exploit its potential. Several levels of maintenance change will therefore been examined, as follows:

- **Level 0:** This represents the benchmark case, as currently implemented.
- **Level 1:** Triplex redundancy, with no change to the maintenance or inspection regime.
- **Level 2a:** Triplex redundancy, with no change to the maintenance regime, but with the system self-inspecting.
- **Level 2b:** Triplex redundancy, with maintenance performed by LRU (2 minute replacement), but no change to the inspection regime.
- **Level 3:** Triplex redundancy, with maintenance performed by LRU (2 minute replacement), and the system self-inspecting.

Furthermore, for each implementation level, there is a choice of architecture to the implementation of the functional redundancy, namely series or parallel, as in Figures 5.9 and 5.10. In the series example, each LRU contains the functionality of a point machine or trackside supply/command unit. When an LRU is replaced (maintenance or failure), the entire unit is replaced as a whole. In the alternative, parallel case, each functional subsystem forms an LRU, and is replaced individually, without affecting functional units of a different subsystem type. Evaluating both arrangements, at 4 different implementation levels and for 3 different POE Classes (the Mechanical Class is omitted from this section) gives a total of 24 possible scenarios, plus baseline.

The same 25-year window RBD and Monte-Carlo approach as Section 5.4.1 has been adopted, with the fixed MTTR replaced by the stated τ value, represented by a normal distribution with $\sigma = \tau/4$ and scheduled maintenance adjusted accordingly for each scenario; a mean of 5000 iterations was used for each of the results below.

5.6.2 Results

Simulation results are presented in 3 tables. Table 5.10 shows the output of the simulation for each of the listed cases, giving availability values at each level of implementation, where the value of τ has been fixed to 106 minutes as per previous sections. Table 5.11 shows the extent to which the τ values can be relaxed, working under the assumption that the

	Classic electro-mechanical		Electro-hydraulic		Modern electro-mechanical	
	Availability	Unavailability hours per annum	Availability	Unavailability hours per annum	Availability	Unavailability hours per annum
Level 0 (Baseline)	0.99828440	15.0	0.99827240	15.1	0.99824710	15.4
Series redundant architecture						
Level 1	0.99708547	25.5	0.99709032	25.5	0.99708846	25.5
Level 2a	0.99893966	9.3	0.99894428	9.3	0.99894329	9.3
Level 2b	0.99808313	16.8	0.99808782	16.8	0.99808607	16.8
Level 3	0.99993738	0.5	0.99994158	0.5	0.99994106	0.5
Parallel redundant architecture						
Level 1	0.99708547	25.5	0.99709032	25.5	0.99708846	25.5
Level 2a	0.99893966	9.3	0.99894428	9.3	0.99894329	9.3
Level 2b	0.99808313	16.8	0.99808782	16.8	0.99808607	16.8
Level 3	0.99993738	0.5	0.99994158	0.5	0.99994106	0.5

Table 5.10 Simulation Results: Availabilities of parallel and series architectures at each implementation level with τ fixed at 106 minutes.

availability must be the equivalent to existing installations as in Section 5.4.1. Table 5.12 imagines a hybrid case where τ is relaxed to one week, and lists the availability achievable in each scenario.

To further illustrate the relationship between τ and availability, three plots are provided. Figure 5.13 illustrates the relationship between availability and τ for each implementation level. Figure 5.14 is a simple bar chart which illustrates the relative contribution of scheduled and unscheduled availability, for each implementation level. Figure 5.15 illustrates the unavailability of each implementation level where τ is fixed to 1 week.

5.6.3 Analysis

- In the baseline case, τ is equal to the emergency response time, therefore increasing τ has an immediate, significant and detrimental effect upon availability (See table 5.12). In reality this approach could not be taken with existing systems.
- Not all levels of implementation demonstrate increased availability. Table 5.10 shows that Level 1 and 2b solutions reduce availability due to the additional maintenance, and the proportionally large contribution of scheduled maintenance to total downtime. It is important to note, however, that in both these cases the unscheduled availability is reduced almost to insignificance, as illustrated in Figure 5.14.
- Level 2a and 3 implementations both show a significant decrease in scheduled and unscheduled unavailability across all POE classes, leading to substantially increased availability (Table 5.10). Level 3, in particular, reduces downtime to around 0.5 hours

	Classic electro-mechanical	Electro-hydraulic	Modern electro-mechanical
Level 0 (Baseline)	1.77	1.77	1.77
Series Redundancy Architecture			
Level 1	n/a	n/a	n/a
Level 2a	117	283	272
Level 2b	n/a	n/a	n/a
Level 3	323	768	623
Parallel Redundancy Architecture			
Level 1	n/a	n/a	n/a
Level 2a	118	292	275
Level 2b	n/a	n/a	n/a
Level 3	327	772	625

Table 5.11 The maximum value τ (Hours) can become whilst achieving baseline availability levels

	Classic electro-mechanical		Electro-hydraulic		Modern electro-mechanical	
	Availability	Unavailability hours per annum	Availability	Unavailability hours per annum	Availability	Unavailability hours per annum
Level 0 (Baseline)	0.99541389	40.2	0.99442105	48.9	0.99175345	72.3
Series redundant architecture						
Level 1	0.99633465	32.1	0.99676096	28.4	0.99668535	29.1
Level 2a	0.99818434	15.9	0.99860429	12.2	0.99858454	12.4
Level 2b	0.99731799	23.5	0.99777751	19.5	0.99777718	19.5
Level 3	0.99913906	7.5	0.99961458	3.4	0.9995266	4.1
Parallel redundant architecture						
Level 1	0.99632192	32.2	0.99675727	28.4	0.99678579	28.2
Level 2a	0.99818434	15.9	0.99860429	12.2	0.99856542	12.6
Level 2b	0.99737159	23.0	0.99777747	19.5	0.99777816	19.5
Level 3	0.99918206	7.2	0.99961458	3.4	0.9995266	4.1

Table 5.12 Simulation Results: Availabilities of parallel and series architectures at each implementation level with τ at 10800 minutes (1 week).

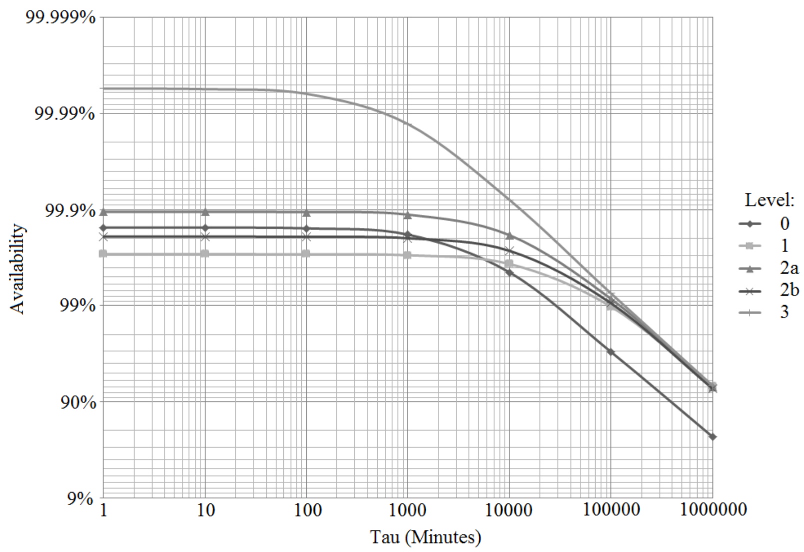


Figure 5.13 Plots showing variation in asset availability vs τ for range of possible implementation levels using classic electro-mechanical baseline data in a series configuration.

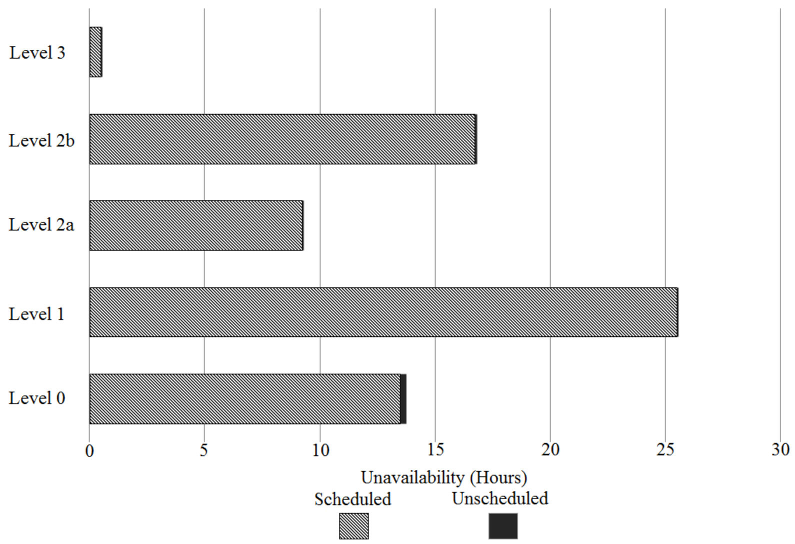


Figure 5.14 Bar chart indicating the relative contribution to unavailability from scheduled and unscheduled maintenance at various implementation levels, for the classic electro-mechanical case with τ fixed at 1.77 hours.

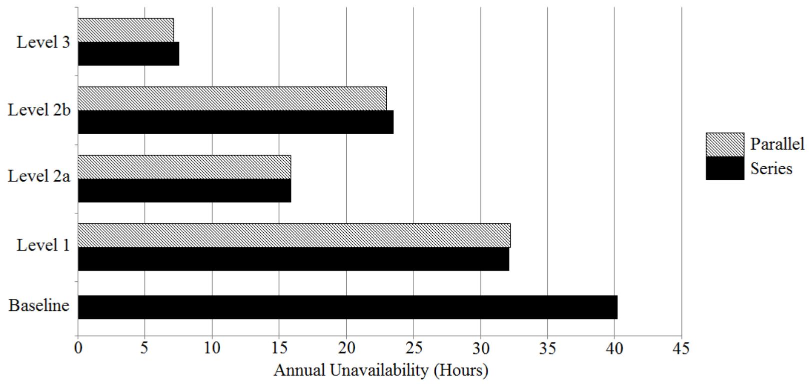


Figure 5.15 Bar chart indicating annual unavailability (hours) for each implementation level, where τ is fixed at 1 week, for the classic electro-mechanical case.

per year, from over 15 hours at benchmark, for every switch type.

- Table 5.10 shows that 'four-nines' availability is achievable with all POE classes with a level 3 implementation.
- Table 5.11 illustrates the extent to which τ can be relaxed, in each case, whilst maintaining the availability provided by the benchmark system. For each deployment level where this is possible, and across all POE classes, the emergency response time can be relaxed by 2-3 orders of magnitude.
- Table 5.11 illustrates that the emergency response times of the classic electro-mechanical design cannot be relaxed to the same extent as the other two actuation methods. This is due to the larger contribution to unreliability of the Permanent Way element in this case, with a significantly lower η value. The stretcher bar and mountings of such designs are a known weakness (Section 3.3.2). However, this could be offset by having separate target response times for different subsystems. It is of note that the Repoint design does not feature stretcher bars, therefore the P-way reliability model would be closer to that of the modern electro-mechanical system.
- Figure 5.13 indicates the availability achievable for each implementation level as τ is relaxed. Of note is that the level 3 implementation outperforms the baseline throughout. At $\tau > 10000$ minutes, all redundantly engineered solutions outperform the baseline. Below this, the baseline outperforms level 1 and level 2b solutions. This is due to the additional maintenance requirements.
- Figure 5.13 indicates that a level 3 implementation can outperform the baseline in availability terms, even with $\tau > 30000$ minutes; 300 times longer than benchmark practice. Similarly, the level 2a deployment can outperform the baseline with $\tau >$ 10000 minutes - two orders of magnitude longer than existing practice.

- Figure 5.15 and Table 5.12 show that when τ is extended to 1 week, all solutions outperform the baseline in availability terms.
- There is little difference in availability (in each circumstance) between parallel and series architecture. Figure 5.15 and Table 5.12 illustrates the case of a fixed τ of 1 week, with the parallel case performing marginally better in the level 2b and 3 implementations, The architectures are not a dominating factor in availability until τ reaches very high levels. A series architecture may perform slightly worse, but line-replaceable units containing all functions may simplify maintenance and reduce human-attributable errors.

5.7 Conclusions

This chapter has established the performance of existing and fault-tolerant track switching solutions with respect to operational reliability, maintenance/maintainability and availability. The operational reliability of existing designs, and that of their constituent subsystems, is established through study of historical failure data. 2P-Weibull failure distributions and confidence intervals for each subsystem have been calculated. Annual downtime from maintenance interventions is established from literature and interviews with maintenance personnel. Inadequacies in recorded and available maintainability data have been identified, and the remaining data were then were then used to calculate availability.

A range of fault-tolerant architectures are studied, including that chosen for the Chapter 7 demonstrator. The results show that with fault-tolerance, considerable gains in whole-system reliability are possible; typical time to failures can be more than five times that of existing solutions, and unscheduled downtime reduced by an order of magnitude. However, as equipment failures are engineered out, reliability plateaus due to the dominant contributor to unreliability becoming human error, which cannot be designed out in the same manner. An important observation from this chapter is that it is possible to improve the availability and maintenance flexibility of track switching solutions through the use of a fault-tolerant, multi-channel architecture. However, as unscheduled unavailability is only a small contributor to total unavailability, a larger improvement arises when maintenance is revised to take full advantage of the ability of a multi-channel system to accommodate subsystem failure and remain functional. It is possible to increase switch availability and reliability at the same time as relaxing tau by several orders of magnitude. Gains in availability are possible even when emergency response times are orders of magnitude longer than currently achieved. The work also demonstrates that the subsystem architecture is of relatively low significance compared to the effect of designing-in fault tolerance.

Chapter 6

Modelling capacity performance

6.1 Introduction

This chapter evaluates the capacity performance of traditional and Repoint track switches. Section 2.4.1.3 established that there is no absolute measure of capacity, therefore this chapter takes the form of five case studies, identified in Section 6.2. The first three case studies are based around London Underground, and are described in Section 6.4. The remaining two are based upon HS2 locations, and described in Section 6.5. In each, plain line capacity is established using timetable compression methods from (UIC406, 2004). The restrictive effects of traditional and fault tolerant switch performance is then examined. Fault tolerant switch performance is based upon calculations in Chapters 4 and 5 and identified in Section 6.3.

Results, presented in consolidated form in Subsections 6.4.6 and 6.5.5, show that a range of enhanced capacity is available across the selected case study nodes with the adoption of fault tolerant switching, though the potential magnitude of the gain varies significantly by location. The work described in this Chapter corresponds to item (7) in the research map in Figure 1.3.

The original work in this chapter formed part of several papers (Bemment et al., 2012a, 2013a,b). The novel contributions of the chapter are threefold. Firstly, the effect of existing practice upon nodal capacity is explored, with the relationships between capacity, actuation time and turnout speed being defined and quantified with respect to equivalent plain line. Secondly, potential capacity impact from the Repoint switch is quantified in the same manner, using performance results from previous chapters. Thirdly, the relative improvement is established as significant.

6.2 Case study selection

It is established in Section 2.4.1.3 that there is no absolute measure of capacity, and that the influence of changes to infrastructure upon capacity is unique to a particular node, necessitating a case-study approach to capacity evaluation. Five case study scenarios (i to v) have been selected for this study, listed in Table 6.1.

	Network Type	Network, Node	Node Type	Traffic	Traffic Speed	Signalling
i	Metro	LU, typical sub-surface	Diverging turnout	Homogenous	Low	2-aspect Colour Light
ii	Metro	LU, typical sub-surface	Converging turnout	Homogenous	Low	2-aspect Colour Light
iii	Metro	LU, typical sub-surface	Double junction, conflicting moves	Homogenous	Low	2-aspect Colour Light
iv	High Speed	HS2, Birmingham Interchange	Diverging turnout	Homogenous	High	ETCS (various levels)
v	High Speed	HS2, Birmingham Interchange	Converging turnout	Homogenous	High	ETCS (various levels)

Table 6.1 Capacity evaluation case study nodes

6.3 Potential performance changes

Several aspects of the Repoint concept could impact capacity. Some aspects can be calculated, others may only indicate a general trend, and not each applies to every scenario, as follows:

1. **Switch actuation time** directly affects headway through junctions; reduced switching time reduces headway. Table 4.6 lists potential switch actuation times for Repoint, which can be compared to circa 3-8 seconds in existing designs. Whilst some existing designs may also be able to actuate the switch more quickly if so adapted, without active control, and with variable slide chair friction, it would be difficult to consistently achieve this in practice.
2. **Turnout route speed limits** affect headways by requiring vehicles to accelerate or brake on mainline. Table 4.4 lists potential turnout speed increases from the adoption of the stub switch geometry across the range of standard British switches.
3. **Assumption of 'safety' for certain moves:** The Repoint switch may, by its fault-tolerant, bi-stable and failure prognostic design features, be declared 'safe' to actuate within the overlap distance. The capacity impact of such a change can be calculated, though no attempt is made to demonstrate safety herein. Whilst noted that a wrongly set stub-switch *guarantees* derailment in a trailing move, capacity impact is nevertheless evaluated for completeness. It is assumed routing onto occupied track is contained by signalling changes.

4. **Enabling further signalling changes:** The particular network signalling specification has a large influence on capacity. The signalling system may have been specified based upon the available performance of particular asset types, including switches. If the performance of the switches is different to the assumption, then it may be the case that alternate signalling systems offering improved performance would be justified. This may be the case with the fixed vs moving block choice for HS2 - more detail is provided in Section 6.5.2. This will be evaluated for the HS2 scenarios only - LU scenarios assume capacity-optimised signalling.
5. **Higher reliability** and capacity form a trade-off (Figure 2.13); greater reliability can lead to greater capacity as a greater CUI can be used. The CUI achievable in practice is obtained empirically or via simulation. Increasing CUI depends upon the improved reliability of the whole infrastructure system. Capacity change from this approach is not explored further herein, other than to state significantly increasing capacity by increasing CUI would require an improvement in reliability across all infrastructure assets, and switches are currently one of the least reliable (Table 2.3).
6. **Reduction in maintenance intensity:** Whilst switches undergo maintenance interventions, the line is out of use (Table 5.7). Whilst individual downtime may be low, switches are maintained sequentially, meaning that junctions or routes can be unavailable to traffic for a larger portion of time. There is, therefore, the potential for capacity gain through revised maintenance practices (Section 5.6). The potential capacity increase is influenced by each unique route, junction layout, traffic pattern, maintenance and access arrangements, and this relationship is not explored further herein other than to state that a reduction in maintenance downtime directly improves capacity.

6.4 London Underground scenarios (i-iii)

6.4.1 Data sources

LU (London Underground) is an urban rapid transit system with many lines of differing rolling stock, track and signalling specifications. Herein, the Bombardier S8-stock (Webb and Tee, 2015), operating on the sub-surface (Metropolitan, Circle, District and Hammersmith & City) lines, with infrastructure close to mainline specification and train services running at metro frequencies is evaluated (London Underground, 2014). These scenarios are representative of dense-service commuter rail. Whilst LU has developed the proprietary 'journey time capability model', detailing operational headway calculation (Dowton and Baker, 2002), in which junctions are identified as critical capacity pinch points, literature

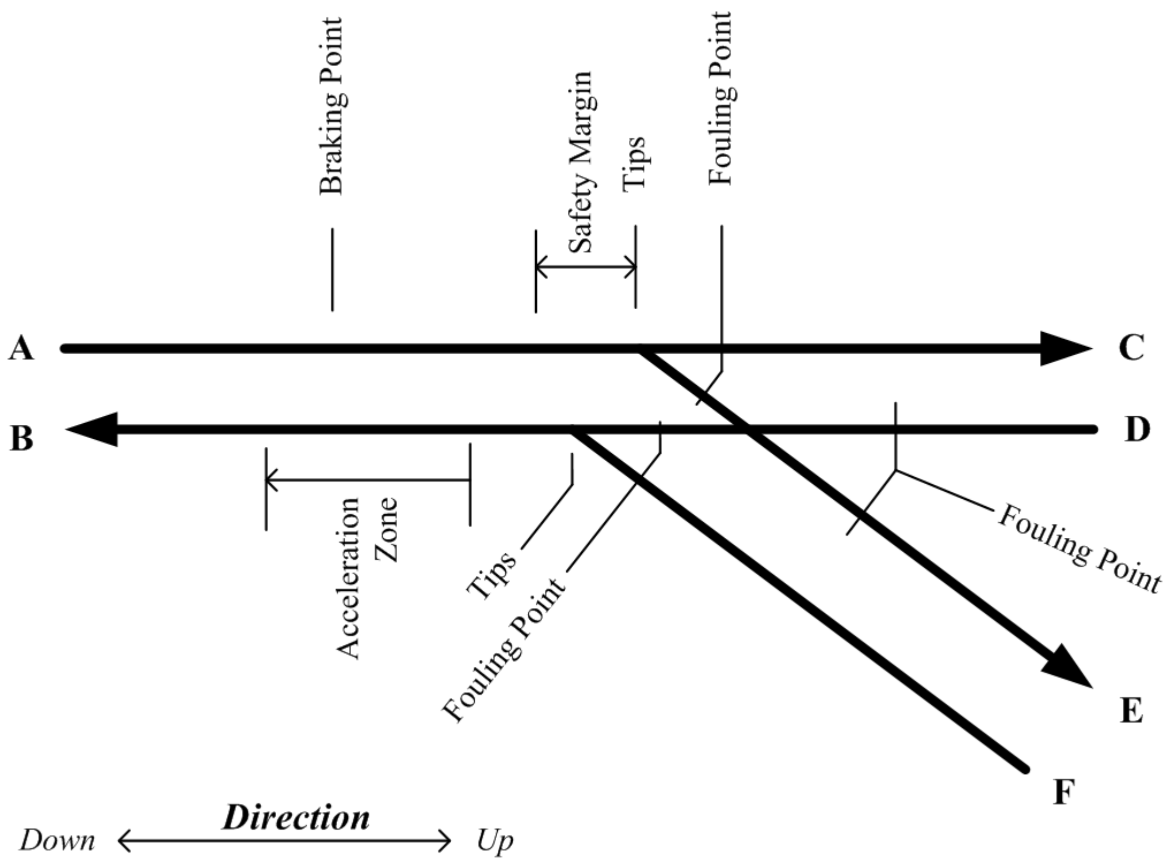


Figure 6.1 Track layout: London Underground double junction showing key locations. Scenario i considers track linking A, C and E in isolation, forming a diverging turnout. Scenario ii considers track linking B, D and F in isolation - a converging turnout. Scenario iii considers the full double junction.

does not evaluate the direct effects of switch performance upon capacity.

Parameters used in this modelling are listed in Table 6.2; where parameters are unavailable for LU specifically, typical metro figures are used (Leach, 1991; Lew and Heede, 2016; Webb and Tee, 2015). At metro speeds, constant acceleration and deceleration rates are assumed, as in industry practice (Dowton and Baker, 2002). It is also assumed that lines are straight and level, driving is perfect, and that signal spacing (or other MA transmission) is optimised for peak capacity (Sections 2.4.1.3 and 2.2.4.6). Speeds and speed restrictions are converted to miles per hour for comparison with switch design speeds.

Symbol	Value	Unit	Description
			Signalling and Infrastructure
d_s	100	m	Safety separation distance between trains
$d_{s(switch)}$	100	m	Safety distance for deceleration at speed restricted turnout
d_{tipfp}	80	m	Distance from point tips to fouling point
$d_{tipfpdbl}$	130	m	Distance from point tips to double junction fouling point
I	3	s	Interlocking response time for issue of MA to train
P	6	s	Time for switch to actuate, lock, detect, communicate
v_{switch}	various	ms^{-1}	Turnout route speed restriction (= v_{line} for no speed restriction)
v_{line}	various	ms^{-1}	Line speed
CUI	75	%	Capacity Utilisation Index
			Rolling Stock
l_{train}	140	m	Length of train
R	2	s	Brake reaction time
b_s	1.14	ms^{-2}	Service braking rate
b_g	0.7		Guaranteed braking rate (expressed as a fraction of b_s)
a_s	1.1	ms^{-2}	Acceleration rate

Table 6.2 Parameters used in modelling London Underground capacity scenarios

6.4.2 Plain line capacity

To evaluate capacity constriction due to switches, capacity of plain line must be established. To maintain safety, trains must be separated by a plain-line minimum headway H_p (Section 2.2.4). Headway is calculated using Equations 6.3 to 6.7, from listed contributors shown in Figure 6.2. Technical capacity C_{Tp}, in TPH (Train Paths per Hour), is calculated from minimum headway using Equation 6.2. Operational capacity, C_{Op}, is the usable fraction of technical capacity defined by the CUI, as in equation 6.1. Headway contributors for plain line are as follows:

- R: A margin to allow for the braking system to react fully when commanded.
- B: A margin to allow for a full brake application to stop.
- S: Time to pass an appropriate safety/overrun distance such that stationary trains are separated.
- L: Time required for the length of the train to pass (at minimum train speed for variable velocity scenarios.)

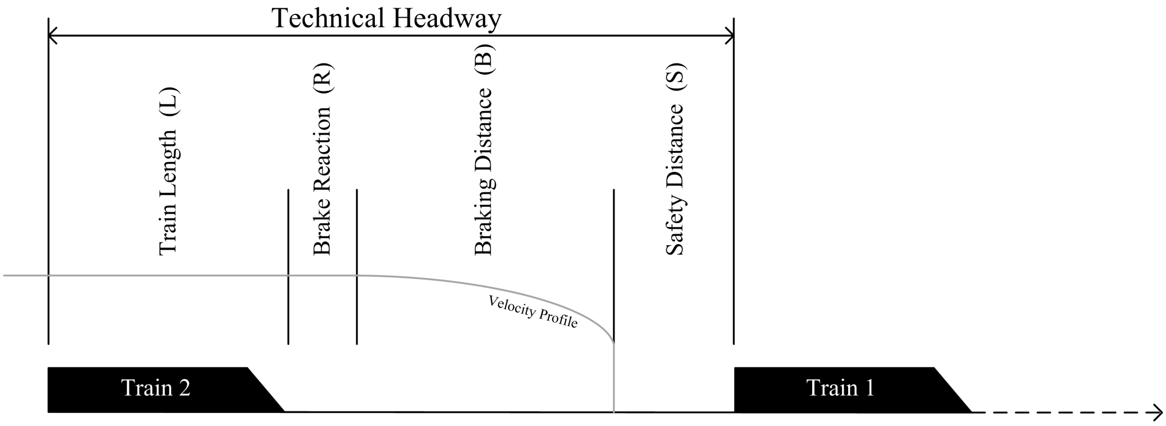


Figure 6.2 London Underground plain line headway contributors.

$$C_{Op} = CUI \times C_{Tp} \tag{6.1}$$

$$C_{Tp} = 3600/H_p \tag{6.2}$$

$$H_p = B + R + L + S \tag{6.3}$$

$$d_b = {v_{line}}^2/2b_s b_g \tag{6.4}$$

$$B = d_b/v_{line} = v_{line}/2b_s b_g \tag{6.5}$$

$$S = d_s/\min\{v_{line}, v_{switch}\} \tag{6.6}$$

$$L = l_{train}/\min\{v_{line}, v_{switch}\} \tag{6.7}$$

Equations 6.5, 6.6 and 6.7 describe the calculation of B, S and L respectively, from parameters in Table 6.2; R is constant. Braking distance d_b is calculated from the service guaranteed braking rate using the equation of motion in 6.4. Service guaranteed braking rate is a worst case deceleration rate expressed as a factor (b_g) of service braking, a lower deceleration rate than achieved in normal running. B is the time it takes to cover this distance at line speed.

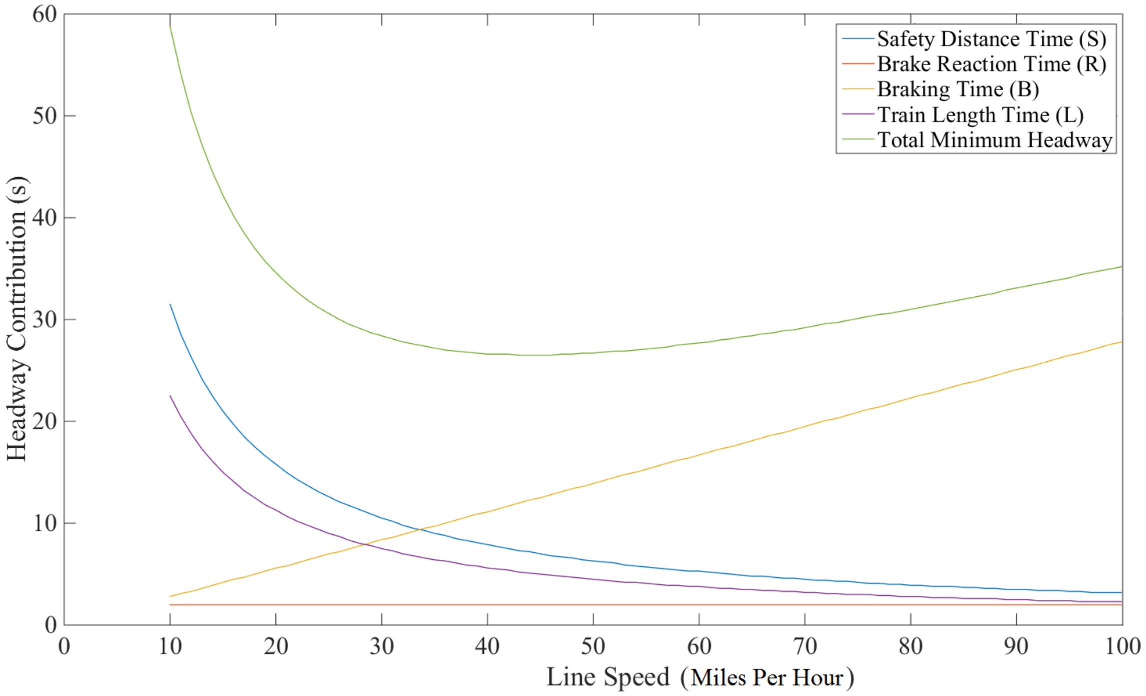


Figure 6.3 London Underground plain line headway contributors as a function of line speed.

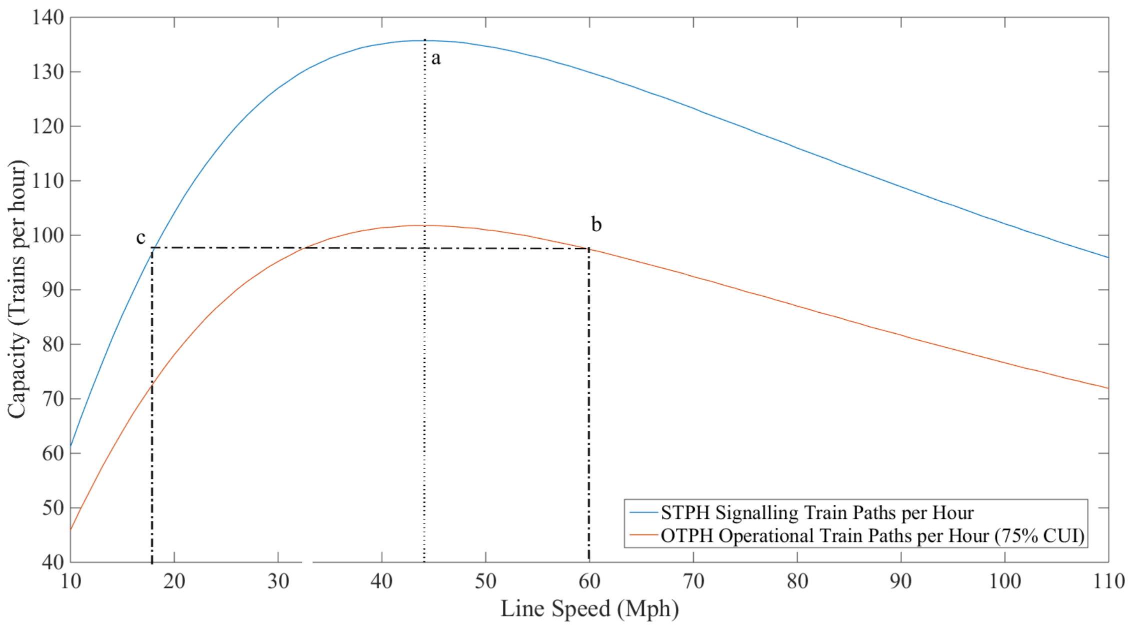


Figure 6.4 Plot showing London Underground plain line capacity as a function of line speed. (a) Peak capacity achieved at 44mph. (b) Line speed is 60mph, meaning slowed trains do not have a negative impact on capacity unless below 18.5mph (c).

Figure 6.3 plots headway and contributors, in seconds, against line speed v_{line}. At low speeds, headway is dominated by the safety margin S and train length L. At more typical line speeds (>30mph), braking margin B becomes dominant. Figure 6.3 identifies that, for this set of parameters, minimum headway of 26.5 seconds is achieved at a line speed of 19.6ms^{-1} (44 mph), equating to a peak capacity of 136 STPH or 102 OTPH. This result corresponds to the S-Stock design speed of 27.7ms^{-1} (62 mph), and line peak design speed of 26.8ms^{-1} (60 mph). Though capacity at line speed of 60mph is below peak, it is important that a speed drop results in a capacity increase, otherwise delay propagation is self-perpetuating (Figure 6.4). Note the calculated capacity is high when compared to real-world service levels, but represents the smallest safe distance between trains on infinite, straight track with no external influence (station calls, terminations/turnarounds, junctions etc).

6.4.3 Case study i: Diverging junction

6.4.3.1 Headway margins

At a diverging turnout, additional margins are added to the plain line headway; not all margins apply to each move, application of each is specified in Table 6.3:

- P: Time for the switch to move, lock and detect its new position.
- I: Time for the interlocking to process and issue movement authority.
- M_d: If the turnout route has a lower speed limit, time for the train to brake to the lower speed on the mainline.
- D_{cd}: If the turnout route has a lower speed limit, additional time for the train to clear the switch at the lower speed, until it no longer encroaches the mainline. Includes an additional safety distance $d_{s(switch)}$.

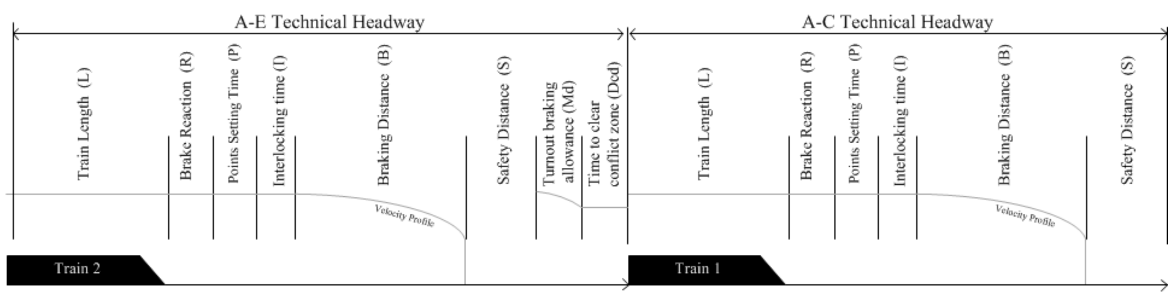


Figure 6.5 London Underground diverging junction, alternating service pattern headway contributors

Speed Restriction?	Previous Train	Current Train	Headway Contributors							
			Plain Line				Junction			
			B	R	L	S	P	I	M_d	D_cd
No	A-C	A-C	1	1	1	1	0	0	0	0
	A-C	A-E	1	1	1	1	1	1	0	0
	A-E	A-C	1	1	1	1	1	1	0	0
	A-E	A-E	1	1	1	1	0	0	0	0
Yes	A-C	A-C	1	1	1	1	0	0	0	0
	A-C	A-E	1	1	1	1	1	1	1	1
	A-E	A-C	1	1	1	1	1	1	0	0
	A-E	A-E	1	1	1	1	0	0	1	1

Table 6.3 Headway contributors for each sequence of trains through a diverging junction (Referring to Figure 6.1).

Figure 6.5 illustrates margins in the case of an alternating service pattern through a junction with a speed restriction. From Table 6.3, with the potential speed restrictions under study, a service pattern of alternating destinations represents the lowest capacity scenario. Capacity is calculated in Equation 6.8, using the mean headway calculated in Equation 6.9. Where different routes have different headways, a mean is used to calculate capacity in Equation 6.8. Equations 6.10 and 6.11 describe the calculation of headway margins. A full table of results across a range of line speeds is presented in Table 6.5.

$$C_{Td} = 3600/H_{d(mean)} \tag{6.8}$$

$$H_{d(mean)} = \frac{2(B+R+L+S+P+I)+M_d+D_{cd}}{2} \tag{6.9}$$

$$M_d = \frac{\left(\frac{v_{line}(v_{line}-v_{switch})}{b_g b_s}\right)-\left(\frac{{v_{line}}^2-{v_{switch}}^2}{2b_g b_s}\right)}{v_{line}} \tag{6.10}$$

$$D_{cd} = (d_{s(switch)}+d_{tipfp})/v_{switch} \tag{6.11}$$

6.4.4 Case study ii: Converging junction

6.4.4.1 Headway margins

At a converging turnout, additional margins are added to the plain line headway; not all margins apply to each move, application of each is specified in Table 6.4. The associated headway margins are illustrated in Figure 6.6.

Turnout Speed restriction?	Previous Train	Current Train	Headway Contributors							
			Plain Line				Junction			
			B	R	L	S	P	I	M_a	D_{cc}
No	D-B	D-B	1	1	1	1	0	0	0	0
	D-B	F-B	1	1	1	1	1	1	0	0
	F-B	D-B	1	1	1	1	1	1	0	0
	F-B	F-B	1	1	1	1	0	0	0	0
Yes	D-B	D-B	1	1	1	1	0	0	0	0
	D-B	F-B	1	1	1	1	O/lay	O/lay	1	1
	F-B	D-B	1	1	1	1	1	1	0	0
	F-B	F-B	1	1	1	1	0	0	1	1

Table 6.4 Headway contributors for each sequence of trains through a converging junction (referring to Figure 6.1.

- P Time for the switch to move, lock and detect its new position.
- I Time for the interlocking to receive detection confirmation, process, and issue a movement authority to the train.
- M_a: If the turnout route has a lower speed limit, time for the train to accelerate to line speed upon the mainline.
- D_{cc}: If the turnout route has a lower speed limit, additional time for the train to clear the switch at the lower speed, to such a position where its rear is beyond the switch tips.

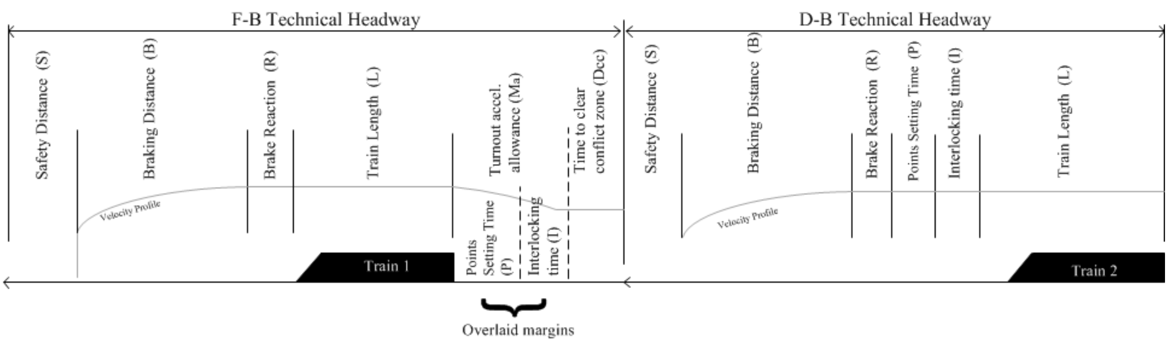


Figure 6.6 London Underground converging junction, alternating service pattern headway contributors

From Table 6.3, it is clear that with or without a speed restriction, a service pattern of alternating routes represents the lowest capacity scenario. Capacity is calculated in Equation

6.12, from mean headway, itself calculated from contributors in equation 6.13. Equation 6.14 describes the calculation of, M_a, the mainline acceleration margin. Where contributions from P and I is present, for one route they can be overlaid (that is, only the greatest of the two margins is used) alongside $M_a + C_d$ as this headway is 'empty' after the junction in an alternating pattern, as per Figure 6.6. A full table of results across a range of line speeds is presented in Table 6.6.

$$C_c = 3600/H_{c(mean)} \tag{6.12}$$

$$H_{c(mean)} = \frac{2(B+R+L+S)+P+I+\max\{(P+I),(M_a+D_{cc})\}}{2} \tag{6.13}$$

$$M_a = \frac{\left(\frac{v_{line}\left(v_{line}-v_{switch}\right)}{a_s}\right)-\left(\frac{v_{line}{}^2-v_{switch}{}^2}{2a_s}\right)}{v_{line}} \tag{6.14}$$

$$D_{cc} = d_{tipfp}/v_{switch} \tag{6.15}$$

6.4.5 Case study iii: Double junction

Many junctions in the LU system are double flat junctions, as depicted in Figure 6.1. The capacity of a flat double junction *in both directions* can be calculated from 6.16, using the mean headway calculated in 6.17. This introduces one additional margin and one constraint for movements as follows:

- D_{cdbl}: Time for trains taking route A-E clearing the junction, at a lower speed if there is a speed restriction, now needs to be calculated with the longer clearance distance $d_{tipfpdbl}$ replacing d_{tipfp} to allow the train to also clear the conflict zone for trains taking route D-B. Calculated in Equation 6.18
- P: Trains cannot receive MA for the D-B route until points set for the A-E route are reset to A-C due to flank protection requirements (Marks, 2000), necessitating a doubling of the points setting margin in this instance.

$$C_{dbl} = 3600/H_{dbl(mean)} \tag{6.16}$$

$$H_{dbl(mean)} = R+B+S+L+P+I+\max\left\{\left(\frac{M_d+D_{cdbl}}{2}\right),\left(P+(\frac{M_a+D_{cc}}{2})\right),\left(\frac{3P+I}{2}\right)\right\} \tag{6.17}$$

$$D_{cdbl} = (d_{s(switch)}+d_{tipfpdbl})/v_{switch} \tag{6.18}$$

The timetable compression method assumes train movements are synchronised to achieve maximum capacity. The capacity of the junction in *either* direction is therefore limited to the lowest of the converging or diverging values (therefore the longest headway). The headway is defined in Equation 6.17, which has three possible values depending whether the diverging (first term), or converging (second and third terms, depending on the greater of the overlaid margins) headway is greater. Full results are presented in Table 6.7.

6.4.6 Case studies i, ii and iii: Collated results and analysis

Tables 6.5 to 6.7 show a range of results for each of the case studies i-iii, using formulae described above. Results are presented for a range of key line speed and speed restriction combinations.

6.4.6.1 Analysis: Case study i, Diverging:

The additional margins present at diverging junctions constrict capacity as follows:

- **Switch actuation and interlocking times** P and I are added to headway through junctions, directly reducing capacity. The reduced switching time of Repoint thus adds less headway margin, and provides a capacity improvement over traditional switches but falling short of plain line.
- **Turnout route speed limits** affect headways by requiring vehicles to brake on mainline, and pass an additional safety distance and the switch at this lower speed, before diverging. This influences parameters M_d, D_{cd} and L. The improved turnout speed of Repoint adds less headway margin, providing a capacity improvement over traditional switches but again falling short of plain line.
- **If Repoint is assumed 'safe'**, the switching time P and interlocking time I can be overlaid onto the time S to cover the safety overlap distance d_s, with the greater of the two being used in the headway equation, reducing overall junction headway for train A-E.

With traditional switches, the junction reduces available capacity to below plain line levels. As expected, the greatest losses occur with the lowest speed restrictions on the highest speed lines; a B-switch on a 90mph line leaving just 50.3% capacity remaining. However, isolated converging and diverging switches are more often found at lower line speeds (depots and stations). Capacity loss is heavily influenced by the presence and magnitude of speed restriction at the switch, influencing M_d, D_{cd} and L, the switch actuation and confirmation time also has an effect, with junctions without speed restriction only achieving around 80%

		Line speed (mph)	15	30	44	62	75	90	15	30	44	62	75	90
Switch type	**Speed restriction (mph)**	**Actuation time (s)**	**Operational Capacity C_o (OTPH)**						**Fraction of plain line capacity (%)**					
Plain line														
n/a			64.3	95.4	101.8	96.3	89.5	81.4	n/a					
Traditional														
	None	6	52.9	72.4	76.0	72.9	68.9	64.0	82.4	75.9	74.7	75.7	77.0	78.7
SG	60	6	52.9	72.4	76.0	66.7	62.1	56.5	82.4	75.9	74.7	69.2	69.4	69.4
F	50	6	52.9	72.4	76.0	64.3	59.5	53.9	82.4	75.9	74.7	66.8	66.4	66.2
E	40	6	52.9	72.4	65.9	60.6	55.9	50.7	82.4	75.9	64.8	62.9	62.4	62.3
D	30	6	52.9	72.4	60.6	55.4	51.1	46.6	82.4	75.9	59.6	57.5	57.1	57.2
C	25	6	52.9	58.0	56.9	52.0	48.2	44.0	82.4	60.8	55.9	54.0	53.8	54.1
B	20	6	52.9	53.5	52.2	47.9	44.5	40.9	82.4	56.1	51.3	49.7	49.8	50.3
Repoint - Reduced actuation time														
	None	0.337	59.6	85.3	90.4	86.1	80.6	73.9	92.6	89.5	88.8	89.4	90.0	90.9
SG	60	0.339	59.6	85.3	90.4	77.6	71.4	64.1	92.6	89.4	88.8	80.5	79.8	78.7
F	50	0.322	59.6	85.4	90.5	74.4	68.0	60.8	92.7	89.5	88.9	77.2	75.9	74.7
E	40	0.304	59.6	85.4	76.6	69.5	63.4	56.8	92.7	89.5	75.2	72.1	70.8	69.7
D	30	0.312	59.6	85.4	69.5	62.7	57.3	51.6	92.7	89.5	68.3	65.1	64.0	63.5
C	25	0.341	59.6	66.1	64.6	58.4	53.6	48.5	92.6	69.3	63.5	60.6	59.8	59.6
B	20	0.404	59.5	60.2	58.6	53.2	49.1	44.7	92.5	63.1	57.5	55.2	54.8	55.0
Repoint - Increased turnout speed restriction														
	None	6	52.9	72.4	76.0	72.9	68.9	64.0	82.4	75.9	74.7	75.7	77.0	78.7
SG	77.46	6	52.9	72.4	76.0	72.9	68.9	59.6	82.4	75.9	74.7	75.7	77.0	73.2
F	59.72	6	52.9	72.4	76.0	66.7	62.1	56.4	82.4	75.9	74.7	69.2	69.3	69.3
E	48.43	6	52.9	72.4	76.0	63.8	59.0	53.5	82.4	75.9	74.7	66.2	65.9	65.7
D	34.72	6	52.9	72.4	63.5	58.1	53.6	48.7	82.4	75.9	62.3	60.3	59.8	59.8
C	29.89	6	52.9	61.3	60.6	55.3	51.1	46.5	82.4	64.2	59.5	57.4	57.1	57.2
B	25.86	6	52.9	58.7	57.6	52.6	48.7	44.5	82.4	61.5	56.6	54.6	54.4	54.7
Repoint - Assumption of safety														
	None	6	58.1	80.4	81.9	76.7	71.7	66.0	90.3	84.3	80.4	79.6	80.1	81.0
SG	60	6	58.1	80.4	81.9	69.8	64.3	58.0	90.3	84.3	80.4	72.5	71.9	71.3
F	50	6	58.1	80.4	81.9	67.2	61.5	55.3	90.3	84.3	80.4	69.8	68.7	67.9
E	40	6	58.1	80.4	70.3	63.2	57.7	51.9	90.3	84.3	69.0	65.6	64.4	63.8
D	30	6	58.1	80.4	64.3	57.5	52.6	47.6	90.3	84.3	63.2	59.7	58.8	58.5
C	25	6	58.1	63.1	60.1	53.9	49.5	44.9	90.3	66.1	59.1	55.9	55.3	55.2
B	20	6	58.1	57.8	54.9	49.5	45.7	41.7	90.3	60.6	54.0	51.4	51.0	51.3
Repoint - Reduced actuation time AND Increased turnout speed restriction														
	None	0.337	59.6	85.3	90.4	86.1	80.6	73.9	92.6	89.5	88.8	89.4	90.0	90.9
SG	77.46	0.339	59.6	85.3	90.4	86.1	80.6	68.1	92.6	89.4	88.8	89.4	90.0	83.7
F	59.72	0.322	59.6	85.4	90.5	77.5	71.4	64.0	92.7	89.5	88.9	80.5	79.7	78.7
E	48.43	0.304	59.6	85.4	90.5	73.8	67.3	60.2	92.7	89.5	88.9	76.6	75.2	74.0
D	34.72	0.312	59.6	85.4	73.2	66.2	60.4	54.2	92.7	89.5	72.0	68.7	67.4	66.6
C	29.89	0.341	59.6	70.3	69.4	62.6	57.2	51.6	92.6	73.7	68.2	65.0	63.9	63.3
B	25.86	0.404	59.5	66.8	65.4	59.1	54.2	49.0	92.5	70.0	64.3	61.3	60.5	60.2
Repoint - Assumption of safety AND Increased turnout speed restriction														
	None	6	58.1	80.4	81.9	76.7	71.7	66.0	90.3	84.3	80.4	79.6	80.1	81.0
SG	77.46	6	58.1	80.4	81.9	76.7	71.7	61.3	90.3	84.3	80.4	79.6	80.1	75.3
F	59.72	6	58.1	80.4	81.9	69.8	64.3	57.9	90.3	84.3	80.4	72.4	71.8	71.2
E	48.43	6	58.1	80.4	81.9	66.7	61.0	54.8	90.3	84.3	80.4	69.2	68.1	67.3
D	34.72	6	58.1	80.4	67.5	60.4	55.2	49.8	90.3	84.3	66.3	62.7	61.7	61.1
C	29.89	6	58.1	67.0	64.2	57.4	52.6	47.5	90.3	70.2	63.1	59.6	58.7	58.4
B	25.86	6	58.1	63.9	60.9	54.6	50.1	45.4	90.3	66.9	59.9	56.6	55.9	55.8
Repoint - Reduced actuation time AND Increased turnout speed restriction AND Assumption of safety														
	None	0.337	61.8	90.1	95.8	90.9	84.3	76.6	96.2	94.4	94.1	94.4	94.2	94.1
SG	77.46	0.339	61.8	90.1	95.8	90.9	84.3	70.3	96.2	94.4	94.1	94.4	94.2	86.4
F	59.72	0.322	61.9	90.1	95.8	81.4	74.3	66.0	96.2	94.5	94.1	84.5	83.0	81.0
E	48.43	0.304	61.9	90.1	95.8	77.2	69.9	62.0	96.2	94.5	94.1	80.2	78.2	76.1
D	34.72	0.312	61.9	90.1	76.7	69.0	62.4	55.6	96.2	94.5	75.3	71.6	69.8	68.3
C	29.89	0.341	61.8	73.5	72.5	65.1	59.1	52.8	96.2	77.1	71.2	67.6	66.0	64.9
B	25.86	0.404	61.8	69.8	68.3	61.4	55.9	50.2	96.1	73.1	67.1	63.7	62.4	61.6

Table 6.5 LU Scenario i results: Diverging junction absolute and relative capacity.

		Line speed (mph)	**15**	**30**	**44**	**62**	**75**	**90**	**15**	**30**	**44**	**62**	**75**	**90**
Switch type	**Speed restriction (mph)**	**Actuation time (s)**	**Operational Capacity C_o (OTPH)**						**Fraction of plain line capacity (%)**					
			Plain line											
n/a			64.3	95.4	101.8	96.3	89.5	81.4	n/a					
			Traditional											
	None	6	52.9	72.4	76.0	72.9	68.9	64.0	82.4	75.9	74.7	75.7	77.0	78.7
SG	60	6	52.9	72.4	76.0	72.8	68.0	62.7	82.4	75.9	74.7	75.5	76.0	77.1
F	50	6	52.9	72.4	76.0	71.7	67.1	62.0	82.4	75.9	74.7	74.5	75.0	76.1
E	40	6	52.9	72.4	75.2	70.3	65.9	60.1	82.4	75.9	73.9	73.0	73.6	73.9
D	30	6	52.9	72.4	72.6	67.7	62.0	56.0	82.4	75.9	71.3	70.3	69.3	68.8
C	25	6	52.9	70.4	70.6	64.2	58.9	53.4	82.4	73.8	69.4	66.6	65.9	65.6
B	20	6	52.9	67.1	65.7	59.7	55.1	50.2	82.4	70.4	64.5	62.0	61.6	61.7
			Repoint - Reduced actuation time											
	None	0.337	59.6	85.3	90.4	86.1	80.6	73.9	92.6	89.5	88.8	89.4	90.0	90.9
SG	60	0.339	59.6	85.3	90.4	85.9	79.1	70.6	92.6	89.4	88.8	89.1	88.3	86.8
F	50	0.322	59.6	85.4	90.5	83.5	76.0	67.8	92.7	89.5	88.9	86.7	85.0	83.3
E	40	0.304	59.6	85.4	87.6	79.2	71.9	64.2	92.7	89.5	86.1	82.2	80.4	78.9
D	30	0.312	59.6	85.4	81.1	72.9	66.4	59.5	92.7	89.5	79.7	75.7	74.2	73.1
C	25	0.341	59.6	77.9	76.5	68.8	62.8	56.6	92.6	81.6	75.1	71.4	70.2	69.5
B	20	0.404	59.5	72.1	70.5	63.7	58.5	53.0	92.5	75.6	69.3	66.1	65.3	65.1
			Repoint - Increased turnout speed restriction											
	None	6	52.9	72.4	76.0	72.9	68.9	64.0	82.4	75.9	74.7	75.7	77.0	78.7
SG	77.46	6	52.9	72.4	76.0	72.9	68.9	63.6	82.4	75.9	74.7	75.7	77.0	78.1
F	59.72	6	52.9	72.4	76.0	72.7	68.0	62.7	82.4	75.9	74.7	75.5	76.0	77.0
E	48.43	6	52.9	72.4	76.0	71.6	67.0	61.8	82.4	75.9	74.7	74.3	74.8	76.0
D	34.72	6	52.9	72.4	74.0	69.2	64.5	58.1	82.4	75.9	72.7	71.8	72.1	71.4
C	29.89	6	52.9	72.4	72.6	67.6	62.0	56.0	82.4	75.8	71.3	70.2	69.2	68.8
B	25.86	6	52.9	70.8	71.0	64.8	59.5	53.9	82.4	74.2	69.8	67.3	66.5	66.2
			Repoint - Assumption of safety											
	None	6	64.3	90.5	88.7	80.8	74.6	68.0	100.0	94.8	87.1	83.9	83.4	83.6
SG	60	6	64.3	90.5	88.7	77.2	70.7	64.2	100.0	94.8	87.1	80.1	79.0	78.9
F	50	6	64.3	90.5	88.7	75.4	69.2	63.0	100.0	94.8	87.1	78.3	77.3	77.4
E	40	6	64.3	90.5	81.7	72.9	67.1	61.2	100.0	94.8	80.3	75.7	75.0	75.2
D	30	6	64.3	90.5	77.0	69.1	63.8	57.5	100.0	94.8	75.6	71.7	71.3	70.6
C	25	6	64.3	78.3	73.5	66.3	60.9	54.8	100.0	82.1	72.2	68.8	68.1	67.3
B	20	6	64.3	73.1	68.9	62.2	56.9	51.4	100.0	76.6	67.7	64.6	63.5	63.2
			Repoint - Reduced actuation time AND Increased turnout speed restriction											
	None	0.337	59.6	85.3	90.4	86.1	80.6	73.9	92.6	89.5	88.8	89.4	90.0	90.9
SG	77.46	0.339	59.6	85.3	90.4	86.1	80.6	73.4	92.6	89.4	88.8	89.4	90.0	90.2
F	59.72	0.322	59.6	85.4	90.5	85.9	79.0	70.6	92.7	89.5	88.9	89.1	88.3	86.7
E	48.43	0.304	59.6	85.4	90.5	83.0	75.5	67.3	92.7	89.5	88.9	86.1	84.3	82.7
D	34.72	0.312	59.6	85.4	84.6	76.1	69.2	61.9	92.7	89.5	83.1	79.0	77.3	76.0
C	29.89	0.341	59.6	81.9	81.0	72.8	66.3	59.5	92.6	85.8	79.6	75.6	74.0	73.0
B	25.86	0.404	59.5	78.6	77.3	69.5	63.4	57.1	92.5	82.4	75.9	72.1	70.9	70.1
			Repoint - Assumption of safety AND Increased turnout speed restriction											
	None	6	64.3	90.5	88.7	80.8	74.6	68.0	100.0	94.8	87.1	83.9	83.4	83.6
SG	77.46	6	64.3	90.5	88.7	80.8	74.6	65.7	100.0	94.8	87.1	83.9	83.4	80.7
F	59.72	6	64.3	90.5	88.7	77.1	70.7	64.2	100.0	94.8	87.1	80.0	78.9	78.9
E	48.43	6	64.3	90.5	88.7	75.1	68.9	62.7	100.0	94.8	87.1	77.9	77.0	77.1
D	34.72	6	64.3	90.5	79.5	71.1	65.6	59.7	100.0	94.8	78.1	73.8	73.2	73.3
C	29.89	6	64.3	82.2	76.9	69.0	63.8	57.4	100.0	86.1	75.5	71.6	71.3	70.6
B	25.86	6	64.3	79.1	74.2	66.8	61.5	55.3	100.0	82.9	72.9	69.4	68.8	67.9
			Repoint - Reduced actuation time AND Increased turnout speed restriction AND Assumption of safety											
	None	0.337	64.3	95.4	101.8	96.3	88.5	79.4	100.0	100.0	100.0	100.0	98.8	97.5
SG	77.46	0.339	64.3	95.4	101.8	96.3	88.5	76.1	100.0	100.0	100.0	100.0	98.8	93.5
F	59.72	0.322	64.3	95.4	101.8	91.1	82.6	73.0	100.0	100.0	100.0	94.6	92.3	89.6
E	48.43	0.304	64.3	95.4	101.8	87.4	78.8	69.5	100.0	100.0	100.0	90.7	88.0	85.3
D	34.72	0.312	64.3	95.4	89.2	79.9	71.9	63.7	100.0	100.0	87.7	82.9	80.4	78.3
C	29.89	0.341	64.3	86.2	85.3	76.2	68.8	61.1	100.0	90.4	83.8	79.1	76.9	75.1
B	25.86	0.404	64.3	82.7	81.2	72.7	65.7	58.6	100.0	86.7	79.8	75.4	73.4	72.0

Table 6.6 LU Scenario ii results: Converging junction absolute and relative capacity.

		Line speed (mph)	**15**	**30**	**44**	**62**	**75**	**90**	**15**	**30**	**44**	**62**	**75**	**90**
Switch type	**Speed restriction (mph)**	**Actuation time (s)**	**Operational Capacity C_o (OTPH)**						**Fraction of plain line capacity (%)**					
Plain line														
n/a			64.3	95.4	101.8	96.3	89.5	81.4	n/a					
Traditional														
	None	6	40.0	53.2	56.2	55.1	53.1	50.3	62.3	55.7	55.2	57.2	59.3	61.8
SG	60	6	40.0	53.2	56.2	53.0	50.4	47.5	62.3	55.7	55.2	55.0	56.3	58.3
F	50	6	40.0	53.2	56.2	51.8	49.3	46.5	62.3	55.7	55.2	53.7	55.1	57.1
E	40	6	40.0	53.2	52.5	50.0	47.8	44.7	62.3	55.7	51.6	51.9	53.4	54.9
D	30	6	40.0	53.2	49.6	47.3	44.5	41.3	62.3	55.7	48.8	49.1	49.7	50.7
C	25	6	40.0	47.5	47.5	44.5	42.0	39.1	62.3	49.7	46.7	46.2	46.9	48.0
B	20	6	40.0	44.4	43.8	41.1	38.8	36.3	62.3	46.6	43.0	42.6	43.4	44.6
Repoint - Reduced actuation time														
	None	0.337	47.2	71.8	79.6	77.6	73.6	68.3	73.3	75.3	78.2	80.5	82.2	84.0
SG	60	0.339	47.2	71.8	79.6	70.8	66.3	61.2	73.3	75.3	78.2	73.4	74.0	75.2
F	50	0.322	47.2	71.8	79.6	67.5	63.4	58.8	73.4	75.3	78.2	70.1	70.8	72.2
E	40	0.304	47.2	71.9	67.1	63.1	59.5	55.0	73.4	75.3	65.9	65.5	66.5	67.6
D	30	0.312	47.2	71.9	60.1	56.9	54.0	50.0	73.4	75.3	59.1	59.1	60.3	61.4
C	25	0.341	47.2	55.3	55.5	52.7	50.2	46.7	73.3	58.0	54.5	54.7	56.1	57.4
B	20	0.404	47.1	49.6	49.7	47.5	45.4	42.8	73.3	52.0	48.8	49.3	50.7	52.5
Repoint - Increased turnout speed restriction														
	None	6	40.0	53.2	56.2	55.1	53.1	50.3	62.3	55.7	55.2	57.2	59.3	61.8
SG	77.46	6	40.0	53.2	56.2	55.1	53.1	48.6	62.3	55.7	55.2	57.2	59.3	59.7
F	59.72	6	40.0	53.2	56.2	52.9	50.4	47.4	62.3	55.7	55.2	55.0	56.3	58.3
E	48.43	6	40.0	53.2	56.2	51.5	49.1	46.3	62.3	55.7	55.2	53.5	54.9	56.9
D	34.72	6	40.0	53.2	51.2	48.8	46.4	43.0	62.3	55.7	50.3	50.7	51.9	52.9
C	29.89	6	40.0	49.5	49.6	47.2	44.4	41.2	62.3	51.9	48.7	49.0	49.6	50.7
B	25.86	6	40.0	47.9	48.0	45.0	42.4	39.5	62.3	50.2	47.1	46.8	47.4	48.5
Repoint - Assumption of safety														
	None	6	48.7	67.0	67.5	63.7	60.2	56.0	75.7	70.2	66.4	66.2	67.2	68.9
SG	60	6	48.7	67.0	67.5	60.9	56.4	51.5	75.7	70.2	66.4	63.2	63.0	63.3
F	50	6	48.7	67.0	67.5	58.6	54.1	49.4	75.7	70.2	66.4	60.8	60.5	60.6
E	40	6	48.7	67.0	61.2	55.2	51.0	46.6	75.7	70.2	60.1	57.3	57.0	57.2
D	30	6	48.7	67.0	56.0	50.5	46.8	42.9	75.7	70.2	55.0	52.4	52.2	52.7
C	25	6	48.7	55.6	52.3	47.3	44.0	40.5	75.7	58.2	51.4	49.1	49.1	49.8
B	20	6	48.7	50.6	47.7	43.4	40.6	37.6	75.7	53.1	46.9	45.1	45.3	46.2
Repoint - Reduced actuation time AND Increased turnout speed restriction														
	None	0.337	47.2	71.8	79.6	77.6	73.6	68.3	73.3	75.3	78.2	80.5	82.2	84.0
SG	77.46	0.339	47.2	71.8	79.6	77.6	73.6	64.3	73.3	75.3	78.2	80.5	82.2	79.0
F	59.72	0.322	47.2	71.8	79.6	70.7	66.2	61.2	73.4	75.3	78.2	73.4	74.0	75.2
E	48.43	0.304	47.2	71.9	79.7	66.9	62.9	58.3	73.4	75.3	78.3	69.5	70.3	71.7
D	34.72	0.312	47.2	71.9	63.7	60.1	56.8	52.5	73.4	75.3	62.6	62.4	63.5	64.5
C	29.89	0.341	47.2	59.8	60.0	56.8	53.9	49.8	73.3	62.7	58.9	58.9	60.2	61.2
B	25.86	0.404	47.1	56.1	56.3	53.4	50.8	47.2	73.3	58.8	55.3	55.5	56.8	58.0
Repoint - Assumption of safety AND Increased turnout speed restriction														
	None	6	48.7	67.0	67.5	63.7	60.2	56.0	75.7	70.2	66.4	66.2	67.2	68.9
SG	77.46	6	48.7	67.0	67.5	63.7	60.2	53.9	75.7	70.2	66.4	66.2	67.2	66.3
F	59.72	6	48.7	67.0	67.5	60.8	56.4	51.5	75.7	70.2	66.4	63.1	63.0	63.2
E	48.43	6	48.7	67.0	67.5	58.2	53.7	49.0	75.7	70.2	66.4	60.4	60.0	60.2
D	34.72	6	48.7	67.0	58.7	52.9	48.9	44.8	75.7	70.2	57.7	55.0	54.7	55.0
C	29.89	6	48.7	59.2	55.9	50.4	46.7	42.9	75.7	62.1	54.9	52.3	52.2	52.7
B	25.86	6	48.7	56.3	53.0	47.9	44.5	41.0	75.7	59.0	52.1	49.7	49.7	50.3
Repoint - Reduced actuation time AND Increased turnout speed restriction AND Assumption of safety														
	None	0.337	50.1	78.8	88.3	86.2	80.5	73.3	77.9	82.6	86.7	89.5	89.9	90.0
SG	77.46	0.339	50.1	78.8	88.3	86.2	80.5	68.3	77.9	82.6	86.7	89.5	89.9	84.0
F	59.72	0.322	50.1	78.8	88.3	77.4	71.5	64.8	77.9	82.6	86.7	80.4	79.8	79.7
E	48.43	0.304	50.1	78.8	88.3	72.9	67.6	61.6	77.9	82.6	86.7	75.6	75.5	75.7
D	34.72	0.312	50.1	78.8	69.1	64.9	60.7	55.2	77.9	82.6	67.9	67.4	67.8	67.8
C	29.89	0.341	50.1	64.6	64.8	61.1	57.3	52.2	77.9	67.7	63.6	63.4	64.0	64.2
B	25.86	0.404	50.1	60.4	60.5	57.3	53.9	49.4	77.9	63.3	59.5	59.5	60.2	60.6

Table 6.7 LU Scenario iii results: Double junction absolute and relative capacity.

of plain-line levels. The reduced actuation time of Repoint alone recovers around half of this lost capacity in non-restricted cases, with between 88.8% and 92.6% of plain line capacity made available in the unrestricted case. Improving the turnout speed restriction has a more marginal effect, partially as the relative magnitude of speed improvement is smaller, and partly due to the squared term in the braking equation being dominant with speed changes. At the peak capacity linespeed of 44mph, combining reduced actuation time and improved actuation time yields circa an additional 13% capacity across all speed restrictions - equating to around an additional 11-14 OTPH.

In the case of assumption of safety alone, there is some capacity gain, but this becomes marginal with higher line speeds as the combined switching and interlocking time margins (P and I) become much longer than the Safety distance margin S, and therefore dominate. This influence is negated in higher speed cases with the use of reduced actuation time, indicated in the lowest section of Table 6.5, which indicates a significant capacity increase across all speed combinations, with 94.1% plain line capacity available in the unrestricted, peak plain-line capacity scenario (compared to 74.7% for traditional). At 15mph line speed (no speed restriction), this means that 96.2% of plain line capacity can be achieved - a significant result, as there are a large number of lower-speed diverging junctions on the network, i.e. at grade-separated station approaches.

6.4.6.2 Analysis: Case study ii, Converging:

The additional margins present at converging junctions constrict capacity as follows:

- **Switch actuation interlocking times** P and I are added to headway through junctions, directly reducing capacity. The reduced switching time of Repoint thus adds less headway margin, and provides a capacity improvement over traditional switches falling short of plain line.
- **Turnout route speed limits** affect headways by requiring vehicles to pass the switch at lower speed and accelerate on mainline. This influences parameters M_a, $D_c c$ and L. The improved diverging speed of Repoint adds less headway margin, providing a capacity improvement over traditional switches but again falling short of plain line.
- **If Repoint is assumed 'safe'**, the switching time P and interlocking time I can be overlaid onto the time S to cover the safety overlap distance d_s for the D-B route, with the greater of the two being used in the headway equation. For the F-B route, the greater of $P+I$ or M_a+S is used. This reduces headways.

With traditional switches, the junction reduces available capacity to below plain line levels; this restriction is to an equal or lesser extent than the diverging case for three reasons. Firstly, the acceleration rate a_s is greater than the guaranteed braking specification $b_s \times b_g$ (the braking rate being safety-related, therefore conservatively set). Secondly, for instances with a speed restriction, the influence of the points setting and interlocking margins P and I are negated for the train taking the F-B route as they are applied concurrently with the acceleration allowance M_a, if present. Thirdly, D_{cc} is of lower magnitude than D_{cd} as the F-B train does not brake for the junction, removing the requirement for the additional safety distance $d_{s(switch)}$. As in the diverging case, capacity loss is heavily influenced by the presence and magnitude of speed restriction at the switch, which influences M_a, C_a and L, and the switch actuation and confirmation times, P and I. The improved actuation times of Repoint now have a greater influence with greater speed restriction as in certain cases they allow the margin to occur entirely concurrently with the mainline acceleration allowance, M_a. The combination of reduced actuation times alongside improved turnout speeds has significant impact, with capacity available at peak capacity line-speed (44mph) being improved to 90.4% from 76.0% without a speed restriction, and 77.3% from 65.7% with the greatest speed restriction.

Under the assumption of safety, the fraction of capacity available is improved over traditional and equivalent diverging cases. The magnitude of this improvement is greater the lower the speed restriction. At 15mph line speed (no speed restriction), this means that 100% of plain line capacity can be achieved. This is due to the relative length of the fixed safety distance margin S being long enough to mask the effects of points operation. As for the diverging case, this result is significant, as there are also a large number of low-speed converging junctions on the network, i.e. departing platforms. This result is replicated for some higher line-speeds, including the peak capacity line-speed (44mph), with a range of speed restrictions, in the case where all changes are made concurrently (the lowest section of Table 6.6).

6.4.6.3 Analysis: Case study iii

The treatment of margins influenced by switch actuation, interlocking, and turnout route speed limits is as per scenarios i and ii. Under the assumption of safety, the same overlay principles apply as in scenarios i and ii, with the flank protection requirement also eliminated, removing one P term from Equation 6.17.

Flat double junctions are more likely to occur away from stations, with trains running at higher speeds; therefore this analysis will focus upon peak capacity line-speed (44mph). As expected, in all cases the capacity of the flat double junction is lower than that for either diverging or converging. In the traditional case, at peak capacity line-speed, capacity falls to between 43.0%-55.2% that of equivalent plain line, depending upon speed restriction.

Due to the multiplicity of switch actuation times P, including the requirement for the flank protection, Repoint's effect of reducing the switch actuation time is significant in recovering a portion of this capacity, giving 48.8%-78.2% across the same restriction range. Improving the turnout speed restriction alone has a much smaller influence (limited to an additional 4.1% at the same line-speed) as the associated margins are overlaid in the headway equation and therefore no longer influential when compared to switch actuation times. There is larger gain when combining the reduced actuation times and improved turnout speed restrictions, across all switches with a restriction, with the peak capacity line-speed capacities improved to 55.3%-78.2%.

The assumption of safety has much less positive effect than in the converging or diverging case. This is due to the fact the assumption cannot extend to conflicting train moves - i.e. the headways over the junction must remain as clear time margins, lessening the effect of this change. This is true even when the turnout speed restriction is improved. If all three changes are made concurrently, as in the lowest section of Table 6.7, then the assumption of safety adds some benefit over the other changes in solitude; in all cases, however, it still falls short of offering the capacity improvement available in scenarios i and ii. At peak capacity line-speed, however, capacity is improved to 59.5%-86.7% of plain line, depending on speed restriction, which represents a significant increase over the benchmark, traditional case described above. The results in table 6.7 are important for two reasons. Firstly, they indicate the double junction scenario is the most capacity-constricted junction type for traditional switching practice on a metro-type system. Secondly, that a significant portion of the available plain-line capacity lost in these locations can be regained through the enhanced performance of Repoint.

6.5 HS2 Scenarios

6.5.1 Data Sources

HS2 is a High-Speed rail link in England, due to commence construction in 2018. It is to consist of a segregated traffic network of high speed and high service frequency (HS2 Ltd, 2011b). Specifications for signalling (McNaughton, 2011) and track (HS2 Ltd, 2012) are public domain, as are a number of third party reports verifying performance data (HS2 Ltd, 2011a; Systra UK, 2011). Data for the 'HS2 reference train' used in this published modelling is proprietary, though key performance figures are published (Connor, 2014; McNaughton, 2011). These figures are used for modelling herein. Data sources identify that all HS2 junctions are to be fully grade separated, removing conflicting moves. The flat-double scenario is therefore not evaluated, leaving diverging (scenario iv) and converging (scenario v) only. Alternating train destinations will again be quantified as this represents the most capacity constricted case.

6.5.2 Plain line capacity

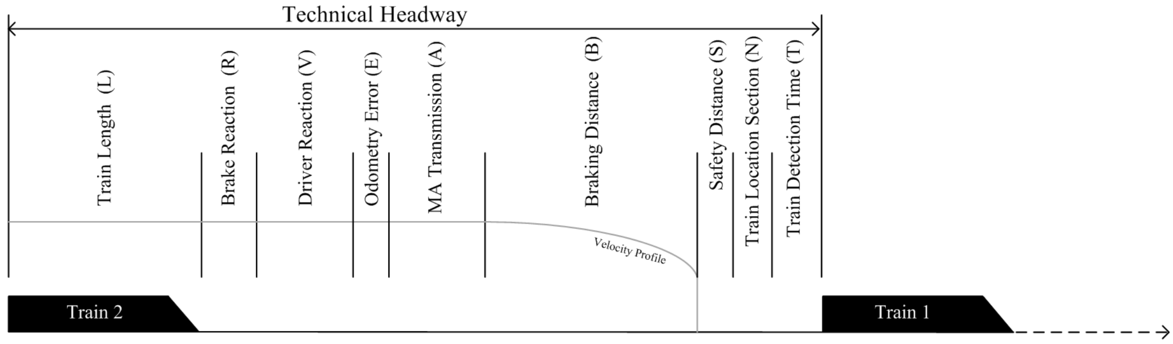


Figure 6.7 HS2 plain line headway contributing margins (Adapted from (McNaughton, 2011)).

As per scenarios i-iii, headway on plain line must be established in order to evaluate the capacity constriction caused by switches. Headway is calculated from margin contributions in the same manner as previously. However, due to different signalling arrangements, to calculate headway, Equation 6.19 needs to be used in place of Equation 6.3, with technical and operational capacity (Train Paths per Hour) calculated from the result using Equations 6.2 and 6.1 respectively. As the proposed HS2 signalling arrangements are publicly available (HS2 Ltd, 2012; McNaughton, 2011), plain line capacity will be evaluated for the in-service case. It is again assumed that the line is straight and level and that driving is perfect, however in this case, the published specifications of the ETCS-L2 signalling system (Section 2.2.4.6) are used as part of the calculation rather than the assumption of signalling optimised for peak capacity as in scenarios i-iii. Headway contributors for ETCS-L2 signalled plain line are shown in Figure 6.7. Whilst there are many more margins in the HS2 headway equation, most are specified as constant times rather than distances, meaning they can be combined into $M_{constant}$ in Equation 6.20. This enables the simplified equation, 6.21. Fixed margins are listed alongside other key parameters in Table 6.8. There are four line-speed variable margins:

- B: A margin to allow distance for a full brake application to stop, at plain line speed (Equation 6.5).

- S: Time to pass an appropriate safety separation distance - in this case, End of Authority to Supervised Location - (Equation 6.6).
- L: Time required for the length of the train to pass, at minimum train speed for variable velocity scenarios (Equation 6.7).
- N: Time for the train to pass the detection section (Equation 6.22). The time contribution of this margin is also dependent upon the length of the block sections, and the speed of the given train.

$$H_p = B + N + E + S + A + T + R + V + L + C \tag{6.19}$$

$$M_{constant} = E + A + T + R + V + C = 20 \tag{6.20}$$

$$H_p = M_{constant} + B + S + L + N \tag{6.21}$$

$$N = l_{block}/(v_{line} \text{ or } v_{switch}) \tag{6.22}$$

Symbol	Value	Unit	Description
			Signalling and Infrastructure - (Source (McNaughton, 2011)).
d_s	300	m	Safety separation distance between trains.
l_{block}	1600	m	Signalling block length (plain line).
l_{block}	400	m	Signalling block length (in junction areas).
v_{switch}	62.5	ms^{-1}	Turnout route speed restriction.
v_{line}	100	ms^{-1}	Design line-speed.
P	9	s	Time for switch to actuate, lock, detect, communicate.
I	3	s	Interlocking processing time for switch movements.
E	1	s	A margin allowed for odometer error.
A	5	s	Time required for the signalling system process the MA. ((Connor, 2014) states 10s)
T	2	s	Time required for the signalling system to detect the train.
R	3	s	A margin to allow for the braking system to react fully when commanded.
V	7	s	Time required for the driver and train systems to respond to the MA .
C	2	s	Time required for the MA to be transmitted to the train, processed, confirmed.
			Rolling Stock
l_{train}	400	m	Length of train.
$b_m (= b_g \times b_s)$	0.687	ms^{-2}	Mean train braking rate.
a_s	0.14	ms^{-2}	Mean train acceleration rate (above $46ms^{-1}$ (Connor, 2014)).

Table 6.8 Parameters used in modelling HS2 capacity scenarios. (Source: (McNaughton, 2011))

Literature uses various HS2 reference train parameters, with particular difference between acceleration and braking performance. Due to the high speeds involved, choice of these values when modelling (and, by extension, the eventual performance of the rolling stock) has a significant impact on capacity. (Connor, 2014) in particular provides an explanation of their derivation, opting for more conservative *mean* braking, and more optimistic acceleration values than other publications (McNaughton, 2011; Systra UK, 2011), leading to lower capacity figures. Official published HS2 parameters are used herein to provide meaningful comparison to published data.

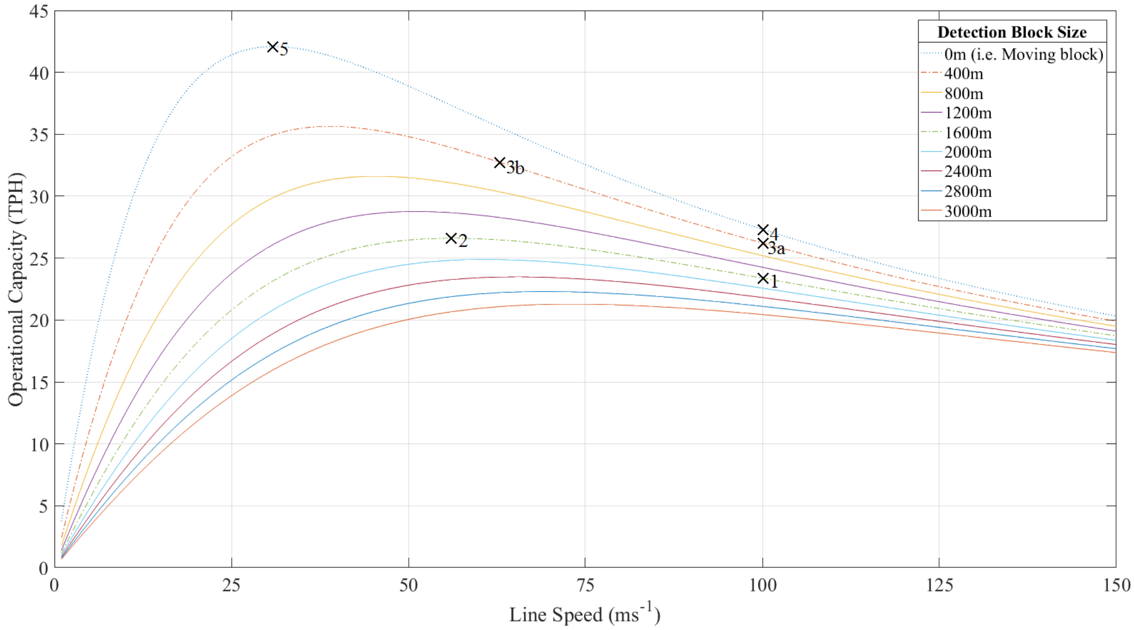


Figure 6.8 HS2 plain line operational capacity vs line speed for a range of signalling block sizes.

Figure 6.8 shows the peak plain-line capacity for a range of signalling block length l_{block} values. This can be compared to Table 6.9, which shows the range of in-service capacity figures published by HS2. Referring to the numbered points in Figure 6.8:

1. With 1600m block sections and a 100ms^{-1} (360km/h) design line speed, peak operational capacity is calculated as 23.3TPH per direction, comparable to the official published value of 23TPH in Table 6.9.
2. If train speed drops, then capacity increases, preventing self-perpetuating delay propagation (as explained in Figure 6.4). Peak capacity of 26.5TPH with 1600m block sections is achieved at 56ms^{-1}.
3. At junctions, the infrastructure specification calls for the block granularity to be improved to 400m to cancel out the effects of the additional margins explored later. At 100ms^{-1}, this gives a capacity of 26.0TPH (a). At the turnout route design speed of 62.5ms^{-1}, capacity is much higher at 32.5TPH (b).

Assumptions	Headway (s)	Signalling capacity (TPH)	Operational capacity (TPH)
		Plain Line	
Worst	139	23	19
HS2	116	31	23
Best	92	39	29
		Diverging Junction	
Worst	149	24	18
HS2	119	29	22
Best	95	38	28
		Converging Junction	
Worst	143	25	19
HS2	125	28	21
Best	106	34	25

Table 6.9 Published capacity of HS2 under different signalling performance assumptions. Reproduced and adapted from (HS2 Ltd, 2011b).

4. 'Moving Block' ETCS Level-3 is equivalent to Level-2 with a vanishingly small block size, illustrated here as 0m. Whilst Level-2 is specified, if Level-3 were adopted then plain line operational capacity at 100ms^{-1} speed rises to 27.1TPH, a 16.3% increase.
5. If Level-3 were adopted, then plain line peak operational capacity is 43TPH, achieved at a line-speed of 31ms^{-1}.

The wide spread of results in Table 6.9 is due to different assumptions of rolling stock (braking and acceleration) and infrastructure (mainly MA transmission) performance. The selection of block size is easily controlled and has a significant impact on capacity. However, block joints are expensive, require maintenance, and have a reliability impact (Stanley, 2011), thus there is a counter-incentive to make detection blocks as long as possible. 1600m has been selected by HS2 as a compromise, with a reduction to 400m at key locations to lessen capacity constriction. Moving block signalling can release extra capacity, and eliminate a fraction of the additional performance impact in these other areas. However, (McNaughton, 2011) includes an important conclusion, which makes the argument to sacrifice the 16.3% extra capacity available from ETCS Level-3 on HS2 due to the capacity-limiting presence of existing junction practice:

> The technical development of ETCS Level 3 ("Moving Block") train control system would have potential benefit for reduction in line-side infrastructure and

hence maintenance workload and cost. However, it would be of little practical benefit to signalling headway at the limiting points on the network at junctions. Therefore it is not considered.

6.5.3 Case study iv: HS2 Diverging turnout

6.5.3.1 Headway margins

At a diverging junction, three additional margins are added to the plain line headway:

- P: Time for the switch to move, lock and detect its new position.
- I: Time for the interlocking to process and issue movement authority.
- M_d: Time for the train to brake to the lower speed on the mainline (diverging trains only).

In addition, the contribution of L increases as it is dependent upon lowest train speed. Unlike the LU scenario's, the D_{cd} margin does not apply as it is allowed for with the l_{block} term in the train detection margin N. The simplified Equation 6.23, calculated using junction speed values, expresses the diverging junction headway, $H_{d(mean)}$. Results are presented in collated form in Section 6.5.5.

$$H_{d(mean)} = \big(H_p + (M_{constant} + B + S + L + N + P + I + M_d\big)/2 \qquad (6.23)$$

6.5.4 Case study v: HS2 Converging turnout

6.5.4.1 Headway margins

At a converging junction, an additional margin is required, M_a, the time for the train to accelerate to line speed after traversing the junction, calculated as for the LU case in Equation 6.14. $H_{c(mean)}$ is calculated with Equation 6.24 using junction speed values. Results are presented in collated form in Section 6.5.5.

$$H_{c(mean)} = \big(H_p + (M_{constant} + B + S + L + N + P + I + M_d\big)/2 \qquad (6.24)$$

6.5.5 HS2 scenarios: Collated results and analysis

6.5.5.1 Capacity Impacts

Diverging junction capacity is impacted in the following ways:

- **Switch actuation interlocking times** Just as in the LU scenarios, a reduction in switching time would directly influence capacity through reducing the $P+I$ term . I is considered constant; changing it would require revising interlocking practice, beyond the scope of the study. The switch specified for HS2 has a divergent speed of 62.5ms^{-1} (140mph), which is higher than any existing British specification. Ideally, actuation time would be established as in Chapter 4, however, this method is dependent on full track specifications (for rail mass, stiffness, curvature, slope etc). which are not yet defined. Linear Extrapolation of the larger values in Table 4.6, i.e. the values where GPE is dominant, indicates an actuation time around 1-1.5 seconds if NR specification rail and switches are used, therefore 3 seconds could be taken as a conservative assumption. Figure 6.9 plots the capacity of a range of reduced switching times in order to quantify the influence of the variable.
- **Turnout route speed limits** influence speed-variant parameters as explained in Section 6.5.3.1. Repoint may offer enhanced turnout route speed limits upon a switch of this size. Again, however, the exact magnitude of change is unknown. The mean speed increase in Table 4.4 is 18%, forming a reasonable first assumption. A range of speeds have been evaluated in order to quantify the capacity influence of the variable.
- **If Repoint is assumed 'safe'**, the switching time P and interlocking time I can be overlaid onto the time S to cover the safety separation distance d_s, with the greater of the two being used in the headway equation, reducing overall junction headway.
- **With ETCS-L3 Signalling**, $l_{block} = 0m$ in plain line areas. At junctions, the assumption is made that $l_{block} = 200m$, which has the effect of ensuring the train is clear of the conflict zone in the same way as D_{cd}, though the practical implementation may be somewhat different. This distance is inferred from the turnout specifications in (Connor, 2014).

Similarly, converging junction capacity is impacted as follows:

- **Switch actuation interlocking times** As for diverging, scenarios, a reduction in switching time would directly influence capacity through reducing the $P+I$ term. However, the influence is not as great as diverging, as the second train's $P+I$ term is overlaid onto the spare headway of the converging train in the same manner as Figure 6.6.

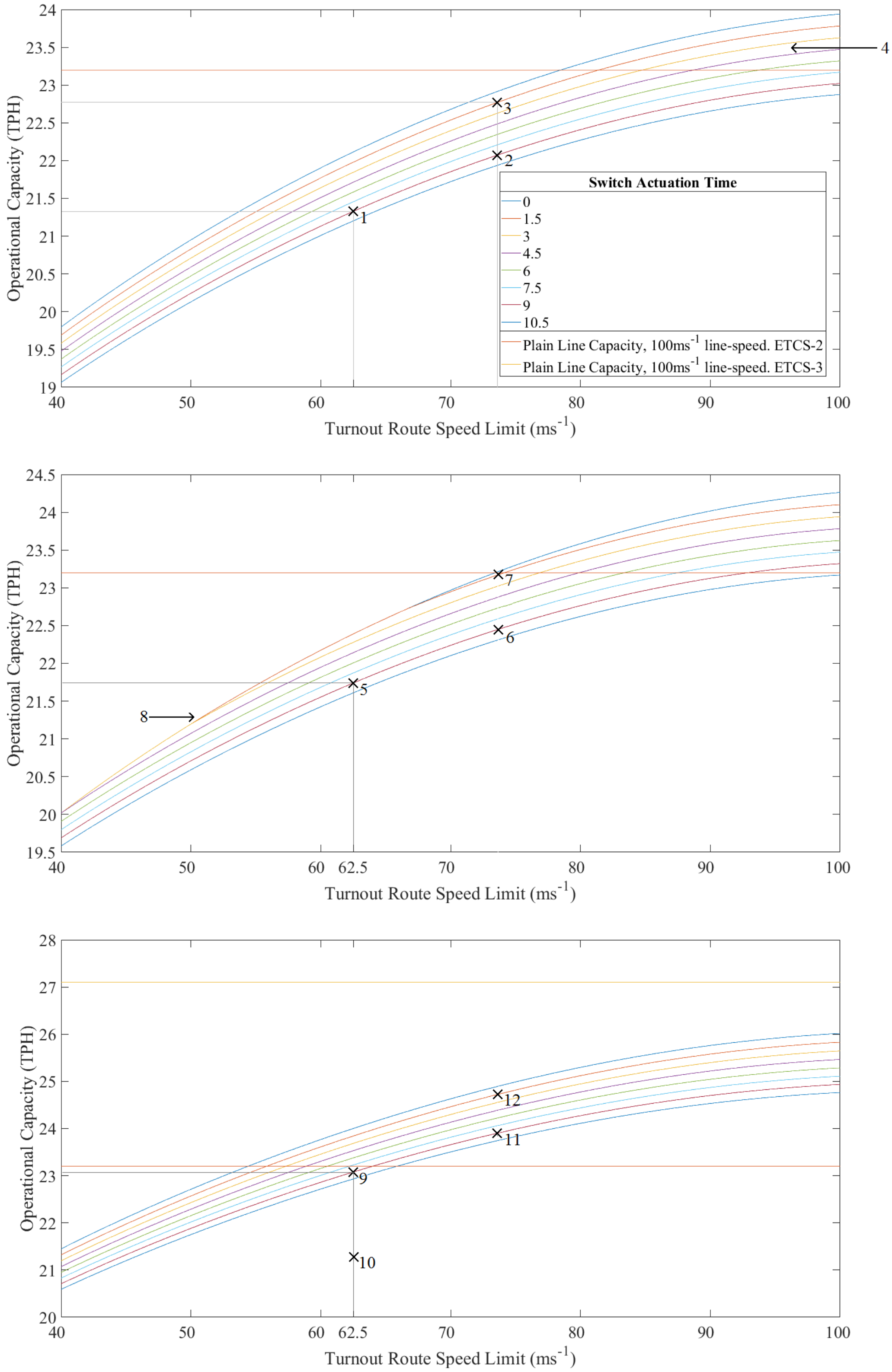


Figure 6.9 Scenario iv results: HS2 diverging junction capacity. Top: Capacity vs. Turnout route speed restriction for a range of switch actuation times. Middle: As top, with the assumption of safety. Bottom: As top, with ETCS Level-3 signalling assumptions.

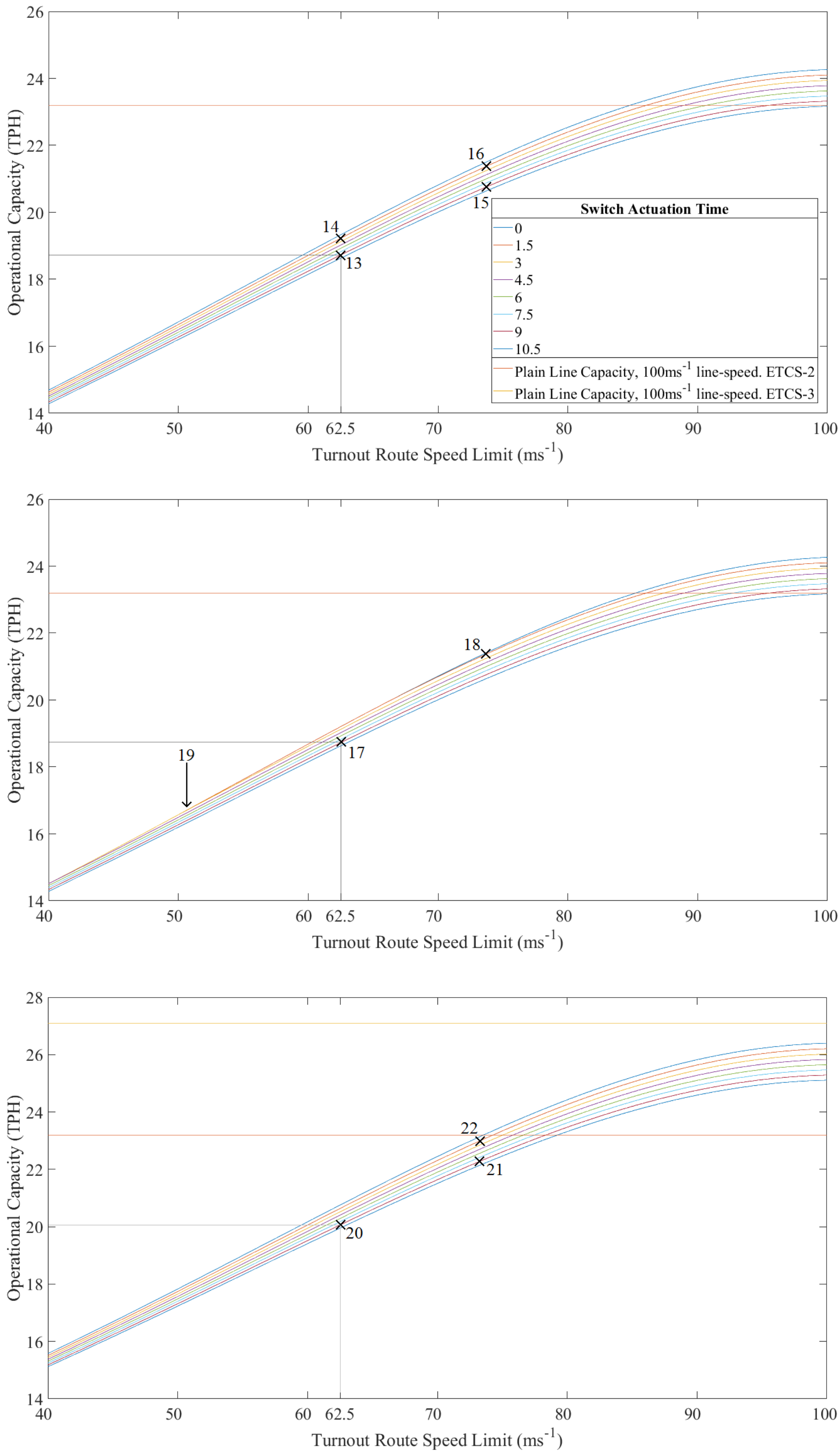


Figure 6.10 Scenario v results: HS2 converging junction capacity. Top: Capacity vs. Turnout route speed restriction for a range of switch actuation times. Middle: As top, with the assumption of safety. Bottom: As top, with ETCS Level-3 signalling assumptions.

- **Turnout route speed limits** influence speed-variant parameters as explained in Section 6.5.3.1. At high speed, the mean acceleration of a high-speed train is significantly lower than the mean braking rate, the opposite of the metro scenarios.
- **If Repoint is assumed 'safe'**, the switching time P and interlocking time I of the first train can be overlaid onto the time S to cover the safety separation distance d_s, with the greater of the two being used in the headway equation, reducing overall junction headway.
- **With ETCS-L3 Signalling**, the same assumptions are made as in the diverging case.

6.5.5.2 Analysis

With reference to the numbered points in Figures 6.9: and 6.10, the following observations are made:

- In the **diverging case**, the HS2 specification junction achieves a capacity of 21.4 TPH (1). If the highest turnout speed NR specification switch were used (H-switch, at 40ms^{-1}, with 6s actuation time) then junction capacity drops to 19.4 TPH.
- With a turnout route speed improved 18% (to 73.8ms^{-1}) then capacity rises to 22.1 TPH (2). If the actuation time is reduced to 1.5s, this increases further to 22.8 TPH (3). These are significant improvements when compared with the plain-line capacity limit.
- Counter-intuitively, for certain combinations of switch performance characteristics, the junction has a higher capacity than equivalent plain line (4). This is due to the reduced detection block length l_{block} of 400m in place at the junction.
- With a Repoint switch under the assumption of safety alone, capacity rises to 21.7 TPH (5), a minimal improvement over standard. With improved turnout speed (6) and improved actuation time (7), this rises to 22.5 and 23.2 TPH respectively, the latter equal to in-service plain line specification.
- At very fast actuation times, the limiting factor becomes S, the time it takes each train to pass the safety separation distance (8). If an NR H-switch were used (90mph or 40ms^{-1}) , the switch could take up to 4.5s to actuate without affecting capacity further.
- Under ETCS level-3 assumptions (i.e. block length $l_{block} = 0$ so the train must just clear the conflict zone before actuation), the capacity of the standard specification diverging junction (9) is nearly equal to the ETCS level-2 plain line case at 23.1 TPH, and significantly greater than the original switch specifiaction (10). With a greater turnout route speed (11), capacity rises to 23.9 TPH, and a reduced actuation time

(12), further to 24.7 TPH; both of which are greater than the proposed in-service plain line capacity.

- In the **converging case**, the HS2 specification junction achieves a capacity of 18.7 TPH (13). If the highest turnout speed NR specification switch were used (H-switch, at 40ms^{-1}, with 6s actuation time) then junction capacity drops to only 14.5 TPH.
- Improving the switch actuation time to 1.5s has relatively little impact (14), giving 19.2 TPH. If turnout route speed is improved 18% (15), capacity improves more to 20.7 TPH. With both improvements, capacity reaches 21.3TPH (16).
- Under the assumption of safety, capacity rises to 18.7 TPH in the traditional switch performance case (17), or 21.3 TPH with reduced actuation time and greater turnout route speed (18) (i.e. the assumption of safety gives no benefit here, as the switch is not required to be actuated in a safety distance.
- At lower turnout route speeds, the limiting factor again becomes S, the time it takes each train to pass the safety separation distance (19). Also at lower speeds, capacity falls more significantly than with the diverging case. This is due to the acceleration rate a_s being less than the braking rate b_m.
- Under ETCS Level-3 assumptions, traditional junction operation restricts capacity at 20.1TPH (20); with greater turnout route speed this becomes 22.3 TPH (21), and with reduced actuation time in addition, 23.0 TPH (22).

It is clear from Figures 6.9 and 6.10 that the converging junction presents the capacity constricted case. This conclusion is supported by official figures, for instance in Table 6.9. Not only is the converging junction more constricting, but capacity is also more sensitive to the specification of turnout route speed limit, with switch actuation time being of lesser importance. This is due to the acceleration rate at high-speed $a_s = 0.14\text{ms}^{-2}$, whereas the braking rate $b_m = 0.687\ \text{ms}^{-2}$. This means the mainline acceleration allowance M_a will be significantly greater than the braking allowance M_d for a given turnout route speed limit. Being able to improve the turnout speed limit is therefore of greater benefit to the network capacity as a whole than an improvement in switching time. However, the results are also sensitive to small changes in a_s; this suggests that if capacity proved an issue for the network at some point in the future, increasing the installed power in each train may provide an adequate improvement.

Under ETCS Level 3, converging junctions are again the capacity limitation for the same reasons as above. Plain line capacity is significantly higher, but constrained without additional changes to the junction operation. These changes, specifically making the junction detection block to be as small as the zone of conflict, in themselves yield a small additional amount of capacity. However, with reduced actuation time and improved turnout speed, a large fraction of lost capacity can be regained with 23TPH possible in the assumed best case. An improvement in constricting case from 18.7 to 23 TPH (23%) may not alone justify the roll-out of ETCS Level-3 on the network, but may negate the earlier claim that it would be of little practical benefit to signalling headway at the limiting points on the network at junctions.

6.6 Conclusions

This chapter has evaluated the capacity performance of traditional and Repoint track switches, across a range of 5 case study nodes from two network types - Metro, and High-speed rail. In each case study, the capacity of plain line was established using timetable compression methods from UIC406. Next, the effects of switches, including a range of fault tolerant switch performance based upon calculations earlier in the thesis, was examined. The effects of faster switch actuation time, improved turnout road speed limit, the assumption of safety, and associated signalling changes have been quantified.

In summary, the headline results are as follows:

For the metro study, the range of capacity improvement achievable through reduction in switch actuation time and higher turnout speed varies significantly depending upon scenario and location, but is of the order of 14.7% - 26.3% at typical metro line- and turnout- speeds (44mph, 25mph). Under the assumption of safety alone, the improvement ranges from 4.1% to 10.1%. Results calculated for a range of parameters indicate that enhanced capacity is available across all implementations, though the greatest enhancements are upon flat double junctions - where extra switch movements occur between each conflicting move. This is significant, as flat double junctions are identified as the capacity-limiting elements of a metro network.

For the HS2 study, conclusions are that Repoint alone could release only a small fraction of additional capacity, as other aspects of the proposed system are the limiting factors - in most cases the acceleration capability of the rolling stock. The capacity limiting case is the converging junction. At these junctions, improvements in switch actuation time and turnout speed could release between 2.7% and 13.9% additional capacity. However, also noted was that Repoint allows a greater portion of the potential capacity of an ETCS Level-3 moving-block signalling system to be realised, giving a 23.0% increase over in-service specification. This is an important conclusion when considering the future development and deployment of signalling systems.

Chapter 7

Design and development of a laboratory concept demonstrator rig

7.1 Introduction

Chapter 4 introduced a new track switching concept. This chapter presents the modelling, design and architecture of a scale Repoint laboratory demonstration and development rig, constructed at 384mm (15") gauge.

The chapter begins by modelling switch operation at this scale, in the same manner as established in Chapter 4, in order to establish size, force and power requirements. The design, construction and features of the rig are explained in detail. The tasks described in this chapter correspond to elements 8-11 in Figure 1.3.

The novel contribution of this chapter is to present the design of the first switch actuator to use passive locking and a semi-circular actuation path. A further contribution is, in a physical sense, the construction of the rig itself which will be used for future research and development projects. The work presented in this chapter forms part of a journal publication (Bemment et al., 2016).

7.1.1 Scaling of the development rig

A 384mm gauge (approximately quarter-scale) was chosen due to space constraints within the laboratory. This is the gauge of the RHDR (Romney, Hythe and Dymchurch Railway) in Kent, England; an option available for the first outdoor demonstrator. Though the smallest gauge in regular passenger use, it is large enough to fall under British ROGS (ORR, 2006). It retains the main features (i.e. sleepers, rail and switch design) of a mainline railway, though noting existing RHDR switches are of a loose-heel design. (Figure 1.1)

7.2 Modelling work for demonstrator development

This section corresponds to element 8 in Figure 1.3. To design an actuator and transmission system for a scale application, it is necessary to perform the same calculations as in Chapter 4 with the revised switch geometry, including revised rail cross-section.

7.2.1 Source Data

RHDR supplied a report on the design of their track, signalling and rolling stock (Head, 2013) including a sample switch panel design which is shown in Figure 7.1. Key parameters taken from the report are listed in Table 7.1. The turnout speed limit is 10mph; mainline speed is limited to 25mph. There are no power switches on the network, all existing switches are mechanically driven. The rail used is BS 35lb per yard as in Figure 7.2, for which no published I_{xx} or I_{yy} values were available; these therefore had to be hand-calculated using a geometric approximation created from three rectangles, indicated in the same figure.

Description	Symbol	Value	Unit	Source, notes
Shuttle Masses	M_{Sx}	40	kg	Estimated
Second moment of inertia (Horizontal)	I_{xx}	663503	mm^4	Estimated from Figure 7.2
Second moment of inertia (Vertical)	I_{yy}	2140925	mm^4	Estimated from Figure 7.2
Centroid in y	C_y	38	mm	From rail foot, estimated from Figure 7.2
Rail Mass	M_R	17.36	kg/m	Figure 7.2
Head width	W_h	43	mm	Figure 7.2
Minimum flangeway	W_f	50	mm	Unspecified; estimated from Figure 7.1
Entry radius	$R1$	201.9	m	Figure 7.1
Switch design radius	$R2$	76.8	m	Figure 7.1
Rail neutral offset	N	$2r$	mm	i.e. straight route and curved route

Table 7.1 Parameters used for Repoint laboratory demonstrator, including sources.

7.2.2 Static turnout rail profiles

As per the modelling process in Chapter 4, the first step in working out the switch geometry is to define the rail end offset ($W_h + W_f$) and therefore cam radius r. In this case, minimum flangeway W_f was unspecified - inspection of Figure 7.1 indicated it is around 50mm, with a railhead width W_h of 43mm. This gives a minimum cam radius r of 46.5mm. The decision was taken to use the offset of the 'full scale' switches modelled in Chapter 4, setting the cam radius to 60mm. This is more than enough offset for the RHDR scale, and means that though the gauge is 'scaled' to 385mm gauge, the actuation components are of an appropriate size for a full-scale switch.

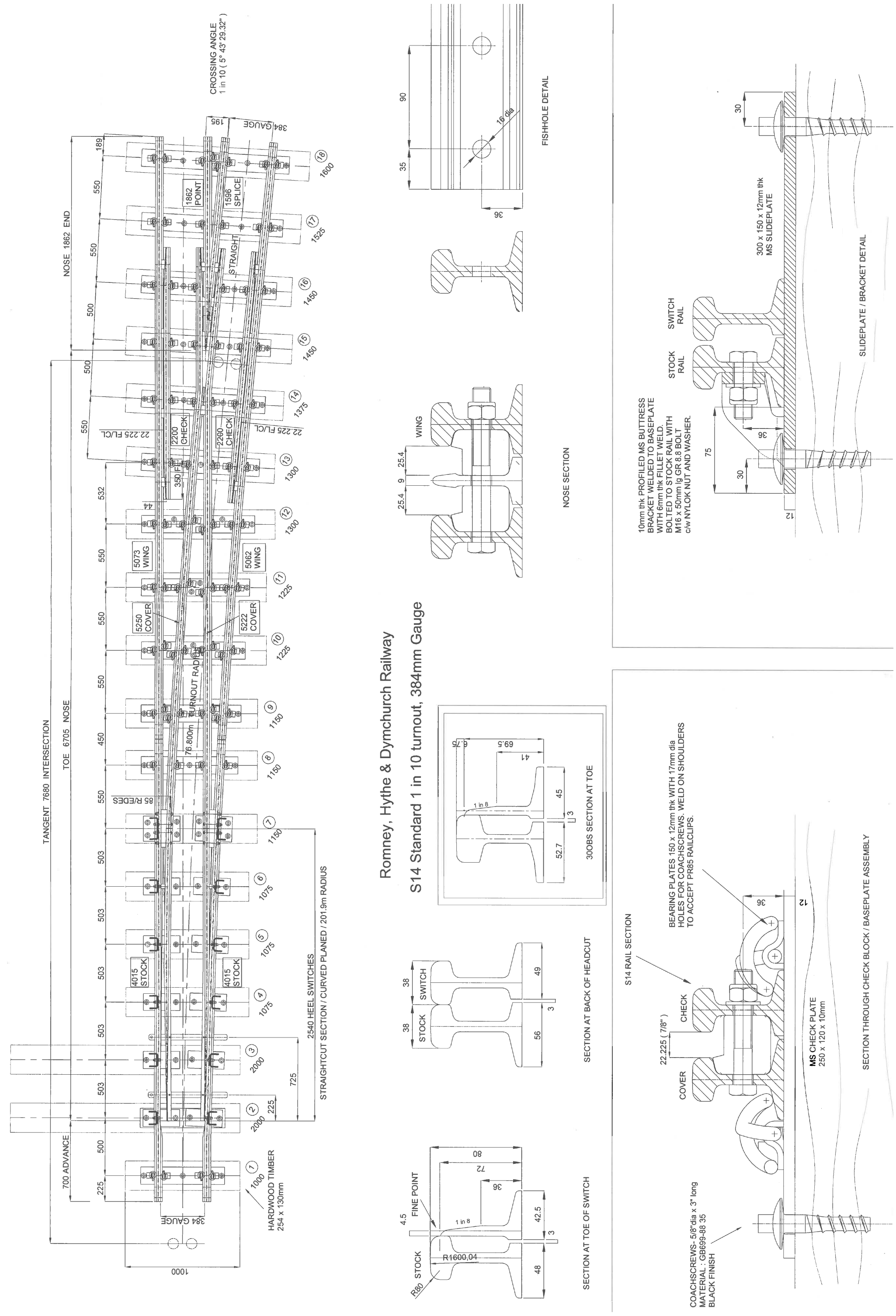


Figure 7.1 Engineering drawing showing layout of existing RHDR Pointwork. Reproduced from (Head, 2013).

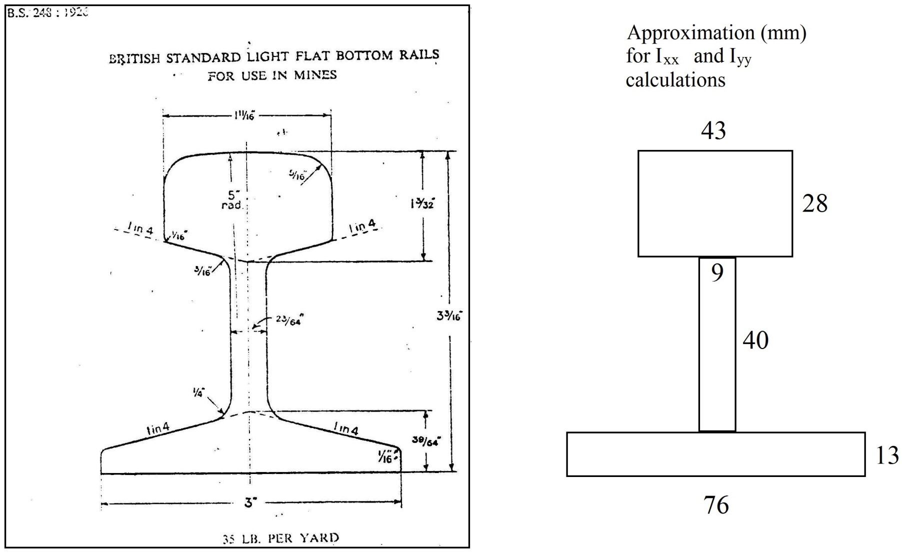


Figure 7.2 BS 35lb per yard mining rail, and geometric approximation from three rectangles used to estimate I_{xx} or I_{yy} values. Reproduced from (Head, 2013).

As the RHDR design is tangential, the next steps are to use Equation 4.11 to calculate the slope γ at cam radius r of 60mm, with switch radius R of 76.8m, and then use Equation 4.14 to calculate the length $l_{repoint}$ of the required natural flexing length. This gives slope $\gamma = 3.203$ and length $l_{repoint} = 3216$mm. Inspection of Figure 7.1 shows the original moving length to be 2515mm, making the latter result interesting, as all Repoint natural flexing lengths calculated in Chapter 4 were shorter than existing (Table 4.3). This elongation is due to the fact that the RHDR switch is a loose-heel design (i.e. hinged, rather than flexing rails) which negate the requirement for longer switch rails to achieve adequate flexing length.

Figure 7.3 plots the proposed turnout road geometry overlaid on the existing geometry extracted from data in Figure 7.1, including the ideal tangential geometry. It can be observed that, as the Repoint natural length is longer than existing in this case, the natural flexure curve forms a reasonable approximation to existing geometry, moreso than the examples in Figure 4.15. In the absence of further work regarding vehicle dynamics, full-section rail will therefore be assumed throughout - i.e. no optimisation of geometry through beam stiffness modification is carried out.

7.2.3 Bearer spacing and differential throw

The demonstrator is constructed with three exit routes, i.e. a straight route and two turnouts. The turnout routes follow the same geometry, with positive or negative offsets to give left or right turnouts.

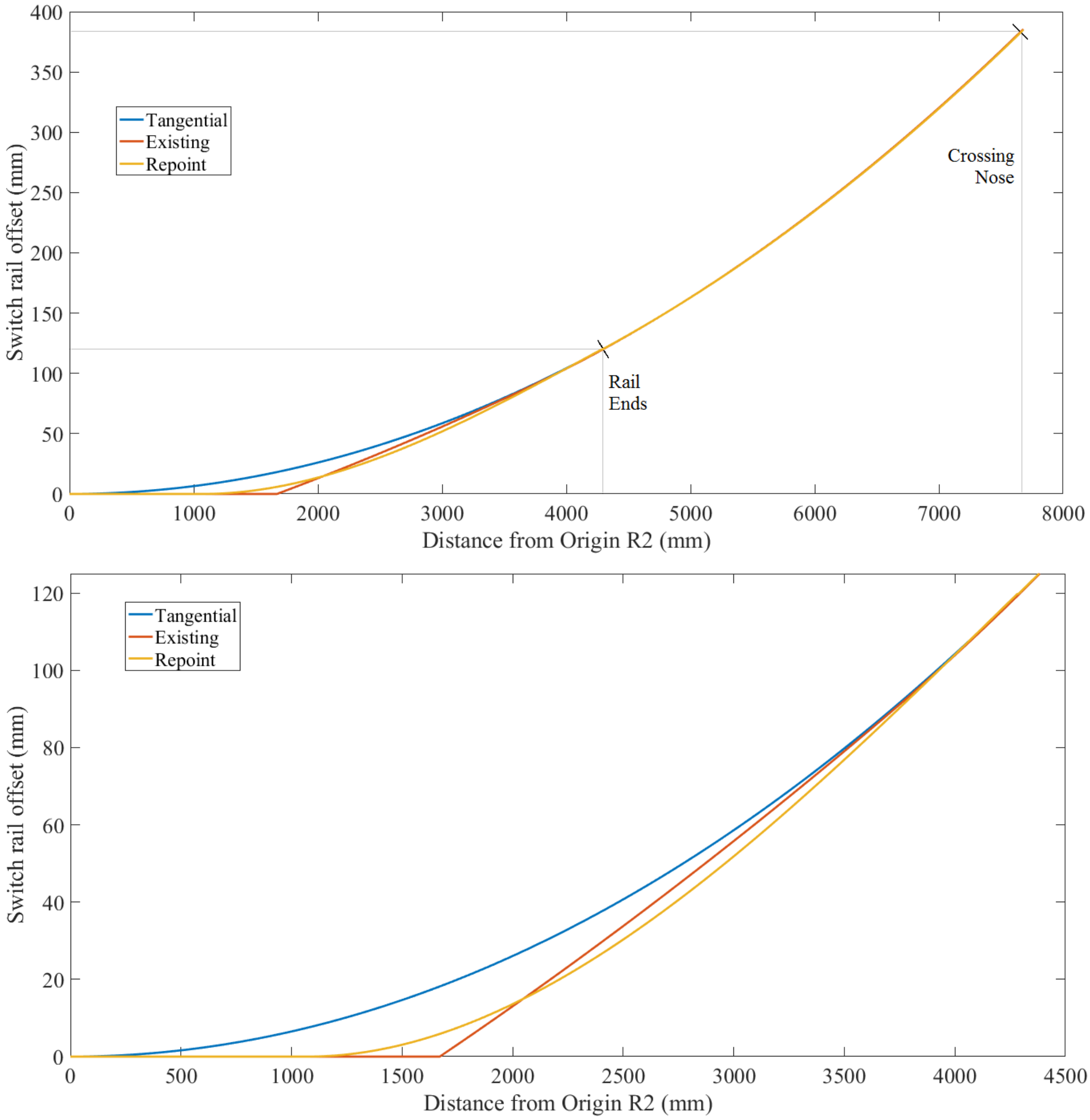


Figure 7.3 Geometry of the turnout routes on the Repoint demonstrator. Top - from R2 origin to crossing nose. Bottom - close-up view of area from R2 origin to 120mm offset.

Distance from R2 Origin	Bearer No	Turnout route offset	Slope	Notes
mm	count	mm	°	
1070	0	0.0	0.000	Last static bearer
1530	1	3.5	0.840	
1990	2	13.3	1.550	
2450	3	28.4	2.176	
2910	4	47.7	2.634	
3370	5	70.1	2.920	Active bearer under software simulation
3830	6	94.6	3.148	Active bearer under software simulation
4290	7	120.0	3.330	Active bearer, physically constructed in laboratory
		Rail end interface		
4750	8	147.0	3.540	First track fan bearer
5238	9	179.0	3.890	
5727	10	214.1	4.230	
6215	11	251.5	4.631	
6703	12	292.8	5.029	
7192	13	337.3	5.370	
7680	14	384.0	5.711	Crossing nose

Table 7.2 Bearer centreline locations and offsets for Repoint laboratory demonstrator.

Figure 7.1 indicates bearer spacing on existing RHDR switches. They are variable between 450-550mm through the switch, but constant at 503mm through the original movable length. The new movable length of 3216mm falls directly between bearers, and as it is not practicable to shorten this length, the demonstrator movable length shall span 7 bearers of equal spacing with bearer 7 of offset 120mm placed at 3216mm. This sets bearer spacing to 460mm. Offsets through the track fan have similarly been adjusted to a value which allows the crossing nose to sit centrally upon a supporting timber, 488.3mm. The offsets at each of the bearers in the Repoint layout are indicated in Table 7.2. Of note are bearers 5, 6 and 7 - the three active bearers, which have offsets of 70mm, 95mm and 120mm, defining the cam radii r in each of the bearers as 35mm, 47mm and 60mm respectively.

7.2.4 Stress in rail during flexure

With knowledge of flexing lengths and tip offset, peak stress in the rail during flexure can be calculated as per Section 4.5.4 Using Equations 4.21 to 4.23 with the scale values in Table 7.1, indicating that:

- Peak stress in the rail head is 138MPa and rail foot 157MPa, equal to 26-29 % of the yield stress of mild steel at 540MPa (Vitaly et al., 2016).
- Peak stress is tensile, occurring in the rail foot, at the root of the curve, at peak lift.

Actuation time t	s	0.2	1	3
Elastic Potential Energy EPE (X)	J	19.2	19.2	19.2
Elastic Potential Energy EPE (Y)	J	61.9	61.9	61.9
Gravitational Potential Energy GPE	J	77.8	77.8	77.8
Kinetic Energy KE	J	34.6	1.4	0.2
E_{total}	J	193.5	160.3	159.0
Mean power	W	1935	320.6	106.0

Table 7.3 Energy requirements of scale Repoint switch at selected actuation times t

- This stress is marginally higher than that experienced by a full-scale B-size switch (124.9MPa compressive, 116.4MPa tensile) as studied in Section 4.5.4, despite being at significantly smaller scale. Peak stress is now tensile in the foot, whereas in the full-size switches, peak compressive stress occurred in the head. With the equivalent tip lift, the effects of a shorter beam length are balanced by the smaller I_{yy} value deriving from the smaller beam cross-section, leading to a similar stress magnitude.

7.2.5 Cam torques, energy use and actuation time

Work in Section 4.5.3 examines the energy required to flex the switch rails, providing an example resolved to a single cam torque for an actuator at the tip of the movable rails. Here, three actuator bearers will be used in a 1-in-3 redundant configuration (as modelled in Chapter 5), enabling any single actuator to move the switch if required, thus meaning each actuator must be sized to move the switch alone. Energy transfer Equations 4.15 to 4.20 were used with the scale switch specifications to calculate mean energy transfers. The results of this calculation presented in Table 7.3, which lists key values at a selection of actuation times. Power requirements related to actuation times are plotted in Figure 7.4, which considers both regenerative and non-regenerative scenarios. The values in the non-regenerative curve will be used to select an actuator. The regenerative curve can be used to select a lower-value power supply, should regenerative braking be used, otherwise, a load bank resistor of equivalent power to the actuator should be adopted.

Also critical to mechanical design is the potential peak cam torque loading. Power/torque for KE requirements can be regulated by the controller as appropriate, but the effects of the spring and mass are directly related to cam angle and are independent of actuation time t. The beam flexure model described in Section 4.5.1 was therefore employed to provide static x- and y- forces (also resolved to torque), for a 180 °motion of the cam each of the three actuator-bearer positions. The results of this simulation are plotted in Figure 7.5. This

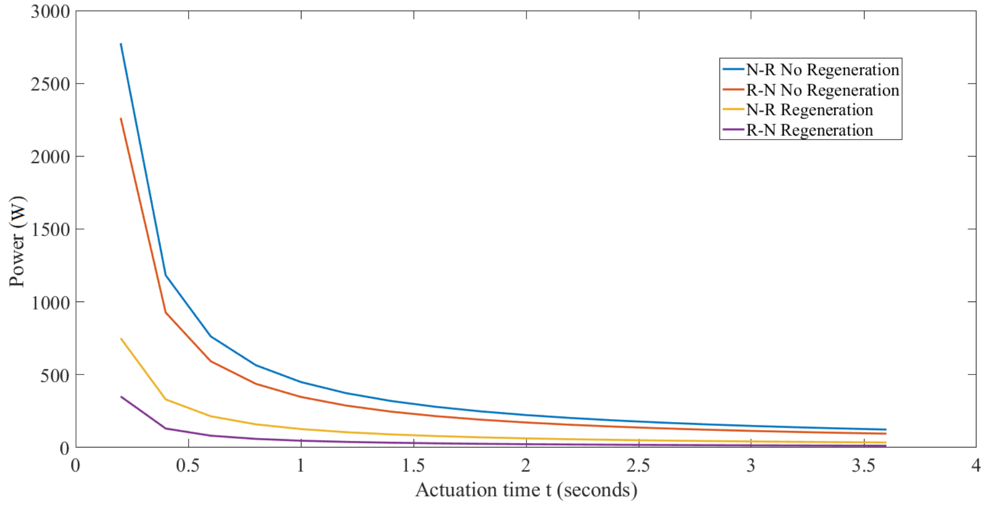


Figure 7.4 Power requirements of the Repoint demonstrator actuator bearers.

figure shows that the peak equilibrium torque experienced at the cam is 218 Nm, which occurs almost equally at bearer 5 and 6 (i.e. furthest from the rail ends), at a 48°cam angle. Whilst forces at bearers 5 and 6 are significantly greater, the shorter cam radii r, identified in Section 7.2.3, leads to a marginally lower torque requirement. The small differences in equilibrium torques result from the differing static beam shapes when applying point forces at different positions, which is illustrated in Figure 7.6. These figures feed into the mechanical design described in Section 7.4.

7.3 Development rig design and construction

This section describes the architecture, design, construction and operation of the 384mm gauge laboratory development rig. This section corresponds to elements 9-11 in Figure 1.3. The goal of the rig was to demonstrate the operation of a Repoint switch, and to act as a platform for future development of control systems to enable fault tolerance and condition monitoring, as described in Chapter 4.

7.3.1 Architecture

For space and cost reasons, the rig was unable to feature an entire track switch panel. Instead, it consists of a single physical actuator-bearer in a HIL (Hardware-In-The-Loop) test environment. The actuator bearer can be commanded to each position from a computer workstation, either automatically on a timer or by manual intervention. The workstation

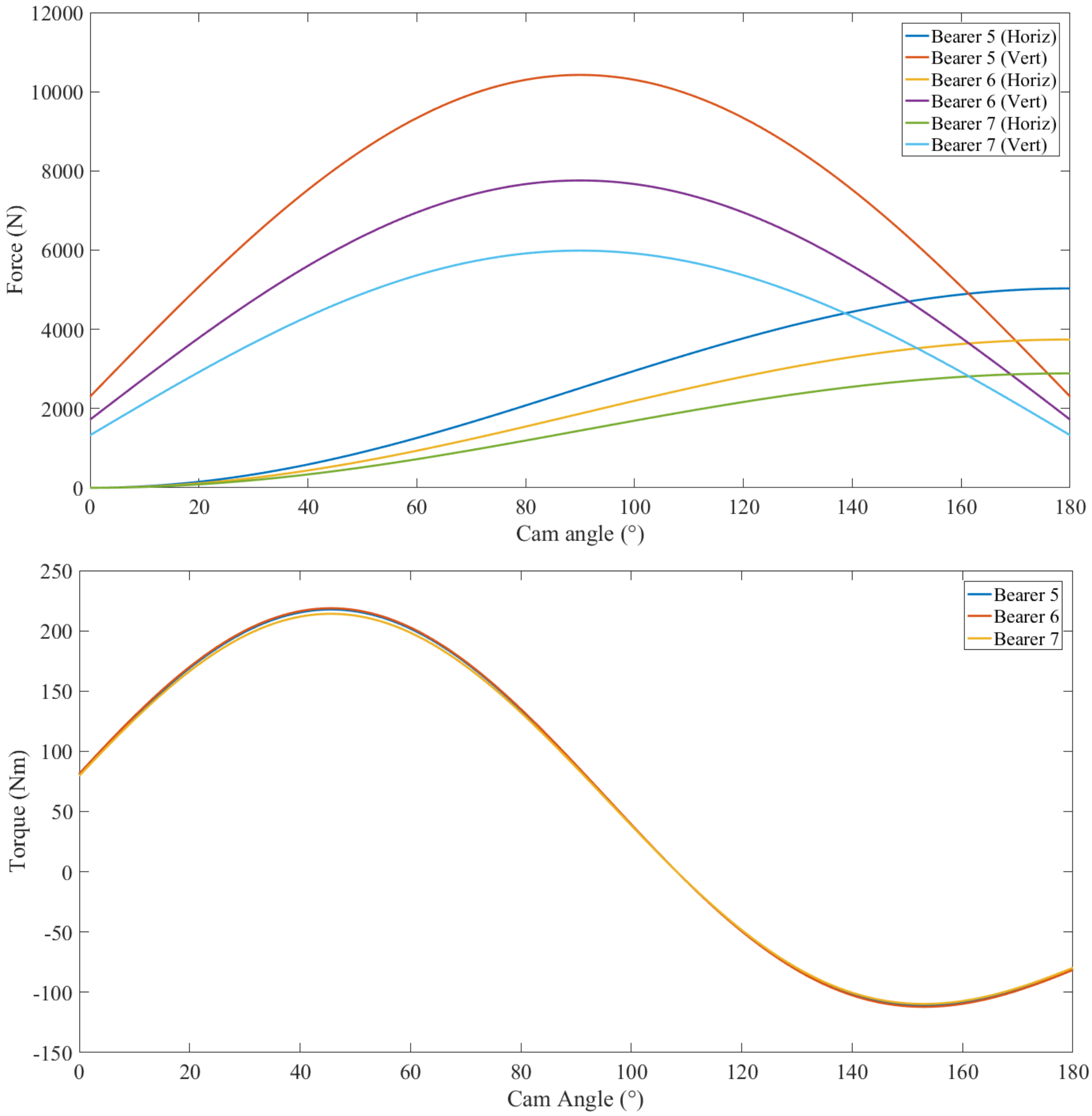


Figure 7.5 Peak static forces (top) and cam torque (bottom) vs cam angle at each actuator bearer position.

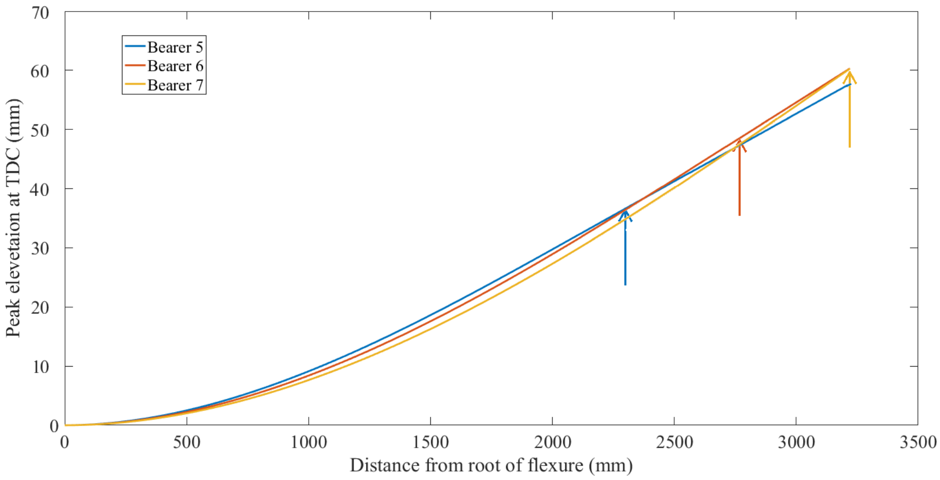


Figure 7.6 Switch rail shapes at peak lift when switch is actuated by Bearer 5, Bearer 6 or Bearer 7 in isolation.

also commands a software simulation of the remaining moveable switch elements. Several photographs of the physical layout are shown in Figure 7.8. The functional architecture of the laboratory rig is shown in Figure 7.7.

To aid visualisation of the switch and its operation, several steps have been taken. Firstly, the stationary rails, switch rails, other bearers and sleepers have been plotted on the laboratory floor. Secondly, interlocking rail ends (2 moveable and 6 stationary) have been machined in ABS plastic to demonstrate the action of the interlocking elements, shown in Figure 4.5. The stationary halves are mounted to the bearer 8 mock-up. Thirdly, the interface workstation is linked to a projector which shows a large-screen image consisting of a mock-up signalling control panel. This also includes a diagnostic panel showing the motion of the active bearer alongside the software simulation bearers, and the whole switch position. This screen is shown in Figure 7.9.

The system architecture is now described in detail referring to each of the five system groups in Figure 7.7. Of the five elements listed, the author was fully responsible for the specification, design and construction of the physical actuator bearer, and the specification and design of the power cabinet and servo drive. These elements will therefore be described in further detail.

7.3.2 Workstation 1 (dSpace)

The Human interface to the rig is provided through two IBM-Compatible workstations running Microsoft Windows 7 Enterprise. The first workstation is for controller and model development work. It runs both MATLAB/Simulink, and dSpace ControlDesk NG.

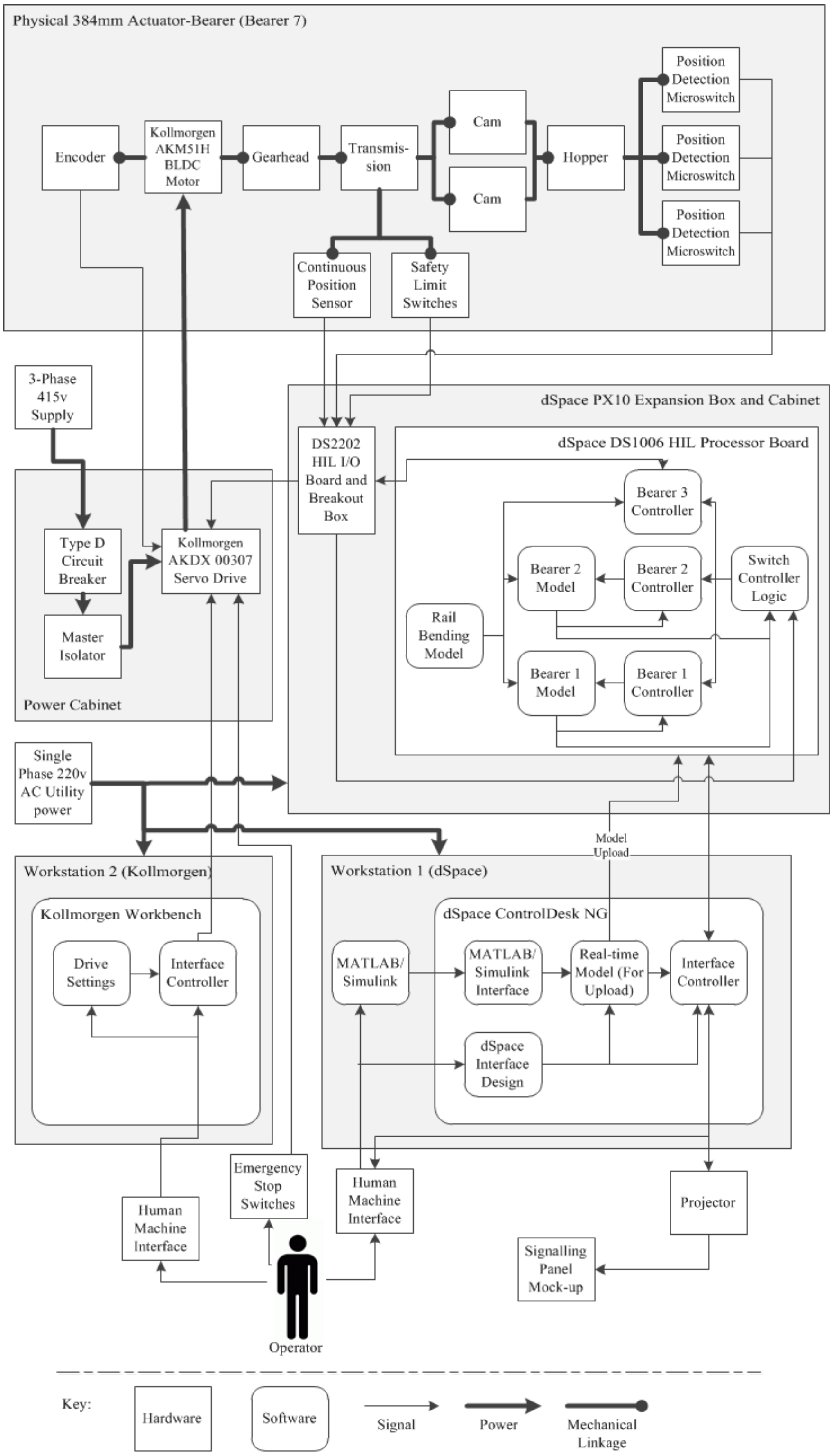


Figure 7.7 Block diagram illustrating the functional hardware and software elements of the Repoint laboratory development rig

At design-time, MATLAB/Simulink can be used to rapid prototype control architectures. These are modelled through the standard Simulink graphical interface, before being compiled and exported for use in ControlDesk. ControlDesk has a specific interface module for loading compiled MATLAB models, which creates a dSpace-compatible real-time model for upload to the processor unit. ControlDesk also provides an interface design suite, through which the inputs and outputs of the MATLAB/Simulink model can be assigned to controls and visual indicators for the operator respectively. This feature has been used to create both a local monitoring and operation panel, alongside the signalling panel mock-up shown on the projector screen during demonstrations (Figure 7.9).

At run-time, the interface controller is used to command the HIL simulation - including physical bearer - between positions. It can also display or log any relevant variables communicated back from the real-time processor. In this implementation, this is the signals from the sensors upon the physical bearer, but for future development could include force transducers, for instance.

7.3.3 Workstation 2 (Kollmorgen)

The second workstation is responsible for interfacing with the Kollmorgen servo drive located in the power cabinet, both at development time and runtime; this is achieved over a direct Ethernet connection. The workstation runs the Kollmorgen Workbench software.

At development time, this provides a suite of setting options which can be saved as unique configuration files and 'flashed' to the drive to change its behaviour. At runtime, in this development application, the Kollmorgen Drive needs to receive a heartbeat signal, which this workstation provides over the Ethernet link. Also at runtime, Workbench can display key drive variables such as motor position.

7.3.4 dSpace PX10 expansion box (Real-time processor)

The dSpace PX10 Expansion box provides both the control of the physical actuator bearer and the facility for co-simulation of the remaining switch elements and rail bending. The PX10 is mounted in an equipment rack, alongside the breakout boxes to which it is connected through proprietary ribbon cables. The PX10 box itself contains a DS1006 Real-time processor board and a DS2202 HIL interface board. The DS1006 can accept compiled models from Workstation 1 via Ethernet at design time. At runtime, the DS1006 can output key variables, whether measured from the rig or calculated as part of the internal simulation. These variables are transmitted real-time over Ethernet, and can be displayed in the ControlDesk NG software on Workstation 1. The DS2202 board is an analogue IO board which takes 24v analogue inputs from the sensors on the physical actuator bearer, in addition to providing an analogue velocity command to the kollmorgen AKDX 00307 Servo Drive in the Power Cabinet.

7.3.5 Power cabinet

The power cabinet is a sealed metal utility cabinet. Power enters the cabinet from the supply through an industry standard 5-pin 63A 415v 3-phase connector. A Type D 15A circuit breaker is fitted to all phases; Type D breakers are designed to isolate in the event of a 10-20x over-current. This rating is sufficient to allow significant inrush into the Servo Drive and Motor without activating. A manual master isolator switch isolates the power electronics from all three phases. The output of the breaker directly feeds the Kollmorgen AKDX 00307 Servo Drive (Kollmorgen, 2014). This drive unit communicates with Workstation 2 over an Ethernet link, such that the correct parameters can be uploaded and monitored. Power is provided to the motor over a direct cable connection, with a secondary connection from the encoder providing a position feedback signal. The drive could be operated in several functional modes; in this case it interprets an analogue velocity command signal from the Dspace PX10 unit. Selection of an optimal control strategy may mean future operation is to accept a position or acceleration command; though this would not alter the physical layout.

The main elements of this cabinet - power supply and motor servo drive, replicate what would be necessary line-side, and what is provided in basic form in the location cases at existing switch installations, under the ‘control and power’ subsystem designation used in Chapter 5. For a fully triplicate redundant switch, three Servo Drives and a master controller would be required. The cabinet also has wiring for two emergency stop switches.

7.4 Mechanical design of bearer 7

7.4.1 Overview

This section discusses the mechanical design of the actuator bearer 7. The bearer consists of independent locking, actuator, gearbox, transmission, sensing and detection elements. Those elements are connected using Dexion slotted angle to form an open box representative of a hollow bearer. The Dexion allows elements to be replaced, adjustments to be made, and the interaction of the drive components to be observed. Each element is now described in turn.

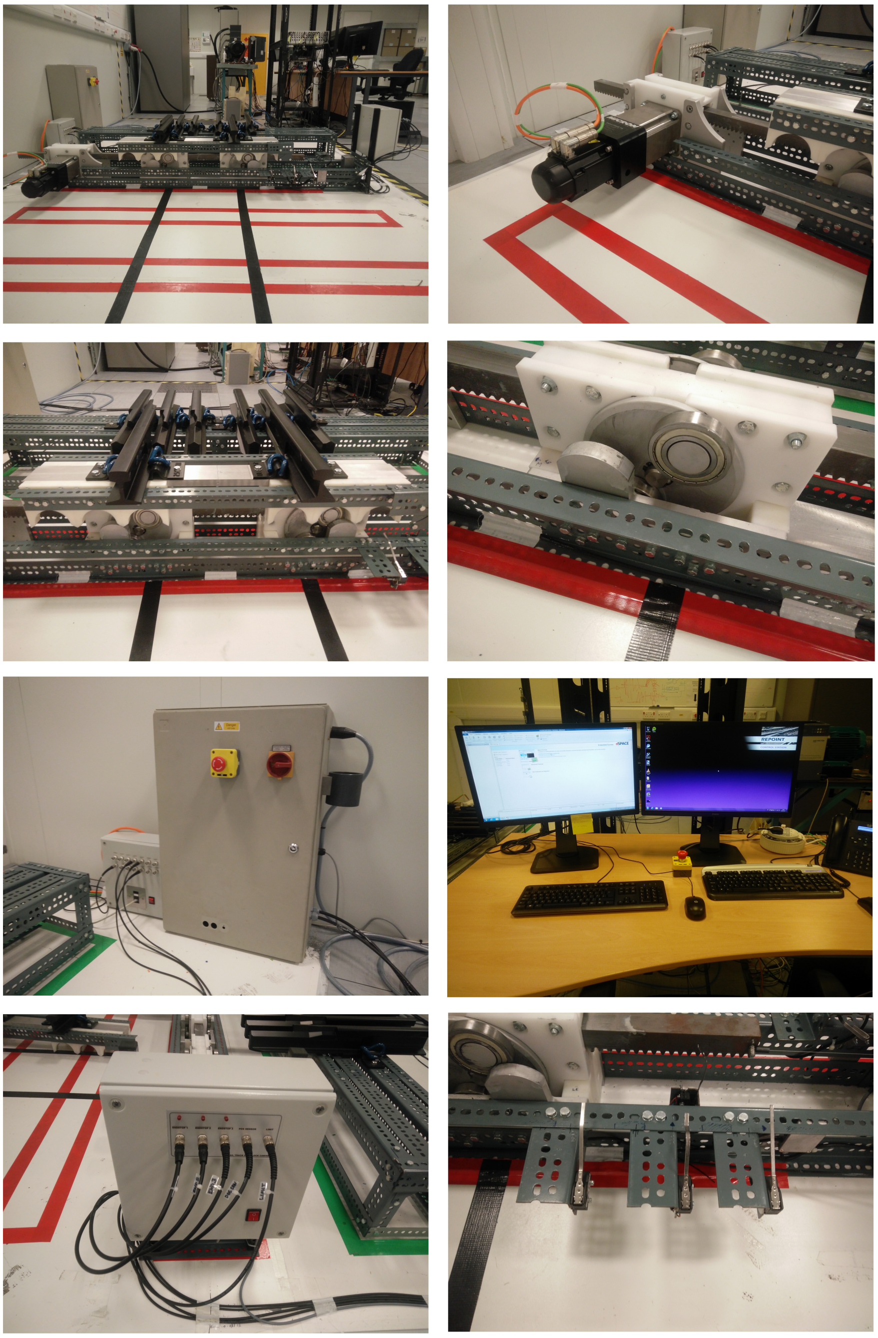


Figure 7.8 Photographs of the laboratory development rig. Clockwise from top left: [1] Front view of the physical actuator bearer [2] Motor, gearbox and rack drive connection [3] View of cam mechanism with hopper removed [4] Operator station [5] Detection Microswitches [6] Sensor connection cabinet on bearer [7] Power cabinet with 3-phase supply and Kollmorgen motor drive [8] Close-up view of cam and locking block arrangement with hopper lifted and unlocked

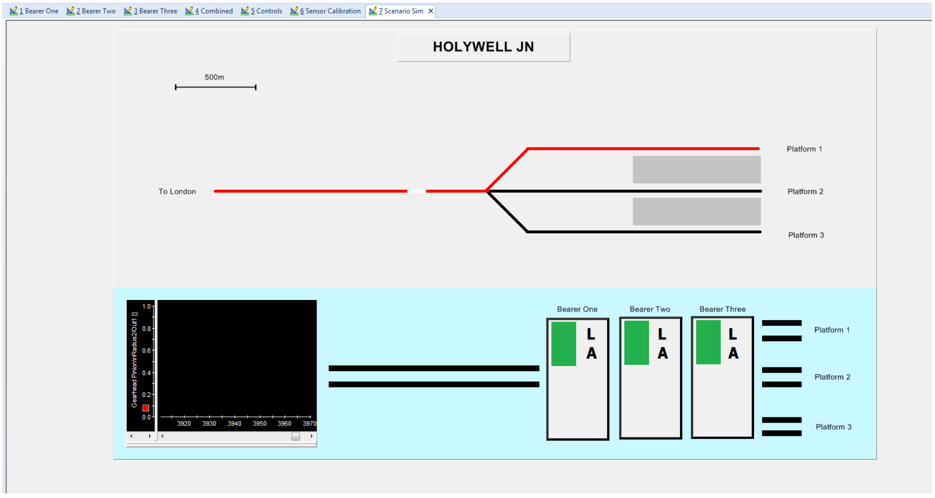


Figure 7.9 Signalling panel mock-up which displays all bearer states as part of demonstration.

7.4.2 Locking elements

Though in a real implementation it is likely the locking elements would be steel, in the demonstrator they are machined from engineering nylon for cost and capability reasons. There are four sets of locking blocks in the bearer, a pair under each rail. All are inverted to reduce the likelihood of foreign object entrapment; i.e. the cutouts are on the upper half. The protrusion and cutouts are semi-circular in shape such that they are accurately self-centring, spreading load in the event of minor misalignment, also allowing one rail to be raised above the other to provide cant through the movable portion - this causing a slight rotation of the shuttle in the z axis.

The horizontal faces of the upper locking blocks reach the vertical, meaning that a horizontal force input does not result in any lifting force vector. The sides of the lower locking protrusion have, however, been slightly cut back to prevent jamming. Figure 7.6 indicates that under certain actuation conditions, namely the use of Bearer 5 in isolation, the rail ends sag below the elevation achieved when Bearer 7 is active. This sag is of the order of 2.5mm. The locking blocks have therefore been chamfered at their furthest natural protrusion, to create 5mm clearance at TDC. Additionally, this has been chamfered such that, if the two halves of the lock did foul during actuation, the resultant force vector would assist the rails over the lower locking protrusion.

During actuation, the inside faces of the locking blocks act against the cam wheels to keep the shuttle stabilised when elevated. The cam followers feature low-friction bearings which act on the recess of the upper locking block. Crucially, the OD of the bearings is 10mm less than the ID of the recess. This means that there is much reduced chance of jamming, and that fine adjustment of locked shuttle position is performed by the interaction of the geometry of the locking elements. This clearance also allows the actuators to move out of synchronisation. The shape and key dimensions of the locking and cam elements are shown in Figure 7.10.

7.4.3 Transmission

The transmission takes motion from the motor/gearbox to the pair of cams, ensuring the cams turn synchronously at a suitable speed. Design was limited to what could be fabricated in the laboratory. Chains and belts were rejected due to the potential sizes required for torque capability, and due to the fact the cams must rotate in both directions requiring complex tensioning arrangements. A shaft was also a possibility, but the accurate alignment required for long-term reliable operation would be difficult to achieve. A rack was therefore chosen. The rack is capable of transmitting high torque/force in plane, but also tolerant of mis-alignment over its length. For demonstration purposes, an additional benefit of it being a simple linkage is likeness to the actuation rods in existing POE designs (Section 2.2.4.4).

The cams engage with the shuttle in the manner described in Section 7.4 and Figure 7.10. Each camshaft has a pinion at the centre, which engages with the rack. Selection of pinion size is a trade-off; a large pinion requires a long rack movement and therefore long rack, but transmission efficiency falls with use of a smaller pinion. To transmit the peak torque, MOD-4 gears were required, space-limiting each pinion to 15 teeth.

7.4.4 Actuator, gearbox and efficiency

The motor and gearbox were selected after careful consideration of the products on the market which were able to perform the required functions in accepting analogue command signals, within the specified torque, speed and power range, at reasonable cost. The motor in the actuator bearer is a Kollmorgen AKM51H Brushless DC type coupled to a Thompson 70:1 Valuetrue ratio sealed unit planetary gearhead, which drives the rack via another pinion. A planetary gearhead was required to acheive the correct torque/speed output, but allow the actuator to be back-driven by the rails in the event of a power failure between positions. The gearbox has an industry standard NEMA mount such that a product from many other manufacturers could be retrofitted. The specifications of the motor and gearbox are shown in Table 7.4. The motor is significantly oversized for application in both power and torque (4 $\times$, for intermittent duty), such that it does not become the limiting factor in future research. The efficiency of the driveline is the product of all component efficiencies, also listed in Table 7.4, which forms an important input to Section 4.5.3.3.

Parameter	Unit	Value	Source
Motor: Kollmorgen AKM51H			
Peak torque	Nm	11.7	(Kollmorgen, 2014)
Max power	W	1240	(Kollmorgen, 2014)
Max mechanical velocity	RPM	6000	(Kollmorgen, 2014)
Quoted thermal efficiency	%	92	(Kollmorgen, 2014)
Gearhead: ValueTRUE, Size 115, 70:1 Ratio VT115-070			
Ratio	:	70:1	(Murphy, 2014)
Max. Input speed	RPM	5000	
Quoted thermal efficiency	%	90	(Murphy, 2014)
∴ Gearhead output			
Max mechanical velocity	RPM	71.4	
Max torque	Nm	819	
Rack and pinion drive			
Pinion to rack efficiency	%	95	(Goswami, 2004)
Rack to camshaft efficiency	%	95	(Goswami, 2004)
Overall driveline efficiency	%	0.74727	

Table 7.4 Key parameters related to the actuator, gearbox and transmission

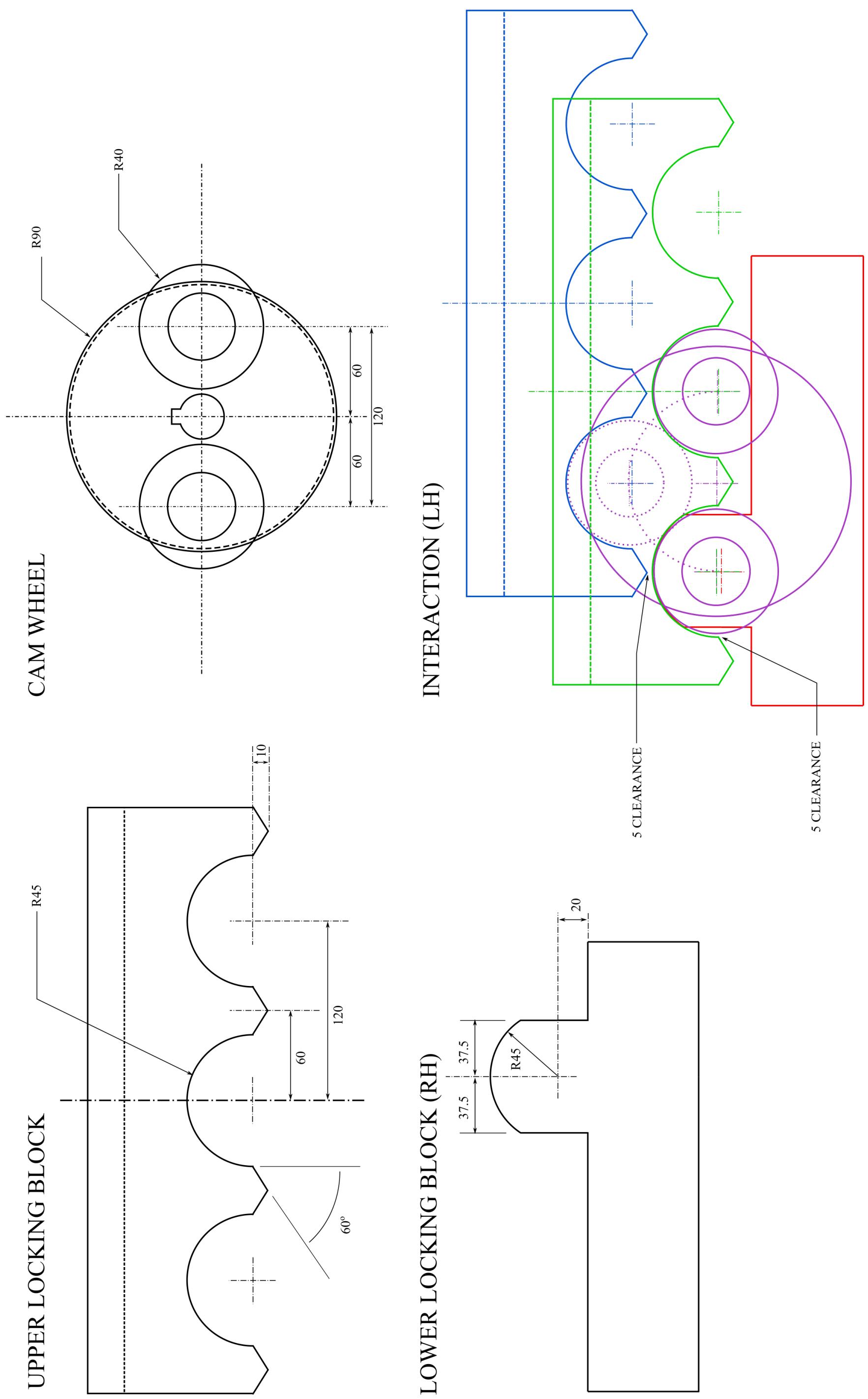


Figure 7.10 Shape and key dimensions of demonstrator locking and actuator cam elements. Bottom right shows interaction of elements: Cam wheel (purple) lifts upper locking block (green) from lower locking block (red) to a top dead-centre position (blue), showing clearances designed into the mechanism.

7.4.5 Electrical design

Rack position is fed to the dSpace PX10 processor via a yo-yo potentiometer, from which cam position can be inferred. Three position detection micro-switches, mimicking the detection subsystem in traditional switches, are installed to indicate hopper position in the lowered and locked position independent of the rack position sensor. These are single channel only in the demonstrator. The motor is linked to the servo drive (power cabinet) via two industry-standard cables - encoder signal and power. Emergency limit switches at the extremities of possible rack movement are wired as part of the emergency stop circuit, used to prevent the motor driving the transmission beyond its physical limits.

7.4.6 Design differences between bearers 5, 6 and 7

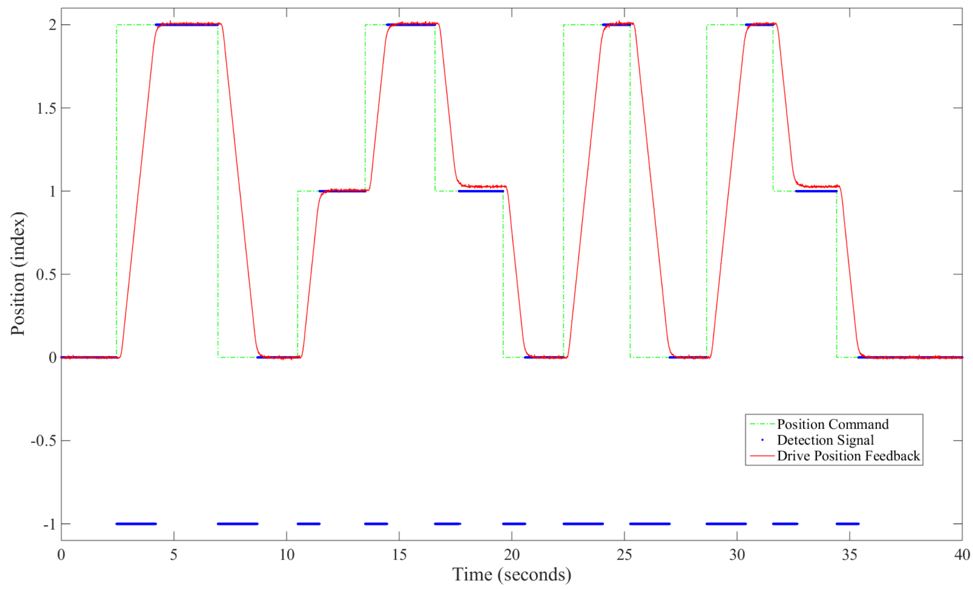
Whilst bearer 7 is the only one physically constructed, it is worth noting the minor differences which would be present between the three should the others be constructed. All elements would remain the same, as the torque and power requirements are equal (Figures 7.5 and 7.4). The cam wheels and locking blocks would need to be changed, to suit the new offsets listed in Table 7.2.

7.4.7 Controller and sample output

Other researchers carried out a basic controller design exercise (Wright et al., 2014a,b) to enable the rig to be run closed-loop and to verify the function of all elements of the system. At rig commissioning, several sample runs were conducted in order to verify operation and calibrate sensors, with sensor data logged. Figures 7.11 and 7.12 show samples of these runs.

Figure 7.11 shows the command signal, detection signal, and lateral (drivetrain) position feedback. The detection signal is assigned a value of 1, 2 or 3 depending whether the left, straight or right route is selected and locked. Actuation time is that between command signal changing, and detection being obtained, which is indicated by a loss of detection (i.e. detection is equal to -1). It can be observed that the switching time during the initial calibration runs is 1.5 seconds. Also shown is the software-generated horizontal and vertical displacement of the shuttle, derived from the rack position sensor, which can be used to calculate and simulate load due to the switch rails.

Figure 7.12 is taken from the controller model validation process (Wright et al., 2014b). It shows the model predicted motor speed and current, and the measured speed and current across the motor during a series of actuations, including the residual error. This demonstrates that the simulation models give a good prediction of the behaviour of the actual units.



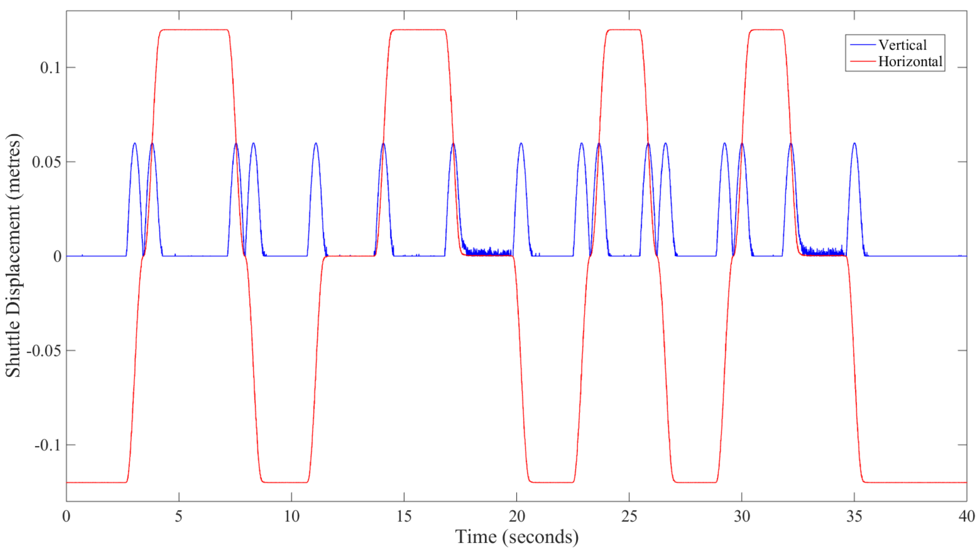
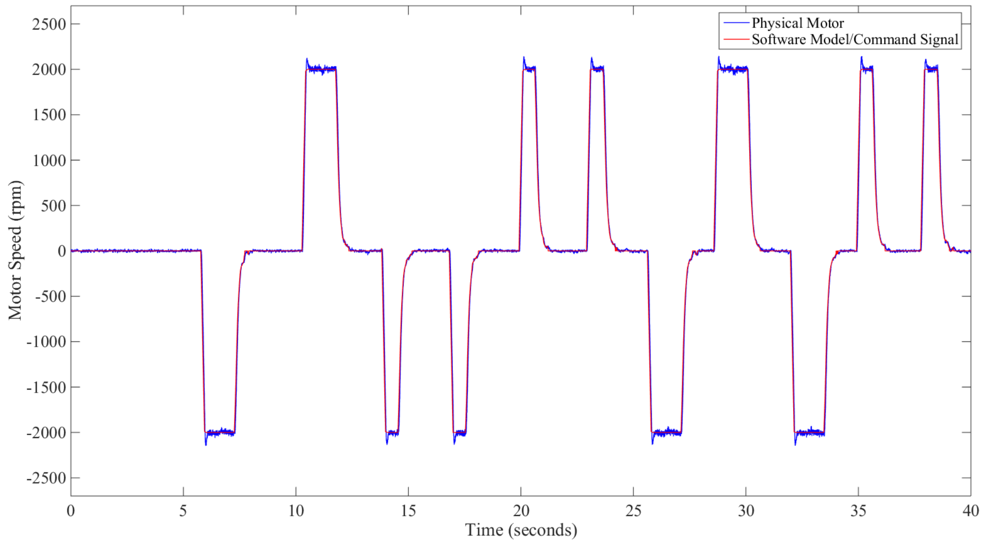


Figure 7.11 Data plots for a series of actuations on the laboratory REPOINT rig, downloaded from the DSpace DS1006. Top: Command, detection signal, and rack position feedback post-filter. Bottom: Software-generated horizontal and vertical displacement of rail ends



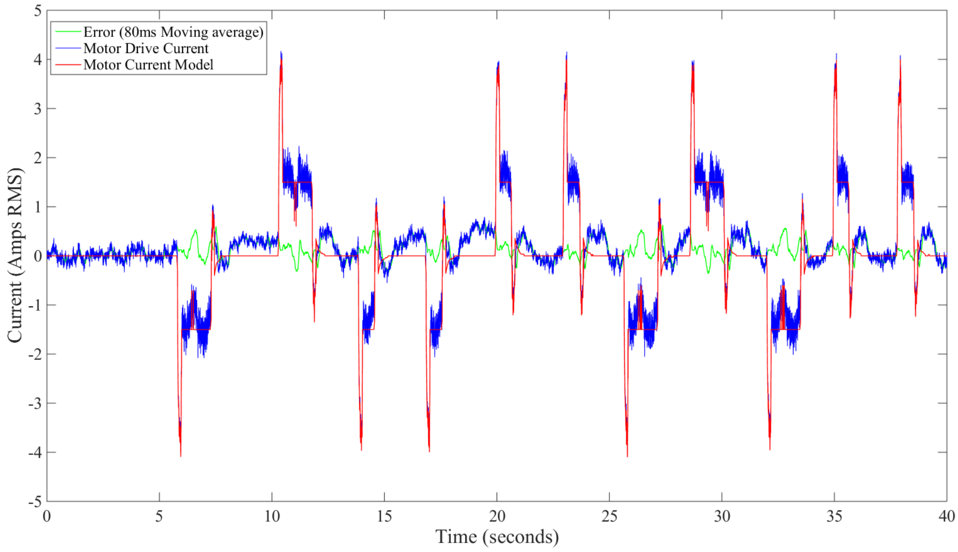


Figure 7.12 Top: Motor speed and modelled motor speed vs time, obtained during the model validation process (Bemment et al., 2016; Wright et al., 2014a), for the same set of runs as Figure 7.11. Bottom: Modelled motor current, actual motor current and residual error, with moving average. There is a considerable level of noise on the signal, residual error during periods of motion is below 15%.

7.5 Conclusions and summary

This chapter has described the design and development of a laboratory-based development rig for the Repoint concept summarised at the end of Chapter 3 and at full scale in Chapter 4.

The chapter first establishes that a switch at this scale is feasible through modelling from first principles, and in order to establish size, force and power requirements. The demonstrator is constructed at 384mm gauge, and consists of a single actuator/bearer coupled with 2 actuator/bearers represented in software co-simulation and a rapid prototyping environment for future control strategies. The tasks described in this chapter correspond to elements 8-11 in Figure 1.3. The novel contribution of this chapter was to present the design, development, commissioning and test of the first switch actuator to use passive locking.

Chapter 8

Conclusions and Future Work

8.1 Conclusions

This thesis presents research relating to relating to the improvement of track switching performance through the introduction of fault tolerance. It presents the conception, development, operation, potential performance and scale demonstration of Repoint, a novel fault-tolerant track switching concept.

Track switches have evolved over time prioritising safety, with performance a lesser consideration. Track switches are complex systems, at the boundary of many operational elements of rail networks. Modern railway systems place ever increasing demands on the performance of assets, and switches are identified as the weakest performer. The rail industry, and other safety- and performance- critical industries, have benefited from the introduction of fault tolerance in order to maintain required operational performance levels when faults occur. However, existing track switching practice does not utilise fault-tolerant principles. The aim herein was, therefore, to investigate the opportunity to engineer fault tolerance into railway track switching, and its potential to improve performance. This aim was to be achieved through the 5 objectives listed in the research map in Figure 1.3.

Chapter 3 establishes the formal requirements for track switching, and creates a framework for evaluating track switching solutions against those requirements. This meets the first thesis objective. The requirements and framework are then used to select a candidate solution for railway track switching from a range of possible solutions, including exploring benchmarking their potential to improve performance versus that of traditional solutions.

The selected candidate solution is termed the 'Repoint' concept. The concept is novel, and based around a stub switch. The concept uses 'passive locking', which enables, for the first time, multi-channel actuation and locking of railway track switches. Its proposed general operation is described in detail in Chapter 4. The concept is then modelled to establish its physical feasibility. The concept is deemed feasible in key engineering and physics terms, thus meeting the third thesis objective of establishing feasibility. Further potential improvements in actuation time and turnout route traffic speeds are identified. However, also identified are significant areas of further understanding required, related to the ride dynamics through revised geometries including the interlocking rail ends (See Further Work section in 8.2).

Chapters 5 and 6 focus on meeting objective 4, which is to quantify the potential performance improvement possible through the design. Chapter 5 studies the reliability, availability and maintainability improvement possible. The analysis is based upon field data, used to create models of the expected failure rates of each switch subsystem. Annual downtime from maintenance interventions is established from literature and interviews. Failure rates are then used as an input to modelling the potential reliability and availability of a range of possible fault-tolerant switch architectures. Results indicated that considerable gains in whole-system performance are possible with time to failure extended and unscheduled downtime reduced by an order of magnitude. Typical B_{50} figures for powered systems are improved from a typical 1-3 years in existing cases to up to 5-12 years.

Capacity performance was examined in Chapter 6 through a series of case studies, around London Underground and HS2. The range of capacity improvement achievable varies significantly, but is in the range of 4.1% - 26.3% at typical LU speeds. Fault tolerant track switching is able to release a large portion of the operational plain-line capacity lost through traditional switching practice, either through a faster actuation time, a higher turnout route speed restriction, or working under the assumption of being reliable enough to actuate within a signalling overlap. In certain cases junction capacity can be 100% of plain-line. Also noted was that Repoint allows a greater portion of the potential capacity of an ETCS Level-3 moving-block signalling system to be realised, giving a 23.0% increase over in-service specification upon HS2. This is an important conclusion when considering the future development and deployment of signalling systems.

The original work of the thesis concludes with Chapter 7, which describes the modelling, design and architecture of a scale Repoint laboratory demonstration and development rig. The chapter began by modelling operation at 384mm (15") gauge, in the same manner as Chapter 4, in order to establish size, force and power requirements. The work in this chapter meets the fifth thesis objective.

Whilst this thesis has demonstrated the principles and benefits of fault tolerant track switching, much work remains to be completed before a real-world implementation, some suggestions for which are provided in the final section.

8.2 Suggestions for Further Work

Chapter 2 established, through literature review, that there were no physical or research examples of fault-tolerant railway track switches. This thesis has, therefore, opened up the sub-field of fault-tolerant railway track switching research. However, whilst the thesis has answered the specific research questions presented in Chapter 1, in doing so it has revealed more areas in which further understanding would be required before the practical implementation of such solutions. The key understanding required is as follows:

- Chapter 4 suggests one mechanical drive arrangement to actuate the cams, as demonstrated in Chapter 7. However, many options are available depending particular requirement mix of cost, reliability, ease of repair, duty cycle, power requirements etc. Other options include belt or shaft transmission, hydraulics, or twin-motor systems. An appraisal of all possible mechanical design options would therefore be important before development to product. The results may be different for different deployment locations.
- Chapter 4 made a comparison between the natural bending curves of a stub switch and traditional switch layouts. However, this comparison did not include the ride dynamics of such differences. These dynamics need to be understood, and potentially the curves optimised for such. This modelling will need to include the effects and behaviour of the rail-end interface, for which much greater understanding will be required before deployment, including differential wear between routes, displacement during load, accuracy of alignment, and dynamic disturbance to rolling stock and additional support requirements.
- Chapter 4 describes the novel rail end interface which enables the use of the stub switch arrangement. Beyond modelling, this rail end will need to be extensively tested in live use before taking passenger traffic. This may involve full instrumentation whilst test traffic passes, over a range of track conditions. Design and execution of this investigation will be a key part of future development of the idea.
- The culmination of the points above would be to develop, design, construct and operate a full-scale demonstrator of the Repoint concept.

The following is a list of other suggested areas of work building upon that in the thesis:

- Chapter 3 presented a range of novel designs which were then evaluated against a set of non-functional requirements for GB mainline. As well as the possibility there may be other methods of switching not explored in this work, performing this process with a different set of requirements may mean a different solution may rank highest and offer greatest performance.

- Chapter 3 used the assumed performance of the ultimate evolution of the traditional track-switch design. The development of existing designs to this point could be a future research area, for instance combining fault tolerance in control or detection only, or research into mechanical elements to enable such.
- Chapter 5 necessarily makes assumptions regarding maintenance response and repair times due to insufficient data from the infrastructure owner. The accuracy of results may be improved with this data, especially with variable repair times for the different subsystems. In addition, another level of analysis could be performed with parts and labour cost data, with the geographical locations of limited maintenance resources, or with access constraints of installation sites, for example.
- Chapter 7 describes the development of a scale laboratory demonstrator which has the additional purpose of being a hardware-in-the-loop rig to enable rapid prototyping of fault-tolerant control strategies. The control strategies for the actuator-bearers need significant further research and development work. Three bearers need to act in unison, potentially with motors isolated, with variable loads. This work may involve loading the demonstrator with masses and/or springs to simulate the effects of the movable rails. Further work could involve making the motors slow to a soft stop at end of stroke to minimise potential wear on the locking elements, and to combine the energy recovery and storage described in Chapter 4.

References

Andersson, C. and Dahlberg, T. (1998). Wheel/rail impacts at a railway turnout crossing. *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, 212(2):123–134.

Andrews, J. D. and Moss, T. R. (2002). *Reliability and risk assessment*. Wiley-Blackwell.

Armstrong, J. and Preston, J. (2011). Developing and calibrating capacity utilisation measures for nodes. In *IT15.Rail Symposium: The industrialised Railway (Harvesting the econmies of scale in planning and production*, Zurich, Switzerland.

Armstrong, J., Preston, J., and Hood, I. (2015). Evaluating capacity utilisation and its upper limits at railway nodes. In *CASPT2015: Conference on Advanced Systems in Public Transport*, Rotterdam, The Netherlands. ERASMUS University.

Armstrong, J., Preston, J., Khadem Sameni, M., Potts, C., Khosravi, B., Bektas, T., and Bennell, J. (2011). Overcoming the capacity constraints imposed by nodes on railway networks. the 4th International Seminar on Railway Operations Modelling and Analysis, RailRome2011.

Asada, T. and Roberts, C. (2013). Improving the dependability of dc point machines with a novel condition monitoring system. *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of rail and rapid transit*, 227(4):322–332.

Bannister, G. (2015). Private Interview.

Bannister, G. (2016). Interview: Mainline poe maintenance, faults, fault teams and asset management (june 2016). By personal communication.

Barber, F., Abril, M., Salido, M., Ingolotti, L., Tormos, P., and Lova, A. (2007). Survey of automated systems for railway management.

Beer, F. P., Johnston, E. R., DeWolf, J. T., and Mazurek, D. F. (1992). Mechanics of materials. *In SI Units, McGraw-Hill, UK, App.*

Bemment, S., Dixon, R., and Goodall, R. (2012a). Redundantly engineered points (repoint) for enhanced reliability and capacity of railway track switching. In *The RRUKA annual conference*, volume 7.

Bemment, S., Dixon, R., and Goodall, R. (2013a). Repoint redundantly engineered points for enhanced reliability and capacity of railway track switching. In *Proc. 10th World Congress on Railway Research (WCRR). Sydney, Australia.*

Bemment, S. D., Dixon, R., and Goodall, R. (2012b). An evaluation of redundancy concepts for fault tolerant railway track switching. In *Fault Detection, Supervision and Safety of Technical Processes*, volume 8, pages 763–769.

Bemment, S. D., Dixon, R., Goodall, R., and Brown, S. (2013b). Redundantly engineered track switching for enhanced railway nodal capacity. In *Control and Automation Theory for Transportation Applications*, volume 1, pages 25–30.

Bemment, S. D., Dixon, R., Goodall, R. M., Ward, C. P., and Wright, N. (2015a). Design, construction and operation of a repoint laboratory demonstrator.

Bemment, S. D., Ebinger, E., Goodall, R. M., Ward, C. P., and Dixon, R. (2016). Rethinking rail track switches for fault tolerance and enhanced performance. *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*.

Bemment, S. D., Goodall, R. M., Dixon, R., and Ward, C. P. (2018). Improving the reliability and availability of railway track switching by analysing historical failure data and introducing functionally redundant subsystems. *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, 232(5):1407–1424.

Bemment, S. D., Goodall, R. M., Ebinger, E., Ward, C. P., and Dixon, R. (2015b). Extending maintenance intervals of track switches utilising multi-channel redundancy of actuation and sensing.

Bemment, S. D., Goodall, R. M., Ebinger, E., Ward, C. P., and Dixon, R. (2017a). The repoint fault-tolerant switch. *Proceedings of Institution of Railway Signal Engineers*.

Bemment, S. D., Harrison, T. J., Goodall, R. M., Ward, C. P., and Dixon, R. (2017b). Extending emergency repair response times for railway track switches through multi-channel redundancy of functional subsystems. *International Journal of Railway Technology*.

Bendfeldt, J. P., Mohr, U., and Muller, L. (2000). Railsys: a system to plan future railway needs. In *Allan J, Brebbia CA, Hill RJ, Sciutto G and Sone S, (eds) Computers in Railways VII, 7th International Conference on Computers in Railways. pp. 249-255.*, Southampton.

Bezin, Y. (2016). Designing future turnouts–where research capabilities meet industry needs. *Rail Tech Expert Series, 26th January 2016, UIC, Paris*.

Blanke, M., Kinnaert, M., Lunze, J., and Staroswiecki, M. (2006). *Diagnosis and fault-tolerant control*. Springer, New York.

Blanke, M., Staroswiecki, M., and Wu, N. E. (2001). Concepts and methods in fault-tolerant control. In *American Control Conference, 2001. Proceedings of the 2001*, volume 4, pages 2606–2620. IEEE.

Boardman, J. and Sauser, B. (2006). System of systems - the meaning of. In *2006 IEEE/SMC International Conference on System of Systems Engineering*, pages 6–pp. IEEE.

British Railways (1962). British Railways Chief Civil Engineer's Dept BR109 / BS110A Continuous Welded Rail adjustment switch assembly. Technical report.

British Railways (1965). British Railways Chief Civil Engineer's Dept: 110A Flat Bottomed Adjustment switch (expansion joint). Technical report.

BS EN 60947 (1996). Bs en 60947: 1996–2003. *Specification for LV switchgear and control gear. British Standards Institution*, 2003.

Cardani, A. (1958). IRSE 'Green Booklet' No.14:- Multiple Aspect Signalling. The Institution of Railway Signal Engineers, London.

Carey, M. and Carville, S. (2003). Scheduling and platforming trains at busy complex stations. *Transportation Research Part A: Policy and Practice*, 37(3):195 – 224.

Champion, D. L. (1957). IRSE 'Green Booklet' No.10:- Mechanical Signalling Equipment (British Practice). The Institution of Railway Signal Engineers, London.

Chen, J. and Patton, R. J. (2012). *Robust model-based fault diagnosis for dynamic systems*, volume 3. Springer Science & Business Media.

Ciobanu, C. and Nogy, L. (2017). Rail thermal force calculations for jointed track, article 3. *The Journal of the Permanent Way Institution*, 135(4).

Colantuono, T., Grossoni, I., Allen, P., Molyneux-Berry, P., and Borczyk, P. (2016). The optimal strength of shear pins: Requirements in point run-throughs. *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, page 0954409716682657.

Coleman, I. (2014). *The Development of modelling tools for railway switches and crossings*. PhD thesis, Imperial College, London, Imperial College, London.

Collis, J. and Hussey, R. (2013). *Business research: A practical guide for undergraduate and postgraduate students*. Macmillan International Higher Education.

Connor, P. (2014). High speed railway capacity. *Citeseer*.

Cope, D. D. L. and Ellis, J. B. (2001). *British Railway Track 7th Edition, Volume 5: Switch and Crossing Maintenance*. The Permanent Way Institution, Derby, UK.

Corbin, R. (2016). Repoint Light actuator torque requirements. Technical report.

Cornish, A. (2014). Life-time monitoring of in service switches and crossings through field experimentation.

Cribbens, A. (1987). Solid-state interlocking (ssi): an integrated electronic signalling system for mainline railways. In *IEE Proceedings B-Electric Power Applications*, volume 134, pages 148–158. IET.

Cross, N. and Roy, R. (1989). *Engineering design methods*, volume 4. Wiley New York.

Davies, J. (2009). *Modelling, control and monitoring of high redundancy actuation*. PhD thesis, Loughborough University, Loughborough University Institutional Repository.

Davies, J., Dixon, R., Goodall, R. M., and Steffen, T. (2014). Multi-agent control of high redundancy actuation. *International Journal of Automation and Computing*, 11(1):1–9.

DeLaurentis, D. (2005). Understanding transportation as a system-of-systems design problem. In *43rd AIAA Aerospace Sciences Meeting and Exhibit*, volume 1. Reno, NV New York, NY.

Ding, S. (2008). *Model-based fault diagnosis techniques: design schemes, algorithms, and tools*. Springer Science & Business Media.

Dixon, R., Steffen, T., Davies, J., Goodall, R. M., Zolotas, A., Pearson, J., and Du, X. (2009). Hra-intrinsically fault tolerant actuation through high redundancy. *IFAC Proceedings Volumes*, 42(8):1216–1221.

dos Santos, G. F. and Barbosa, R. S. (2015). Modeling of a railway vehicle travelling through a turnout. *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*.

Dowton, A. and Baker, C. (2002). A Guide to the Journey Time Capability Model Workbook (PROPRIETARY). Technical report, London Underground Ltd.

Dwyer, V. M., Goodall, R. M., and Dixon, R. (2012). Reliability of 2-out-of-n: G systems with nhpp failure flows and fixed repair times. *International Journal of Reliability, Quality and Safety Engineering*, 19(01):1250003.

Ellis, I. (2006). *Ellis' British Railway Engineering Encyclopaedia*. Lulu Enterprises, UK Ltd, London, UK.

Ellis, I. W. (2001). *British Railway Track 7th Edition, Volume 9: Track Terminology*. The Permanent Way Institution, Wakefield, UK.

EN50126 (1999). 50126, railway applications–the specification and demonstration of reliability, availability, maintainability, and safety (rams). *British Standard*.

EN61508 (2002). 61508-1: 2002 functional safety of electrical/electronic/programmable electronic safety-related systems.

Esveld, C. (2001). *Modern Railway Track, 2nd Edition*. MRT-Productions, NL-5300 AH Zaltbommel, The Netherlands.

Fargher, M. (1999). Categorisation of track. *Railway Group Standard*, GCRT5023.

Fleming, E. (2000). Asset Management for the Safety of Signalling and Operational Telecommunication Systems and Equipment. Safety & Standards Directorate, Railtrack PLC, London.

Fleming, E. (2015). GE-RT8000: Rule Book (Master Manual). Rail Safety and Standards Board Limited, London.

Foan, A. (2014). Application of RePoint Concept to GB Switch Geometries. Technical report.

Fox, F. (1904). *River, road, and rail: some engineering reminiscences*. J. Murray.

Garcia, F. P., Schmid, F., Collado, J. C., et al. (2003). A reliability centered approach to remote condition monitoring. a railway points case study. *Reliability Engineering & System Safety*, 80(1):33–40.

GB Patent: Loughborough University (2013a). ‘Railway Points’ (GB 2516706).

GB Patent: Loughborough University (2013b). ‘Railway Points Operating Apparatus’ (GB 2516707).

GB Patent: Loughborough University (2013c). ‘Railway Track Crossing’ (GB2516712).

Genner, R. (1997). Railway group standard gk/rt0062: Control of points. Safety & Standards Directorate, Railtrack PLC, London.

Goodall, R., Bemment, S., Fujiyama, T., Mei, T., Preston, J., Romanovsky, A., and Roggenbach, M. (2013). The future of train control systems. *Proceedings of Institution of Railway Signal Engineers*, pages 1–12.

Goodall, R. M., Dixon, R., and Dwyer, V. M. (2006). Operational Reliability Calculations for Critical Systems. In *Sixth IFAC Symposium on Fault Detection, Supervision and Safety of Technical Processes, Tsinghua University, P.R. China, Aug 29 - Sept 1st*. © Elsevier.

Goswami, D. Y. (2004). *The CRC handbook of mechanical engineering*. CRC press.

Goverde, R. M. and Hansen, I. A. (2013). Performance indicators for railway timetables. In *Intelligent Rail Transportation (ICIRT), 2013 IEEE International Conference on*, pages 301–306. IEEE.

Hadaway, H. W. (1950). IRSE ‘Green Booklet’ No.5:- Principles of power point control and detection (British Practice). The Institution of Railway Signal Engineers, London.

Hayter, S. (2000). Railway group standard gi/rt7004: Requirements for the design, operation and maintenance of points. Safety & Standards Directorate, Railtrack PLC, London.

Hayter, S. (2011). Railway group standard gc/rt5021: Track system requirements. RSSB (Rail Safety and Standards Board), London.

Head, S. (2013). RHDR Track, Vehicle and Site Descriptions to Support the Repoint Demonstrator. Technical report.

Hecht, H. (2004). *Systems reliability and failure prevention*. Artech house.

Hibbeler, R. (2005). Mechanics of materials 6th edition pearson prentice-hall. *Upper Saddle River, NJ*.

HS2 Ltd (2011a). HS2 Birmingham to Leeds - Design Trade-Offs for Stations (HS2-ARP-000-ZZ-RP-RS-00001). Technical report, Ove Arup and Partners Ltd.

HS2 Ltd (2011b). Summary Report on the Capacity and Capability for the High Speed Network. Technical report, High Speed Two Ltd.

HS2 Ltd (2012). HS2 Project Specification. Technical report, High Speed Two Ltd.

HSE (2005). Railway safety principles and guidance part 2: Guidance on signalling. Health and Safety Executive and HM Rail Inspectorate, London.

IAD Rail Systems (2001). High Performance Switch System, powered by the High Performance Switch Actuator and the ‘Powerlink’ Backdrive. IAD Rail Systems HPSS specifications sheet, London.

IEEE (2004). 1474.1-2004 - IEEE Standard for Communications-Based Train Control (CBTC) Performance and Functional Requirements. Technical report.

IRSE (1993). IRSE Report No. 2: Operational Availability of Railway Control Systems. Technical report, The Institution of Railway Signal Engineers (IRSE), London, UK.

IRSE (2001). *Introduction to Railway Signalling*. Fericon, Reading.

IRSE (2011). Institution of Railway Signal Engineers, Minor Railways Section: Guidelines On: Glossary of Signalling and Telecommunications Terminology. http://www.irse.org/minorrailways/publicdocuments/GlossaryV1.pdf, Accessed 30-06-2012.

Iserman, R. and Balle, P. (1997). Trends in the application of model-based fault detection and diagnosis of technical processes. *Control Engineering Practice*, 5(5):709–719.

Isermann, R. (2005). Model-based fault-detection and diagnosis – status and applications. *Annual Reviews in Control*, 29(1):71 – 85.

Isermann, R. (2006). *Fault-Diagnosis Systems: An Introduction from Fault Detection to Fault Tolerance*. Springer, Berlin.

Isermann, R. and Ballé, P. (1997). Trends in the application of model-based fault detection and diagnosis of technical processes. *Control engineering practice*, 5(5):709–719.

Ison, S., Frost, M., and Watson, R. (2012). Uk rail transport: a review of demand and supply. *Proceedings of the Institution of Civil Engineers - Transport*, 165(3):225–234.

Iwnicki, S. (2014). The academic response to the rail technical strategy 2012. Technical report, Rail Research UK Association (RRUKA), London, UK.

Jamshidi, M. (2011). *System of systems engineering: innovations for the twenty-first century*, volume 58. John Wiley & Sons.

Jönsson, J., Arasteh Khouy, I., Lundberg, J., Rantatalo, M., and Nissen, A. (2014). Measurement of vertical geometry variations in railway turnouts exposed to different operating conditions. *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*.

Kollmorgen (2014). AKM Servomotor Selection Guide. Technical report.

Kossiakoff, A., Sweet, W. N., Seymour, S., and Biemer, S. M. (2011). *Systems engineering principles and practice*, volume 83. John Wiley & Sons.

Kroon, L. G., Romeijn, H. E., and Zwaneveld, P. J. (1997). Routing trains through railway stations: complexity issues. *European Journal of Operational Research*, 98(3):485 – 498.

Landex, A. (2009). Evaluation of railway networks with single track operation using the uic 406 capacity method. *Networks and Spatial Economics*, 9(1):7–23.

Landex, A., Kaas, A. H., Schittenhelm, B., and Schneider-Tilli, J. (2006a). Evaluation of railway capacity. *Trafikdage/Trafficdays*.

Landex, A., Kaas, A. H., Schittenhelm, B., and Schneider-Tilli, J. (2006b). Practical use of the uic 406 capacity leaflet by including timetable tools in the investigations. *WIT Transactions on The Built Environment*, 88.

Leach, M. (1991). *Railway Control Systems*. Miscellaneous Series. A & C Black.

Lee, P. A. and Anderson, T. (2012). *Fault tolerance: principles and practice*, volume 3. Springer Science & Business Media.

Lew, M.-A. and Heede, J. (2016). Repoint Light Benefits Justification. Technical report.

Liu, R., Whiteing, A., and Koh, A. (2013). Challenging established rules for train control through a fault tolerance approach: applications at a classic railway junction. *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, 227(6):685–692.

London Underground (2014). London underground timetables. `https://tfl.gov.uk/travel-information/timetables/`. Accessed: 2014-06-02.

Loosemore, J. P. (1958). IRSE 'Green Booklet' No.7:- Signal Control Circuits. The Institution of Railway Signal Engineers, London.

Marks, M. (2000). Railway Group Standard GK/RT0064: Provision of Overlaps, Flank Protection and Trapping. Safety & Standards Directorate, Railtrack PLC, London.

Marquez, F. G., Roberts, C., and Tobias, A. M. (2010). Railway point mechanisms: condition monitoring and fault detection. *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, 224(1):35–44.

Marquez, F. P. G., Lewis, R. W., Tobias, A. M., and Roberts, C. (2008). Life cycle costs for railway condition monitoring. *Transportation Research Part E: Logistics and Transportation Review*, 44(6):1175–1187.

Marquez, F. P. G., Tercero, D. J. P., and Schmid, F. (2007). Unobserved component models applied to the assessment of wear in railway points: A case study. *European Journal of Operational Research*, 176(3):1703 – 1712.

Marshall, N. (1961). IRSE 'Green Booklet' No.19:- Principles of relay interlocking and control panels (British practice). The Institution of Railway Signal Engineers, London.

Mason, R. L. and Young, J. C. (2002). *Multivariate statistical process control with industrial applications*, volume 9. Siam.

McNaughton, A. (2007). Intelligent infrastructure - good practice guide. Network Rail, London.

McNaughton, A. (2011). Signalling Headways and Maximum Operational Capacity on High Speed Two London to West Midlands Route. Technical report, HS2 Ltd.

McNulty, S. R. (2011). Realising the potential of gb rail: final independent report of the rail value for money study. *Department for Transport and Office of Rail Regulation, London*.

Mitchell, D. L. (1958). IRSE 'Green Booklet' No.11:- Railway Signalling Power Supplies (British Practice). The Institution of Railway Signal Engineers, London.

Modarres, M., Kaminskiy, M. P., and Krivtsov, V. (2009). *Reliability engineering and risk analysis: a practical guide*. CRC press.

Morgan, J. C. (2009). *British Railway Track 7th Edition, Volume 1, Design Part 2: Switches and Crossings*. The Permanent Way Institution, Derby, UK.

Murphy, T. I. (2014). Thomson linear: Gearhead, true planetary, valuetrue, size 115, 70:1 specifications. `https://www.thomsonlinear.com/en/product/27-119360-J341`. Accessed April 4, 2014.

Murthy, D. and Hussain, A. (1995). Warranty and optimal redundancy design. *Engineering Optimization+ A35*, 23(4):301–314.

NASA (1995). Fault Tolerant Design (Tech. Report No. PD-ED-1246. Technical report, National Aeronautics and Space Administration.

Neill, C. J. and Laplante, P. A. (2003). Requirements engineering: the state of the practice. *IEEE software*, 20(6):40.

Network Rail (2012). Fixed Assets Team: Data from Intelligent Infrastructure relating to fault-free POE energy use. By personal communication.

Network Rail (2006). Standard NR/C&TM/TR/BSD 123/9 - Network Rail Training - Basic Signalling Design (Section 11): Signalling Power Supplies . Technical report.

Network Rail (2008). Progress Report on the Development of the Asset Information Strategy and Asset Register. Technical report.

Network Rail (2010a). NR/L2/TK/2049: Network Rail Level 2 Standard. Track Design Handbook, Issue 12. Network Rail, London.

Network Rail (2010b). NR/SIG/SG0079: Signalling Responsibilities for S&C Maintenance, Issue 3. Network Rail Engineering Standard, Network Rail, London.

Network Rail (2011a). Network Rail, London and South East Route Utilisation Strategy.

Network Rail (2011b). NR/L2/SIG/10660: Implementation of Signalling Maintenance Specifications, Issue 8. Network Rail Engineering Standard, Network Rail, London.

Network Rail (2012a). Performance Modelling Team: Data from asset location database and FMS (Fault Management System relating to points faults and failures for period 1 april 2008 and 17 september 2011. By personal communication.

Network Rail (2012b). Standard: NR/L2/TRK/001/MOD14 - Network Rail Standard - Inspection and Maintenance of Permanent Way: Managing track in hot weather. Technical report.

Network Rail (2013a). NR/SIG/10661: Signalling Maintenance Task Intervals, Issue 12;. Network Rail Engineering Standard, Network Rail, London.

Network Rail (2013b). NR/SIG/10663: Signal Maintenance Specifications (SMS), Issue 4. Network Rail Engineering Standard, Network Rail, London.

Network Rail (2013c). NR/SIG/11231: Signalling Maintenance Testing Handbook (SMTH), Issue 7. Network Rail Engineering Standard, Network Rail, London.

Network Rail (2015). Discussion with Switches and Crossings Team (2015) on POE types, populations, preferred installation types and future deployments. By personal communication.

Network Rail (2016). Briefing document: Analysis on existing point operating equipment. By personal communication (Proprietary, unpublished).

Nicklisch, D., Kassa, E., Nielsen, J., Ekh, M., and Iwnicki, S. (2010). Geometry and stiffness optimization for switches and crossings, and simulation of material degradation. *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, 224(4):279–292.

Odijk, M. A. (1999). Sensitivity analysis of a railway station track layout with respect to a given timetable. *European Journal of Operational Research*, 112(3):517 – 530.

ORR (2006). Office for Rail Regulation: The Railways and Other Guided Transport Systems (Safety) Regulations 2006. Technical report, UK Parliament.

ORR (2013). ORR (Office of Rail Regulation) Online Data Portal - Total journey count reporting. `http://dataportal.orr.gov.uk/`. Accessed: 2013-10-12.

ORR (2014). The office of rail regulation: Strategy for the regulation of health and safety risks, chapter 6: Infrastructure asset safety. Office of Rail Regulation, London.

ORR (2015). Performance regime, track access guidance (performance). Office of Rail Regulation, London.

Palmer, J. (2012). The need for train detection. In *IET Conference Proceedings*. The Institution of Engineering & Technology.

Pohl, K. (1994). Fifth international conference on advanced information systems engineering (caise '93) the three dimensions of requirements engineering: A framework and its applications. *Information Systems*, 19(3):243 – 258.

Pope, R. (1975). IRSE 'Green Booklet' No.27:- Signalling the Layout (British Practice). The Institution of Railway Signal Engineers, London.

Proschan, F. (1996). Mathematical theory of reliability.

RAIB (2011). Rail Accident Report - Derailment at Grayrigg, 23 February 2007 (Report 20/2008 version 5). Technical report, Rail Accident Investigation Branch, Department for Transport, The Wharf, Stores Road, Derby, UK, DE21 4BA.

Rail, N. (2009). Meeting the capacity challenge: The case for new lines. Technical report, Network Rail, New Lines Progamme, Route Planning, Network Rail, Kings Place, 90 York Way, London, N1 9AG.

Rama, D. and Andrews, J. D. (2013). A reliability analysis of railway switches. *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of rail and rapid transit*, 227(4):344–363.

Rao, B. (1996). *Handbook of condition monitoring*. Elsevier.

Rausand, M. and Hoyland, A. (2004). *System Reliability Theory: Models, Statistical Methods and Applications*. John Wiley & Sons, Ltd, Hoboken, NJ.

Rausand, M. and Vatn, J. (2008). *Reliability Centred Maintenance*, chapter 4, pages 79–108. Springer London, London.

Raymond, W. G., Riggs, H. E., and Sadler, W. C. (1937). *The Elements of Railroad Engineering*. John Wiley & Sons, New York, USA, fifth edition.

Rolt, L. T. C. (1982). *Red for Danger: The Classic History of British Railway Disasters*. David & Charles, London, UK, fourth edition.

RSSB (2005). Formal Inquiry: Derailment of train 1T60, 1245 hrs Kings Cross to Kings Lynn at Potters Bar on 10 May 2002. Technical report, Rail Safety and Standards Board, Rail Safety and Standards Board, Evergreen House, 160 Euston Road, London, NW1 2DX.

Sarmiento-Carnevali, M., Bemment, S., Harrison, T., Ward, C., Bezin, Y., Neves, S., Kostovasilis, D., and Sichani, M. S. (2017a). Repoint track switch wheel-rail mechanical interface analysis.

Sarmiento-Carnevali, M., Bemment, S., Harrison, T., Ward, C., Dixon, R., Bezin, Y., Neves, S., Kostovasilis, D., and Sichani, M. (2017b). Repoint track switch wheel-rail mechanical interface analysis. In *Proceedings of the 25th international symposium on Dynamics of Vehicles on Roads and Tracks (IAVSD 2017), Volume 2: The Dynamics of Vehicles on Roads and Tracks*, pages 711–717. IAVSD.

Scholz, F. W. (2004). *Maximum Likelihood Estimation*. John Wiley & Sons, Inc.

Sharp, H., Finkelstein, A., and Galal, G. (1999). Stakeholder identification in the requirements engineering process. In *Database and Expert Systems Applications, 1999. Proceedings. Tenth International Workshop on*, pages 387–391. Ieee.

Silmon, J. and Roberts, C. (2010). Improving railway switch system reliability with innovative condition monitoring algorithms. *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, 224(4):293–302.

Simmons, A. (2001). NR/PS/SIG/2001: Requirements for Powered Point Operating Equipment. Network Rail company standard, London.

Simmons, A. and Ventry, D. (2001). Requirements for Powered Point Operating Equipment (Formerly RT/SRS/2001). Network Rail Standard, Network Rail, London.

Stanley, P. (2011). *ETCS for Engineers*. Eurail Press, Hamburg, Germany.

Steel, T. (2014). Rail technical guide (EN). Technical report.

Steffen, T., Schiller, F., Blum, M., and Dixon, R. (2013). Analysing the reliability of actuation elements in series and parallel configurations for high-redundancy actuation. *International Journal of Systems Science*, 44(8):1504–1521.

Stratton, D., of Railway Signal Engineers (Great Britain), I., and Leach, M. (1988). *Solid State Interlocking*. "Green" booklet. Institution of Railway Signal Engineers.

Stratton, D. H. (1988). IRSE 'Green Booklet' No.29:- Solid State Interlocking (British Practice). The Institution of Railway Signal Engineers, London.

Such, W. H. (1956). IRSE 'Green Booklet' No.2:- Principles of Interlocking (British Practice). The Institution of Railway Signal Engineers, London.

Sun, Y. Q., Cole, C., and McClanachan, M. (2010). The calculation of wheel impact force due to the interaction between vehicle and a turnout. *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, 224(5):391–403.

Systra UK (2011). Operational Concept Study, Technical Note: HS2 Capacity and Reliability. Technical report, High Speed Two Ltd/SYSTRA.

UIC406 (2004). UIC 406(R): Capacity (English Version, 1st edition). International Union of Railways (UIC), Paris, France.

Vitaly, M., Ludmila, V., and Irina, B. (2016). Analysis of stress distribution in a rail by electromagnetic-acoustic method. In *AIP Conference Proceedings*, volume 1785, page 030016. AIP Publishing.

Von Neumann, J. (1956). Probabilistic logics and the synthesis of reliable organisms from unreliable components. *Automata studies*, 34:43–98.

Ward, C. P., Mei, T., Hubbard, P. D., and Mirzapour, M. (2014). Railway vehicle optimisation using the concept of" design for control".

Webb, M. and Tee, J. (2015). *IHS Jane's Urban Transport Systems*. IHS.

White, R. V. and Miles, F. M. (1996). Principles of fault tolerance. In *Applied Power Electronics Conference and Exposition, 1996. APEC'96. Conference Proceedings 1996., Eleventh Annual*, volume 1, pages 18–25. IEEE.

Winter, A. (2006). European Patent: 'Device for connecting railways' (EP 1860238 (A2)).

Wright, N., Bemment, S., Ward, C., and Dixon, R. (2014a). A model of a repoint track switch for control. In *Control (CONTROL), 2014 UKACC International Conference on*, pages 549–554. IEEE.

Wright, N., Bemment, S. D., Ward, C. P., Dixon, R., and Goodall, R. M. (2014b). The performance and control requirements of a repoint track switch.

Yearout, R. D., Reddy, P., and Grosh, D. L. (1986). Standby redundancy in reliability-a review. *IEEE Transactions on Reliability*, 3(35):285–292.

Yianni, S. (2012). Railway Technical Strategy 2012: The future railway, The industry's rail technical strategy 2012. Technical report, Technical Strategy Leadership Group, RSSB, London, UK.

Young, R. R. (2001). *Effective requirements practices*. Addison-Wesley Longman Publishing Co., Inc.

Zhang, Y. and Jiang, J. (2003). Bibliographical review on reconfigurable fault-tolerant control systems. *5th IFAC Symposium on fault detection, supervision and safety for technical processes*, pages 265–276.

Appendix A

Journal Publications

This appendix contains verbatim copies of three first-author journal papers published as part of the work described in this thesis.

Institution of MECHANICAL ENGINEERS

Journal of RAIL AND RAPID TRANSIT

Original Article

Rethinking rail track switches for fault tolerance and enhanced performance

Proc IMechE Part F:
J Rail and Rapid Transit
2017, Vol. 231(9) 1048–1065

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Abstract

Railway track switches, commonly referred to as 'turnouts' or 'points,' are a necessary element of any rail network. However, they often prove to be performance-limiting elements of networks. A novel concept for rail track switching has been developed as part of a UK research project with substantial industrial input. The concept is currently at the demonstrator phase, with a scale (384 mm) gauge unit operational in a laboratory. Details of the novel arrangement and concept are provided herein. This concept is considered as an advance on the state of the art. This paper also presents the work that took place to develop the concept. Novel contributions include the establishment of a formal set of functional requirements for railway track switching solutions, and a demonstration that the current solutions do not fully meet these requirements. The novel design meets the set of functional requirements for track switching solutions, in addition to offering several features that the current designs are unable to offer, in particular to enable multi-channel actuation and rail locking, and provide a degree of fault tolerance. This paper describes the design and operation of this switching concept, from requirements capture and solution generation through to the construction of the laboratory demonstrator. The novel concept is contrasted with the design and operation of the 'traditional' switch design. Conclusions to the work show that the novel concept meets all the functional requirements whilst exceeding the capabilities of the existing designs in most non-functional requirement areas.

Keywords

Track switch, capacity, reliability, multi-channel redundancy, fault tolerance

Date received: 20 August 2015; accepted: 28 March 2016

Introduction

A novel concept for rail track switching has been developed as part of a UK research project with substantial industrial input. The concept is currently at the demonstrator phase, with a scale (384 mm) gauge unit currently operational in a laboratory – as depicted in Figure 1, and is covered by published patents.[1,2] The design meets the set of functional requirements for track switching solutions, in addition to enabling multi-channel actuation and rail locking, to provide a degree of fault tolerance. The concept also offers several features that the current designs are unable to, in particular more than two routes out of a single switching element. This paper describes the formation, design and operation of the novel switching concept, from requirements capture and solution generation through to the construction of the laboratory demonstrator.

Track switches ('turnouts' or 'points') are a necessary element of any rail network. Switches enable vehicles to take many different routes through the network. A single switch, or a clustered group of switches (e.g. at a station throat), is variously considered a junction, and/or a 'node.' It is generally the nodes which define the capacity and performance of any transport system, as extensively explored in literature – for example in the European case by Abril et al.,[3] and by the Transportation Research Board in the US case.[4] Waterloo station throat, one of the most complex pieces of track work in the United Kingdom, is responsible for the safe arrival of just under 108 million passengers per year[5] and features 80 switches within just 500 linear metres of route. Figure 2 shows the simplest junction element – a single turnout arrangement, which also forms the simplest possible node.

However, because of their nodal nature, track switches represent single points of failure, and their

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failures can prevent use of extensive sections of the network. It is for this reason that rail network performance is negatively affected by switch failures to a greater degree than any other asset.[5] Due to this, extensive plans have been put in place to minimise the impact of switch failures, involving hand-signallers at each node manually winding points and flagging trains through, as further explored later. Switches are expensive and are of complex designs when compared to the equivalent plain line sections.

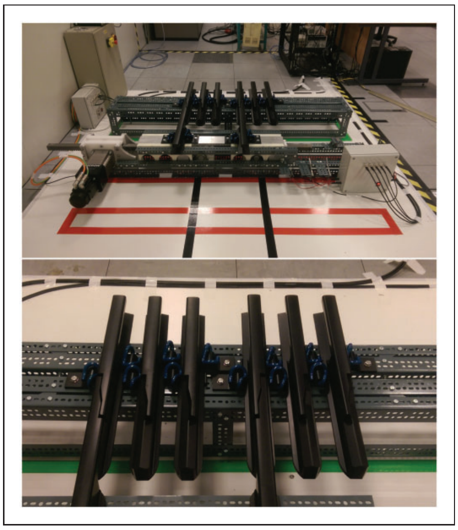

Figure 1. Photographs of the general arrangement of the novel track switching demonstrator in the laboratory at Loughborough University, at 384 mm gauge. Top: general arrangement. Bottom: detail of interlocking rail ends.

Their population is therefore generally optimised at design time – alongside a known timetable – in order to minimise initial outlay and substantial ongoing maintenance costs. The result of this optimisation is the availability of few, if any, diversionary options should a failure occur. This can compound the negative effects upon network delay performance, especially during timetable perturbation. Even when fully operational, switches can introduce capacity constraints due to the design of physical track components and the associated signalling systems for control and operation.[6,7]

On the European network, there is an anticipated move towards universal in-cab signalling.[8] With the gradual removal of other line-side assets related to signalling and control, the only remaining active line-side elements will be switches and level crossings. Switches will thus contribute to an ever-increasing portion of network delay totals without significant further work to improve performance. Open-access statistics[5] show UK passenger counts are at their highest level since re-privatisation in 1993, with some lines now running at or near operational vehicular capacity. This fact, when coupled with cross-industry initiatives such as the '24/7 Railway,'[9] 'On-time Railway,' and increasing overnight freight utilisation as suggested in the recent IMechE Rail Freight Report,[10] further reduces the portion of time available to take maintenance possessions of infrastructure. Importantly, it is often not the physical maintenance act itself which is expensive in monetary terms, but rather the time the asset is out of use – whether this be for a planned maintenance intervention or unanticipated failure. Capacity cost is explored by Nash et al.[11] This monetary cost is associated to a nodal and, consequently, network-capacity cost.

Existing track switch systems are the result of the evolution of a single design solution dating to early mining railways in the 1700 s.[12] The operating

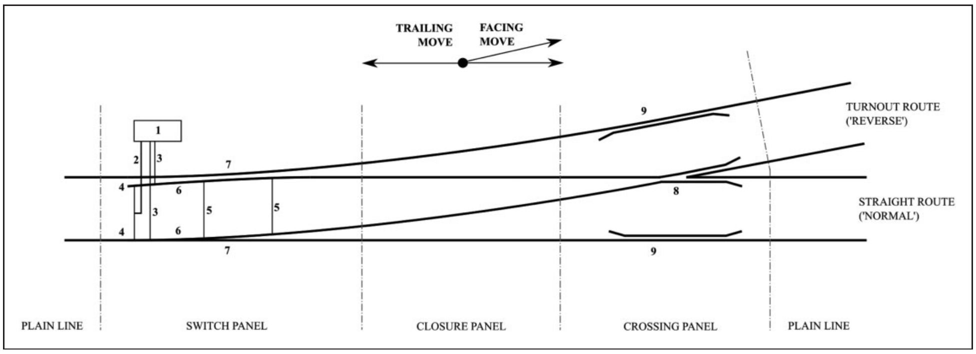

Figure 2. Typical traditional switch layout, with sleepers/bearers omitted for clarity. (1) Line-side type electromechanical actuator featuring integral lock and detection; (2) Drive rod and drive stretcher; (3) Detection rods; (4) Switch rail toes; (5) Stretcher bars; (6) Switch rails; (7) Stock rails; (8) Common crossing (of given angle); (9) Check rails.

parameters of a modern railway system are much changed from those early days. Other elements of rail systems have undergone step changes as disruptive technologies have made an impact. Notable examples are the moves from steam to diesel and electric traction, the widespread adoption of reinforced concrete for viaducts and tunnels, and the move to solid state interlocking (SSI). However, apart from small incremental changes, for instance to actuation methods, a modern track switch is of the same design and operation as those early days despite the requirements having changed significantly.

This paper considers the design and operation of track switches with a view to improving their negative impact upon network performance. Performance, in this instance, is considered as maintainability, system capacity, reliability and cost, though it is accepted that other measures could be utilised. Existing systems, their limitations and impact upon performance are considered in 'Existing systems' section. A requirements capture exercise follows in the 'Requirements analysis' section, which sets out the minimum functional set required of a track switching solution. The following section, 'Generation and evaluation of solutions,' presents some switching concepts generated from a series of expert focus groups, and follows the process used to down-select these options to the most appropriate. The paper then presents more detail on what has been termed 'The Repoint solution,' including its general arrangement, feasibility, and the qualitative benefits and drawbacks. Conclusions to the Repoint study are then presented alongside the possible future work.

Existing systems

Mechanical design

There are many methods of achieving a solution to the conflicting issues posed by track switching. However, all major railway systems throughout the world utilising the 'traditional' arrangement of twin steel running rails and flanged wheels have adopted a broadly similar mechanical arrangement, extensively detailed in both industry publications[12] and academic literature.[13,14] This arrangement is shown in Figure 2. Switch arrangements consist of three distinct elements, or panels; namely 'switches,' 'crossings' and 'closure panels.'

Referring to the numbered elements in Figure 2, a pair of longitudinally extending switch rails (6) are free to bend or pivot beyond a given point, and slide upon supporting plates or chairs, between two fixed 'stock' or 'running' rails (7). Actuation power and transmission is variously provided by humans and mechanical lever arrangements, pneumatics, hydraulics or electro-mechanics (1). A mechanical linkage from the power source links the two switch rails (2, 5), operating so as to open one rail and close the other, either synchronously or sequentially. In most jurisdictions, mainline switches that carry passenger traffic also feature a locking arrangement, which prevents the switch rails moving uncommanded, or when incorrectly commanded, for instance under the wheels of a passing train. However, in spring or 'train-operated points,' the switch rails are free to pivot in order that the wheelsets of a train in a trailing move can move the rails to provide a constantly supported route throughout. Standard design switches of different lengths and crossing (8) angles exist to satisfy different turnout speeds, longer switches generally being more complex and expensive, but capable of handling traffic turning out at much higher speeds. There are a range of generic switch designs approved for use upon British mainline infrastructure, and their properties differ depending upon purpose – the main differentiator being the design speed. Note that, whilst there is a 'standard set' of switch designs, in practice each installation would have its particular layout adapted for a given location. For example, a turnout placed on a curve needs differential curves on either route, meaning a different crossing angle. Designers of guided transport systems have to consider the trade-off of space, cost, line speed and capacity in selecting and locating switches for a given application.[15]

Switch rails can be of the same cross section as the running rails, or in some designs, speciality 'shallow depth' rail. Switch rails are reduced in cross section along their length in a process termed 'planing,' in order that they accurately mate up against the full-section stock rails when closed, therefore providing a smooth dynamic transfer of load under a passing train. However, as the switch rails require a minimum cross section to support loads, there is some sacrifice of track alignment along one or both routes to enable the practical manufacture and wear management of the switch. Design for specific requirements, and maintenance thereof, is extensively covered in Morgan[12] and Cope and Ellis.[16]

At the point where the outer rails of the two diverging routes cross, provision must be made for the wheel flanges to pass through unhindered. In common use are built-up and cast crossings, which have a gap in both running rails to allow this. As line speeds increase and curve radii become correspondingly larger, crossing angles become finer, and geometry dictates this gap – where the axle is unsupported or running on the flange – necessarily gets longer. This has led to the development of the swing-nose and swing-wing crossing, which have active components moving synchronously with the point ends in order to provide a continuously supported route. This solution has also been applied to very heavy axle loads where resultant impact forces on the crossing nose would be unacceptable. A closure panel then fills in the space between the movable switch rails and the crossing element, to provide support and guidance to traversing vehicles throughout the switch. The switch would generally be bracketed on all routes by sections of plain line, but in more complex junctions – especially those where footprint is restricted – switches may be adjacent or even overlap.

Signalling and operational rules

Switches remain in position and locked until commanded to move via the signalling system. The position of the blades, and the integrity of the position lock, is continually fed back to the interlocking via a subsystem known as detection. When changing position, traditional switch designs move through a state, which can be considered dangerous due to the inherent derailment risk, when the moveable blades are between the two set positions. Trains can be issued a movement authority (either by radio in communication-based signalling systems, or else by a lineside signal aspect) to pass the switch only once the movement process is complete. Switches under UK practice follow a move–lock–detect cycle. This means, upon command from the interlocking, the actuator moves the blades to the correct position, then locks them in place, then detects the position of both blades and the integrity of the lock before transmitting this information back. This process normally takes several seconds; around 8 s is allowed in British signalling practice. A more detailed discussion of the British practice of switch control and operation is provided in 'Principles of power point control and detection.'[17] Additional time is often required for remote interlocking processing and transmission of the authority. As the switch represents a derailment danger when between positions or unlocked, under no circumstance can the switch be moved within a previously issued movement authority. For instance, a switch actuated within the effective braking distance of the train, which subsequently fails to fully change positions, could cause derailment or a potentially disastrous misrouting. As nodes become more complex, this requirement becomes increasingly restrictive due to safety rules surrounding actuation of switches on adjacent lines and around conflicting moves, e.g. flank protection.[18] There is generally an element of the interlocking responsible for releasing the switch to be reset some time after a train has passed, for example train operated route release (TORR). Crucially, the signalling system is designed to pass back no more information on the current state of a switch than whether it is locked and detected normal or reverse, or not detected in either position.[17]

Capacity

These restrictions upon movement lead to a reduction in the theoretical maximum capacity of a junction below what could be expected from an equivalent section of plain line. Additional capacity is lost in installations where the turnout route has a speed restriction below that of the straight route; in these cases some braking or acceleration must take place upon the mainline, which further consumes the available capacity. It is not possible to define capacity as an absolute value, thus it is not possible to calculate, in the general sense, what this capacity restriction equates to. Capacity consumption is the method utilised by the industry, as detailed in various literature,[3,4,11] and further explored in standard UIC406.[19] The value for capacity consumption at a junction is linked to the proposed service pattern through that junction over a given time period. Previously published work has explored and, subsequently, modelled these capacity constraints and methods to alleviate, both from the authors of this paper,[20,21] and others, for example Liu et al.[22] The application of moving block signalling schemes will not necessarily alleviate capacity constraints at junctions, as the fixed obstruction provided by a switch causes the signalling operation to revert to fixed block at this point.[23]

Reliability

Table 1 shows incident counts and subsequent delay minute counts for asset failures on the UK infrastructure between 2007 and 2012.[5] A delay minute is a method of measuring the impact of a failure. One delay minute is accrued for each minute each train arrives late at its final destination. Depending upon the type of incident, 'knock-on' delay minutes can outnumber the number of minutes of the directly affected trains. Catch-up running after an incident can serve to cancel out some delay minutes. Allocation of delay minutes is an inexact science, subject to human judgement – all minutes are allocated by teams in relevant control centres. They should be used as indicative values only. There are 21,602 switches upon the UK network, as of 2012.[5] With a mean of 5917 failures per year amongst this population, this equates to a mean time between service affecting failure (MTBSAF) of 3.65 years network-wide. It is important to note that the issue is compounded by the fact that switches are often co-located at nodes, meaning many individual failures could affect the same node and cause repeated disruption. Switch failures do, however, cause a lower average delay minute count than some other failure types. Despite the nodal location, switches have built-in manual overrides to enable response teams to begin to hand-signal trains past the junction upon arrival, reducing the delay impact. These plans have been put in place to reduce the impact of commonly occurring and critically located switch failures. This could not be matched for some other infrastructure failures, examples being rail breaks or bridge failures, both of which have much higher mean delay minute counts. However, this response plan comes at a substantial monetary cost as response teams are kept on standby at all times.

Table 1. Incident count and subsequent delay minutes incurred for infrastructure asset failures between 2008–2014 upon UK mainline network, for top 18 incident categories by total count.

	Incident count							Delay minutes ('000s)						
	08-09	09-10	10-11	11-12	12-13	13-14	Mean	08-09	09-10	10-11	11-12	12-13	13-14	Mean min/ incident
Track	**7750**	**6665**	**5879**	**5519**	**5346**	**5997**	**6193**	**957**	**764**	**763**	**804**	**855**	**931**	**137**
Speed restrictions	1428	1278	932	717	685	747	965	204	147	107	78	71	100	122
Track faults	6322	5387	4947	4802	4661	5250	5228	753	617	655	726	784	831	139
Non-track	**32,001**	**30,109**	**27,157**	**25,767**	**25,121**	**25,491**	**27,608**	**2829**	**2596**	**2612**	**2609**	**2673**	**2700**	**97**
Points	8022	7118	5803	5162	5021	4376	5917	752	663	646	597	577	514	106
Level crossings	2261	2162	2003	1932	1857	1936	2025	101	96	101	93	100	104	49
OLE/Third rail	1458	1241	1281	1276	1265	1259	1297	238	245	251	227	325	309	205
Signals	6559	6202	5116	5018	4449	4278	5270	313	256	216	240	235	258	48
Track circuits	5381	5145	4567	4243	3902	3729	4495	585	517	550	605	534	515	123
Axle counters	1096	913	648	683	706	799	808	122	107	67	72	86	114	117
Signalling/Power	3750	4016	4422	4202	4494	4684	4261	442	419	517	486	517	545	114
Other signalling	1495	1430	1513	1505	1300	1338	1430	64	56	60	60	53	60	41
Telecoms	1406	1352	1252	1176	1513	2406	1518	70	70	53	56	73	95	46
Cables	573	530	552	570	614	686	588	142	167	150	172	173	187	281
Other	**12,633**	**9303**	**9084**	**9212**	**9289**	**10,753**	**10,046**	**779**	**601**	**639**	**654**	**795**	**977**	**74**
Structures	397	436	385	279	444	574	419	80	79	62	60	161	194	253
Other infra.	5478	3772	3455	3774	3612	4739	4138	251	204	213	253	297	318	62
Track patrols	3362	2565	2269	1949	2213	2075	2406	68	34	33	30	34	34	16
Mishaps	1839	1183	1493	1838	1836	2009	1700	191	108	133	145	147	228	93
Fires	197	221	250	257	116	218	210	17	32	34	22	13	64	145
Bridge strikes	1360	1126	1232	1115	1068	1138	1173	172	144	163	144	144	139	129
Total	52,384	46,077	42,120	40,498	39,756	42,241	43,846	4565	3961	4013	4066	4323	4608	97

Source: ORR Data Portal.[5]

The data shows that, for every published year apart from 2013 to 2014, points failures contribute the highest total of delay incidents. However, it can also be observed that points failure incidents, and subsequent delay minutes incurred, have fallen significantly over the same period. This is due, in part, to Network Rail's Intelligent Infrastructure programme, more details of which are provided by Silmon and Roberts.[14] This programme aims to remotely monitor switch installations in order to detect faults in the period before they develop into system failures. However, there is a limit to the projected benefit without the provision of a backup system to take over if a fault is detected, as the switch still has to survive in a serviceable state until a maintenance team can attend. Should the fault detection algorithm be too sensitive, the number of false positives may serve to offset much of the benefit. Isermann[24] provides a comprehensive discussion of the benefits of fault detection versus fault tolerance.

Human factors

Considering the whole life-cycle of switches and crossings, there are several cases where humans come into contact with the system. Design, installation and commissioning, and end-of-life decommissioning are of consideration. Choices regarding the type of machine and location, and the practicalities and practices at installation are known to have a significant effect upon the performance of the switch. These will not be discussed further in this paper as the issues would affect all designs and there is much ongoing research into this field.[25] The primary human contact through the working life of the switch installation is via signallers, who operate (but may be remote from) the switch, and the maintainers, who visit regularly to perform inspections, maintenance and adjustments, but are generally unable to operate the switch locally. A systems context diagram of existing track switch solutions is shown in Figure 3. It identifies the main actors in the lifetime of a switch installation, and with which subsystems they primarily interact.

The signaller. In mechanical signal boxes, the signaller manually sets a route through a junction by operating levers. Levers are connected to points and signals, some of which may be out of sight of the signaller. If the switch was blocked, for instance, the signaller would receive feedback through the lever as he/she would be unable to complete the movement. The length of the mechanical rodding used to transmit the motion has a practical limit of around 200 m, so in the event of any issues the signaller may be able to inspect the site to establish the problem. In a more modern control centre, the signaller's interaction with a switch is several levels removed. The signaller commands a route to be set by telling a computer or control panel the entry and exit points, and the control system then commands switches to move to correspond to this. The panel indicates the route is in the process of being set, generally with a flashing light, until the route is set at which point the lights change colour. If any of the switches fail to move to the commanded position, the lights continue to flash, and there is little the signaller can do apart from retry the route set command or contact the maintenance organisation. In the latest systems, automatic route setting (ARS) abstracts the signaller one layer further, in that human intervention is expected only when there is a failure or unresolvable conflict of traffic. Thus, no matter what the signalling installation type, the signaller is the daily user of the switch but acts at a level abstracted from its actual operation. The level of abstraction increases the more modern the signalling system, and this can compound issues when there is a switch failure.[26]

The maintainer. Switches require a level of inspection and maintenance in excess of plain line due to additional moving parts.[16,27] Failures of individual subcomponents almost inevitably lead to whole-system failures as there is minimal, if any, designed-in fault tolerance. Hence, switches are subject to careful inspection and maintenance regimes. UK switches undergo a rigorous and highly prescribed maintenance schedule to ensure all safety critical components are in good order. This involves two independent teams – Signalling and Permanent Way Departments – visiting each switch; the latter at a frequency of once per week. The maintenance organisations are not able to move the switch locally; instead they contact the signaller to effect this for them. In addition to time-interval maintenance, the maintenance organisation has a rapid response unit, which is responsible for attending any asset failures, including switches. These teams may have a large area to cover and, if several incidents occur at once, response times can be over 1 h. To reduce this impact, recent literature shows extensive research has been conducted into condition-based maintenance of existing designs,[13] and Network Rail, the UK infrastructure custodian, is currently rolling out condition monitoring equipment across its active assets. However, even condition-based switch maintenance requires a possession of the line and human intervention which is not always possible. With the drive in the United Kingdom towards a 24-7 railway, any planned maintenance requiring an exclusive track possession must occur in ever shrinking time windows. In any case, it is unlikely that regular inspections can be reduced to zero, due to the design of switches having several safety concerns for which regular inspection is the mitigation. This includes, but is not limited to, stretcher bar to switch blade mountings (see (5) in Figure 2), which when loosened are almost guaranteed to cause a facing move derailment.

For any switch redesign to be successful, concern must therefore be given to maintainability. It would be of specific benefit for any proposed design to:

1. Enable the continued and safe functioning of the switch despite a given number of known faults in subsystems.
2. Communicate known faults to a control centre such that repair work can be managed and scheduled appropriately.
3. Enable as many maintenance operations as possible to be conducted without maintenance possession.
4. Enable as many maintenance operations as possible to be mechanised or conducted off-track to minimise risk to personnel, improve output and reduce costs.
5. Use a minimum, commercial off-the-shelf (COTS) component set such that spares can be carried without needing adapting to specific switch installations.

Requirements analysis

Overview

The requirements of the system reduce to a simple set of key technical requirements. Those requirements are a combination of those for a track system, those for a safety-critical asset, and those for a mission-critical asset. The track system function is to support and guide vehicles. The active element has two functions: to direct vehicles along the correct path; and to confirm the route to the interlocking, or provide information that the switch is unsafe. This operation must be performed within a given timeframe. Traditionally, these have been the only requirements of a switching solution. However, given the high performance standards of a modern railway and the criticality of switch availability, another necessary requirement could be included, namely to communicate back to maintenance resources the current ability of the switch to perform its task, and the requirement for any immediate intervention. The following requirements set is proposed.

Essential requirements of a track-switching solution

1. The switch shall adequately support and guide all passing vehicles (from relevant track standards[28]).
   (a) It shall be strong enough for the required static loading.
   (b) It shall be strong enough for the required dynamic loading.

   (c) It shall guide the wheelsets with maximum deviations as specified for the given track quality.
   (d) It shall manage the wear and degradation of support and guidance elements to allowable levels.
2. The switch shall direct vehicles along the path specified by the interlocking.[7,17]
   (a) When commanded to, and not otherwise, it shall align any movable elements so as to direct the wheelset of a vehicle along the specified route.
   (b) When commanded to, it shall align any movable elements for the requested route within a specified timeframe.
   (c) It shall ensure all wheelsets of a passing vehicle are directed along the same route.
3. The switch shall confirm to the interlocking the route vehicles will be directed along, and that all active elements are safe for the vehicle to pass.[7,17]
   (a) It shall provide feedback to the interlocking that the requested route is set.
   (b) It shall provide feedback to the interlocking if the requested route is unable to be set.
   (c) It shall provide feedback to the interlocking on (3a) and (3b) within a given timeframe.
4. The switch system shall provide information to maintenance organisations regarding the future projected ability to perform requirements (1), (2) and (3).
   (a) It shall monitor wear of wear-susceptible parts and adjustment of adjustable parts.
   (b) It shall communicate current state of wear and adjustment to maintenance organisations.
   (c) It shall calculate and communicate the remaining time of useful operation of the asset without maintenance intervention.
   (d) It shall achieve a given level of reliability commensurate with the operations at the node.
   (e) It shall minimise the amount of time the node is unavailable due to maintenance activity, and the amount of time maintainers must spend trackside.

How do traditional switches perform these functions?

Referring to the functions specified above, traditional switches have evolved a particular design and operation in order to meet given requirements.

Requirement (1) is generally achieved by designing the track elements of the switch to be of equivalent rating to the surrounding plain line and traffic requirements. However, in order to meet (1c), in some cases this has meant relaxing the standards, notably around the switch toes, in order to prevent having infinitely thin blades at the point of intersection of routes.[28]

For requirement (2), routing of vehicles is currently achieved by the combination of an actuator and two moveable switch rails, as detailed in the 'Existing systems' section. The actuator acts to close one switch rail against the corresponding stock rail, and open the opposite to create a flange-way. The same actuator, by means of a mechanical arrangement, then provides a locking function to prevent uncommanded movement of the rails. However, the use of a single actuator without any level of redundancy means that component failures may easily prevent the actuation elements performing this requirement on demand, even with appropriate maintenance as per (4).

Requirement (3) is provided through the detection elements of existing designs. Components essentially forming limit switches indicate that the two movable switch rails are in the correct position, and that the lock preventing movement to fulfil requirement (2c) is engaged. This signal is then passed back to the interlocking. If the switch is unable to be set for a particular route, then not all of the limit switches can be engaged, thus no detection signal is transmitted, and after a given timeframe as allowed for in (2b), the signaller would deduce there was a problem with the switch. Note that switches do not, in the signal to the interlocking, differentiate between 'currently moving to desired position' and 'unable to move to desired position,' as both states appear the same to the available set of limit switches.

Requirement (4) is perhaps the requirement subset which is most lacking in existing switch designs, as the requirement itself has only evolved with the enhanced performance requirements of a modern railway system. There has been a drive in the United Kingdom, over the preceding few years, to retro-fit condition monitoring equipment to better meet (4a) and (4b).[9] However, despite this, the safety-critical monitoring element is still achieved by sending teams out to complete regular inspections (as high a frequency as once per week), though this clearly clashes with requirement (4e). Requirements (4c) and (4d) are currently not catered for; however, work in the field seeks to improve these aspects, as discussed above.[14]

Non-functional requirements

There are further requirements which need to be established, but can be considered non-functional. Whilst all switching solutions need to satisfy the full set of functional requirements, non-functional requirements form a set of trade-offs. For instance, UK and European infrastructure owners have goals to reduce the hours teams must spend working line-side with live traffic for safety reasons. There are political pressures to reduce the monetary costs of building and maintaining infrastructure.[29] In some locations, space is at a premium, and the alignment of track, or capacity, is sacrificed as there is not the space to fit a switch of the ideal specification. These elements form trade-offs, which are unique to each location. Non-functional requirements were considered and the most significant listed:

- Degree of fault tolerance: How susceptible is the design to a single fault/failure rendering the switch unusable? How long could the switch survive in a usable state until such a time as repair can be performed?
- Design adaptability: Switches must handle many types of traffic at many speeds. Whilst it could be argued many different designs could fulfil these different purposes, a single, adaptable design is preferable.
- Cost: Monetary cost of the solution, estimated using engineering judgement.
- Space utilisation: Physical footprint of the solution.
- Energy requirements: Any actuation must require a level of energy which a reasonable existing power supply installation is capable of providing
- Ease of manufacture: Able to be mass-manufactured using existing techniques and processes.
- Likelihood of acceptance: The rail industry has strict process and standards regarding the design of products for use upon the network.
- Switching speed: The faster the switch can change positions, the better.
- Maintainability: There are pressures to reduce the amount of time personnel spend performing maintenance tasks trackside. Does the design help to achieve these ambitions?
- Standardisation: Can the design maximise the use of COTS components, or minimise custom components?
- Human factors: Maintenance teams and trespassers may be exposed to movable elements of the switch. How big is the risk posed compared to that currently present?

In order to evaluate potential solutions, it is necessary to assign weightings that represent the relative importance of the non-functional requirements. The method and outcome is shown in Table 2. The highest total represents the most important non-functional requirement. Each requirement is then given a weight, *w*, representing its importance, which is used as a multiplier. The values in this table are used in Section 0.0.2. The table shows that the three most important requirements are judged to be the likelihood of acceptance, the degree of fault tolerance, and the adaptability of the design.

Generation and evaluation of solutions

Solution generation

A cross-industry focus group was assembled on three occasions through 2011–2012, to generate candidate

Table 2. Non-functional requirements ranking and weighting matrix. If row is more important than column, then cell is equal to 1; of equal importance, 0.5; of lesser importance, 0.

	Degree of Fault tolerance	Design adaptability	Unit cost	Space utilisation	Energy requirements	Ease of manufacture	Likelihood of acceptance	Switching speed	Maintainability	Standardisation	Human factors	Total	Weighting (w)
Degree of fault tolerance	-	0	0.5	1	1	0.5	0	1	1	1	0.5	6.5	0.12
Design adaptability	1	–	0	1	1	0.5	0	1	0	0.5	1	6	0.11
Unit cost	0.5	1	–	0	1	0.5	0	1	0.5	0	0.5	5	0.09
Space utilisation	0	0	1	–	0.5	1	0	1	0.5	1	0.5	5.5	0.10
Energy requirements	0	0	0	0.5	–	1	0	0	0	0	0	1.5	0.03
Ease of manufacture	0.5	0.5	0.5	0	0	–	0	0	1	0.5	0	3	0.05
Likelihood of acceptance	1	1	1	1	1	1	–	1	1	1	1	10	0.18
Switching speed	0	0	0	0	1	1	0	–	0	0	0.5	2.5	0.05
Maintainability	0	1	0.5	0.5	1	0	0	1	–	0.5	0.5	5	0.09
Standardisation	0	0.5	1	0	1	0.5	0	1	0.5	–	1	5.5	0.10
Human factors	0.5	0	0.5	0.5	1	1	0	0.5	0.5	0	–	4.5	0.08

track switching solutions. The panel was UK-focussed, due to the funding arrangements, but with substantial international experience. Membership comprised personnel from rolling stock and infrastructure backgrounds (Track and Permanent Way), across: design; maintenance; operations; 'head office' (modelling and performance) functions; and regulatory bodies. Further to these sessions, a series of remote and face-to-face meetings was conducted with other stakeholders within UK infrastructure custodians – namely Network Rail and London Underground. Academics with a background in reliability engineering and fault-tolerant design were also invited to contribute.

These sessions resulted in just under 420 individual ideas related to improvements to switches and crossings, covering their physical design, signalling and operation and maintenance activities.

Initial filtering and down selection

The first filter for down-selection was to exclude any ideas which were mechanically implausible. Construction/operation of some ideas will not be possible, and these ideas must necessarily be rejected at an early stage.

Secondly, any ideas which would require wholesale modification of the entire rolling stock fleet were excluded. These included, for example, the removal of all wheel flanges or steerable bogies. It is generally accepted that one option, 'vehicle-based switching' (VBS) may deliver higher levels of performance than track based switching; primarily as system failures are generally limited to a single vehicle.[30] However, the panel felt the development of such a solution in the United Kingdom would be prevented by the fragmented nature of rolling stock and related interface standards ownership.

Thirdly, any ideas which would require more than 20 years estimated 'time to market' were excluded. For example, novel vehicle control solutions which require European Rail Traffic Management System ERTMS Level 3/4 or higher.[23] The academic team were advised by regulatory bodies that the rail industry would be very unlikely to adopt such solutions due to the cyclic nature of development funding in the sector.

This left around 60 solution options to be investigated and ranked.

Ranking solutions

A selection of the highest scoring remaining solutions is briefly presented here.

- A: 'The Track Substitution Switch': *A whole section of track is lifted out of place and replaced with another section*
- B: 'The Single Flange Controlled Switch': *Only one flange of the wheelset is controlled through the switch, the other free.*
- C: 'The Wheel-face Switch': *Rails move into place which act upon the face of the wheel to select a route*
- D: 'Interlocking Rails': *A specially crafted rail end design locks itself in place when under the mass of a train*
- E: 'The Stub Switch': *Reverses the components in a traditional switch, and has stub ends which bend or move between positions to select route*
- F: 'The Over-Running Rail Switch': *Uses a removable ramp to lift one wheel over the corresponding running rail*
- G: 'Raising and Lowering the Switch Rails': *Existing switch rails move laterally, but it is possible to raise and lower them into position instead.*
- H: 'The Swing-nose Switch': *A moveable element similar to that in a swing nose crossing acts to select a route for the flange to follow.*
- I: 'The Hopping Switch': *Switch rails move vertically between positions such that when at rest they have dropped into a groove preventing them from moving.*
- J: 'The Spring Switch': *A passive design which always directs facing traffic in one direction, but allows trailing moves from both by allowing the switch rails to spring out of the way.*
- K: 'Hopping Stub Switch' (D, E and I Combined): *These concepts could be combined to provide the potential benefits of all three.*

Each design was then scored out of 10 in each area of the non-functional requirements, using engineering judgement. The results of this scoring are shown in Table 3. It can be seen that concept K scores most highly. Concept J also scores highly, especially in the areas of energy consumption (zero) and switching speed (instant). This is to be expected for a passive solution, though it is clear spring switches could not be used in every location. However, the weighted matrix places less emphasis upon those areas. Concepts D and E also score highly. Concept K is a combination of concepts D, E and I, where each offers a unique set of benefits, but are complementary as none of the features of the individual concepts prevent them being used together. It is this combination of designs which was therefore selected for further investigation. This concept is now termed the 'Repoint' concept and is discussed in further detail in the following section.

The 'Repoint' solution

General mechanical arrangement

The design is based around an arrangement known as a stub switch. The stub switch reverses the elements in a traditional switch, and replaces the long, planed down switch rails shown in Figure 2 with short, stub-ends formed of full section rail which are able to move between positions. Figure 4 shows the general

Table 3. Results of the weighted scoring exercise, including concept rankings.

		Traditional		Concept										
Requirement	*w*	Now	Max	A	B	C	D	E	F	G	H	I	J	K
Degree of fault tolerance	0.12	5	5	3	3	6	5	3	8	5	3	8	9	9
Design adaptability	0.11	5	5	3	5	7	7	9	3	5	5	7	1	9
Unit cost	0.09	5	7	2	8	7	8	5	7	7	9	5	6	6
Space utilisation	0.10	5	5	1	7	5	7	10	5	5	7	5	5	10
Energy requirements	0.03	5	6	2	7	7	7	4	7	5	8	3	10	7
Ease of manufacture	0.05	5	7	2	7	6	5	8	4	5	6	6	8	6
Likelihood of acceptance	0.18	10	10	8	8	5	8	7	2	3	5	8	10	8
Switching speed	0.05	5	6	3	6	7	7	5	4	4	8	4	10	8
Maintainability	0.09	5	5	2	6	8	5	8	6	3	3	5	8	7
Standardisation	0.10	5	6	5	5	5	8	5	3	5	8	8	6	7
Human factors	0.08	5	5	3	5	3	8	7	3	5	9	3	8	3
Weighted sum		5.91	6.37	3.65	6.08	5.83	6.93	6.64	4.45	4.59	6.05	6.21	7.18	7.51
rank				11	6	8	3	4	10	9	7	5	2	1

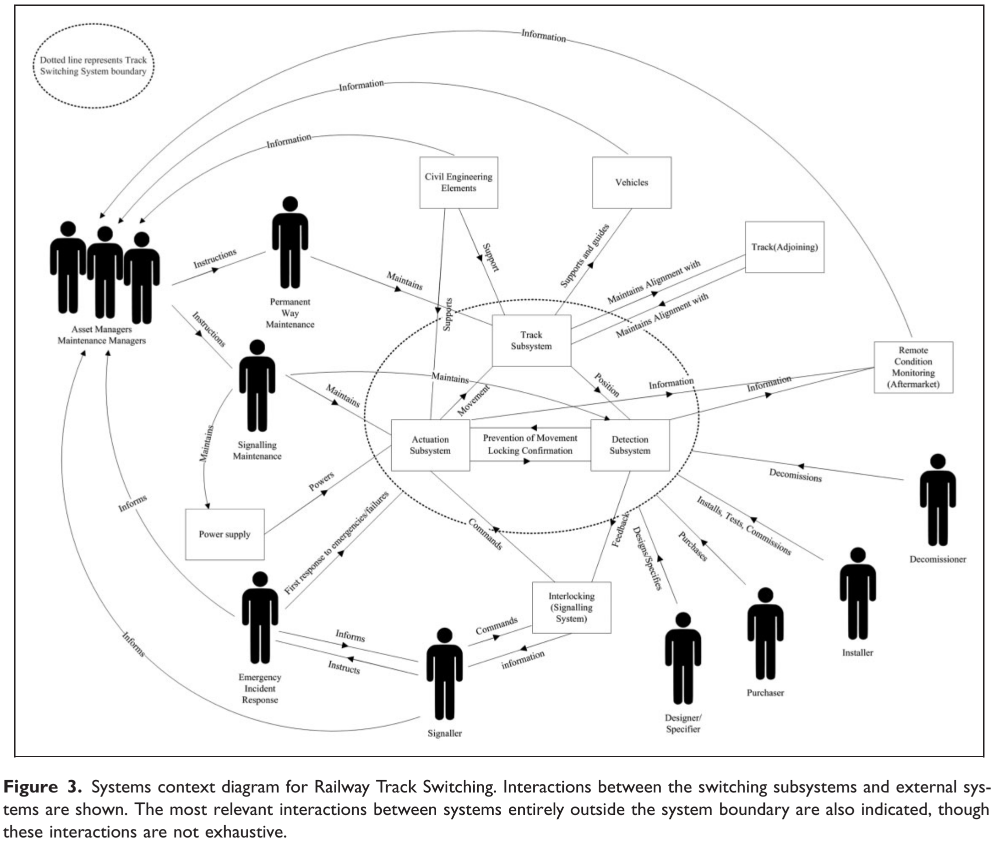

Figure 3. Systems context diagram for Railway Track Switching. Interactions between the switching subsystems and external systems are shown. The most relevant interactions between systems entirely outside the system boundary are also indicated, though these interactions are not exhaustive.

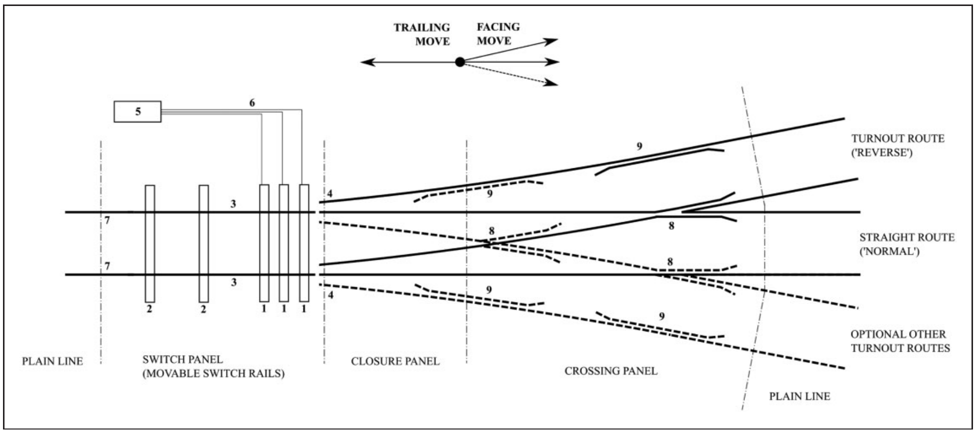

Figure 4. Repoint stub switch general arrangement with electro-mechanical in-bearer type actuators, with most sleepers/bearers omitted for clarity. Numbered elements as follows: (1) In-bearer type electromechanical actuators featuring integral passive locking elements with detection system; (2) Bearer featuring integral passive locking elements; (3) Bendable, full-section switch rails; (4) Interlocking rail ends; (5) Line-side processing and condition monitoring cabinet; (6) Power, position and monitoring signal cables; (7) Stationary point of curve; (8) Common crossings (of given angles); (9) Check rails.

arrangement of a 'Repoint' stub switch, with an optional second turnout route shown. A bank of actuators is responsible for moving the full-section switch rails between each position. The actuators bend the rail between each position, from a stationary point, beyond which the track can be considered plain line. There is no hinge. To ensure the correct bending profile, it may be necessary to alter the cross section of the rail around the stationary point, and an established method such as flange relief could be applied to achieve this. Where the open, moving rail ends interact with the static rails in the track panel, a novel design of interlocking rail end is necessary. This is to allow the expansion and contraction (with temperature variation) of all rails in the assembly, whilst still providing support and guidance for wheelsets. The general arrangement of this rail end is shown in Figure 5. As the rail ends interlock to provide a consistent track alignment, when moving them between positions the required actuation path involves lifting them out of register.

Actuation is provided by a multi-channel actuation bank, with the actuation elements contained within bearers near the movable rail ends. Each actuator is capable of moving the switch alone. Triplex redundancy is shown in Figure 4; however, the exact number of actuators required could be tailored to the particular requirements of each location on the basis of an operational reliability figure. A line-side processing and condition monitoring unit, abstracted from the interlocking, provides control of the elements. It is also responsible for isolation of suspected faulty elements, and may feature controls for maintenance teams to do the same. The moveable rail is supported upon said actuator-bearers, which transmit the static and dynamic loading from vehicles to the track substructure. These bearers have a movable top surface, termed a 'shuttle,' to which the rails are attached using appropriate traditional rail clips. The lower casing of the actuator-bearer is embedded in ballast, or affixed to concrete in the case of a slab track installation. Vehicle load is transmitted from the rails, through the shuttle and then locking blocks to the bearer casing, where it distributed to and through the substructure in the usual way. Additional support may be required at the rail ends, and the support conditions here are the subject of further study.

Multi channel actuation is provided through an arrangement which has been termed 'passive locking.' The theory of passive locking is that when the rail is in one of its stationary, lowered positions, it is unable to move in any direction apart from directly upwards. There are no significant uplift forces present compared to other axes, and a significant net downward force when the mass of a train is present. It is a requirement to lift the interlocking rail ends to disengage them. When the track is lifted, it is free to move laterally, but not longitudinally. Thus, the rail hops between adjacent positions. If an actuator is isolated for whatever reason, the adjacent unit(s) can still actuate the switch, as the lifting action will unlock the isolated unit. It is this feature which enables redundant actuation to be provided as part of the 'Repoint' concept, something not possible with the conventional switch. There are many ways to provide drive inside the actuator units, and one simple method utilising a rack, two cams and followers is shown in Figure 6(a). This is the method chosen for the laboratory

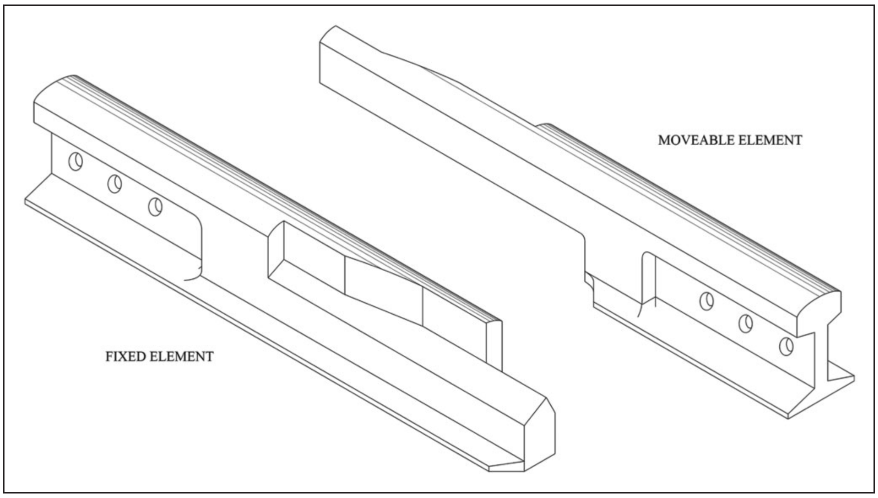

Figure 5. Interlocking rail ends. Holes are shown for possible bolted mounting, but units could be welded in place. The chamfer in the horizontal plane locates the rails laterally, meaning the moveable rails require lifting to disengage this chamfer before they can be moved laterally. The concept allows for some longitudinal movement in the rails in the same way an expansion switch operates, with the chamfer in the vertical plane giving a smooth transfer of load from one rail to the other.

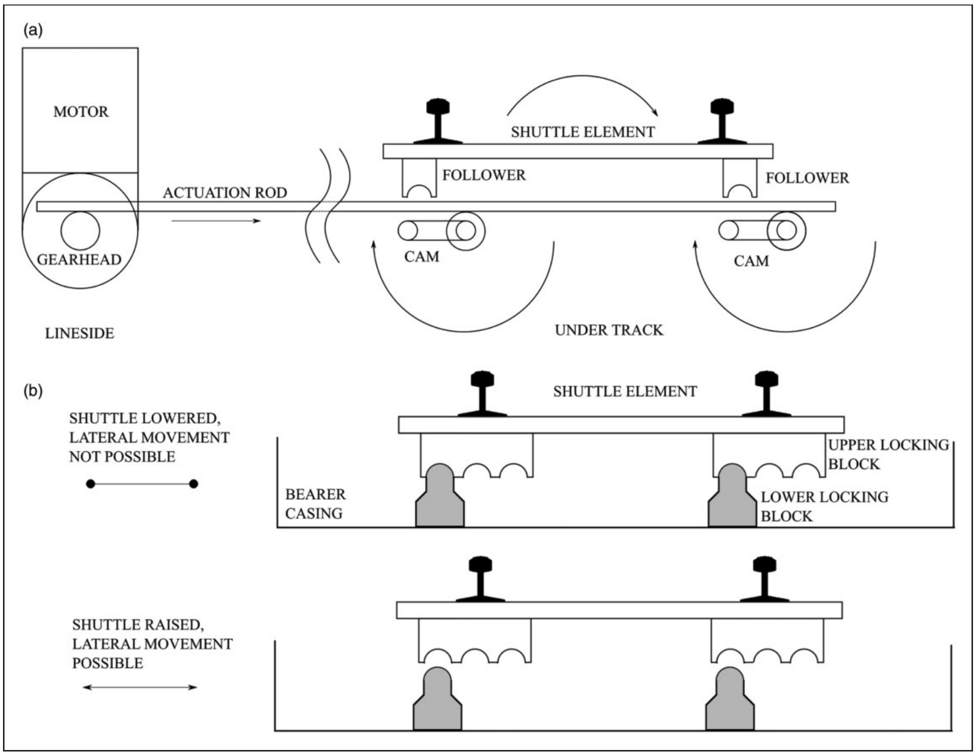

Figure 6. Cross sections of each actuator-bearer. (a) shows internal elements related to the actuation system chosen for the demonstrator system, though other arrangements to provide the necessary lift-move-drop curve would suffice. A motor and sealed gearbox drive a toothed rod, which acts upon two cams; a 180° rotation of the cams causes the shuttle to move between adjacent routes. (b) shows the associated locking elements, which would be present inside each bearer alongside (a).

demonstrator described in the later section. The actuators are enclosed in sealed, line-replaceable units. The motor and gearbox arrangement is back-drivable, in order that should a failure occur between positions, the mass and spring force of the lifted rail will cause the switch to drop back into one of the safe, lowered and locked positions. Modelling has been conducted, detailed in other papers, e.g. Ebinger and Wright[31] and Wright et al.,[32] to verify that the approach is mechanically feasible.

Satisfying the requirements

Referring to the functional requirements specified in the 'Requirements analysis' section, we can postulate that the Repoint solution can meet all requirements and, therefore, exceed the extent to which existing systems meet the requirements with regards several elements:

1. Adequately support and guide all passing vehicles:
   (a) The solution is constructed of the same, full section rail as surrounding plain line.
   (b) Dynamic loading is reduced due to the track alignment through the switch being of full-section rails.
   (c) The solution has full-section rail throughout, accurately aligned at each sleeper/bearer, exactly as for plain-line.
   (d) (1b) means that wear could be reduced. The wear element is now the interchangeable and standardised chamfered rail end, rather than long switch rails. Wear will be easier to manage and the rail ends are replaceable as a relatively short pair.
2. Direct vehicles along the path specified by the interlocking:
   (a) The switch can move to a new route when commanded; however, it can unambiguously form a route when commanded due to the multiplicity of actuators.
   (b) The concept can switch at a faster rate as the actuators do not have to be sized to overcome the variable friction on plates, and instead store energy in a spring (the rails) which can be used to assist in the motion for the second half of the throw.
   (c) The locking elements of each bearer ensure the switch remains locked on a single route for traffic until commanded otherwise. The switch is even less likely to move under the mass of a train, as the mass acts downwards and thus further locks the switch. The mechanism eradicates the ambiguous failure state between routes, for facing moves.
3. Confirm to the interlocking the route vehicles will be directed along, and that all active elements are safe for the vehicle to pass:
   (a) Limit switches can provide confirmation to the interlocking that each bearer is in a given lowered position, and therefore which route is set.
   (b) The local condition monitoring processor can determine if there is an issue preventing a route being set through comparing signals, and indicate such to the operator. The incidence of 'unable to set' would fall due to the parallel-channel actuation and reduced chance of blockages.
4. Provide information to maintenance organisations regarding the future projected ability to perform requirements (2) and (3):
   (a) In-built condition monitoring, for the function of the multiply-redundant actuation, monitors wear points.
   (b) Line-side processing can communicate switch prognosis through existing channels.
   (c) See (4b).
   (d) The redundant elements enable a higher level of operational reliability to be achieved; additionally this level can be tailored to the particular location by selecting the number of actuator-bearers used according to operational requirements.
   (e) Redundant channels mean the active elements of the switch are fault tolerant, improving operational availability. They also allow any maintenance to be carried out in existing downtime, for example overnight. Line-replaceable units mean that maintenance tasks performed trackside are reduced in length.

Development of a laboratory-based demonstrator

A scale demonstrator of the concepts has been constructed in a laboratory at Loughborough University (Figure 1). The demonstration actuator/bearer features all components which would be required in a full-size design – controller, motor, gearbox, drive arrangement, roller-cams and passive locking elements. These components are mounted at the correct spacing in a substantial Dexion frame. There are three routes – one straight ahead, and two turnout. The demonstrator is at 384 mm gauge but all actuation components are sized for CEN-60 type rail, at the most common size of switch upon the UK infrastructure, termed a 'C' switch. Note that extensive associated dynamic modelling work was undertaken in MATLAB/Simulink, in order to demonstrate the viability of the full scale design.[21,31,33] The demonstrator is a hardware-in-the-loop implementation of a full Repoint track switch. A single, physically constructed active actuator/bearer exists in the laboratory, in parallel with two virtual bearers simulated within a real-time software environment (utilising MATLAB/Simulink and D-Space). As the physical demonstrator is switched between positions, the software model

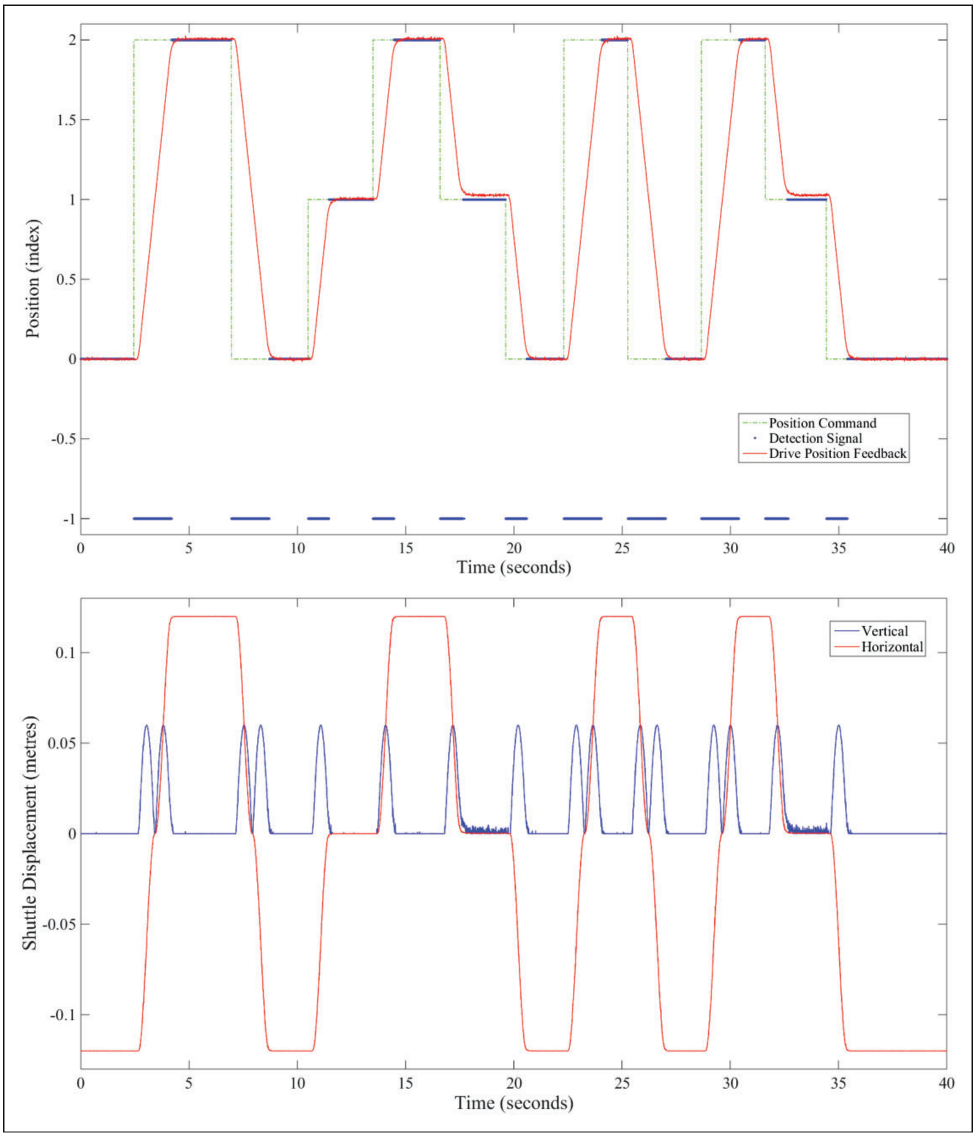

Figure 7. Data plots for a series of actuations on the laboratory Repoint rig. Data is plotted for the physical actuator/bearer only. Top: Plot of command signal, detection signal, and lateral (drivetrain) position feedback. Position feedback has been filtered in software to provide a more easily interpreted signal. Actuation time is that between command signal changing, and detection being obtained, which is indicated by a loss of detection (i.e. detection is equal to -1). Bottom: Inferred horizontal and vertical displacement of rail ends, used to calculate and simulate load due to rail bending.

co-simulates this motion for the other two bearers in the alignment. The modelling work presented in previous publications has been used to inform the design of the co-simulation. The demonstrator is equipped with a graphical front-end which can either simulate a maintenance control panel, showing traces of key operational parameters, or a signallers control console.

Critical to the operation of such a proposed switch arrangement is the ability for the three switch

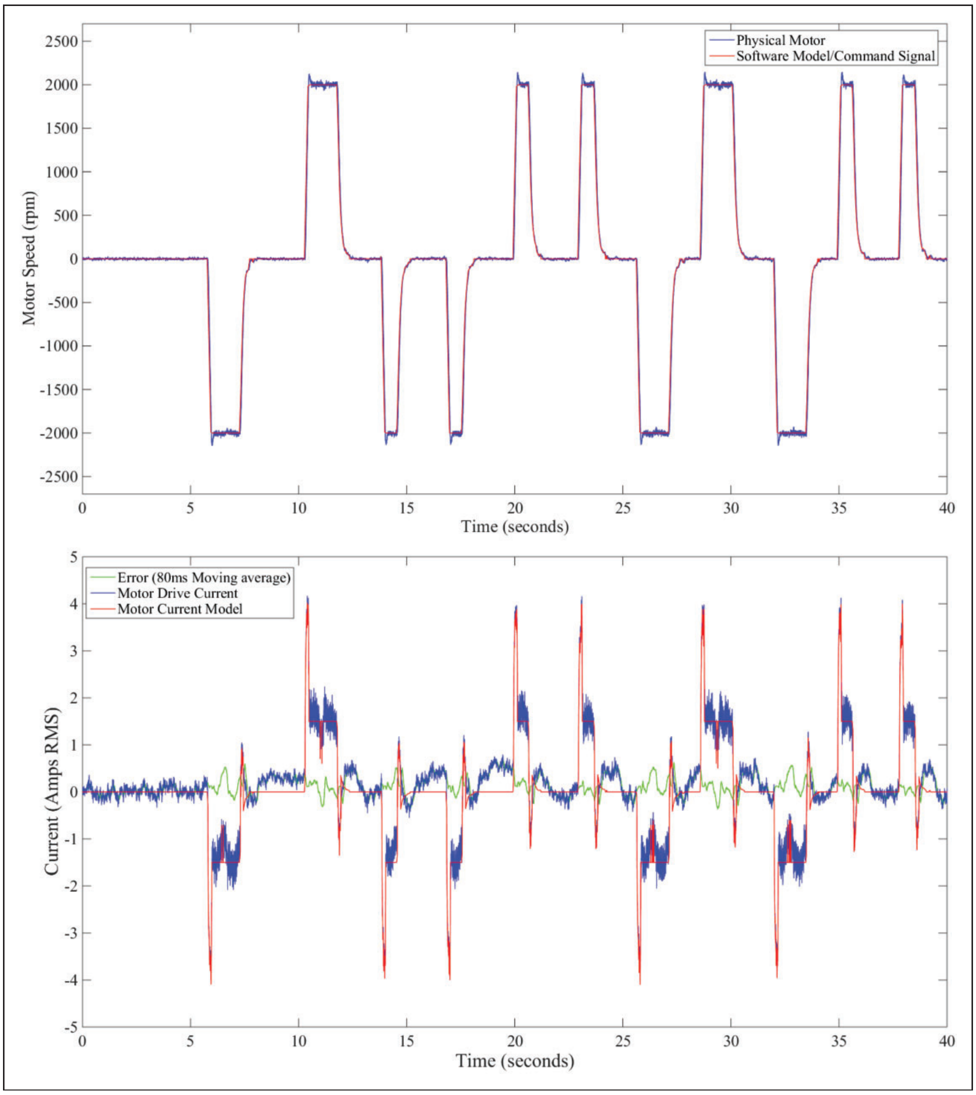

Figure 8. Plots from Repoint model validation process, for same set of runs as Figure 7. Top: Motor speed and modelled motor speed vs time. The modelled motor speed is also used as a command signal to the physical motor. Bottom: Modelled motor current, actual motor current and residual error, with moving average. There is a considerable level of noise on the signal, but residual error during periods of motion is around 10–15%.

machines to operate in unison and in-phase whilst coupled to a traditional interlocking arrangement. By extension, also critical is the ability of two machines to operate in unison should a single machine be isolated when faulty or for maintenance. As only one machine is present, the first step of work towards development of a full-scale installation has been to validate the software models of the actuator bearers in order that a suitable control algorithm, and associated detection logic laws, can be designed to enable this motion. The validation of these models is also important to ensure the viability of the actuation, locking and detection elements of a full-scale design. In the physical implementation, detection is obtained when the shuttle element triggers one of three representative micro-switches when lowered and locked. In the software implementation, position detection is inferred from the coordinate position of the shuttle. A representative and validated model is also important for model-based condition monitoring algorithms, which are vital to fulfilling requirement (4).

The scale rig has been run at a range of speeds and with a range of loadings in order to validate the software models, and to tune the parameters within. Figure 7 shows a trace of position versus time for the physical actuator bearer, operating in the unloaded case. This includes the position commanded by the interlocking, and the detection signal returned to the interlocking. Note that whilst a traditional command or detection signal would be 'Normal' or 'Reverse,' with a three-position switch, we have adopted '0', '1' and '2' to represent the three possible positions, with '1' being centre. A detection signal of '-1' indicates that no detection is currently made. For this plot, rig operation is governed by a script which, upon detection being made, selects a subsequent position at random, at a random time interval, in order to quickly and automatically collect large amounts of data; a 40 s time window is shown here for illustration. Switching time can be measured by examining the time for which the detection state is at -1, which indicates the time between detection being broken by the interlocking and the time detection is made in correspondence with the command signal. It can be noted from the plot that the switch machine can cycle between adjacent positions in just under 0.9 s. This is comparable to, and in many cases better than, contemporary machines. Additionally, the machine can move from extreme positions in around 1.7 s. The lower plot shows the vertical and horizontal displacement of the shuttle element. In a full implementation, the rail is attached to the shuttle and, therefore, in the co-simulation these displacements can be used to calculate the load upon the actuator which results from bending the full-section rail, at any point in the operation cycle.

Figure 8 illustrates the comparison between the software model and rig over time, for the same sample of switch operations. It can be observed that the tuned software models presented in previous literature,[32] are a reasonable fit to the real-world data. Motor speed closely follows the simulated speed. This is to be expected as the simulated speed is also used as a basis for a speed profile to which all three motors are driven. There is a more significant error, however, in the motor current modelling. This is most noticeable in the period between rig operation, and comes from the inner current control loop amplifying sensor noise for the command signal. Sensor noise is not part of the software model, therefore the 'at rest' signal appears much cleaner. During periods of motion, the typical error is just over 200 mA on a 1.5 A command signal, equating to a mean model error of around 14% for the unloaded case. There is also significant error during the motor inrush period, though the inrush is to be eradicated in future implementations with a soft-start controller. Parameters have been built into the software model such that an actuator bank at full-scale and under a range of load cases can be simulated, as presented in Ebinger and Wright.[31] This will also be used in future work developing a full-scale implementation.

Conclusion

This paper has presented the background and context to railway track switching, including how track switches can limit the performance of rail networks. These limitations come about as track switch designs have evolved over time to fulfil a particular purpose, meaning they may not be optimised to provide the kind of performance a modern railway network requires. Specifically, the paper has established the formal requirements of track switching solutions, and presented the argument that traditional solutions do not meet all of these requirements. A shortlist of possible design options was generated alongside a non-exhaustive range of design options generated by a cross-industry panel. These options were then reviewed and ranked, with several of the options being combined to create a novel solution to the track switching problem. This novel solution, presented in academic literature for the first time, has been termed the 'Repoint' solution, and is described in mechanical detail, including how it satisfies the functional requirements. A scale demonstrator implementation of this solution has been constructed in a laboratory as a first step towards deployment.

Future work

The design has now been taken to a concept demonstrator phase, therefore the most obvious piece of follow-on work is to build a prototype upon a functioning railway and test – both the operation of the switch, and with the passage of traffic. Suggested, but non-exhaustive, areas of related research are as follows:

- Further modelling of the capacity improvements brought about by a Repoint installation in real-world scenarios.
- Further investigation into, and modelling of, the reliability and maintainability improvements brought about by Repoint installations, singly or across a network.
- A full, formal fault tree analysis (FTA) of any proposed design.
- Investigation into wear and fatigue of the bending rails and part-section rail ends with a range of use cases.
- Investigation into other promising ideas from the concept down-selection phase, including ideas which were rejected for political or standards reasons, such as VBS.

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References

1. Railway points operating apparatus. GB Patent, Loughborough University, UK, GB 1322660, 2013.
2. Railway points. GB Patent, Loughborough University, UK, GB 1322641, 2013.
3. Abril M, Barber F, Ingolotti L, et al. An assessment of railway capacity. *Transport Res Part E* 2008; 44: 774–806.
4. Transportation Research Board, National Research Council. TCRP Report 13: Rail Transit Capacity. Technical report, Transit Cooperative Research Program, The Federal Transit Administration, Washington, D.C., 1996.
5. ORR (Office of Rail Regulation) Online Data Portal - Total journey count reporting. dataportal.orr.gov.uk. (accessed 12 October 2013).
6. Such WH. *IRSE 'Green Booklet' No. 2: Principles of interlocking (British Practice)*. London: The Institution of Railway Signal Engineers, 1956.
7. Genner R. Railway Group Standard GK/RT0062: Control of Points. Safety & Standards Directorate, Railtrack PLC, London, 1997.
8. Technical Strategy Leadership Group. The Future Railway: The Industry's Rail Technical Strategy 2012. Technical report, Future Railway, London, UK, 2012.
9. Network Rail Strategic Business Plan. Network Rail October 2007 SBP Supporting document: Seven Day Railway. Technical report, Network Rail, 2007.
10. Institution of Mechanical Engineers. Rail freight: Getting on the right track. Technical report, Institution of Mechanical Engineers, 2009.
11. Nash C, Coulthard S and Matthews B. Rail track charges in Great Britain - the issue of charging for capacity. *Transport Policy* 2004; 11: 315–327.
12. Morgan JC. *British railway track 7th edition, Volume 1, Design Part 2: Switches and crossings*. Derby, UK: The Permanent Way Institution, 2009.
13. Eker OF, Camci F, Guclu A, et al. A simple state-based prognostic model for railway turnout systems. *IEEE Trans Ind Electron* 2011; 58: 1718–1726.
14. Silmon J and Roberts C. Improving switch reliability with innovative condition monitoring techniques. *Proc IMechE, Part F: J Rail and Rapid Transit* 2010; 224: 293–302.
15. Pope R. *IRSE 'Green Booklet' No*. 27: Signalling the layout (British Practice) ed. London: The Institution of Railway Signal Engineers, 1975.
16. Cope DDL and Ellis JB. *British railway track 7th edition, Volume 5: Switch and crossing maintenance*. Derby, UK: The Permanent Way Institution, 2002.
17. Hadaway H. *IRSE 'Green Booklet' No. 5: Principles of power point control and detection (British Practice)*. London: The Institution of Railway Signal Engineers, 1950.
18. Marks M. Railway Group Standard GK/RT0064: Provision of overlaps, flank protection and trapping. Safety & Standards Directorate, Railtrack PLC, London, 2000.
19. International Union of Railways (UIC). *UIC 406(R): Capacity (English Version)*. 1st ed. Paris, France: International Union of Railways (UIC), 2004.
20. Bemment S, Dixon R and Goodall R. Repoint redundantly engineered points for enhanced reliability and capacity of railway track switching. In: *Proceedings of 10th world congress on railway research (WCRR)*. Sydney, Australia, November 2013.
21. Bemment S, Dixon R, Goodall R, et al. Redundantly engineered track switching for enhanced railway nodal capacity. In: *Proceedings of 1st IFAC ACATTA workshop*, Istanbul, Turkey, September 2013.
22. Liu R, Whiteing A and Koh A. Challenging established rules for train control through a fault tolerance approach: Applications at a classic railway junction. *Proc IMechE, Part F: J Rail and Rapid Transit* 2013; 227: 685–692.
23. Stanley P. *ETCS for engineers*. Hamburg, Germany: Eurail Press, 2011.
24. Isermann R. *Fault-diagnosis systems: An introduction from fault detection to fault tolerance*. Berlin: Springer, 2006.
25. COMSA (Lead); Collaborative project, Theme SST201152-6: Cost-effective improvement of rail transport infrastructure. Deliverable 3.3: Rail switches and crossings. EU 7th Framework Programme, 2014.
26. Lee JD and Seppelt BD. Human Factors and Ergonomics in Automation Design. In: G Salvendy (ed.) In: *Handbook of Human Factors and Ergonomics*, Fourth Edition, Chapter 59. Hoboken, NJ, USA: John Wiley & Sons, Inc. doi: 10.1002/9781118131350.ch59, 2012.

27. García FP, Schmid F and Conde JC. A reliability centered approach to remote condition monitoring. A railway points case study. *Reliab Eng Syst Safety* 2003; 80: 33–40.
28. Railway Group Standard. GC/RT5021: Track system requirements. Technical report, RSSB (Rail Safety and Standards Board), 2009.
29. McNulty R. Realising the potential of GB rail: Report of the rail value for money study, Summary Report. Technical report, Department for Transport and Office of Rail Regulation, 2011.
30. Ward C, Mei T, Hubbard P, et al. Railway vehicle optimisation using the concept of 'design for control'. In: *Proceedings of the second international conference on railway technology: Research, development and maintenance*, Corsica, France, May 2014.
31. Ebinger E, Bemment SD, Dixon R, et al. IN PRINT: A model of a Repoint Track switch for design optimisation and control. *Control Eng Pract* 2015.
32. Wright N, Bemment S, Ward C, et al. A model of a repoint track switch for control. In: *2014 UKACC international conference on control*, Loughborough, UK, June 2014.
33. Wright N, Bemment S, Ward C, et al. The performance and control requirements of a repoint track switch. In: *Proceedings of 2nd international conference on railway technology*, Ajaccio, Corsica, May 2014.

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Improving the reliability and availability of railway track switching by analysing historical failure data and introducing functionally redundant subsystems

Samuel D Bemment, Roger M Goodall, Roger Dixon and Christopher P Ward

Abstract

Track switches are safety critical assets that not only provide flexibility to rail networks but also present single points of failure. Switch failures within dense-traffic passenger rail systems cause a disproportionate level of delay. Subsystem redundancy is one of a number of approaches, which can be used to ensure an appropriate safety integrity and/or operational reliability level, successfully adopted by, for example, the aeronautical and nuclear industries. This paper models the adoption of a functional redundancy approach to the functional subsystems of traditional railway track switching arrangements in order to evaluate the potential increase in the reliability and availability of switches. The paper makes three main contributions. First, 2P-Weibull failure distributions for each functional subsystem of each common category of points operating equipment are established using a timeline and iterative maximum likelihood estimation approach, based on almost 40,000 sampled failure events over 74,800 years of continuous operation. Second, these results are used as baselines in a reliability block diagram approach to model engineering fault tolerance, through subsystem redundancy, into existing switching systems. Third, the reliability block diagrams are used with a Monte-Carlo simulation approach in order to model the availability of redundantly engineered track switches over expected asset lifetimes. Results show a significant improvement in the reliability and availability of switches; unscheduled downtime reduces by an order of magnitude across all powered switch types, whilst significant increases in the whole-system reliability are demonstrated. Hence, switch designs utilising a functional redundancy approach are well worth further investigation. However, it is also established that as equipment failures are engineered out, switch reliability/availability can be seen to plateau as the dominant contributor to unreliability becomes human error.

Keywords

Railways, track switch, points, reliability, availability, asset management, system failure

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Introduction

This paper demonstrates the possible reliability benefits from the adoption of functionally redundant subsystems in railway track switching, using baseline data from a modern, high-performance rail network. A background in the existing track switch design and practice is first established. The reliability performance of existing installations is examined by using a dataset provided by the UK infrastructure owner, Network Rail. These data are analysed to provide failure distributions of switch installations, and individual subsystems thereof, in the section titled 'Establishing Failure Rates and Distributions'. An RBD (reliability block diagram) modelling approach is used to establish the analytical reliability (static) and availability (dynamic) benefit of applying a multi-channel architecture to track switch designs, to provide a degree of redundancy. The results are presented and examined in the 'Analysis' section and show that the approach can deliver track switching with operational reliability much enhanced when compared to existing installations.

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Background

Rail networks requiring more than a single vehicle upon a single line are dependent upon the ability to provide multiple routes for traffic. Switches (UK: Points) serve this purpose, allowing the track to merge and diverge. The standard switch design, in use throughout the world, consists of two 'switch blades' upon a suitable supporting structure, which are able to slide laterally between two 'stock rails'. Whilst recognising that switch actuation has evolved over time – from mechanical rods and levers to more modern electro-mechanical or electro-hydraulic designs – the basic mechanical arrangement of switches has remained identical since the first railways were envisioned. An extensive description of switch design is provided by Morgan.[1]

Despite their necessity, switch failures can rapidly cripple rail operations. Unlike road transportation, where vehicles can simply steer around failed vehicles or roadway, in a guided transport system the vehicles are reliant upon switches in order to change direction. This means that a switch failure renders all vehicles upon direct approach unable to move until it is repaired. This disruption is magnified where no wider diversionary route is available, and the consequent 'knock-on delays' increase rapidly. Ison et al.[2] list some UK routes now running at over 90% capacity, and similar situations exist upon major commuter railways in continental Europe. In such situations, the effects of switch failures are profound. Literature explores optimisation options for managing perturbed traffic to reduce these knock-on delays, for instance the work of Pellegrini et al.[3] Eliminating the cause of delays and perturbations by preventing switch failures is another approach explored in literature, for instance by García et al.,[4] and Silmon and Roberts[5] – both papers exploring condition monitoring algorithms and architectures with the goal of reducing failures. García et al.[6] also explore a move to reliability-centred maintenance, rather than the periodic maintenance regime currently in place. However, these approaches do not render the system truly 'fault tolerant' and are instead aimed at reducing the incidence of failure through predicting when failures are likely to occur. In addition, with a single-point-of-failure system and limited time/budget to cope with false positives, these strategies may have a diminishing return when looking to enhance system availability, a problem which is discussed by Bemment et al.[7]

Fault tolerance

A fault tolerant system is able to prevent faults developing into failures through design, as described by Blanke and Schröder.[8] This design can include:

- Systems which isolate or compensate for faulty components
- Functional design providing a level of capability without given components
- Parallel channels which can each perform a given set of requirements alone

In most cases, the first two options cost less in monetary terms, but some safety critical systems are forced to follow the third principle, despite cost/weight penalties, to achieve the level of reliability/integrity deemed necessary for the safe operation of the system. Fault tolerance is important in safety-critical engineering, such as in aircraft, bridges, cars and nuclear power. Without fault tolerance, many designs could not function to the standard required by their regulatory environment. A prime example is aircraft flight control surfaces, which would typically have triplex or quadruplex sensor, control and actuation systems to ensure control of the aircraft in the case of concurrent failure of several actuation systems. Literature explores options for fault tolerance at rail junctions, for instance by Ursani et al.[9] However, this approach is related to tolerance of faults in the optimum scheduling of traffic by reconfiguring the signalling, and not the tolerance of asset failures.

Other applications involving safety-critical systems have utilised redundancy as a method of achieving high-availability and/or fault-tolerant operation, as described in Hecht[10] and Isermann.[11] Redundant systems have seen use in the rail sphere, a successful and internationally adopted example being the architecture of solid state interlocking.[12] This has provision for both fault detection and tolerance; triplex individual processing units vote and any singular disagreement in output is discarded, with the whole system continuing to function at a degraded level. This approach has not yet, however, been adopted for physical elements of the track switching system.

Current practice

Physical arrangement

Figure 1 shows the diagram of a typical UK installation, consisting of two stock rails, two switch rails and a common crossing, fastened by clips, bolts and/or chairs to supporting bearers of wood or concrete, themselves supported upon a bed of ballast or concrete slab. The stock rails are securely fixed to prevent movement, whilst the ends of the switch rails are free to slide upon supporting cast iron chairs, their movement restricted by the attached stretcher bars and the lock and drive arrangement provided by the POE (points operating equipment).

There are several different designs of POE (see 'Subsystem Identification' section) which are located variously in between the running rails, at the line side or a combination of both. Detection rods and/or switches provide feedback that the blades have reached an acceptable position (and are locked) to the POE, and subsequently the interlocking system.

Higher line speeds necessitate shallower divergence angles due to limitations on lateral acceleration and cant deficiency at the common crossing. This in turn requires longer switches. Longer designs require multiple actuation points upon the switch blades to ensure the entire moveable blade length (up to around 40 m in some designs) is positioned correctly for the passage of traffic. This actuation is provided either by a power take-off from the main actuator or additional actuators situated along the length of the movable portion – though crucially, not in a redundant configuration because all actuators must be operating correctly.

The principles of power point operation were established in the early 20th century as the power point machines and electric signalling became widespread. The operating principles are extensively described by Hadaway.[14] The principles have more recently been combined into an industry standard, in *GKRT0062*.[15] For the UK case, the turnout is commanded to be in either of two positions – labelled 'normal' or 'reverse' – at all times by the interlocking. If the required position changes, the command signal from the interlocking will change over, triggering a sequence of events in the line-side control circuitry and POE which is referred to as the 'move-lock-detect' cycle, which occurs as follows:

1. Detection of the current position is broken, allowing the actuator to move.
2. The actuator begins movement, first unlocking the switch blades, allowing them to move freely.
3. The actuator moves both switch blades simultaneously to their commanded position.
4. The blades reach their commanded position, and the actuator ceases to move them.
5. The actuator re-engages the locking mechanism.
6. Detection is made for both switch blades and the lock, automatically shutting down and isolating the actuator.

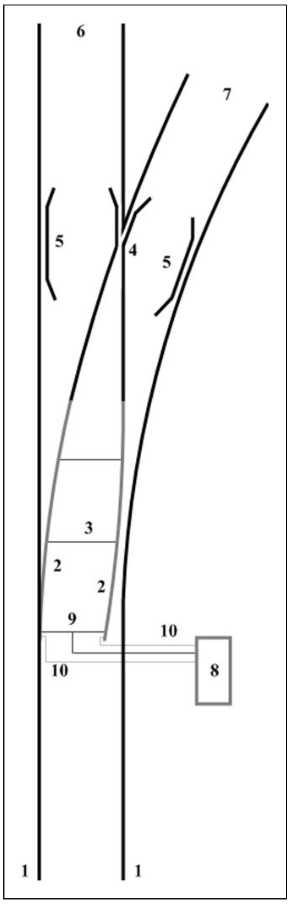

Figure 1. Typical switch arrangement, taken from Bemment et al.[13] 1: stock rails; 2: moveable switch rails; 3: stretcher bars; 4: common crossing; 5: check rails; 6: straight route; 7: turnout route; 8: POE (points operating equipment), line-side type shown; 9: drive bar and drive stretcher; 10: detector rods.

Most POE designs offer combined actuation, locking of both switch rails and full detection through single combined motion mechanisms. The turnout is considered unsafe without a detected position, even though both switch rails may be locked in the correct position. Without detection, the interlocking cannot clear the route, and trains are prevented from passing the switch. This has the effect that, even for functional switches, signals on the approach must show restrictive aspects when the switch is moving, representing a capacity constraint explored by Bemment et al.[16] and in a report by the Transportation Research Board.[17]

It is beyond the scope of this paper to provide a detailed discussion of switch design and operation; this is extensively covered in literature. Full details of switch design and operation are presented by Morgan[1] and Cope and Ellis.[18] Bemment et al.[7] provide a list of the functional requirements of track switching solutions.

Asset reliability: The magnitude of the problem

Data are published by the United Kingdom's ORR (Office of Road and Rail[19]) pertaining to the reliability of the existing switch installations. An excerpt of these data is reproduced in Table 1 to illustrate the magnitude of the issue of switch reliability facing the GB mainline. This table includes a breakdown of the number of failure incidents over financial years (FY) 07/08–11/12. The delay minute total is the sum of all delays, to all trains, caused as a direct result of an asset failure. The cost data are calculated as the sum of the total of delay minute compensation,

Table 1. Cost and delay minute incursion for various asset types.

	Cost		Delay minutes	
Asset type	(MGBP)	%	(1,000 s)	%
Track	131.9	19.2	3,977	18.8
Switches	121.1	17.6	3,874	18.3
Track circuits	99.5	14.5	3,208	15.2
Signalling system	95.2	13.9	2,727	12.9
Electrification	75.4	11.0	1,529	7.2
Signals	40.2	5.9	1,428	6.8
Cabling	37.4	5.4	1,013	4.8
Track TSRs	34.5	5.0	1,630	7.7
Axle counters	18.5	2.7	495	2.3
Level crossings	13.2	1.9	521	2.5
Other signalling	11.6	1.7	363	1.7
Telecoms	9.1	1.3	363	1.7
Totals	687.8		21,128	

Values are totals for period FY07–08 and FY11–12. Public domain obtained from Office of Road and Rail.[16]
MGBP: Great Britain Pounds; TSR: Temporary Speed Restriction.

Table 2. General statistics showing size of pre- and post-cleansing dataset obtained from Network Rail for the period 1 April 2008 and 17 September 2011.

Total records obtained/analysed	39,339
Minus	
Blank/insufficient data/corrupted/irrelevant	966
Pneumatic machines	1,519
GRS Type 5 machines	253
Remaining useable data records	36,601
Of which:	
Criticality 1–3 (service affecting failure)	17,603
Criticality 4 (non-service affecting)	18,998
Within the useable data	
Unique Switch assets identified	12,042
(from an analysed population of)	19,915
Switches without a failure event in the period	9,560
Showing only a single failure event	4,756
Showing two failure events	2,516
Showing three failure events	1,567
Showing four or more failure events	3,203

essentially the compensation paid by the network custodian to the train operators for unscheduled downtime. This figure does not allow for the subsequent economic impact of any such failure. It can be observed that track switch failures are the second biggest contributor – both financially and in time – after track faults, at around £26m/FY.

Baseline data

Mainline failure logging

Network Rail keeps records of all known asset failure events in a database called 'FMS' (Fault Management System). This database contains many fields which are relevant to this study. The database records both faults and failures, identifying the difference between the two with a 'criticality index' between 1 and 4. Criticality indices 1 to 3 represent failures requiring immediate rectification. Index 4 is a known fault, which will need rectifying when possible, but one which has not yet developed to a system failure. The data held by FMS do not include the number of delay minutes incurred (or subsequent monetary cost) for individual failure events; these data are held in a separate database called TRUST, without historical cross-referencing. Data are entered by human operators, often line-side and in difficult conditions, and as such there is a significant portion of records which may be incomplete or considered corrupt. Data accuracy improves considerably after 2009 when free-text entry was replaced by option selection in several fields.

Dataset for this study

For this study, Network Rail provided a dataset extracted directly from FMS. This consisted of a database query for all entries pertaining to Points for dates between 1 April 2008 and 17 September 2011. This resulted in 39,339 fault/failure records, which were supplied in CSV format. The population of switches on the UK mainline was 21,602 in 2011,[20] but has stayed broadly constant during the period, and populations will be considered constant throughout this analysis. These data correspond to a cumulative operating time of 74,800 years.

Cleansing the dataset

Since the data were directly extracted from the database, extensive processing was required before use. Of the obtained fields, several fields contain duplicate information, but not every field was populated for every record; therefore, identifying these duplicates was important for data cleansing. First, a script was created which back-populated missing fields based on the contents of populated entries, in order to give a more complete dataset. Certain switch types were then excluded from the data due to specialist applications, for example, those with very small populations or obsolete technology already being phased out (e.g. pneumatic machines). Hydraulic derailers, identified as switches in the database, were also discounted. Table 2 shows the number of records discounted for each reason.

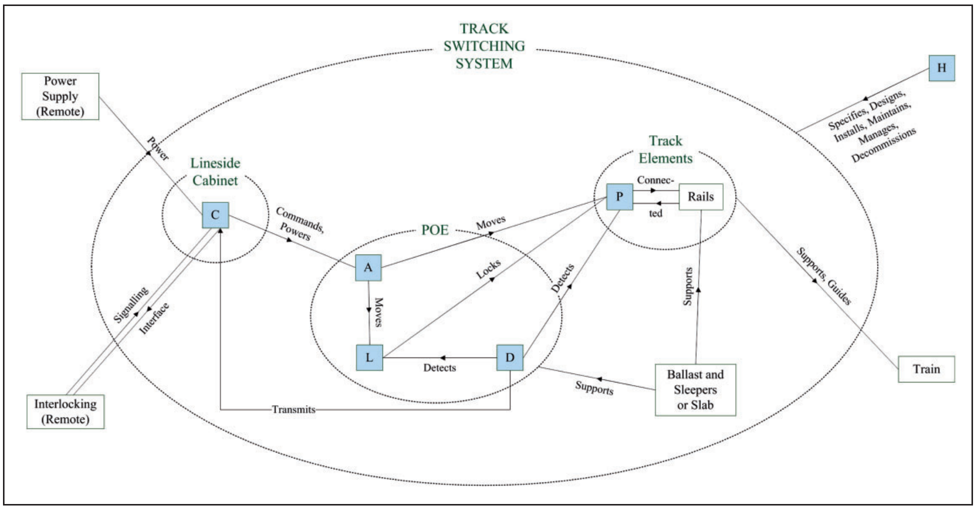

Figure 2. System context diagram showing relationship between functional subsystems, and where appropriate, their relationship with the wider railway environment.
POE: points operating equipment.

Subsystem identification and event assignment

Understanding the design and operation of switches allows their decomposition into a number of functional subsystems for further analysis. The division of functionality into subsystems is in some cases, however, an exercise of engineering judgement, as some components in switch designs can be seen to cross the established subsystem boundaries. The subsystem divisions used for the modelling presented herein were established as part of a series of workshops held in 2011–2013, with representatives from across the GB rail industry, detailed in Bemment et al.[7] The following functional subsystems are identified; a shorthand identifying letter is adopted for each, and the relationship between these subsystems is shown in Figure 2:

- (A) *Actuation*: Elements for moving the track between positions and actuating the locking mechanism: actuator/gearing, transfer of power/motion, including backdrive arrangements.
- (C) *Control/Power*: Elements which locally control the other subsystems and provide power: signalling relays, transformers, back-up supplies.
- (D) *Detection*: Elements which sense and transmit the position of the switch rails and lock back to the control system: microswitches, contacts, Linear Variable Differential Transformer(LVDT).
- (H) *Human*: Humans responsible for the design, maintenance and operation of the switch, including fault finding and repairs.
- (L) *Locking*: Elements which prevent the un-commanded movement of one or both switch blades: lock bodies, lock dogs, associated mechanisms.
- (P) *Permanent Way*: Elements which support and guide vehicles, maintain the gauge and alignment of the track: stretcher bars, track clips, slide chairs.

Several designs of POE are analysed. 'Mechanical' refers to those switches driven by rod from signalbox levers or ground frame, and subsystem interactions therefore differ slightly from Figure 2. HW and W63 designs are both electromechanical in nature. They are from different suppliers and have different internal designs and components. The source data do not explicitly distinguish between them, thus they remain grouped herein. For the same reason, Clamplock designs are grouped with Hydrive designs. Both Clamplock and Hydrive are hydraulic POE designs with a separate power pack and hoses linked to rams between the running rails. The HPSS (high-performance switch system) machines are the newest design on Network Rail infrastructure and use a screw jack actuator.

By comparing the switch type, assembly type and component type identified in each dataset record, each failure event can be assigned to a particular subsystem, for a given POE type. The total number of records in each assignment is shown in Table 3. Note that it is not possible to separate the Locking and Actuation functions in the HPSS machine, as the locking is carried out by the same screw jack mechanism within the actuation element; all failures have thus been grouped under the Actuation category. Failure counts for 'Control/Power' upon mechanical switches are unrealistically low. This does not indicate a much

Table 3. Switch populations and fault/failure incidence count for each subsystem classification within each switch type, for the period 1 April 2008 and 17 September 2011.

		All recorded fault/failure incidents (FRI)							Service affecting failures only (SAF)						
POE type	(Pop)	A	C	D	H	L	P	Total	A	C	D	H	L	P	Total
Clamplock/ Hydrive	6,852	5,412	1,780	2,358	256	5,129	885	15,821	2,494	921	1,120	115	2,235	346	7,231
HPSS	599	345	548	872	32	–	20	1,817	175	328	601	17	–	13	1,134
HW/W63	9,153	5,799	2,607	2,681	349	1,483	1,687	14,606	2,874	1,466	1,327	178	778	655	7,278
Mechanical	3,311	2,102	52	1,251	50	837	66	4,357	656	23	494	21	320	18	1,533
Total	19,915	13,658	4,987	7,162	687	7,449	2,658	36,601	6,200	2,738	3,542	331	3,332	1,033	17,176

POE: points operating equipment.

higher reliability, but instead that not every mechanical switch is fitted with electronic interlocking; at the time of analysis, data were not available on the portion of the population with/without this feature.

Establishing failure rates and distributions

Operational reliability – Definition

It is necessary to distinguish between *unsafe* failures (i.e. resulting in a system in an unsafe state), *operational* failures and *faults* when discussing the reliability of safety critical systems. Literature on the topic can cause confusion by representing any and all by the terms Mean Time Between/To Failure, abbreviated 'MTBF' or 'MTTF'. The time between unsafe failures is not considered any further herein, but these are essentially undetected failures which make the switch dangerous to traffic. These would be included in operational failures, but are comparatively so rare as not to affect the analysis.

- *MTTSAF* – Mean Time to Service Affecting Failure, describes how often the system can be expected to suffer a failure which is service affecting (operational reliability).
- *MTTFRI* – Mean Time to Fault Requiring Intervention, describes the frequency that maintenance crews must visit the asset to rectify faults *and* failures.
- *MTTR* – Mean Time to Repair – the mean time from notification of a failed asset (or subsystem thereof) to returning that asset or subsystem to an as-good-as-new state.

MTTSAF and MTTFRI figures are included here as they are used as a de-facto measure within industry; however, when comparing skewed distributions, the 50% survivor function, or B_{50}, provides a better indicator. Unless otherwise stated, the B_{50} refers to service affecting failures. B_{50} indicates the time at which half the population is expected to have failed, i.e. the median.

MTTR is difficult to quantify as the actual repair time for operational failures (i.e. the time the switch is unavailable following a failure in use) is not recorded by the infrastructure operator. For this modelling exercise, the mean number of 'delay minutes' per incident will be used – 106 min. The calculation, and attribution, of delay minutes to particular faults is not through a particular scientific process, but values provided in Table 1 are used herein to provide a first estimate of MTTR of the correct order of magnitude. More accurate knowledge of the distribution of MTTR figures would be of significant benefit to such a study, especially in the case of different subsystems having very different repair times. However, with the absence of further information, the influence of this figure upon the results has been mitigated by assuming a constant throughout.

Constant failure rates

Assuming a constant failure rate, the well-known equations (equations (1) to (3)) presented by Hecht[10] can be used to calculate MTTSAF and MTTFRI figures for each subsystem and assembly using the data in Table 3. Equation (1) expresses the sum of the operational time between events (TTF) and observational suspensions (*TTS*) for each failure event (*NFT*) in the total (N_{SAF} or N_{FRI}) and observational suspension event (*NST*), divided by the number of observed failure events (N_F). An observational suspension, sometimes referred to as a censored lifetime, is a subsystem reaching the end of the observation window in a functional or repaired state; the asset is known not to have failed in that period, but its exact point of failure subsequent to the observation period is unknown. In the case of a fixed observation window across all assets, as here, this can be simplified to equations (2) and (3), including the known population (*P*) and observation time window (*T*). For a constant failure rate, the rate can be expressed as the reciprocal of the mean, as per equations (4) and (5).

$$MTTF = \frac{\sum_{i=1}^{NFT} TTF_i + \sum_{j=1}^{NST} TTS_j}{N_F} \tag{1}$$

$$MTTSAF = \frac{P \times T}{N_{SAF}} \quad (2)$$

$$MTTFRI = \frac{P \times T}{N_{FRI}} \quad (3)$$

$$\lambda_{SAF} = \frac{1}{MTTSAF} \quad (4)$$

$$\lambda_{FRI} = \frac{1}{MTTFRI} \quad (5)$$

$$SAFB_{50} = \frac{\ln 2}{\lambda_{SAF}} \quad (6)$$

$$FRIB_{50} = \frac{\ln 2}{\lambda_{FRI}} \quad (7)$$

The results of these calculations are tabulated in Table 4. Mean times calculated in this way are indicative only of the relative unreliability contribution of each subsystem to the whole system and of the relative reliability of the different POE designs. To provide baseline values for comparison with variable-frequency analysis later in the paper, the B_{50} values of the same assets are shown in Table 5. The B_{50} values in Table 5 have been derived from equations (6) and (7), which are valid under the assumption of constant failure rates only. All B_{50} values calculated as part of the later, variable failure rate analysis are established as part of the Monte-Carlo modelling process.

Lifetime distribution selection

A range of suitable variable failure rate models were evaluated upon the data, including 2P- and 3P-Weibull, Gamma, Normal and 1P- and 2P-Exponential, using a correlation coefficient test and the maximum likelihood estimation (MLE) approach described below. For each subset of data, the 2P- or 3P-Weibull distribution proved the best fit for the data.

The Weibull distribution is a general purpose reliability distribution used to model times-to-failure of electronic and mechanical components, equipment or systems. The 2P-Weibull distribution, described by Hecht,[10] has two parameters, the shape factor β and the characteristic life, or scale parameter, η. Equations (8) and (9) show the relationship between the failure frequency and failure rate and the distribution parameters at given time, t. β indicates whether a subsystem has a tendency towards early-life, 'infant mortality' failures ($\beta < 1$), constant failure rate ($\beta = 1$) or late-life, 'wear-out' failures $\beta > 1$. η indicates the scale of the probability density function in time, a larger η indicating a longer time to failure; though noting that η values are not directly comparable, as they

Table 4. MTTFRI and MTTSAF figures for functional subsystems of different POE types upon the GB mainline network, calculated using data sampled between 1 April 2008 and 17 September 2011.

	MTTFRI (years)							MTTSAF (years)						
	A	C	D	H	L	P	All	A	C	D	H	L	P	All
Clamplock/Hydrive	4.4	13.3	10.1	92.7	4.6	26.8	1.5	9.5	25.8	21.2	206.1	10.6	68.5	3.3
HPSS	6.0	3.8	2.4	65.0	n/a	102.2	1.1	11.8	6.3	3.5	121.1	n/a	157.4	1.8
HW/W63	5.5	12.1	11.8	90.6	21.4	18.8	2.2	11.0	21.6	23.9	178.4	40.7	48.3	4.4
Mechanical	5.5	219.9	9.2	230.9	13.7	174.3	2.6	17.5	490.6	23.2	548.3	35.8	621.4	7.5
All	5.0	13.8	9.6	100.3	9.3	25.9	1.9	11.1	25.2	19.5	208.4	20.7	66.7	4.0

MTTSAF: mean time to service affecting failure, describes how often the system can be expected to suffer a failure which is service affecting (operational reliability); *MTTFRI*: mean time to fault requiring intervention, describes the frequency that maintenance crews must visit the asset to rectify faults *and* failures.

Table 5. B50 figures corresponding to the MTTSAF and MTTFRI figures presented in Table 4.

	FRIB50 (years)							SAFB50 (years)						
	A	C	D	H	L	P	All	A	C	D	H	L	P	All
Clamplock/Hydrive	3.0	9.2	7.0	64.3	3.2	18.6	1.0	6.6	17.9	14.7	142.8	7.4	47.4	2.3
HPSS	4.2	2.6	1.6	45.1	n/a	70.8	0.8	8.2	4.4	2.4	83.9	n/a	109.1	1.3
HW/W63	3.8	8.4	8.2	62.8	14.8	13.0	1.5	7.6	15.0	16.5	123.6	28.2	33.5	3.0
Mechanical	3.8	152.4	6.4	160.0	9.5	120.8	1.8	12.1	340.0	16.1	380.0	24.8	430.7	5.2
All	3.5	9.6	6.7	69.6	6.4	18.0	1.3	7.7	17.4	13.5	144.5	14.3	46.2	2.8

depend upon the corresponding β value. The 3P-Weibull distribution also requires γ, which represents an offset in time for the origin of the curve.

In the analysed cases where the 3P-Weibull distribution proved most suitable, it did so with an offset parameter which was insignificantly small; therefore, the 2P-Weibull was selected as the most suitable distribution for this modelling exercise. Published work by Rama and Andrews[21] obtains a similar though more targeted dataset from the same source and fits distributions to the grouped data. The work also establishes that the Weibull distribution is the most appropriate distribution to model switch component lifetimes and also selects the two-parameter model over the three-parameter model for the same reasons.

One drawback of the Weibull function is that it is not capable of exhibiting non-monotonic shapes in the hazard function. This means the bathtub curve, typically observed over a whole component and population lifetime, cannot be replicated. However, this drawback is offset by the sample period being across a range of component ages, and the use of confidence intervals to give an indication of the goodness-of-fit of the distributions identified.

Rama and Andrews[21] also list a number of assumptions which need to be made when modelling lifetime distributions in this way, namely:

1. Each failure is rectified by repairing or replacing the failed component.
2. Equipment can either be in a good (operational) or bad (failed) state.
3. Repair/replacement returns components to the as-good-as-new state.
4. Times to failure of individual components are independent of each other.
5. Time duration of the component in the failed state is insignificant in comparison to the functioning period.

$$f(t) = \frac{\beta}{\eta}\left(\frac{t}{\eta}\right)^{\beta-1} e^{-\left(\frac{t}{\eta}\right)\beta} \tag{8}$$

$$\lambda(t) = \frac{\beta}{\eta}\left(\frac{t}{\eta}\right)^{\beta-1} \tag{9}$$

$$B_{50} = \eta(\ln(2))^{\frac{1}{\beta}} \tag{10}$$

$$MTTSAF_{Weibull} = \eta_{SAF}\Gamma\left(1+\left(\frac{1}{\beta_{SAF}}\right)\right) \tag{11}$$

Distribution fitting process

First, records were grouped by each unique asset and then placed upon failure event timelines. The output from this process is, for each established subsystem/switch type group, an array of 'time to event' figures, where the event is either a failure or suspension of test. This process was automated using an iterative script; however, due to historical changes in data entry methods, significant manual intervention was also required. Figure 3 shows a histogram of the time-to-failure data for all Clamplock/Hydrive failures. Figure 4 shows the cumulative proportion of observed failures over time; as the gradient of the

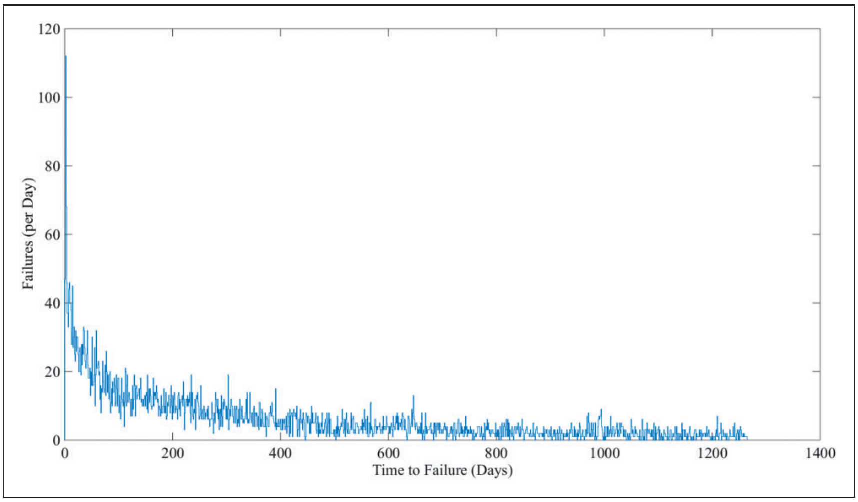

Figure 3. Histogram of all Clamplock/Hydrive failure intervals.

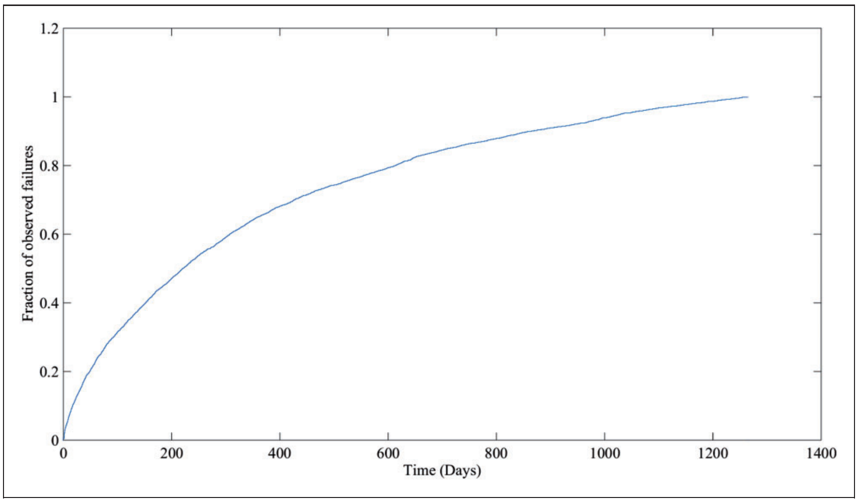

Figure 4. Cumulative portion of all Clamplock/Hydrive failure events over observed time.

plot is shallower with time, it indicates that the failure pattern tends towards infant mortality.

The output arrays can be used as the input to an MLE algorithm. MLE is an estimator technique suitable for data that have a relatively high portion of observational suspensions; the proportion of observational suspensions in these data prevents the use of other techniques, e.g. rank regression. MLE works by developing a likelihood function based on sampling the data and by finding the values of parameter estimates that maximise this likelihood function. It is an iterative method. The process is well established and documented, for example by Scholz.[22] β and η values were established (for service affecting failures only) in each of the subsystems in each switch classification, and the computed values are tabulated in Table 6. Values of the parameters at the extremes of a 90% confidence interval are also provided to indicate the goodness of fit. Table 6 also lists the computed B_{50} values for each subsystem, and (for the sake of compatibility with existing practice only) the computed MTTSAF values, also with 90% confidence intervals. The calculation of these values for a given 2P-Weibull distribution uses equations (10) and (11), where Γ represents the Gamma function. An example of a fitted exponential model for failure distributions, for the Actuation subsystem of an HW/W63 machine type, is plotted in Figure 5. Figure 6 is a plot of the same failure data, with a fitted 2P-Weibull distribution. These two plots illustrate the relative unsuitability of the constant failure rate model with these data.

Analysis of fitted distributions

- The distributions reveal HPSS – the most modern POE type – to be the least reliable solution, and mechanical points, the oldest approach, to be the most reliable. The low reliability of HPSS may be due to the observation window coinciding with the roll out of HPSS, and the subsequent final development and testing period with live traffic. A more recent observation window would be required to confirm this.
- The models established in Table 6 can be compared to those independently established by Rama and Andrews.[21] Notably, the shape parameter $\beta < 1$ indicates a high infant mortality rate. There are some differences between the B_{50} values in the constant and variable failure rate models.
- Comparing the values presented in Table 5 with those in Table 6 indicates that assuming a constant failure rate when modelling switch failures is not an ideal approach, as in all cases the whole-system β values are significantly less than 1 – a conclusion which further agrees with those of Rama and Andrews.[21] This indicates that the accuracy of many predict-and-prevent models used by industry could be significantly improved with the use of variable failure rates.
- Comparing the values presented in Table 5 with those in Table 6 further highlights the weakness of the industry-standard MTTSAF measure – the MTTSAF for mechanical switches at almost 50 years, for instance, would be a misleading value for an asset manager, when considering the B_{50} is nearer to 10 years.
- Most elements show a tendency towards $\beta < 1$, indicating a higher incidence of early life failures. This is not what is expected of an electromechanical device, which would typically be seen to wear out in use. Permanent way elements, with β approximately 1, have a broadly constant failure rate.

Table 6. Calculated values of β, η, B50 and MTTSAF, including 90% confidence intervals, tabulated by POE type and subsystem type.

		Service affecting failures only						
		A	C	D	H	L	P	All
Clamplock/Hydrive	β_{lower}	0.716	0.750	0.674	1.268	0.709	0.809	0.636
	β	0.738	0.789	0.707	1.477	0.732	0.882	0.647
	β_{upper}	0.760	0.829	0.740	1.707	0.755	0.959	0.658
	η_{lower}	4,639	12,822	13,920	13,267	5,329	26,688	1,332
	η (days)	4,940	14,739	15,941	19,418	5,713	35,548	1,374
	η_{upper}	5,276	17,104	18,434	30,914	6,144	49,022	1,417
	$B_{50,lower}$	7.8	22.5	23.2	29.3	8.9	49.8	2.1
	B_{50} (years)	8.2	25.4	26.0	41.5	9.5	64.3	2.1
	$B_{50,upper}$	8.7	28.8	29.4	63.5	10.1	85.6	2.2
	$MTTSAF_{lower}$	15.3	40.0	47.4	33.3	17.7	77.5	5.0
	MTTSAF (years)	16.3	46.2	54.8	48.1	19.0	103.7	5.2
	$MTTSAF_{upper}$	17.5	54.0	64.0	75.4	20.6	143.7	5.3
HPSS	β_{lower}	0.594	0.519	0.599	0.641	n/a	0.809	0.545
	β	0.671	0.564	0.637	0.967	n/a	1.253	0.569
	β_{upper}	0.754	0.612	0.676	1.389	n/a	1.836	0.593
	η_{lower}	6,481	3,496	1,492	15,058	n/a	8,756	644
	η (days)	8,641	4,243	1,671	47,391	n/a	22,730	701
	η_{upper}	12,130	5,267	1,887	326,420	n/a	119,097	766
	$B_{50,lower}$	22.9	5.1	2.3	31.5	n/a	19.6	0.9
	B_{50} (years)	31.2	6.1	2.6	88.9	n/a	46.5	1.0
	$B_{50,upper}$	45.2	7.3	2.9	509.1	n/a	208.7	1.1
	$MTTSAF_{lower}$	10.8	15.3	5.7	41.7	n/a	22.8	2.8
	MTTSAF (years)	13.7	19.1	6.4	131.7	n/a	58.0	3.1
	$MTTSAF_{upper}$	18.2	24.4	7.3	914.0	n/a	292.4	3.4
HW/W63	β_{lower}	0.643	0.771	0.622	1.454	0.594	1.199	0.600
	β	0.662	0.804	0.650	1.652	0.629	1.275	0.611
	β_{upper}	0.682	0.838	0.679	1.866	0.667	1.354	0.622
	η_{lower}	7,388	11,327	22,576	10,515	51,175	8,277	2,211
	η (days)	7,953	12,645	26,253	13,991	65,123	9,405	2,293
	η_{upper}	8,592	14,207	30,800	19,611	84,455	10,805	2,378
	$B_{50,lower}$	11.8	20.0	35.9	23.7	80.7	17.3	3.3
	B50 (years)	12.5	22.0	40.9	30.7	99.7	19.3	3.4
	$B_{50,upper}$	13.4	24.3	46.9	41.8	125.2	21.8	3.6
	$MTTSAF_{lower}$	26.9	34.9	83.5	26.1	195.2	21.1	8.9
	MTTSAF (years)	29.2	39.1	98.3	34.3	252.9	23.9	9.2
	$MTTSAF_{upper}$	31.7	44.1	116.8	47.3	334.5	27.3	9.6
Mechanical	β_{lower}	0.512	0.690	0.649	1.151	0.554	0.910	0.474
	β	0.544	1.011	0.698	1.641	0.608	1.360	0.494
	β_{upper}	0.578	1.417	0.751	2.253	0.665	1.938	0.513
	η_{lower}	20,682	43,684	16,604	11,066	43,218	17,734	6,706
	η (days)	25,687	188,915	20,797	25,454	62,510	56,200	7,531
	η_{upper}	32,496	2,022,138	26,696	93,985	94,833	381,088	8,505
	$B_{50,lower}$	29.9	92.2	27.8	25.7	67.9	40.2	8.9
	B50 (years)	35.9	360.2	33.7	55.8	93.7	117.6	9.8
	$B_{50,upper}$	43.8	3,269.6	41.8	187.6	134.9	699.8	10.9
	$MTTSAF_{lower}$	95.3	119.3	56.9	27.9	169.7	45.7	36.9
	MTTSAF (years)	121.8	515.3	72.3	62.4	253.3	141.0	42.3
	$MTTSAF_{upper}$	158.9	5,504.0	94.3	219.9	398.0	916.2	48.8

(continued)

Table 6. Continued

		Service affecting failures only						
		A	C	D	H	L	P	All
All	β_{lower}	0.641	0.729	0.626	1.443	0.661	1.021	0.595
	β	0.654	0.751	0.643	1.576	0.679	1.073	0.601
	β_{upper}	0.667	0.774	0.660	1.717	0.698	1.127	0.608
	η_{lower}	11,035	16,225	17,562	13,109	15,862	16,625	1,962
	η (days)	11,675	17,767	19,115	16,281	17,225	19,090	2,008
	η_{upper}	12,364	19,520	20,882	20,770	18,770	22,139	2,055
	$B_{50,lower}$	17.4	27.6	27.5	29.0	25.6	32.9	2.9
	B50 (years)	18.3	29.9	29.6	35.3	27.5	37.2	3.0
	$B_{50,upper}$	19.2	32.4	31.9	44.2	29.6	42.4	3.1
	$MTTSAF_{lower}$	40.8	52.6	66.1	32.5	56.3	44.4	8.0
	MTTSAF (years)	43.4	57.9	72.4	40.0	61.5	50.9	8.3
	$MTTSAF_{upper}$	46.2	63.9	79.8	50.6	67.5	58.9	8.5

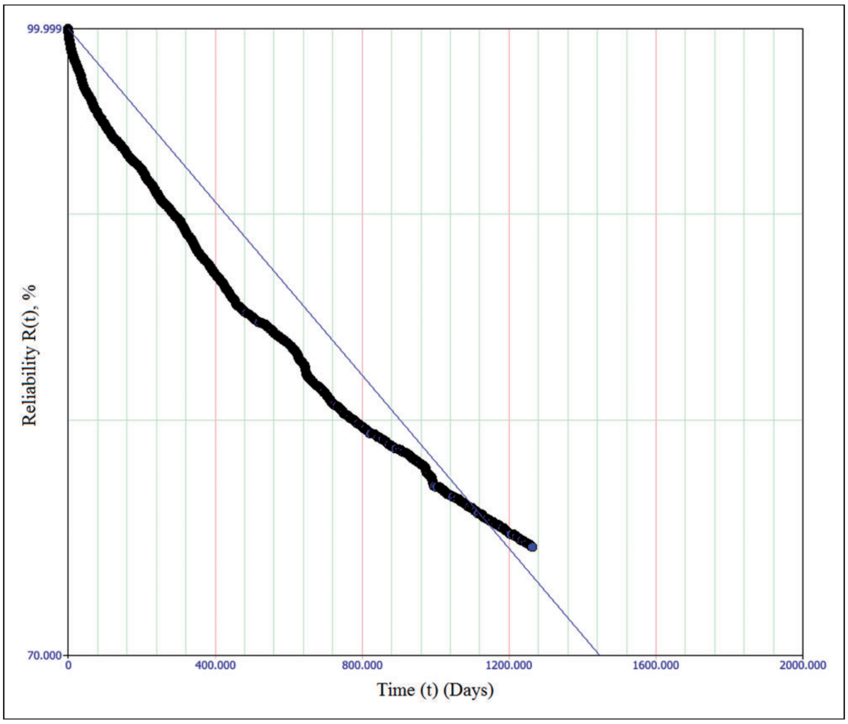

Figure 5. Best-fit line for exponential failure distribution (i.e. constant failure rate) of Actuation subsystem of HW/W63 machine class, showing a considerable deviation from observed data.

- An electro-mechanical or electro-hydraulic element showing high infant mortality is an indication of three main possible failure contributors. First, that insufficient burn-in testing is being completed. Second, that there are negative human factors with regard to installation and adjustment, which lead to the components operating outside a design envelope. Third, that the components have not been designed for the correct operating environment. Further analysis would be required to establish which particular cause (or combination thereof) was prevalent.

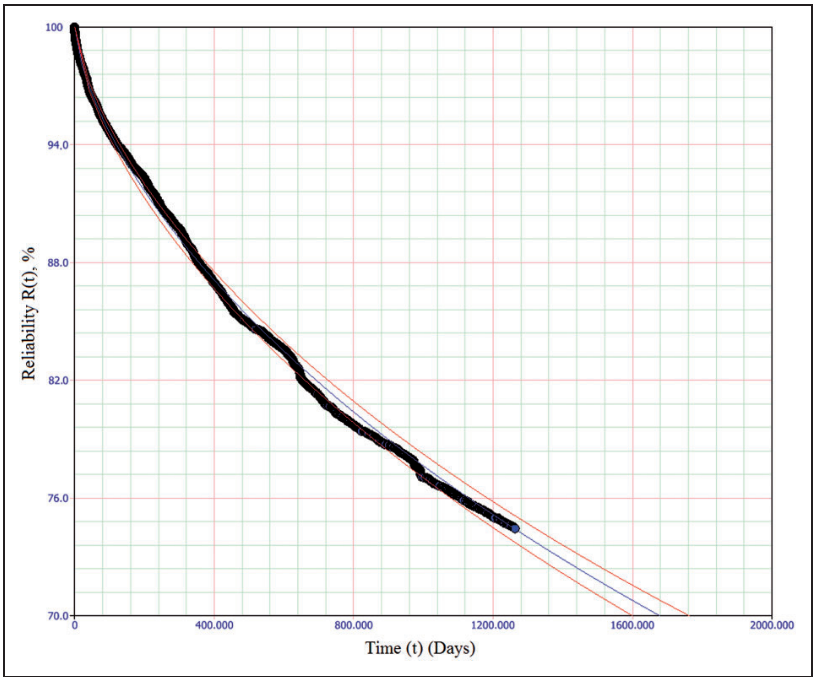

Figure 6. 2-P Weibull failure distribution ($\beta = 0.662, \eta = 7953$) and 90% confidence interval of Actuation subsystem of HW/W63 machine class, showing a much closer correlation to the observed data than Figure 5.

- 'Human error' failures – that is, failures directly attributable to human error rather than those manifesting themselves through the failure of a component – have a relatively high beta. However, the confidence bands of these values are very wide, as there are relatively few failures attributable to this cause. As there is no obvious reason the likelihood of human error should increase with time, it may prove a better approach in future work to fit a constant failure rate model to this element.
- Note that values in the 'all' column are calculated using all data points for a given machine to construct a distribution, which because of the mix of β values discovered is not an accurate method, a better method being the mixed-Weibull, which is used for the baseline models in the next section.

These subsystem models can now be used to evaluate the benefits of a redundant approach.

Fault tolerance through redundancy

Modelling approach

With the β and η values established in the previous section, conceptual designs featuring redundancy of subsystems can now be modelled. This modelling takes an RBD approach. An RBD represents a system by a series of blocks; each block can be in a 'functional' or 'failed' state. The system is considered to be in a functional state if a path can be created from start (left) to end (right) which encompasses only blocks in the functional state. The modelling considered here is purely analytical, that is it is assumed that no repair of failed subsystems takes place. Three examples of RBDs are provided graphically in this paper; other combinations are represented in shorthand only. This shorthand notation is adopted for brevity, whereby a number (representing number of channels) or fraction (representing x-out-of-y redundancy) is followed by the abbreviation adopted for each subsystem as used in the source data analysis. Figure 7 shows the baseline example. This has a single instance of each subsystem and would be termed *A C D H L P* in shorthand. As all subsystems are connected in series, a failure of any one will cause a system failure. Another arrangement is shown in Figure 8, which has duplicate, triplicate and 2-out-of-3 elements. The shorthand for this implementation is *2/3A 2/3D 3L C 2P H*.

Scenarios and strategy

- *Actuation* elements can be combined in parallel-channel redundancy. A range of actuation options

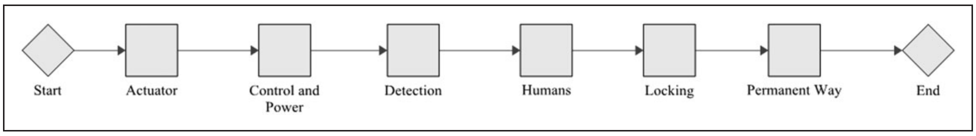

Figure 7. An example RBD showing the baseline case, with a single subsystem of each category. As all subsystems are connected in series, a failure of any one will cause a system failure.

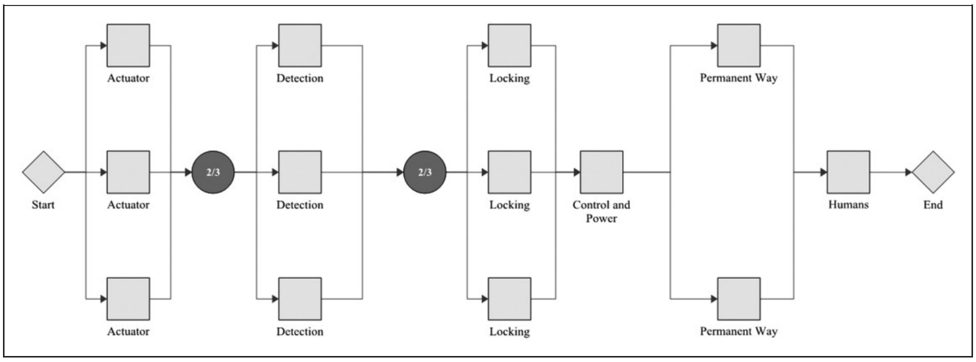

Figure 8. An example RBD showing replication of individual subsystems, with 2-out-of-3 voting (for actuation and detection), triplication (locking) and duplication (permanent way).

can be examined. Singular (i.e. current practice), duplicate, triplicate (including 2-out-of-3) are considered here. However, actuators are also relatively expensive. Cost is not calculated in this paper, but 2-out-of-3 may enable smaller/cheaper units to be utilised.

- *Control/Power* elements could be paralleled in a number of ways; however, it is anticipated that x-out-of-y approaches would not be suitable due to the complexity of the control signalling. Therefore, the options examined are singular, duplicate and triplicate.
- *Detection* elements can easily be paralleled. However, the sole purpose of detection is to sense the system state, so a problem exists in a duplicate system showing two differing positions, which would likely still be regarded as a failure. Options considered are therefore singular, and the voting systems 2-out-of-3 and 3-out-of-4. The processing element is considered perfect.
- *Human* failures caused by human error must necessarily form part of the system analysis. However, a full analysis of the human factor elements of track switch design, operation, maintenance and repair is not part of this work (see 'Future Work' section). The human element is therefore considered consistent with existing practice.
- *Locking* elements can be paralleled. As the fundamental purpose of the lock means a failure could lead to it preventing movement of the switch, it could be deduced that paralleling this subsystem may in fact reduce the overall system reliability. However, in practice, nearly all lock failures result from a lock failing to engage. For this analysis, it is assumed there is an engineering solution to this which enables locks to function as separate units.[7]
- *Permanent Way* elements could be duplicated or triplicated, but no voting approaches could apply as these elements are entirely passive.

Another approach to be considered (for the power operated points only) is the duplication, triplication and 2-out-of-3 voting for several identical point machines fitted to a single end. This would parallel detection, actuation and locking channels grouped together, in a larger framework of voting and processing, again considered perfect. An example of this approach is shown in Figure 9, the shorthand for which is *3(ADL) C P H*. These grouped elements would each have an associated permanent way, control/power and human elements, which could take the form of the strategies above. It is also not possible to apply each of these strategies to each points type, exceptions are:

- *Actuation* upon the mechanical points type consists of rodding and cable runs from a lever frame to the points. Therefore, a redundancy of actuators would not be practicable.
- *Control/Power* elements upon mechanical points type are rare, yet the failure distribution listed is

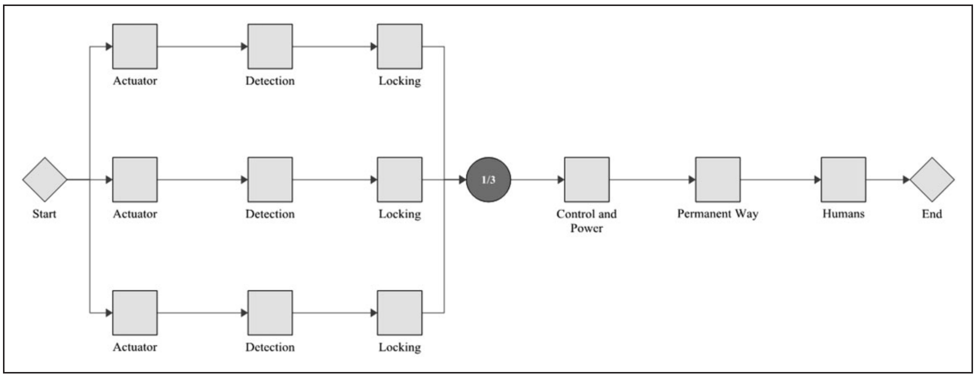

Figure 9. An example RBD showing parallel replication of whole POE units, wherein each unit has actuation, locking and detection elements.

very low as it is for the whole population analysed. This has therefore been left as a singular item.

- *Locking* elements upon HPSS points type are combined with actuation as established earlier.

When all possible approaches listed above are combined, there are approximately 350 possible permutations per machine type. For brevity, therefore, this paper will present a baseline machine and several concepts for each machine type, demonstrating the most reliable scenarios in each case. Many architectures are evaluated as each will incur a different monetary cost; evaluating relative cost is the subject of further work. The scenarios were selected by way of a sensitivity analysis of each subsystem, which iteratively examined the static contribution to unreliability of each subsystem. The process for creating the distributions is based on the Monte-Carlo approach. The completed RBDs are used, with random inputs, to predict first failure times of the system. This process is repeated until a dataset of 500 simulated failure points is created, for each combination. This dataset can then be subject to the same MLE process detailed earlier, in order to calculate the β and η parameters, and B_{50} values. For completeness, $MTTSAF$ figures are also calculated. Note that this is a different method to that used to calculate the 'All' column in Table 4, which was to fit a single 2P-Weibull distribution to a dataset which was known to be a mix of different distributions. The results of the two processes are therefore expected to be marginally different. Table 4 can be used to validate the Monte-Carlo approach.

Static versus dynamic analysis

One of the benefits of a multi-channel approach is that the system continues to function until such a time as a repair has been effected, unless all channels fail simultaneously. Whilst a static analysis can reveal the expected system reliability, a more relevant measure can be obtained from a dynamic simulation – using the same RBD and Monte-Carlo approach – to establish the availability. To establish availability, the benchmark MTTR is used as the time to fix any failed subcomponent. As the failure distributions are significantly time-variant, the dynamic simulations are run over an observation window of 25 years (a typical asset lifetime for a switch installation) and the mean unavailability per annum, in minutes, taken as a measure for comparison. Note that this availability figure relates to unscheduled downtime only and does not allow for scheduled maintenance downtime, which is considered part of the system.

Analysis

The results of the static modelling are presented in Table 7. The results of the dynamic modelling are presented in the right-hand column of Table 7. The B_{50} figures show that redundancy can provide a considerable improvement over baseline for every POE type. The mean annual downtime for each redundantly engineered solution is an order of magnitude lower than the baseline scenario. The following further points are of note:

- Industry practice is to use mean-times as a measure of reliability. However, with highly skewed distributions, as calculated here, this measure can be significantly misleading. This paper suggests use of the B_{50} value as a more representative measure, whether or not failure rates are considered constant.
- In all cases, parallel redundancy of functional subsystems acts to improve overall system reliability.
- For HPSS, fitting three machines in a parallel configuration results in a fivefold improvement in B_{50} value.

Table 7. β, η, MTTSAF and B50 values for a selection of redundantly engineered switch solutions based upon existing POE types.

		Static				Dynamic
Machine type	Concept structure	β	η (days)	MTTSAF (years)	B50 (years)	Mean Unavailibility (min per annum)
Clamplock/Hydrive	A C D H L P (Baseline)	0.750	1,136	3.7	1.9	24.1
	2/3A 3C 2/3D H 2L 2P	1.253	2,587	6.7	5.1	1.3
	2/3A 3C 2/3D H 3L 2P	1.276	2,861	7.4	5.7	1.3
	2/3A 3C 3/4D H 2L 2P	1.252	2,345	6.1	4.7	1.3
	2/3A 3C 3/4D H 3L 2P	1.270	2,572	6.6	5.2	1.3
	3A 3C 2/3D H 2L 2P	1.353	4,181	10.6	8.6	1.3
	3A 3C 2/3D H 3L 2P	1.468	4,802	12.1	10.0	1.3
	3A 3C 3/4D H 2L 2P	1.319	3,603	9.2	7.3	1.3
	3A 3C 3/4D H 3L 2P	1.393	4,088	10.3	8.5	1.3
	2/3(ADL) 3C H 2P	1.152	1,319	3.6	2.5	1.3
	3(ADL) 3C H 2P	1.431	3,610	7.3	9.3	1.3
HPSS	A C D H P (Baseline)	0.623	555	2.1	0.9	36.2
	2/3A 3C 2/3D H 2P	1.055	1,104	2.1	3.1	0.9
	2/3A 3C 3/4D H 2P	1.037	710	2.0	1.3	0.9
	3A 3C 2/3D H 2P	1.033	1,261	3.5	2.3	0.8
	3A 3C 3/4D H 3P	1.020	770	2.2	1.4	0.9
	2/3(AD) 3C H 2P	1.026	863	2.5	1.6	0.9
	3(AD) 3C H 2P	1.256	2,531	6.7	4.9	0.9
HW/W63	A C D H L P (Baseline)	0.716	1,568	5.0	2.7	18.9
	2/3A 3C 2/3D H 2L 2P	1.036	3,618	9.5	7.1	1.8
	2/3A 3C 2/3D H 3L 2P	1.035	3,682	9.7	7.3	1.8
	2/3A 3C 3/4D H 2L 2P	1.037	3,251	8.6	6.4	1.9
	2/3A 3C 3/4D H 3L 2P	1.036	3,303	8.8	6.5	1.9
	3A 3C 2/3D H 2L 2P	1.114	5,845	14.7	12.2	1.7
	3A 3C 2/3D H 3L 2P	1.119	5,995	15.0	12.5	1.7
	3A 3C 3/4D H 2L 3P	1.086	5,025	12.8	10.3	1.9
	3A 3C 3/4D H 3L 2P	1.078	5,143	13.1	10.6	1.8
	2/3(ADL) 3C H 2P	0.989	2,398	6.6	4.5	1.9
	3(ADL) 3C H 2P	1.155	5,603	14.1	11.6	1.8
Mechanical	A C D H L P (Baseline)	0.621	3,357	12.5	5.3	8.1
	A C 2/3D H 2L 2P	0.685	5,193	16.6	9.0	3.7
	A C 2/3D H 3L 2P	0.680	5,412	17.3	9.4	3.6
	A C 3/4D H 2L 2P	0.716	4,148	12.8	7.3	3.9
	A C 3/4D H 3L 2P	0.713	4,282	13.3	7.5	3.7
	A 2/3(DL) C H 2P	0.713	3,967	12.5	6.9	3.8
	A 3(DL) 3C H 2P	0.648	7,090	23.1	12.4	3.8

MTTSAF: mean time to service affecting failure, describes how often the system can be expected to suffer a failure which is service affecting (operational reliability).

- For the HW/W63 electromechanical machines, up to 12.5 year B_{50} values are achievable, a fivefold improvement.
- For Clamplock/Hydrive types, B_{50} can also exceed 10 years, also a fivefold improvement.
- As expected, different architectures have different effects upon whole system reliability. To select a suitable architecture for a given situation, cost constraints must also be taken into account, alongside the maintenance and repair policy.
- Figure 10 shows the relative reliability importance of each subsystem type, for the HW/W63 baseline example. Reliability importance is calculated as the subsystem reliability divided by system reliability and gives an indication of how likely a failure of that subsystem is to cause a system failure. It can be seen that for the series case, the failure of any block is of similar likelihood to cause a system failure at any point in the observation window. This result is to be expected for a series system.

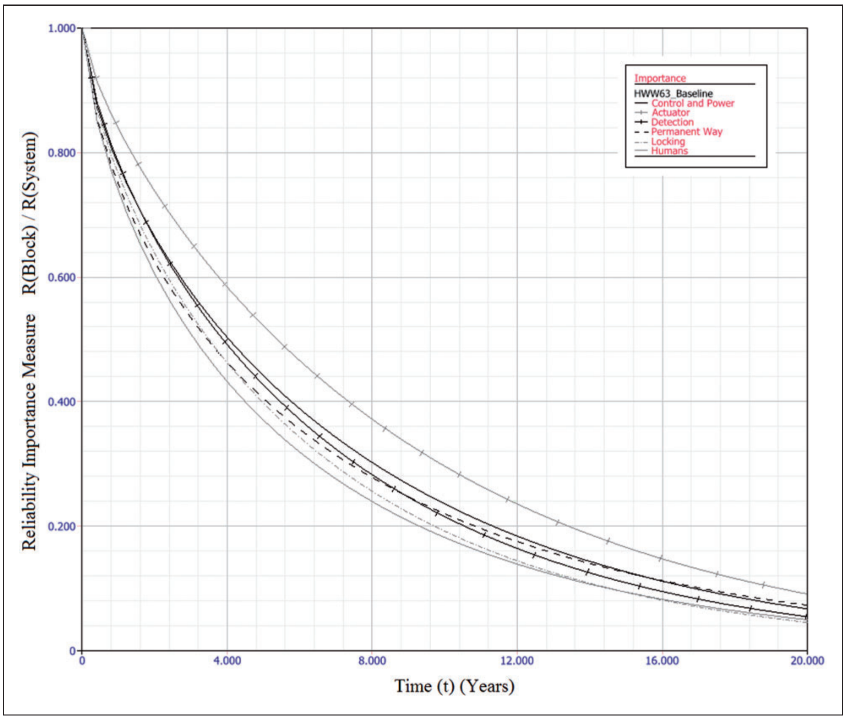

Figure 10. Reliability Importance of each subsystem type for baseline case of HW/W63 machine type, over 20 years of operation. As it is a series system, all elements contribute similar levels of unreliability at each point in time.

- Figure 11 shows the relative reliability importance for a sample case, *3A 3C 2/3D H 3L 2P* of the HW/W63 POE type. The importance of all physical subsystems has been considerably reduced, indicating a good fault tolerance. However, the human element is now of dominant importance throughout the observation window. The same is true for *all* evaluated architectures, as it is not possible to add redundancy to the human element in the same way. There is also the possibility that the Human element would be less reliable with a multi-channel system, as the extra complexity may lead to additional human error. Adding additional redundancy beyond that explored herein does not significantly further improve system reliability, as the Human element becomes the limiting factor. This result is important in indicating that when implementing functionally redundant track switching solutions, human factors elements are important in gaining the full reliability benefits. Any neglect of human factors in this instance may mean that there may be no reliability improvement at all.
- The results of the dynamic modelling show that an order of magnitude reduction in unscheduled downtime is possible across all asset types, when a functionally redundant design approach is taken.
- The dynamic modelling also shows that the particular architecture has a relatively insignificant effect upon the unscheduled downtime for each switch type. This is because the likelihood of parallel channels failing concurrently, within the comparatively short MTTR, is diminishingly small.
- The main contributor to the unscheduled downtime in each scenario is errors directly attributable to humans. This is further highlighted in Figure 11. HPSS performs better than the other drive types in the mean unavailability per annum due to the fact the eta value for human-induced failures is much higher – there is less likelihood of error as the machine has built-in monitoring and diagnostics.
- As the MTTR is insignificantly small when compared with the MTTSAF, there may be some scope in a multi-channel architecture to respond to subsystem failures in a much longer time frame – perhaps weeks or months – without having a significant detrimental effect upon availability. Further modelling work will be necessary to establish this relationship.
- This modelling has not considered the practical limitations to implementation. Of note is the fact that providing redundancy in locking with existing designs may not be possible. A novel design of locking system allowing multiple

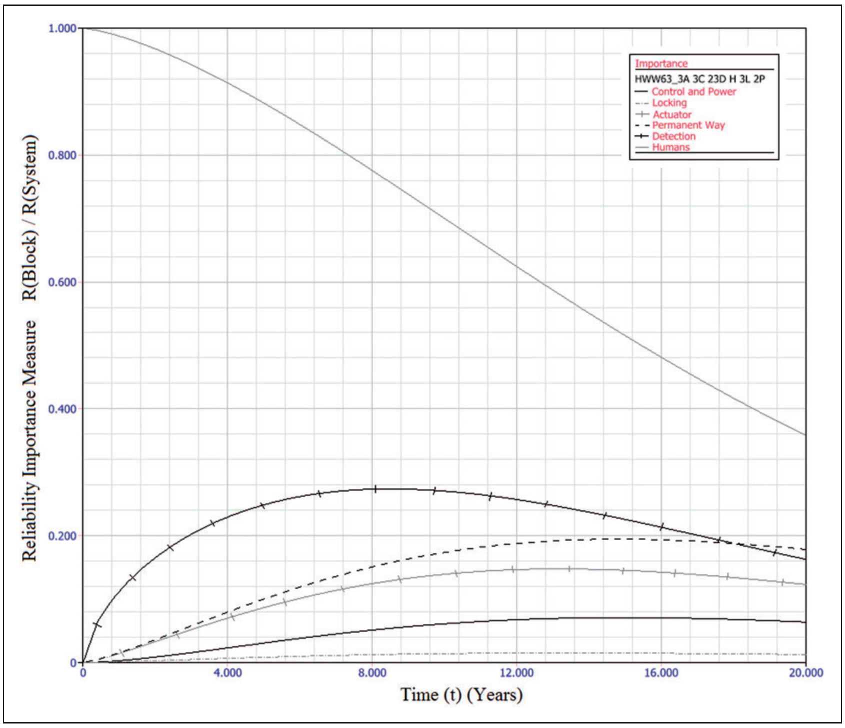

Figure 11. Reliability Importance of each subsystem type for *3A 3C 2/3D H 3L 2P* case of HW/W63 machine type, over 20 years of operation. System reliability is dominated by human error over the entire time period.

channels would therefore be required. The proposed 'REPOINT' design, first presented in Bemment et al.,[7] is one option which enables a redundancy of locking systems.

Conclusions

This paper has established that adopting a fault tolerant approach to railway track switching is able to bring considerable gains in reliability and availability. Reliability of track switches is a problem on the UK mainline, causing much delay to trains and with an associated cost to the infrastructure manager. This paper has analysed failure data from the UK mainline infrastructure custodian, covering 74,800 years of operation, in order to establish failure distribution parameters and reliability figures for different switch machine types when decomposed into their functional subsystems. These parameters have then been used as inputs to a range of RBD models which establish analytically the increase to reliability possible when taking a parallel-subsystem approach to fault tolerance. The results show that considerable gains in whole-system reliability are demonstrated in a range of possible implementations; typical time to failures can be more than five times that of existing solutions, and unscheduled downtime reduced by an order of magnitude. However, as equipment failures are engineered out, switch reliability can be seen to plateau. This is due to the dominant contributor to unreliability becoming human error, which cannot be designed out in the same manner. As considerable reliability gains are demonstrated, this paper makes a strong case for developing track switch designs utilising functional redundancy. The potential impact of such designs on reliability and availability is significant.

Future work

Future work investigating fault tolerant track switching will centre around three main areas:

- Dynamic reliability modelling of suggested architectures for fault tolerant track switching solutions. The work contained herein is analytical only, and clearly one of the main benefits to the implementation of parallel-channel redundancy is the extension of the window where repair/replacement can occur. This work will require extensive modelling but build directly upon the failure distributions established in this paper.

- A more detailed engineering appraisal of the physical constraints of fault tolerant track switching needs to be carried out. This paper does not consider for example the space, cost or time constraints within which the track switching solutions must perform, or indeed whether engineering a physical embodiment of the proposed redundant architectures is possible.
- Seek a greater understanding of the human factors elements of track switch installation, maintenance and repair. In any future implementation, minimising the human contribution to failures will be just as important as engineering out service affecting failures, as demonstrated by this paper.

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References

1. Morgan JC. *British railway track, 7th edition, volume 1, design part 2: switches and crossings*. Derby, UK: The Permanent Way Institution, 2009.
2. Ison S, Frost M and Watson R. UK rail transport: a review of demand and supply. *Proc Inst Civil Eng Transport* 2012; 165: 225–234.
3. Pellegrini P, Marlière G and Rodriguez J. Optimal train routing and scheduling for managing traffic perturbations in complex junctions. *Transport Res B Meth* 2014; 59: 58–80.
4. García FP, Roberts C and Tobias AM. Railway point mechanisms: condition monitoring and fault detection. *Proc IMechE, Part F: J Rail and Rapid Transit* 2010; 224: 35–44.
5. Silmon J and Roberts C. Improving switch reliability with innovative condition monitoring techniques. *Proc IMechE, Part F: J Rail and Rapid Transit* 2010; 224: 293–302.
6. García FP, Schmid F and Conde JC. A reliability centered approach to remote condition monitoring. A railway points case study. *Reliab Eng Syst Saf* 2003; 80: 33–40.
7. Bemment SD, Ebinger E, Goodall RM, et al. Rethinking rail track switches for fault tolerance and enhanced performance. *Proc IMechE, Part F: J Rail and Rapid Transit*. Epub ahead of print 1 May 2016. DOI: 10.1177/0954409716645630, 2016.
8. Blanke M and Schröder J. *Diagnosis and fault-tolerant control,* vol. 691. Berlin: Springer, 2006.
9. Ursani Z, Mei TX and Whiteing A. A fault tolerance approach for railway scheduling and train control. *Transport Res B Meth* 2013; 56: 161–173.
10. Hecht H. *Systems reliability and failure prevention*. Norwood, MA: Artech House, 2004.
11. Isermann R. *Fault-diagnosis systems: an introduction from fault detection to fault tolerance*. Berlin: Springer, 2006.
12. Cribbens AH. Solid-state interlocking (SSI): an integrated electronic signalling system for mainline railways. *IEEE Proc Electr Power Appl B* 1987; 134: 148–158.
13. Bemment SD, Dixon R, Goodall RM, et al. Redundantly engineered track switching for enhanced railway nodal capacity. In *Proceedings of the 1st IFAC ACATTA Workshop*, Istanbul, Turkey, 9 September 2013.
14. Hadaway HW. *IRSE 'Green Booklet' No. 5 – principles of power point control and detection (British Practice)*. London: The Institution of Railway Signal Engineers, 1950.
15. Genner R. *Railway Group Standard GK/RT0062: control of points*. London: Safety & Standards Directorate, Railtrack PLC, 1997.
16. Bemment S, Dixon R and Goodall RM. Repoint redundantly engineered points for enhanced reliability and capacity of railway track switching. In *Proceedings of 10th World Congress on Railway Research (WCRR)*, Sydney, Australia, November 2013.
17. Transportation Research Board. *TCRP Report 13: rail transit capacity*. Technical report. Washington, DC: Transit Cooperative Research Program, The Federal Transit Administration, 1996.
18. Cope DL and Ellis JB. *British railway track, 7th edition, volume 5: switch and crossing maintenance*. Derby, UK: The Permanent Way Institution, 2002.
19. Office of Road and Rail. *ORR (Office of Road and Rail) Online Data Portal – Total journey count reporting*, dataportal.orr.gov.uk (2013, accessed 12 October 2013).
20. Network Rail Asset Management. Asset management data related to logged S&C failures, personal communication, October 2011.
21. Rama D and Andrews JD. A reliability analysis of railway switches. *Proc IMechE, Part F: J Rail and Rapid Transit* 2013; 227: 344–363.
22. Scholz FW. *Maximum likelihood estimation*. Wiley Online Library: John Wiley & Sons, 2004.

Extending emergency repair response times for railway track switches through multi-channel redundancy of functional subsystems

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Abstract

A novel track switch concept has been developed at Loughborough University, which allows parallel-channel, fault-tolerant functions for the first time. This paper demonstrates, through mathematical modelling, real-world data and conservative assumptions, that using a multi-channel, fault-tolerant switching concept can allow an increase in switch availability over baseline scenarios. Performance of four existing switch types is analysed for baseline performance using field data. Multi-channel architectures are then analysed across a range of reactionary maintenance regimes. Availability measures are obtained which show the range of possible switch availability against maintenance response times. The most significant improvements occur when maintenance practice is also revised, the novel system offering the option to run to subsystem failure and remain functional. Results indicate that for multi-channel installations, gains in system availability are possible even when emergency response times are set orders of magnitude longer than currently achieved, indicating a significant reduction in ongoing maintenance commitment. The work also demonstrates that the particular choice of subsystem architecture is of low significance.

Keywords: Track Switch, Capacity, Reliability, Multi-channel Redundancy, Fault Tolerance, Maintenance

1 Introduction

Industries with safety critical or performance critical systems often replicate key components in order to increase whole-system satety and availability and reduce system failure rates [1]. To date, though literature explores the option of making the junction control fault tolerant [2, 3], railway track switch designs have used only a single-channel architecture, without fault tolerance. A project called Repoint has devised a novel arrangement for railway track switching. It is described in GB Patents [4,5] and extensively in [6–8]. The new architecture enables multi-channel actuation, locking and detection to be used to provide improved switch performance in ways that are not possible with conventional designs. Performance refers to increased availability and reliability, and improved maintainability, possibly leading to reduced whole-life cost. When taken alongside signalling changes which allow a turnout to be treated more like plain line, it may allow for more capacity through existing junction layouts [9]. A condition monitoring scheme, designed to automatically reconfigure the control algorithm to isolate suspected faulty subsystems, enables the ongoing use of the switch with minimal performance degradation until such a time as repair becomes feasible. The concept features LRU's (line-replaceable units) in order to minimise maintenance team time trackside and system downtime. General arrangements of a traditional switch [10], and a contrasting Repoint arrangement are shown in Figure 1, described later.

Replicating critical elements of a system generally improves theoretical reliability. However, achieving the same in practice requires consideration of human and economic factors. The fitment of a Repoint switch is envisioned as part of an industry wide trend towards 'predict and prevent' eliminating the need for regular human intervention or inspection [6]. With replication of elements, the asset manager has more freedom to select the target reliability of the asset given available resources. One variable to aid in this decision is τ, which represents the target time in which maintenance teams must have replaced any failed components. With a single channel system, τ is equivalent to the emergency response time, thus a very high (and consequently expensive) labour commitment is necessary. However, with fault tolerance, τ can potentially be relaxed whilst still providing the necessary availability. No attempt is made herein to quantify τ in monetary terms, as this value would be unique to the particular staffing arrangements at each specific locality (See Future Work section).

This paper demonstrates, through mathematical modelling based upon field-data of historical points failures, that an increase in switch availability is possible alongside a corresponding decrease in ongoing maintenance intensity using a fault tolerant (multi-channel functional redundancy) approach. The paper firstly analyses four benchmark existing switch types for baseline performance, using data from real-world scenarios and a Monte-Carlo RBD (Reliability Block Diagram) approach. Several architectures of multi-channel switch are then analysed using the same method and data - with redundant actuation, sensing and control channels as an example, across varying levels of implementation of reactionary maintenance regimes. Availability measures are obtained, including as functions of τ, which show the range of possible switch availability against maintenance response times, with a given set of conservative assumptions. The results show that for a multi-channel installation, gains in whole-system availability are possible even when maintenance response times are set many times longer than current standards, indicating a significant reduction in ongoing maintenance cost

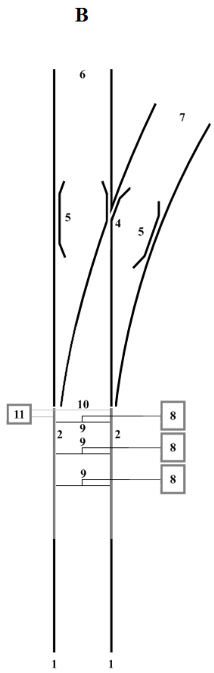

Figure 1: Traditional (A) and REPOINT (B) switch arrangements. 1 Stock Rails; 2 Moveable Switch Rails; 3 Stretcher Bars; 4 Common Crossing; 5 Check Rails; 6 Straight Route; 7 Turnout Route; 8 POE (Points Operating Equipment), line-side type shown; 9 Drive Bar and Drive Stretcher ; 10 Detection Rods, 11 Supplementary Position (Detection) Sensor.

is achievable in parallel with an increase in availability and reduction in unscheduled downtime.

This paper is based upon the work presented in the earlier paper *'Extending maintenance intervals of track switches utilising multi-channel redundancy of actuation and sensing'*, [11], delivered at STECH2015 in Chiba, Japan. It has been extended and modified to include data obtained from analysis of real-world switch performance obtained from [12] and [13], in order to more accurately quantify the original conclusions. The original contributions of this paper are to establish the magnitude of availability and maintainability improvements possible from using the fault tolerant approach, and to compare this to the baseline scenarios calculated from the cited field-data.

2 Existing track switching solutions

UK track switching practice is discussed in literature relating to the design [10], operation [14], and maintenance [15] of switches. Switches are actuated remotely by electro-mechanical devices 'point machines', of various designs, which are responsible for the setting and locking of the switch blades, and the communication of that position back to the control system. A arrangement of device and moving rails is shown in Fig. 1. In this paper, 3 types of powered point actuation will be considered, with non-powered points included in the baseline analysis for comparison:

- **Classic Electro-Mechanical:** for instance *HW* and *W63* designs which use an electric motor and gearbox with cam arrangement, generally with bang-bang control and an integral point lock.
- **Electro-Hydraulic:** for instance *Clamplock* and *Hydrive* designs which use an external power pack with actuation provided by hydraulic rams. An arrangement of lever elements, or external mechanical module, provides lock.
- **Modern Electro-Mechanical:** primarily the *HPSS* design which uses an electric motor and gearbox, with more modern sensing and control elements. Locking is provided by means of a screw jack mechanism in the drive.
- **Mechanical:** Arrangements without power operation, where the blades are moved and locked by the provision of rodding runs to levers in a signal box.

Point Machines can be situated many miles from available emergency response teams. Any system failure, whilst not necessarily a safety risk due to the inbuilt controls and associated operational procedure, causes much disruption to the network whilst a team is despatched to repair the system. This disruption is magnified where there is no diversionary route around the failed switch, a common occurrence as switch population is minimised by infrastructure owners in order to cut costs.

To reduce failures, switches undergo a labour-intensive maintenance programme. A typical set of maintenance interventions is shown in Table 2. Recent UK improvements include an extensive fitment of remote condition monitoring equipment since 2009 with much academic input into algorithm design [16–19]. This effort has, in part, been responsible for a downward trend of switch failures, which can be observed in Table 1. However, this downward trend does not necessarily correspond to a downward trend in maintenance costs, because the switches are now subject to both periodic and condition based maintenance. This is primarily as the condition monitoring technology used is not capable of monitoring the state of all safety-critical elements of the switch, necessitating the continuation of regular human inspection. For a conventional switch, all significant failures create an unsafe condition and are therefore accommodated at a system level by the signalling system, i.e. an operational failure because functional redundancy in the switch itself is not possible.

Infrastructure Element	Incident Count I_c 08-09	09-10	10-11	11-12	12-13	13-14	(Mean)	Delay mins per Incident (Mean)
Points	8022	7118	5803	5162	5021	4376	5917	106
Signals	6559	6202	5116	5018	4449	4278	5270	48
Track Faults	6322	5387	4947	4802	4661	5250	5228	139
Track Circuits	5381	5145	4567	4243	3902	3729	4495	123
Signalling/Power	3750	4016	4422	4202	4494	4684	4261	114
Other Infra.	5478	3772	3455	3774	3612	4739	4138	62
Track Patrols	3362	2565	2269	1949	2213	2075	2406	16
Level Crossings	2261	2162	2003	1932	1857	1936	2025	49
Mishaps	1839	1183	1493	1838	1836	2009	1700	93
Telecoms	1406	1352	1252	1176	1513	2406	1518	46
Other Signalling	1495	1430	1513	1505	1300	1338	1430	41
OLE/Third Rail	1458	1241	1281	1276	1265	1259	1297	205
Bridge Strikes	1360	1126	1232	1115	1068	1138	1173	129
Speed Restrictions	1428	1278	932	717	685	747	965	122
Axle Counters	1096	913	648	683	706	799	808	117
Cables	573	530	552	570	614	686	588	281
Structures (Civils)	397	436	385	279	444	574	419	253
Fires	197	221	250	257	116	218	210	145
Total	52384	46077	42120	40498	39756	42241	43846	

Table 1: Incident count for infrastructure assets between 2008-2014 upon UK mainline, for top 18 incident categories (by count), including mean number of delay minutes incurred per incident. Note that Points have the highest mean failure count over the period. Source: Office of Rail Regulation [20]

ID	Intervention Type	Event Frequency f_m (per Year)	Intervention Time t_m *hours*	Possession Requirement	Intervention Class
1	Track Visual Inspection	52	0.1	No	Inspection
2	Track Gauging/Component Inspection	13	0.5	Yes	Inspection
3	Track Element Renewals	0.1	10	Yes	Maintenance
4	Signalling A Service	13	0.25	Yes	Inspection
5	Signalling B service	4	0.5	Yes	Maintenance
6	Signalling C Service	1	2	Yes	Maintenance
7	Location Case Inspection	4	0.5	No	Inspection

Table 2: Typical scheduled interventions for UK switch installations, including total labour time. Note labour time does not include travel to site. Source: Network Rail/Interview.

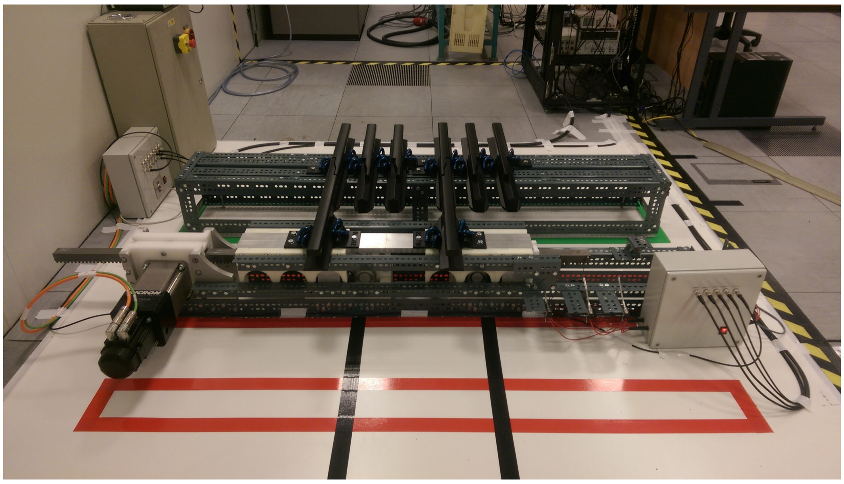

Figure 2: View of the 384mm gauge Repoint demonstrator in the Control Systems Group laboratory at Loughborough University.

3 Multi-channel redundancy of track switching elements - the Repoint approach

An ongoing project at Loughborough University, called Repoint, has devised a novel architecture of track switch which allows multi-channel actuation of the movable track elements. Full detail of this design is provided in literature [4–8]. The key enabler of the multi-channel architecture is that the locking function is provided passively, such that each actuator can operate the switch alone, and with no performance degradation, with other channels isolated. The rails are actuated in a semi-circular motion, rather than laterally. In each at-rest position, switch rails are positively located in a locking recess, unable to move in any direction but directly upwards. The actuator lifts the rails out of this recess, before bending them over to another set position and dropping them in another, equivalent recess for a different route. Each actuator is capable of lifting the rail alone, enabling any of a bank of actuators to unlock all others through the simple mechanical arrangement. Each individual actuator is designed to have a standardised, line replaceable active element which can be exchanged in the order of 2 minutes. These features open up the possibility of a truly condition-based maintenance regime.

A demonstrator of the concept has been created in the laboratory at Loughborough University. The demonstrator consists of a 384mm gauge actuator bearer, which has been physically assembled. This is coupled to two software simulated bearers and a rail bending co-simulation in a hardware-in-the-loop environment. The rail bending is co-simulated in real-time on D-Space processing hardware [21]. The same processing hardware allows simulated faults to be injected into the software bearers, in addition to fault cases which can be caused through physical means on the hardware bearer. The demonstrator has a 1-out-of-3 architecture, though it is possible that in practice the number of channels could be adjusted for the requirements of a particular junction or route. Condition monitoring of each bearer is able to isolate any single unit in the event of a suspected fault. This monitoring is currently functional at a basic level with more advanced algorithms the subject of further investigation. The demonstrator is able to switch between routes on a constant cycle at user-selectable service intensity. The physical element of the demonstrator is shown in Fig. 2.

4 Operational availability and τ

4.1 Operational Availability

It is necessary to distinguish between the mean time between unsafe failures (i.e. system in an unsafe state), and the mean time between operational failures. Literature, especially industrially-focussed documents, can cause confusion by representing either by the term MTBF or MTTF (Meant Time Between/To Failure). The distinction is made here between MTBF, the mean time between unsafe failures, and MTBOF (Mean Time Between Operational Failures), which describes how often the system can be expected to suffer a failure which interrupts operations. The latter would generally be expected to be substantially lower, and reflects the service quality that the system must provide. This concept is explored in [22], with further mathematical modelling work on the reliability of k-out-of-N systems discussed in [23].

To make the distinction defined in [22] for railway track switching systems specifically, the MTBF would be required to be of a level of a modern high-integrity system, around SIL-4 ($10^8 - 10^9$ hours) - i.e. not normally expected to occur within the working life of the entire population (see Standard BS:EN61508 for a further discussion of SIL levels and their calculation). However, the MTBOF - the mean time to a switch failure causing network disruption - is much lower, and of the order of $10^4 - 10^5$ hours, as can be observed from Table 1. In practice, if a single fault can directly cause an unsafe condition in any system then some level of functional replication or redundancy is necessary. This will usually ensure a satisfactory level of safety, whilst compromising reliability in some manner. The classic formula MTBF/(MTBF + MTTR) takes account of repair time to indicate availability, but this differs from operational availability because operation continues while the repair is being effected in a fault-tolerant system with redundancy. The functional elements in the Repoint track switching system are Line Replaceable Units (LRUs). These will not be repaired; instead there will be a stock of functioning units that maintenance technicians can use to replace the faulty or failed unit. The unit may subsequently be repaired in the background.

4.2 Emergency Response time - τ

Accepting that the MTBF cannot be relaxed for safety reasons, there is still scope to provide an improved availability by improving the track switching system and its associated maintenance practices. This may, or may not, come at additional financial cost. Mathematical modelling can be used to provide an indication of the potential change in MTBOF and availability for a given set of maintenance regimes. Traditional reliability modelling of a system may deliver results which are somewhat abstracted from the realities of the day-to-day operation of a railway. The modelling herein takes a railway asset management perspective, in that the primary controlled variable is one which can be directly affected by the asset manager to bring about the level of availability required of the asset. This variable is τ, which describes the target time period in which a failed (or isolated as identified faulty) unit must be replaced by a maintenance team to deliver a given system MTBOF.

4.3 Operational Deployment Levels

The internal drive arrangements of the multi-channel concept could take any of the mechanical approaches listed in section 2. This analysis will therefore examine each drive-line approach to evaluate the performance available. The multi-channel concept could be implemented alone, under existing maintenance regimes, or alongside condition-based maintenance to better exploit its potential. Several levels of maintenance change have therefore been examined, which are identified as follows:

- **Level 0:** This represents the benchmark case, as currently implemented.
- **Level 1:** Triplex redundancy, with no change to the maintenance or inspection regime.
- **Level 2a:** Triplex redundancy, with no change to the maintenance regime, but with the system self-inspecting and adjusting.
- **Level 2b:** Triplex redundancy, with maintenance performed by LRU (2 minute replacement), but no change to the inspection regime.
- **Level 3:** Triplex redundancy, with maintenance performed by LRU (2 minute replacement), and the system self-inspecting and adjusting.

For each implementation level, there is a choice of architecture to the implementation of the functional redundancy, namely series or parallel. Figure 4 shows the series case, whereby each LRU contains the functionality of a point machine or trackside supply/command unit. When an LRU is replaced (maintenance or failure), the entire unit is replaced as a whole. This is the equivalent of, for example, fitting three whole point machines to a single track switch. Figure 5 shows the alternative case, whereby each functional subsystem forms an LRU, and is replaced individually, without affecting functional units of a different class. Evaluating both arrangements, at 4 different implementation levels and for 3 different actuation types gives a total of 24 possible scenarios.

5 Modelling approach, data and benchmarking existing switches

Previous publications have analysed historical failure data from the GB Infrastructure owner/operator, Network Rail, to establish the performance of switches in the field. It is established in [12] that the 2P-Weibull distribution is the most appropriate model for switch failure analysis, the paper also compares the frequency of switch failures to actuation frequency and traffic intensity. [13] extends this work, analysing 40,000 failure events over 74,800 years of continuous operation to establish 2P-Weibull failure distributions of each of the principle subsystems of each switch type. These distributions will be used as a baseline within this work. As the distributions are significantly time-variant, all calculations herein will be on the basis of a 25-year time window from the moment of installation in an 'as-new' state.

The availability of a switch can be affected by both scheduled and unscheduled maintenance downtime. The availability for a given observation window can be established using RBD (Reliability Block Diagrams) and the Monte-Carlo approach. An RBD of each switch arrangement is first created, with elements representing the arrangement of the multiple channels of each functional subsystem. The subsystem division is established in [13]. An example baseline RBD is shown in Figure 3. Each block in the RBD has a 2P-Weibull reliability model describing failure frequency. The parameters for the failure rate models were calculated in earlier work [13], and are reproduced in Table 3. Of note is that all elements have been modelled with 2-parameter Weibull distribution, though the failures attributable to the 'Human' element have been taken as a constant failure rate (i.e. $\beta = 1$). This element is unique in that it essentially represents the likelihood the design and installation of the switching system is incorrect, and not human error related to the individual component elements, which is already catered for in the respective distributions; it is therefore unsuitable to represent this with a time-variant distribution. The functional blocks also have periodic scheduled maintenance downtime assigned, as per table 2, during which time the blocks are considered unavailable and non-functional.

With an RBD approach, the system is considered functional if a path can be found from start to end, through functional blocks only. When a block fails, the single channel arrangement means the system is instantly unavailable. After a prescribed time, the block is repaired as-good-as-new, and the system functional again. In this way, failure rates of individual subsystems do not affect other subsystems. The simulation is executed for 25 years with a random seed, and the total downtime noted. This is repeated

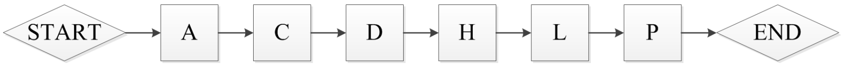

Figure 3: Example RBD representing an Electro-Hydraulic Switch installation. The switch is considered functioning for all time there is a path from Start to End which passes through functional blocks only. Each element is single-channel. The performance of each block, for each switch type, is described by a unique failure distribution from Table 3.

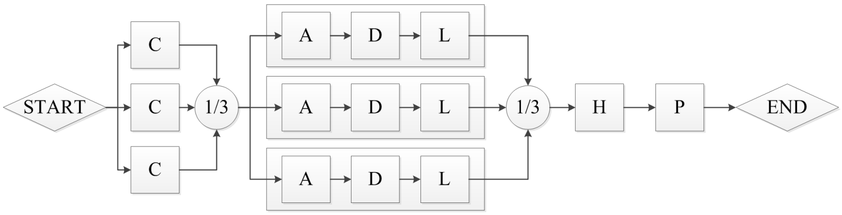

Figure 4: Example of functional redundancy by connecting elements in series, for instance in multiple point machines.

for 5,000 iterations, and a mean taken to establish the unscheduled availability of that system. Table 4 indicates the baseline availability of each existing, single-channel switching solution as currently maintained.

6 Evaluating multi-channel track switching

6.1 Results

The simulation results are presented in 3 tables. Table 5 shows the output of the simulation for each of the listed cases, giving availability values at each level of implementation, where the value of τ has been fixed to 106 minutes. Table 6 shows the extent to which the τ values can be relaxed, working under the assumption that the availability must be the equivalent to existing installations. Table 7 imagines a hybrid scenario in which the τ value is relaxed to one week, and lists the availability achiev-

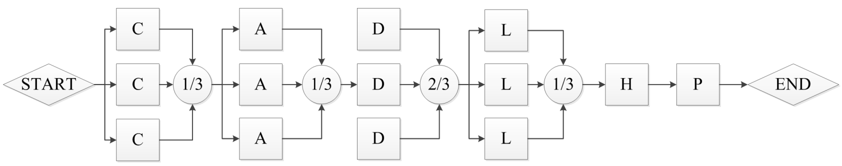

Figure 5: Example of functional redundancy by connecting elements in parallel, for instance with redundant units inside a single point machine.

ID	Element	Classic Electro-Mechanical β	Classic Electro-Mechanical η (Days)	Electro-Hydraulic β	Electro-Hydraulic η (Days)	Modern Electro-Mechanical β	Modern Electro-Mechanical η (Days)	Mechanical β	Mechanical η (Days)
A	Actuation	0.662	7953	0.738	4940	0.671	8641	0.544	25687
C	Control/ Power	0.804	12645	0.789	14739	0.564	4243	1.011	188915
D	Detection	0.650	26253	0.707	15941	0.637	1671	0.698	20797
H	Human	1.000	67317	1.000	71634	1.000	42096	1.000	174517
L	Locking	0.629	65123	0.732	5713	n/a	n/a	0.608	62510
P	Permanent Way	1.275	9405	0.882	35548	1.253	22730	1.360	56200

Table 3: 2P-Weibull parameters used in the RBD Monte-Carlo modelling of switch unscheduled unavailability. Note that Modern Electro-Mechanical devices do not specify a separate model for Actuation and Locking as these functions are combined; in this case the 'Actuation' model accounts for both.

For 25-year Window		Classic Electro-Mech.	Electro-Hydraul.	Modern Electro-Mech.	Mechanical
Unavailability (Sched.)	hours per year	14.75	14.75	14.75	14.75
Unavailability (Sched.)	hours, total	369	369	369	369
Unavailability (Sched.)		0.0016826	0.0016826	0.0016826	0.0016826
Unavailability (Unsched.)	mean hours per year	0.2893	0.3945	0.6136	0.1227
Unavailability (Unsched.)	hours, total	7.23	9.86	15.34	3.07
Unavailability (Unsched.)		0.000033	0.000045	0.000070	0.000014
Availability		0.998284	0.998272	0.998247	0.998303
τ	hours	1.77	1.77	1.77	1.77

Table 4: Unavailability contributions, and Availability, of each switch type based upon analysis of historical data and current maintenance practices.

	Classic Electro-Mechanical		Electro-Hydraulic		Modern Electro-Mechanical	
	Availability	Annual Unavail. (Hours)	Availability	Annual Unavail. (Hours)	Availability	Annual Unavail. (Hours)
Level 0 (Baseline)	0.99828440	15.0	0.99827240	15.1	0.99824710	15.4
Series Redundancy Architecture						
Level 1	0.99708547	25.5	0.99709032	25.5	0.99708846	25.5
Level 2a	0.99893966	9.3	0.99894428	9.3	0.99894329	9.3
Level 2b	0.99808313	16.8	0.99808782	16.8	0.99808607	16.8
Level 3	0.99993738	0.5	0.99994158	0.5	0.99994106	0.5
Parallel Redundancy Architecture						
Level 1	0.99708547	25.5	0.99709032	25.5	0.99708846	25.5
Level 2a	0.99893966	9.3	0.99894428	9.3	0.99894329	9.3
Level 2b	0.99808313	16.8	0.99808782	16.8	0.99808607	16.8
Level 3	0.99993738	0.5	0.99994158	0.5	0.99994106	0.5

Table 5: Simulation Results: Availabilities of parallel and series architectures at each implementation level with τ fixed at 106 minutes.

able in each scenario.

To further illustrate the relationship between τ and availability, three plots are provided. Figure 6 illustrates the relationship between availability and τ for each implementation level. Figure 7 is a simple bar chart which illustrates the relative contribution of scheduled and unscheduled availability, for each deployment level. Figure 8 illustrates the unvailability of each implementation level where τ is fixed to 1 week.

7 Analysis and Interpretation

7.1 Baseline Results

- Baseline availablities are at levels to be expected when consulting published data (e.g. [12]).
- The majority of unavailability in the baseline case (369 Hours vs 3-15 Hours per lifetime, depending upon switch type) comes from scheduled maintenance downtime.
- The ratio of cost between scheduled and unscheduled downtime is not currently known, but will be evaluated in future work. However, in the UK, the current push towards a 24/7 railway will mean that both elements of downtime will need to be reduced.
- The modern electromechanical design is the least reliable, with 5x the unscheduled unavailability of an unpowered, mechanical solution. [13] established this is due to the unreliability of the detection and control/power elements, which

	Classic Electro-Mechanical	Electro-Hydraulic	Modern Electro-Mechanical
Level 0 (Baseline)	1.77	1.77	1.77
Series Redundancy Architecture			
Level 1	n/a	n/a	n/a
Level 2a	117	283	272
Level 2b	n/a	n/a	n/a
Level 3	323	768	623
Parallel Redundancy Architecture			
Level 1	n/a	n/a	n/a
Level 2a	118	292	275
Level 2b	n/a	n/a	n/a
Level 3	327	772	625

Table 6: The maximum value τ (Hours) can be relaxed to whilst achieving baseline availability levels

	Classic Electro-Mechanical		Electro-Hydraulic		Modern Electro-Mechanical	
	Availability	Annual Unavail. (Hrs)	Availability	Annual Unavail. (Hrs)	Availability	Annual Unavail. (Hrs)
Level 0 (Baseline)	0.99541389	40.2	0.99442105	48.9	0.99175345	72.3
Series Redundancy Architecture						
Level 1	0.99633465	32.1	0.99676096	28.4	0.99668535	29.1
Level 2a	0.99818434	15.9	0.99860429	12.2	0.99858454	12.4
Level 2b	0.99731799	23.5	0.99777751	19.5	0.99777718	19.5
Level 3	0.99913906	7.5	0.99961458	3.4	0.9995266	4.1
Parallel Redundancy Architecture						
Level 1	0.99632192	32.2	0.99675727	28.4	0.99678579	28.2
Level 2a	0.99818434	15.9	0.99860429	12.2	0.99856542	12.6
Level 2b	0.99737159	23.0	0.99777747	19.5	0.99777816	19.5
Level 3	0.99918206	7.2	0.99961458	3.4	0.9995266	4.1

Table 7: Simulation Results: Availabilities of parallel and series architectures at each implementation level with τ fixed at 10800 minutes (1 week).

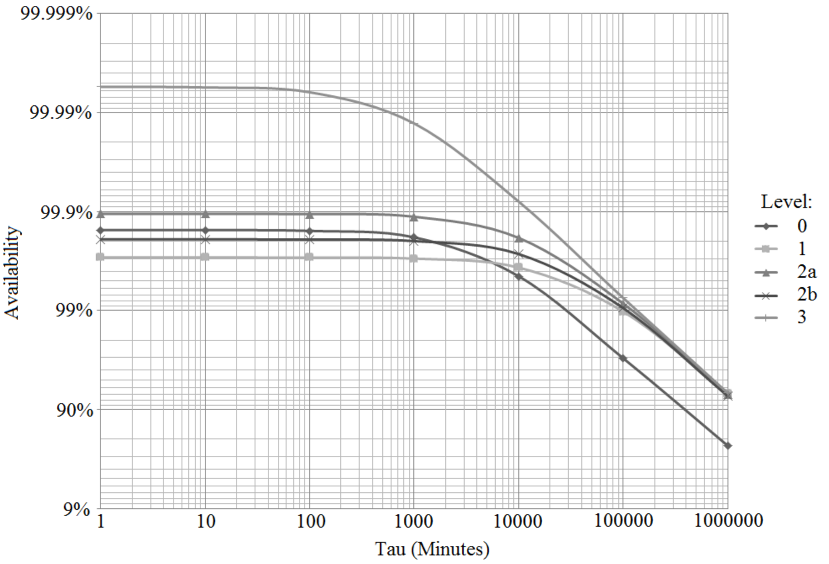

Figure 6: Plots showing variation in asset availability vs Tau figures for range of possible implementation levels using classic electro-mechanical baseline data in a series configuration.

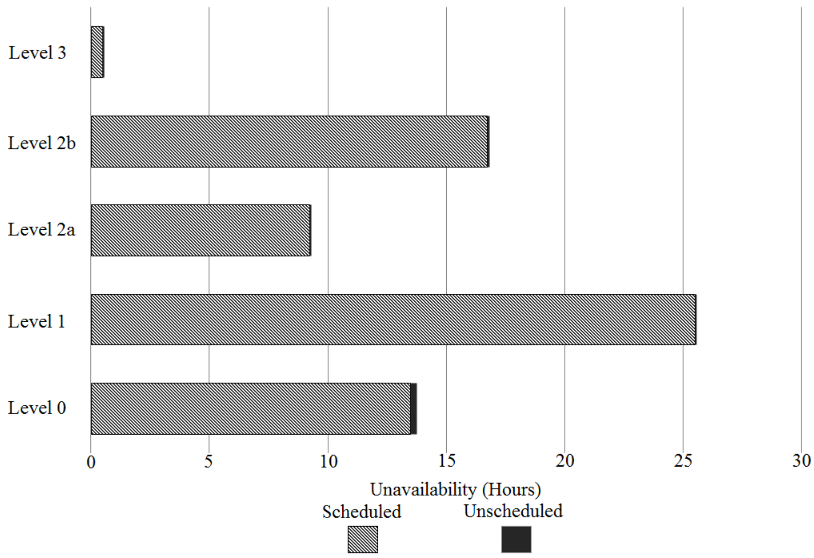

Figure 7: Bar chart indicating the relative contribution to unavailability from scheduled and unscheduled maintenance at various levels of deployment, for the classic electro-mechanical case with τ fixed at 1.77 hours.

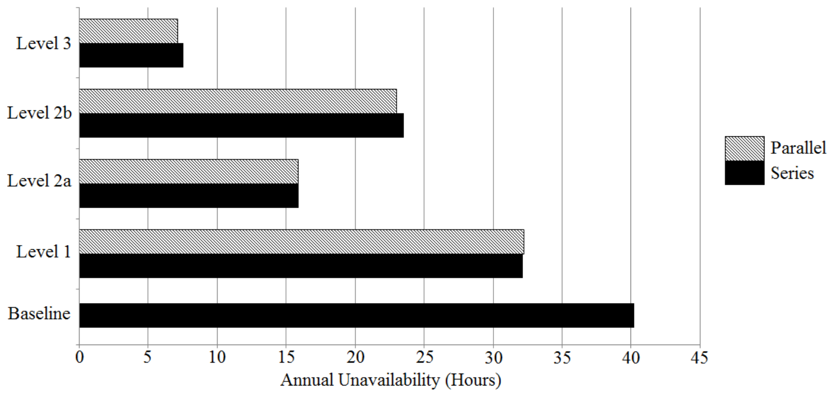

Figure 8: Bar chart indicating annual unavailability (hours) for each implementation level, where τ is fixed at 1 week, for the classic electro-mechanical case.

have η values significantly lower than the other powered solutions. The mechanical solution performs best, perhaps due to it's simplicity, but the same simplicity prevents it being used in high-density situations or far from signal boxes.

- All switch types attain an availability in the 'two-nines' region, which is not a particularly high value when compared to those attained by mission-critical assets in other industries, e.g. Nuclear. However, this is deemed acceptable due to the time currently available for maintenance.
- In the baseline case, τ is equal to the emergency response time, therefore increasing τ has an immediate, significant and detrimental effect upon availability (See table 7). In reality this approach could not be taken by infrastrructure owners with existing systems.

7.2 Redundantly Engineered Solutions

- Not all levels of implementation demonstrate increased availability. Table 5 shows that Level 1 and 2b solutions reduce availability due to the additional maintenance downtime, and the proportionally large contribution of scheduled maintenance to total downtime. It is important to note, however, that in both these cases the unscheduled availability is reduced almost to insignificance, as illustrated in Figure 7.
- Level 2a and 3 implementations both show a significant decrease in scheduled and unscheduled downtime across all point machine types, leading to substantially increased availability (Table 5). Level 3, in particular, reduces downtime to around 0.5 hours per year, from over 15 hours at benchmark, for every switch type.
- Table 5 shows that 'four-nines' availability is achievable with all switching types when a level 3 implementation.
- Table 6 illustrates the extent to which τ can be relaxed, in each case, whilst maintaining the availability provided by the benchmark system. For each deployment level this is possible, and across all switch types, the emergency response time can be relaxed by 2-3 orders of magnitude.
- Table 6 illustrates that the emergency response times of the classic electromechanical design cannot be relaxed to the same extent as the other two actuation methods. This is due to the larger contribution to unreliability of the Permanent Way element in this case, with a significantly lower η value. This is a known weakness of the classic design (the stretcher bar and mountings in particular), and it is not possible to add a multi-channel approach to this element. However, this could offset by having separate target response times for different subsystems. It is of note that the Repoint design does not feature stretcher bars,

therefore the P-way reliability model should be closer to that of the modern electro-mechanical system.

- Figure 6 indicates the availability achievable for each implementation level as τ is relaxed. Of note is that the level 3 implementation outperforms the baseline throughout. At $\tau > 10000$ minutes, all redundantly engineered solutions outperform the baseline. Below this, the baseline outperforms level 1 and level 2b solutions. This is due to the additional maintenance requirements.
- Figure 6 indicates that a level 3 deployment can not only outperform the baseline in availability terms, but it can do this with $\tau > 30000$ minutes; 300 times longer than benchmark practice. Similarly, the level 2a deployment can outperform the baseline with $\tau > 10000$ minutes - two orders of magnitude longer than existing practice.
- Figure 8 and Table 7 show that when τ is extended to 1 week, all solutions outperform the baseline in availability terms.
- There is little difference in availability (in each circumstance) between the parallel and series architecture Figure 8 and Table 7 illustrate the case of a fixed τ of 1 week. In this case, the difference is primarily revealed in the level 2b and 3 implementations, with the parallel case performing marginally better in each. The architectures are not a dominating factor in availability until τ reaches very high levels, which is to be expected. A series architecture may perform slightly worse, but it is likely that line-replaceable units containing all functions will simplify maintenance and therefore reduce human-attributable errors; they may therefore prove more reliable in practice.

The headline observation from the modelling exercise is that it is possible to boost the availability of track switching solutions - whether electro-hydraulic or electro-mechanical, through the use of a fault-tolerant, multi-channel architecture. However, downtime due to failures is only a small fraction of the total downtime, and a larger improvement arises when the approach to maintenance is revised to take full advantage of the new architecture. If a full 'level 3' approach is embraced, it is possible to boost switch availability and reliability at the same time as relaxing τ by several orders of magnitude.

8 Conclusions

A concept for a novel track switch arrangement has been developed at Loughborough University, which, through a novel locking arrangement, allows parallel, multi-channel actuation and locking functions for the first time. This paper has demonstrated, through mathematical modelling and conservative assumptions, that using a multi-channel, fault-tolerant switching concept allows an increase in switch availability over the baseline. For a railway which does not operate overnight, or at weekends, the baseline availability figures may be satisfactory. However, on the GB network in particular, there is much pressure to begin to use these traditional maintenance windows for additional traffic. The most significant availability increase comes when the maintenance practice is also changed due to the ability of a multi-channel system to run to subsystem failure and remain functional. This can be alongside a corresponding extension of emergency response times. The results show that for a multi-channel installation, gains in system availability are possible even when emergency response times are set orders of magnitude longer than currently achieved, indicating a significant reduction in ongoing maintenance cost. The work also demonstrates that the particular choice of subsystem architecture is an insignificant variable.

9 Future Work

The work presented herein regards the operational performance of a fault-tolerant track switching installation in terms of availability and emergency response times. Future extensions to this work will involve weighting scheduled vs unscheduled downtime, in a cost function in order to establish the best operational balance. The work will also be extended to assigning monetary costs to assets, maintenance interventions and downtime, in order to calculate the lifetime cost of a fault tolerant, LRU-based multi-channel approach vs baseline scenario.

Acknowledgements

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References

[1] R Isermann. *Fault-Diagnosis Systems: An Introduction from Fault Detection to Fault Tolerance*. Springer, Berlin, 2006.

[2] Paola Pellegrini, Gregory Marliere, and Joaquin Rodriguez. Optimal train routing and scheduling for managing traffic perturbations in complex junctions. *Transportation Research Part B: Methodological*, 59:58 – 80, 2014.

[3] Ziauddin Ursani, T.X. Mei, and Anthony Whiteing. A fault tolerance approach for railway scheduling and train control. *Transportation Research Part B: Methodological*, 56:161 – 173, 2013.

[4] GB Patent: Loughborough University. 'Railway Points Operating Apparatus' (GB 1322660), 12 2013.

[5] GB Patent: Loughborough University. 'Railway Points' (GB 1322641), 12 2013.

[6] Samuel D. Bemment, Emma Ebinger, Roger M. Goodall, Christopher P. Ward, and Roger Dixon. Rethinking Rail Track Switches for Fault Tolerance and Enhanced Performance. *Journal of The Institution of Mechanical Engineers, Part F: Rail and Rapid Transit*, 2016.

[7] Samuel D. Bemment, Roger Dixon, Roger M Goodall, and Steve Brown. Redundantly engineered track switching for enhanced railway nodal capacity. In *Proc. 1st IFAC ACATTA Workshop,*, Istanbul, Turkey, September 2013, 9 2013.

[8] N. Wright, S. Bemment, C. Ward, R. Dixon, and RM Goodall. The performance and control requirements of a repoint track switch. In *Proc. 2nd international conference on railway technology*, Ajaccio, Corsica, May 2014, May 2014.

[9] S. Bemment, R. Dixon, and RM Goodall. Repoint redundantly engineered points for enhanced reliability and capacity of railway track switching. In *Proc. 10th World Congress on Railway Research (WCRR)*, Sydney, Australia, November 2013, November 2013.

[10] John C Morgan. *British Railway Track 7th Edition, Volume 1, Design Part 2: Switches and Crossings*. The Permanent Way Institution, Derby, UK, 2009.

[11] Samuel D. Bemment, Roger M Goodall, Emma Ebinger, Christopher Ward, and Roger Dixon. Extending maintenance intervals of track switches utilising multichannel redundancy of actuation and sensing. In *Proc. The International Symposium on Speed-up and Sustainable Technology for Railway and Maglev Systems (STECH2015)*, Chiba, Japan, November 2015, 11 2015.

[12] Dovile Rama and John D Andrews. A reliability analysis of railway switches. *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of rail and rapid transit*, 227(4):344–363, 2013.

[13] S. D. Bemment, R. Dixon, R. M. Goodall, and C. P. Ward. Modelling a multichannel approach to railway track switching by analysing historical failure data. *Transportation Research Part B: Methodological*, TBC(TBC):TBC, 2016.

[14] H.W. Hadaway. IRSE 'Green Booklet' No.5:- Principles of power point control and detection (British Practice). The Institution of Railway Signal Engineers, London, 1950.

[15] Dr D L Cope and J B Ellis. *British Railway Track 7th Edition, Volume 5: Switch and Crossing Maintenance*. The Permanent Way Institution, Derby, UK, 2002.

[16] J Silmon and C Roberts. Improving switch reliability with innovative condition monitoring techniques. *Proceedings of the IMechE, Part F: The Journal of Rail and Rapid Transit*, 224:293–302, 2010.

[17] F P García, C Roberts, and A M Tobias. Railway Point mechanisms: condition monitoring and fault detection. *Proceedings of the Institution of Mechanical Engineers, Part F: The Journal of Rail and Rapid Transit*, 224:35–44, 2010.

[18] Fausto Pedro García Márquez and Jesús Miguel Chacón Muñoz. A pattern recognition and data analysis method for maintenance management. *International Journal of Systems Science*, 43(6):1014–1028, 2012.

[19] JM Chacón Munoz, FP García Márquez, and Mayorkinos Papaelias. Railroad inspection based on acfm employing a non-uniform b-spline approach. *Mechanical Systems and Signal Processing*, 40(2):605–617, 2013.

[20] Office of Road and Rail. ORR (Office of Road and Rail) Online Data Portal - Total journey count reporting. url: dataportal.orr.gov.uk, 2013. Accessed: 2013-10-12.

[21] Tim Harrison, Samuel D Bemment, Emma Ebinger, Roger M Goodall, Christopher P Ward, and Roger Dixon. Rethinking rail track switches for fault tolerance and enhanced performance. *IFAC-PapersOnLine*, 49(21):260–266, 2016.

[22] Roger M Goodall, Roger Dixon, and Vincent M Dwyer. Operational reliability calculations for critical systems. In *Proc. Sixth IFAC Symposium on Fault Detection, Supervision and Safety of Technical Processes*, volume 39, pages 771–776, Tsinghua University, P.R.China, 2006., 2006. © Elsevier.

[23] Vincent M Dwyer, Roger M Goodall, and Roger Dixon. Reliability of 2-out-of-n: G systems with nhpp failure flows and fixed repair times. *International Journal of Reliability, Quality and Safety Engineering*, 19(01):1250003, 2012.

Appendix B

Patents

Description

This appendix contains verbatim copies of three patents which were filed as a result of the research work presented in this thesis.

(12) UK Patent Application (19) GB (11) 2516706 (13) A

(43) Date of A Publication 04.02.2015

(21) Application No: 1322641.0

(22) Date of Filing: 20.12.2013

(51) INT CL:
E01B 7/08 (2006.01)

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GB 1329048 A
DE 002046391 A1
US 1112965 A
US 0934086 A
US 0175699 A
GB 191115538

(58) Field of Search:
INT CL **E01B**
Other: **EPODOC, WPI, INSPEC**

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(54) Title of the Invention: **Railway Points**
Abstract Title: **Railway points with switch rail keying with stock rail**

(57) Railway points 10, based on a stub switch design, comprise pairs of parallel static stock rails 12, 14, and a pair of parallel switch rails 16 movable between first and second positions aligning respectively with stock rail pairs 12, 14. At least one switch rail 16 cooperates with a stock rail 12, 14 when switch rails 16 are in the first and second positions, with a mating profile 50 aligning a switch rail 16 and a stock rail 12, 14 and preventing a switch rail 16 from moving transversely relative to a stock rail 12, 14. Mating profile (50, Figure 4) may be a U-section or V-section; suitably a convex profile (26, Figure 4) extends upwardly from stock rails 12, 14 and a concave profile (32, Figure 4) is formed in switch rails 16, allowing switch rails 16 to move vertically to engage stock rails 12, 14. Switch rails 16 and stock rails 12, 14 may taper, forming a mitred connection allowing movement between them.

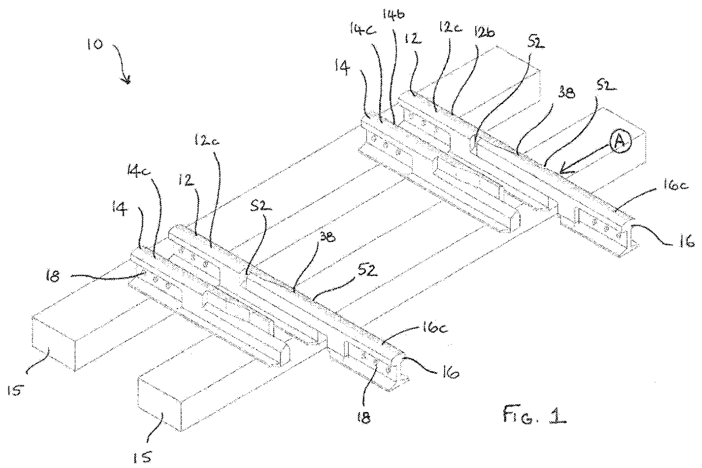
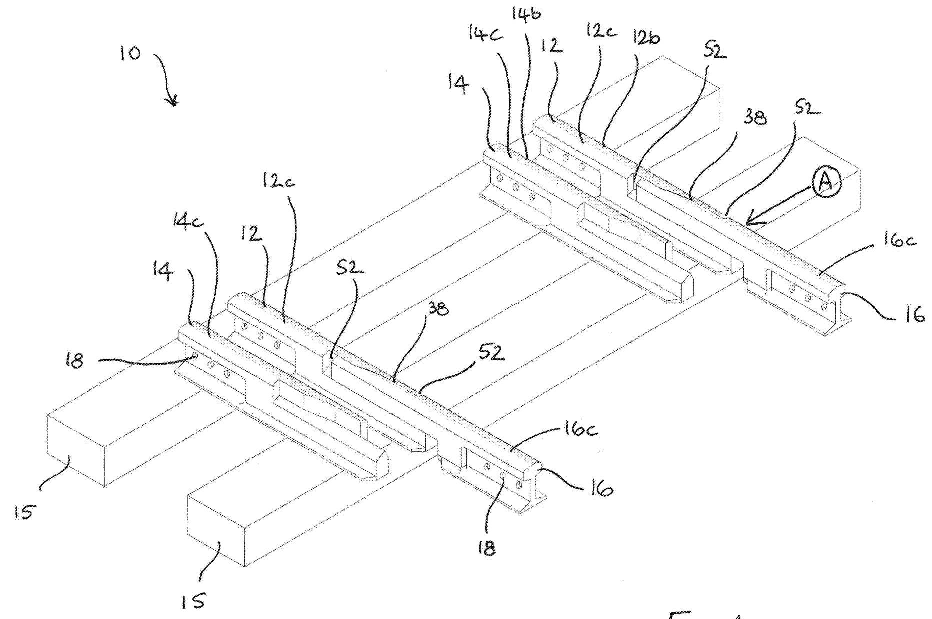


Fig. 1

GB 2516706 A



10
14b
14c
12
12c
12b
52
14
38
52
A
12c
16c
14c
12
14
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38
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16c
16
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18
15

FIG. 1

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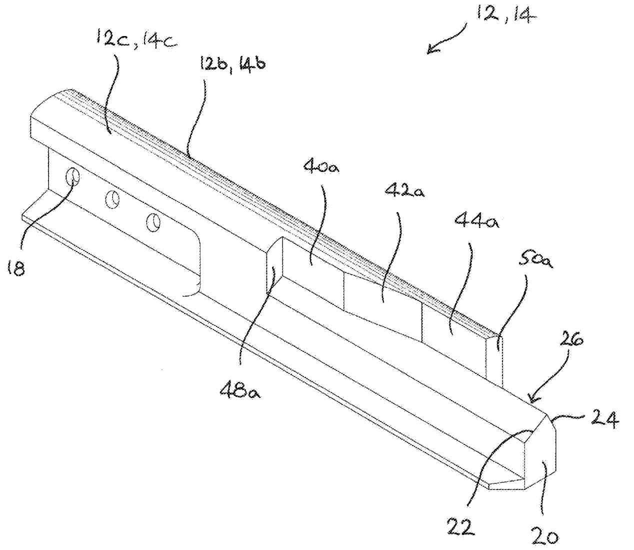

FIG. 2

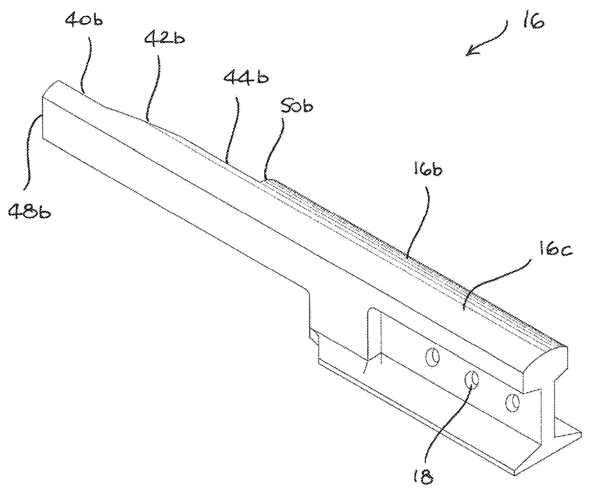

Fig. 3

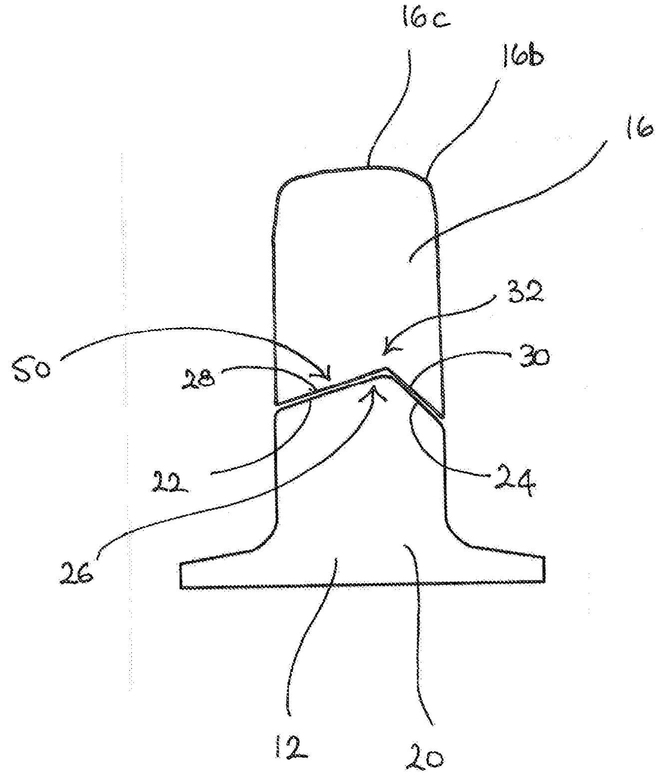

FIG. 4

RAILWAY POINTS

Technical Field

The present disclosure relates generally to railway points and more particularly to a railway points arrangement for a railway track junction.

Technical Background

Railway points, also known as railway track switches, are a necessary part of all railway networks as they enable different routes through the network to be selected. They are a critical part of the network as a points failure often leads to delays, re-routing and cancellations. Even when fully operational, railway points represent a significant capacity constraint because they have to be operated in such a way to ensure that a route has been correctly set before rolling stock is allowed to pass the railway track junction.

In a traditional set of railway points, movable switch rails are located between stock rails. The stock rails are securely fixed to prevent movement and the free ends of the switch rails, which are linked together via stretcher bars, slide on suitable supports when commanded to move enabling either a straight route or a turnout route to be selected. Upon request from the signalling system, an actuator, which forms part of the lineside points operating equipment, moves the two switch rails via a linkage before locking the switch rails in position and communicating the detected position of the rails and the lock back to the signalling system. It is only once this process is complete that a train can be authorised to safely pass the track junction because during the ‘transition’ state, when the switch rails are not properly set to select either the straight route or the turnout route, the points present a derailment risk.

In an alternative type of railway points, commonly known as a stub switch, the ends of a pair of movable switch rails are moved between different positions into alignment with pairs of static stock rails to form a continuation of the main fixed rails on either side of the railway track junction. Stub switches have never achieved widespread usage for a number of reasons. One reason is difficulty aligning the free rail ends. If not correctly aligned, the loads on the free rail ends imparted by rolling stock can lead to premature wear of the rail ends and hence failure of the stub switch. Severe misalignment can, of course, also present a derailment risk. Another reason is that, as the rails expand during hot weather, the clearance between the free rail ends decreases and in extreme cases they can become jammed preventing movement of the switch rails and hence failure of the stub switch. Nevertheless, stub switches arguably offer significant advantages over the traditional railway points discussed above, including a reduced likelihood of blockages, the possibility of multiple routes from a single set of points, and cheaper modular construction using standard components.

The present disclosure seeks to provide a railway points arrangement, based on the stub switch design, which overcomes the drawbacks outlined above that are associated with railway points based on the traditional and stub switch designs.

Summary of the Disclosure

According to a first aspect of the present disclosure, there is provided a railway points arrangement for a railway track junction, the railway points arrangement comprising:

at least first and second pairs of longitudinally-extending, parallel-spaced static stock rails defining respectively a first route and a second route;

a pair of longitudinally-extending, parallel-spaced switch rails movable between a first position in alignment with the first pair of stock rails to select the first route and a second position in alignment with the second pair of stock rails to select the second route;

wherein at least one of the movable switch rails cooperates with at least one stock rail of each of the first and second pairs of stock rails when the movable switch rails are in the first and second positions, said at least one switch rail and said at least one stock rail being shaped to define a mating profile which aligns the switch rail and stock rail and prevents transverse movement of the switch rail relative to the stock rail.

The mating profile between the switch rail and stock rail ensures that the switch rail and stock rail are correctly aligned when the switch rails are in the first and second positions and further ensures that the switch rails cannot move from either the first or second position in a transverse horizontal direction unless specifically commanded to do so. The railway points do not, therefore, rely exclusively on lineside points operating apparatus to accurately align the switch rails with the stock rails and to lock the switch rails in the selected position.

It is possible, in one embodiment, that only one of the movable switch rails cooperates with a corresponding stock rail of each of the first and second pairs of stock rails when the movable switch rails are in the first and second positions. In this embodiment, only one of the switch rails and one of the stock rails of each of the first and second pairs of stock rails are shaped to define a mating profile. The other switch rail and stock rail of each pair can have a conventional stub switch design in which the facing ends of the rails are longitudinally separated. Such an arrangement typically requires that the switch rails are secured together, for example by a stretcher bar, to ensure proper alignment between both switch rails and both stock rails of each of the first and second pairs and to ensure that both switch rails are constrained against transverse horizontal movement relative to the stock rails.

In preferred embodiments, both of the movable switch rails cooperate with both stock rails of each of the first and second pairs of stock rails when the movable switch rails are in the first and second positions, and both switch rails and both stocks rails in each of the first and second pairs are shaped to define a mating profile which aligns the switch rails and stock rails and prevents transverse movement of the switch rails relative to the stock rails. This arrangement may be preferred because each switch rail is independently aligned with a corresponding stock rail and independently transversely constrained.

The mating profile may be arranged to permit the switch rail to be moved vertically relative to the stock rail to engage and disengage the mating profile. The vertical motion may be about an arcuate path. The switch rails can, thus, be moved transversely and vertically, possibly simultaneously transversely and vertically, about said arcuate path between the first and second positions so that either the first or second route can be selected. Because the switch rail must be raised, for example by an actuator arrangement, to disengage the mating profile to permit movement of the switch rails between the first and second positions, there is no risk of unintended movement of the switch rails between the first and second positions in a transverse horizontal direction.

The mating profile may be arranged to permit relative longitudinal movement between the switch rail and the stock rail with which it cooperates when the switch rails are in the first and second positions. By arranging the mating profile to permit relative longitudinal movement, thermal expansion and contraction can take place at the interface between the switch rail and the stock rail without the switch rails and stock rails becoming jammed together. The running surfaces of the switch rail and stock rail remain coplanar in the event of any relative longitudinal movement.

The mating profile may comprise a convex profile section and a complementary shaped concave profile section. The convex profile section may extend upwardly from the stock rail and the concave profile section may be formed in the switch rail, for example in a lower surface thereof. This arrangement is advantageous because the concave profile section is inverted and cannot become blocked with debris which could prevent the convex profile section from properly locating in the concave profile section. Nevertheless, it is possible that the convex profile section could extend downwardly from the switch rail, for example from a lower surface thereof, and that the concave profile section could be formed in the stock rail, for example in an upper surface thereof.

The mating profile could comprise a plurality of cooperating mating surfaces. For example, the stock rail could include a plurality of mating surfaces which cooperate with corresponding mating surfaces on the switch rail.

Generally, a relatively simple geometry is preferred to facilitate manufacture of the rails. Accordingly, the mating profile may comprise a generally V-section profile. Thus, the switch rail and the stock rail may each include two cooperating mating surfaces. The V-section profile may be inverted which provides an arrangement in which the convex profile section advantageously extends upwardly from the stock rail and the concave profile section is advantageously formed in the switch rail.

In an alternative embodiment, the mating profile may be a generally U-section profile and the U-section profile may be inverted.

In typical embodiments, a recess or expansion gap may be defined between facing end surfaces of the switch rail and the stock rail with which it cooperates when the switch rails are in the first and second positions. The recess or gap ensures that any longitudinal movement due to thermal expansion can be readily accommodated without the switch rails and stock rails becoming jammed together.

The switch rail and the stock rail may be tapered in the longitudinal direction to define a mitred connection between the switch rail and the stock rail. The mitred connection advantageously permits relative longitudinal movement between the switch rail and the stock rail. Again, this ensures that any longitudinal movement due to thermal expansion can be readily accommodated without any resultant discontinuity in the running surface at the interface between the switch rail and the stock rail.

Brief Description of the Drawings

Figure 1 is a diagrammatic perspective view of a railway points arrangement according to the present disclosure comprising switch rails and stock rails;

Figure 2 is an enlarged diagrammatic perspective view of one of the stock rails shown in Figure 1;

Figure 3 is an enlarged diagrammatic perspective view of one of the switch rails shown in Figure 1; and

Figure 4 is a diagrammatic cross-sectional view of the regional labelled ‘A’ in Figure 1 showing one possible form of mating profile between the switch rail and the stock rail.

Detailed Description of Embodiments

Embodiments of the present disclosure will now be described by way of example only and with reference to the accompanying drawings.

Figure 1 illustrates a railway points arrangement 10 for a railway track junction which enables different routes to be selected through the junction. The points arrangement 10 comprises first and second pairs of longitudinally-extending, parallel-spaced static stock rails 12, 14 mounted on fixed supports 15 in the form of sleepers or bearers. The stock rails 12, 14 have running surfaces 12c, 14c. The first pair of stock rails 12 defines a first route, for example a straight route. The second pair of stock rails 14 defines a second route, for example a turnout route.

The points arrangement 10 also includes a pair of longitudinally-extending, parallel-spaced switch rails 16 having running surfaces 16c. In Figure 1, the switch rails 16 are shown in a first position in which they are aligned with the first pair of stock rails 12 and have coplanar running surfaces 16c, 12c thus enabling rolling stock to follow the first route through the railway track junction. As will be explained in further detail below, the switch rails 16 can be moved between the illustrated first position and a second position in which they are aligned with the second pair of stock rails 14 and have coplanar running surfaces 16c, 14c thus enabling rolling stock to follow the second route through the railway track junction.

Although not illustrated in Figure 1, it will be appreciated that the stock rails 12, 14 and the switch rails 16 are secured to plain line rails which define the respective route either side of the railway track junction, for example the straight route and the turnout route. The stock rails 12, 14 and switch rails 16 could, for example, be secured to the plain line rails by suitable fastenings which are passed through openings 18 provided in a web section of each rail 12, 14, 16 and which engage in corresponding openings in a fish plate arrangement that is also secured to the plain line rails. Alternatively, the stock rails 12, 14 and switch rails 16 could be secured to the plain line rails by welding, in which case openings 18 do not need to be provided in the web section.

Referring now to Figures 1 to 4, the switch rails 16 cooperate with the stock rails 12, 14 when the switch rails 16 are in the first position (shown in Figure 1) and the second position (not shown). In particular, the switch rails 16 and stock rails 12, 14 are shaped to define a mating profile 50 (see Figure 4) which aligns the switch rails 16 with the stock rails 12, 14 and prevents the switch rails 16 from moving transversely, in the horizontal direction, relative to the stock rails 12, 14. The particular arrangement and geometry of the mating profile 50, a preferred embodiment of which will be explained in further detail below with respect to one of the switch rails 16 and stock rails 12, acts as a self-alignment feature which ensures that the switch rails 16 and the stock rails 12, 14 are always accurately aligned when the switch rails 16 are in either the first position or the second position.

The stock rail 12, 14 includes a base portion 20 having upwardly sloped converging surfaces 22, 24 which define an upwardly extending convex profile section 26 extending longitudinally along at least part of the stock rail 12. Similarly, the switch rail 16 includes a concave profile section 32 defined by upwardly sloped converging surfaces 28, 30. The convex profile section 26 is accommodated in the concave profile section 32 when the switch rails 16 are in the first and second positions and the switch rail 16 is thus constrained against movement in the transverse horizontal direction. In the illustrated embodiment, the convex profile section 26 and the concave profile section 32 form an inverted generally V-section profile 50. Other configurations, such as an inverted generally U-section profile, are however possible.

In order to move the switch rails 16 between the first and second positions, an actuator arrangement (not shown) is used to raise the switch rails 16 by at least a distance which is sufficient to disengage the convex profile section 26 from the concave profile section 32. The actuator arrangement transversely and vertically moves the switch rails 16 to a position in which they are transversely and vertically aligned with either the first pair of stock rails 12 or the second pair of stock rails 14 depending on the desired route, the switch rails 16 being lowered to engage the convex profile section 26 in the concave profile section 32. Any suitable actuator arrangement can be used to raise/lower and move the switch rails 16 transversely between the first and second positions. A particularly suitable actuator arrangement is described in a related co-pending patent application filed by the applicant on the same date as the present application and entitled “Railway Points Operating Apparatus”.

In accordance with aspects of the present disclosure, when the switch rails 16 are moved between the first and second positions, the actuator arrangement does not need to move the switch rails 16 to a position in which they are perfectly transversely aligned with the stock rails 12, 14. This is because the cooperation between the sloped mating surfaces 22, 28 and 24, 30 guides the switch rails 16 transversely and downwardly, for example about an arcuate path, into a position in which the running surfaces 16c, 12c, and 16c, 14c are coplanar and the switch rails 16 and stock rails 12, 14 are transversely aligned. The mating surfaces 22, 28 and 24, 30 thus ensure that the switch rails 16 are always in proper alignment with the stock rails 12, 14 when the switch rails 16 are in the first or second position.

In order to allow a gradual transfer of rolling forces between the running surface 16c (in particular the running edges 16b) of the switch rails 16 and the running surfaces 12c, 14c (in particular the running edges 12b, 14b) of the stock rails 12, 14, the switch rails 16 and stock rails 12, 14 are shaped to provide a mitred connection 38. As can be clearly seen in Figure 1, the mitred connection 38 provides a continuous and smooth running edge surface for rolling stock passing the railway track junction.

In the illustrated embodiment, the mitred connection 38 is defined by cooperating pairs of substantially vertical faces 40a, 40b, 42a, 42b and 44a, 44b which may also help to transversely align the switch rails 16 and the stock rails 12, 14. Any suitable geometry can, however, be adopted to form the mitred connection.

The stock rails 12, 14 and the switch rails 16 have pairs of facing end surfaces 48a, 48b and 50a, 50b. The respective pairs of facing end surfaces 48a, 48b and 50a, 50b are spaced from each other when the switch rails 16 are in the first and second positions to define expansion gaps 52 which are best seen in Figure 1. These gaps 52 ensure that if there is longitudinal thermal expansion of the stock rails 12, 14 and/or the switch rails 16, the ends of the switch rails 16 do not become jammed or fouled against the ends of the stock rails 12, 14.

Although exemplary embodiments have been described in the preceding paragraphs, it should be understood that various modifications may be made to those embodiments without departing from the scope of the appended claims. Thus, the breadth and scope of the claims should not be limited to the above-described exemplary embodiments. Each feature disclosed in the specification, including the claims and drawings, may be replaced by alternative features serving the same, equivalent or similar purposes, unless expressly stated otherwise.

For example, although the illustrated embodiment has only first and second pairs of stock rails 12, 14 which enable the points arrangement 10 to select between first and second routes through the railway track junction, further pairs of stock rails could be provided with which the switch rails 16 can cooperate thereby enabling more than two routes to be selected.

Unless the context clearly requires otherwise, throughout the description and the claims, the words “comprise”, “comprising”, and the like, are to be construed in an inclusive as opposed to an exclusive or exhaustive sense; that is to say, in the sense of “including, but not limited to”.

Any combination of the above-described features in all possible variations thereof is encompassed by the present invention unless otherwise indicated herein or otherwise clearly contradicted by context.

Claims

1. A railway points arrangement for a railway track junction, the railway points arrangement comprising:

at least first and second pairs of longitudinally-extending, parallel-spaced static stock rails defining respectively a first route and a second route;

a pair of longitudinally-extending, parallel-spaced switch rails movable between a first position in alignment with the first pair of stock rails to select the first route and a second position in alignment with the second pair of stock rails to select the second route;

wherein at least one of the movable switch rails cooperates with at least one stock rail of each of the first and second pairs of stock rails when the movable switch rails are in the first and second positions, said at least one switch rail and said at least one stock rail being shaped to define a mating profile which aligns the switch rail and stock rail and prevents transverse movement of the switch rail relative to the stock rail.

2. A points arrangement according to claim 1, wherein the mating profile is arranged to permit said at least one switch rail to be moved in a vertical direction relative to said at least one stock rail to engage and disengage the mating profile and thereby permit transverse movement of the switch rails between the first and second positions.

3. A points arrangement according to claim 1 or claim 2, wherein the mating profile is arranged to permit relative longitudinal movement between said at least one switch rail and said at least one stock rail when the switch rails are in the first and second positions.

4. A points arrangement according to any preceding claim, wherein the mating profile comprises a convex profile section and a complementary concave profile section.

5. A points arrangement according to claim 4, wherein the convex profile section extends upwardly from said at least one stock rail and the concave profile section is formed in said at least one switch rail.

6. A points arrangement according to any preceding claim, wherein the mating profile comprises a plurality of cooperating mating surfaces.

7. A points arrangement according to any preceding claim, wherein the mating profile is a generally V-section profile.

8. A points arrangement according to claim 7, wherein the V-section profile is inverted.

9. A points arrangement according to any of claims 1 to 5, wherein the mating profile is a U-section profile.

10. A points arrangement according to claim 9, wherein the U-section profile is inverted.

11. A points arrangement according to any preceding claim, wherein an expansion gap is defined between the facing end surfaces of said at least one switch rail and said at least one stock rail when the switch rails are in the first and second positions.

12. A points arrangement according to any preceding claim, wherein said at least one switch rail and said at least one stock rail are tapered in the longitudinal direction to define a mitred connection that permits relative longitudinal movement between said at least one switch rail and said at least one stock rail.

13. A points arrangement according to any preceding claim, wherein both of the movable switch rails cooperate with both stock rails of each of the first and second pairs of stock rails when the movable switch rails are in the first and second positions, and both switch rails and both stocks rails of each of the first and second pairs are shaped

to define a mating profile which independently aligns each switch rail with a corresponding stock rail and prevents transverse movement of the switch rails relative to the stock rails.

14. A railway points arrangement for a railway track junction substantially as hereinbefore described and/or as shown in the accompanying drawings.

Intellectual Property Office

Application No:	GB1322641.0	**Examiner:**	Simon Rose
Claims searched:	1-14	**Date of search:**	1 August 2014

Patents Act 1977: Search Report under Section 17

Documents considered to be relevant:

Category	Relevant to claims	Identity of document and passage or figure of particular relevance
X	1, 3-11, 13	GB 1329048 A (ELEKTRO-THERMIT) See particularly Figures 1-5, wedges 32, 33, 34, 35, tongues 28, 29, 30, 31
X	1, 4, 6, 9-10, 12	DE 2046391 A1 (ELEKTRO-THERMIT) See particularly Figures 1-5, stock rail 4, recess 3, locking wedge 5, switch rail 1, front end 2, and WPI abstract accession number 1977-86685Y
X	1-2, 4, 6	GB 191115538 A (BROWN et al) See particularly Figures 1-7, main rail 10, switch rail 21, and abstract
A		US 175699 A (HARRETT) See particularly Figure 1, stock rail B, tongue C, tongue end b, notch b'
A		US 1112965 A (ANDERSON) See particularly Figures 1-3, 5, 8 and 11, stock rails 1, 2, recess 3, switch rails 24, 25, projection 28
A		US 934086 A (MOORE) See particularly Figures 1-5, stock rails 1, 2, tongues 4, 5

Categories:

X	Document indicating lack of novelty or inventive step	A	Document indicating technological background and/or state of the art.
Y	Document indicating lack of inventive step if combined with one or more other documents of same category.	P	Document published on or after the declared priority date but before the filing date of this invention.
&	Member of the same patent family	E	Patent document published on or after, but with priority date earlier than, the filing date of this application.

Field of Search:

Search of GB, EP, WO & US patent documents classified in the following areas of the UKC^{X} :

Worldwide search of patent documents classified in the following areas of the IPC

E01B

The following online and other databases have been used in the preparation of this search report

EPODOC, WPI, INSPEC

Intellectual Property Office

International Classification:

Subclass	Subgroup	Valid From
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(51) INT CL:
E01B 7/02 (2006.01) ***B61L 5/02*** (2006.01)
B61L 5/10 (2006.01)

(56) Documents Cited:
EP 0922807 A
DE 102008028862 A1
SU 001194939 A1
GB 191115538
GB 191228636
CH 000684939 A5
SU 001221268 A1

(58) Field of Search:
INT CL **B61L, E01B**
Other: **EPODOC, WPI**

(54) Title of the Invention: **Railway points operating apparatus**
Abstract Title: **Railway points operator moving tongue vertically and transversely in an arc**

(57) A railway points operator 22 is particularly suitable for operating railway points 10 comprising pairs of parallel, static stock rails (12, 14, Figure 1) and a pair of switch rails 16 movable between first and second positions to select a first or second route defined respectively by the stock rail pairs, and comprises an actuator 35 and a lock 56. Actuator 35, preferably driven by an electric motor 38, moves switch rails 16 transversely and vertically about a preferably semi-circular arc between the first and second positions to raise and lower switch rails 16 relative to the stock rails during transverse movement. Lock 56 prevents transverse horizontal movement of the switch rails 16 from the first and second positions. Switch rails 16 may be mounted on an upper surface of a support member 26 having a plurality of transversely spaced semi-circular recesses 32 on a lower surface.

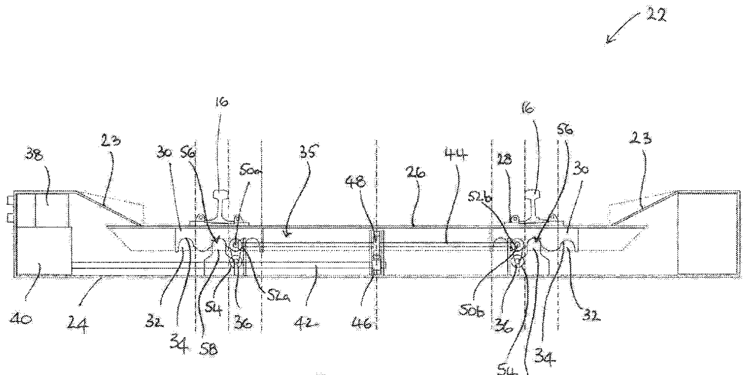

Fig. 4

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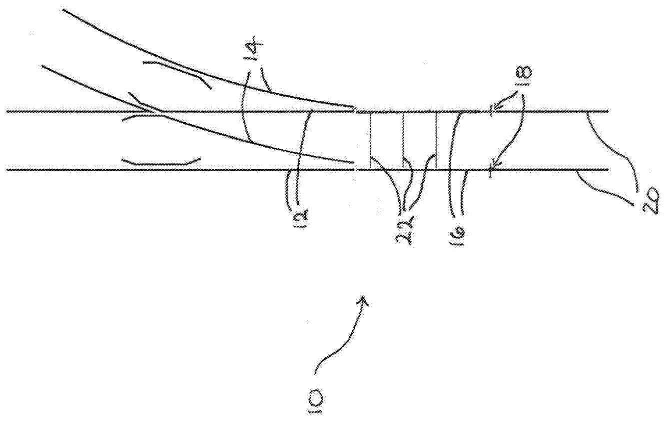

FIG. 1

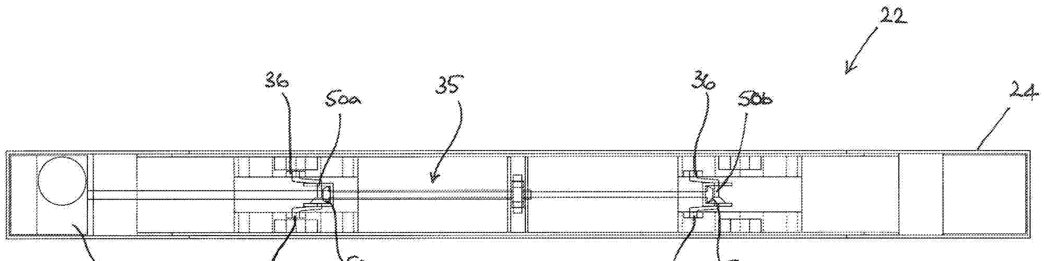

FIG. 3

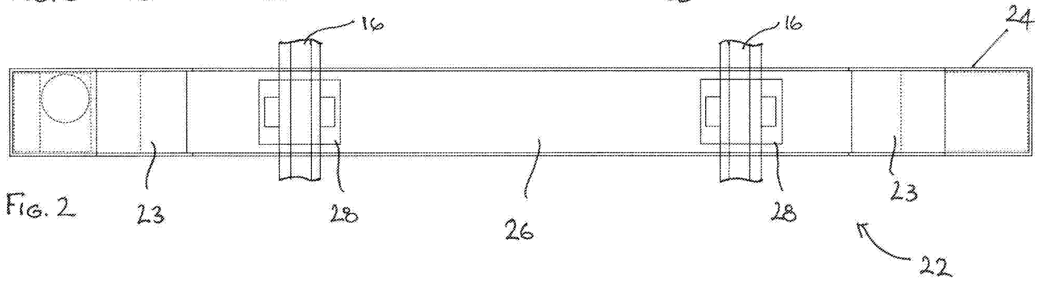

FIG. 2

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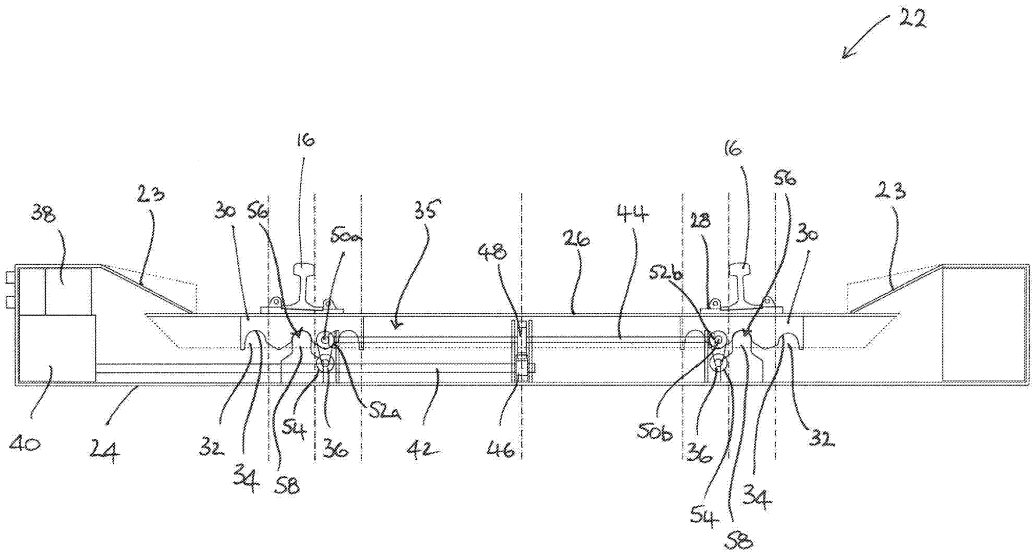
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Fig. 4

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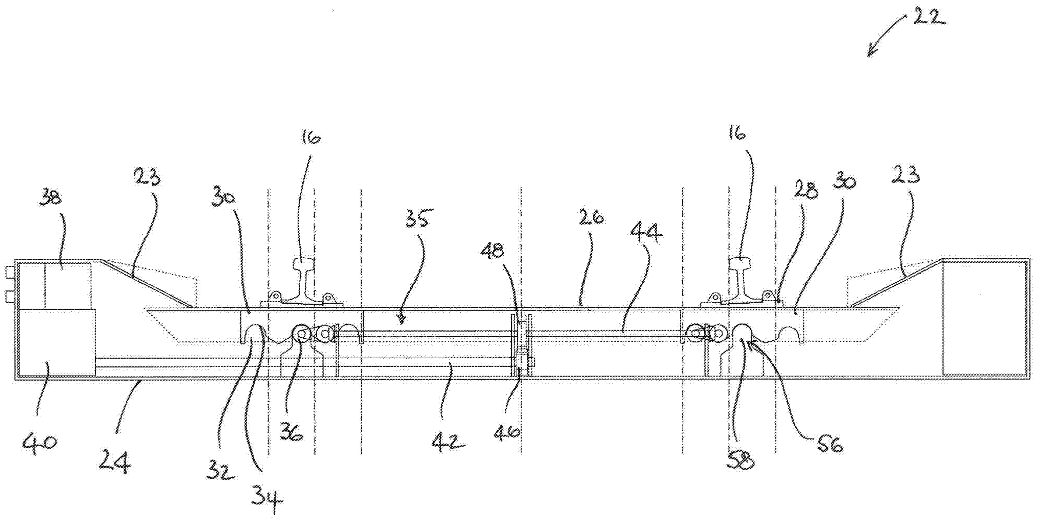

Fig. 5

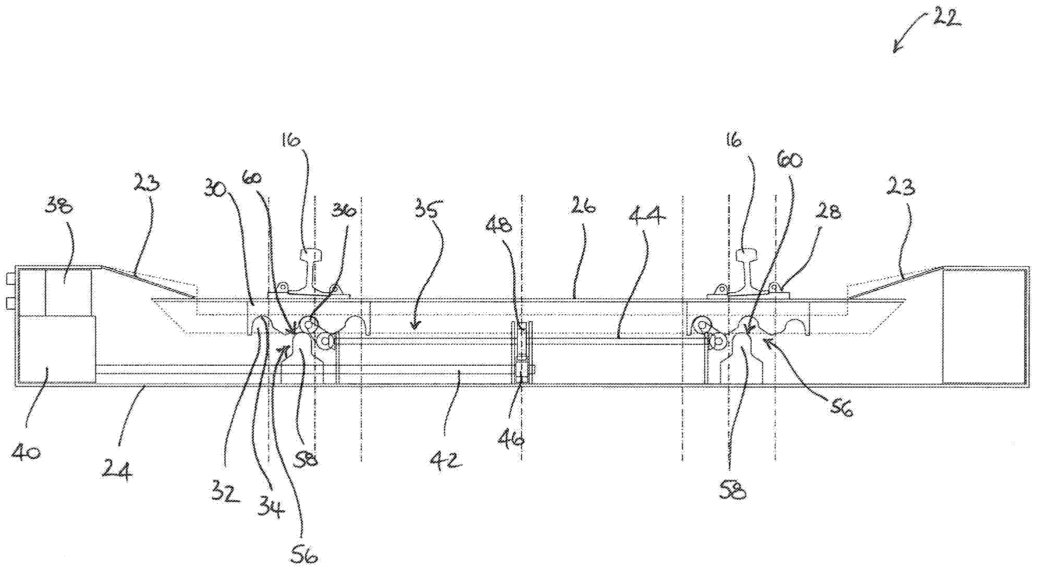
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Fig. 6

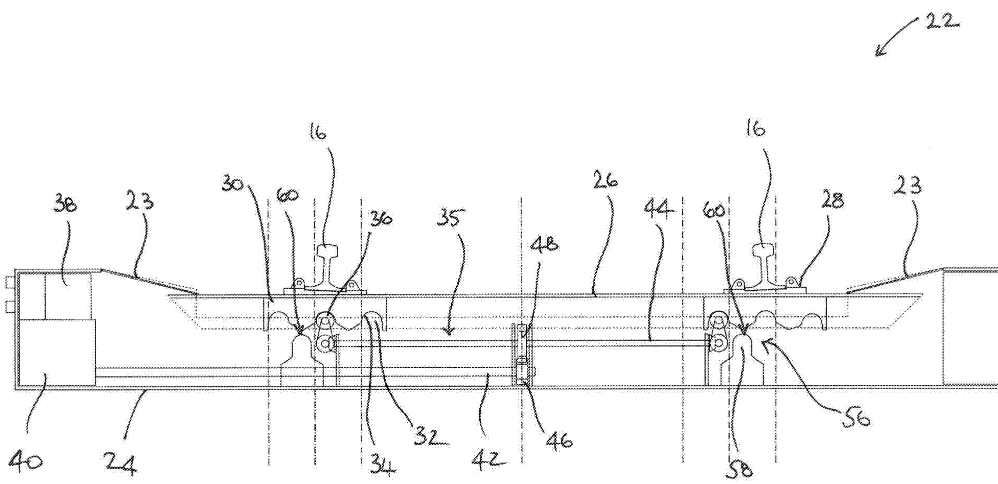

FIG. 7

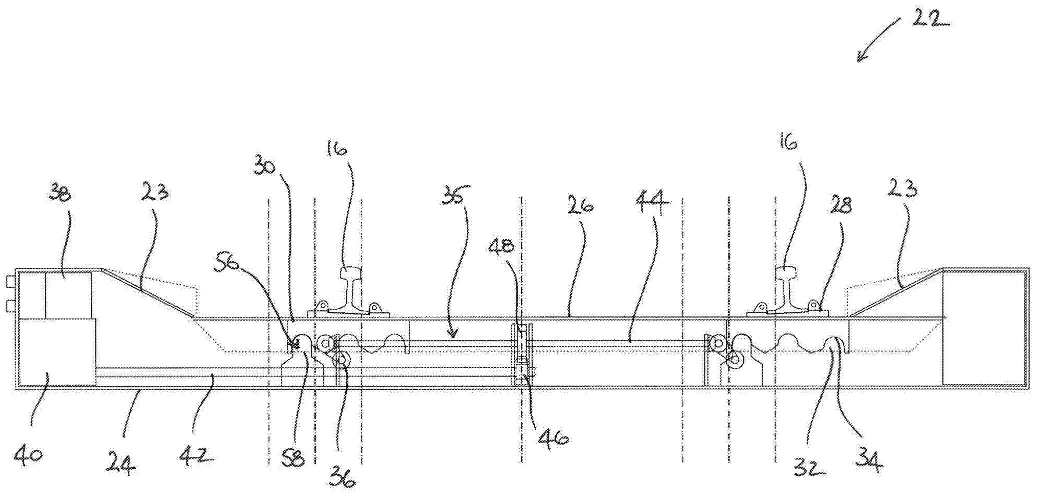

Fig. 8

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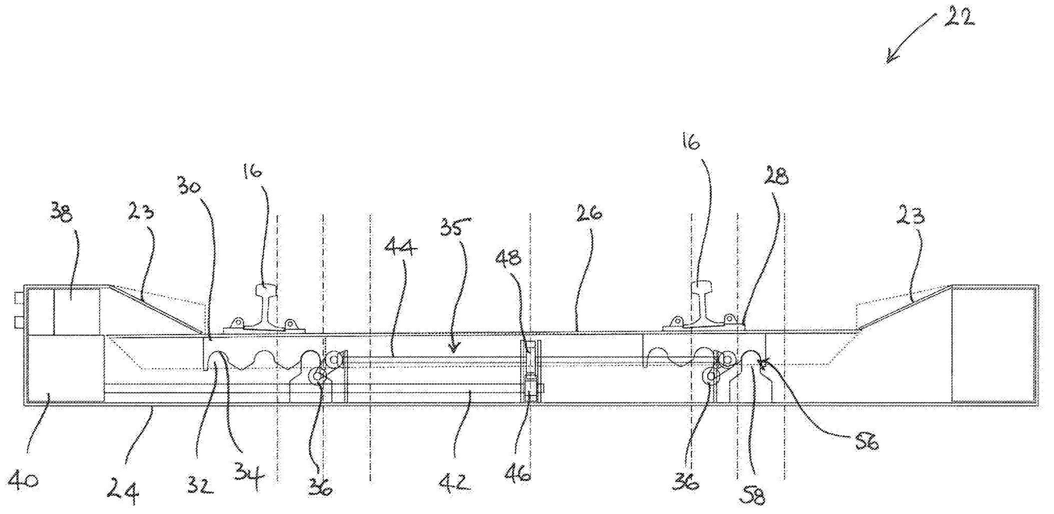

Fig. 9

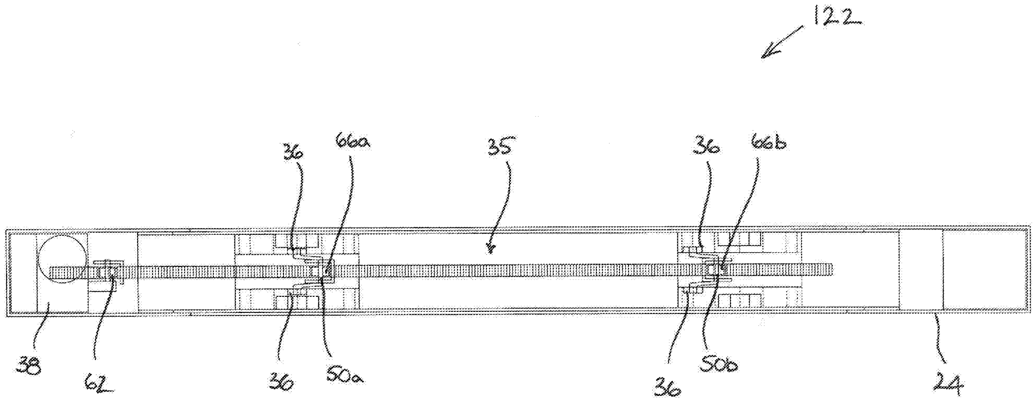

Fig. 10

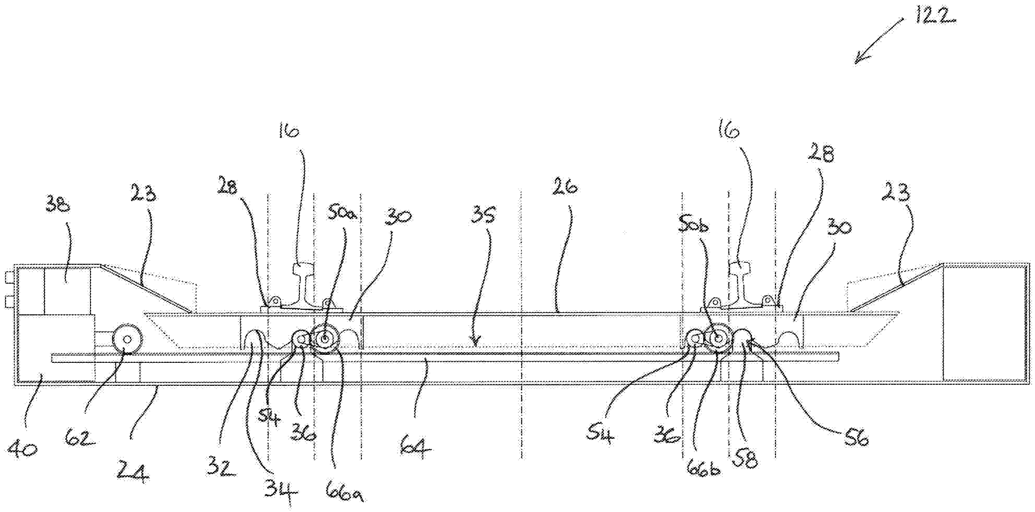
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Fig. 11

- 1 -

RAILWAY POINTS OPERATING APPARATUS

Technical Field

The present disclosure relates generally to railway points operating apparatus for operating a railway points arrangement so that different routes can be selected through a railway track junction.

Technical Background

Railway points, also known as railway track switches, are a necessary part of all railway networks as they enable different routes through the network to be selected. They are a critical part of the network as a points failure often leads to delays, re-routing and cancellations.

Points operating apparatus (often referred to as lineside points operating equipment) is a key element of all railway points arrangements. Conventional points operating apparatus includes an actuator arrangement which moves the switch rails between different positions to select a desired route, for example a straight route or a turnout route, through a railway track junction. The actuator arrangement also locks the switch rails in the selected position.

In a traditional railway points arrangement, there is always a 'transition' state when the switch rails are not properly set to select either the straight route or the turnout route. When the switch rails are in this transition state, the points present a derailment risk, especially when rolling stock is executing a facing-point movement. If there is a failure of the points operating apparatus, for example a failure of part of the actuator arrangement, during this transition state, the switch rails of a conventional points arrangement become stuck in the transition state and cannot be moved by adjacent points operating apparatus because the faulty actuator arrangement prevents such movement. The points arrangement is consequently rendered inoperable and rolling stock cannot safely pass the railway track junction until remedial action is taken to repair or replace the points operating apparatus so that the points arrangement can be put back into service.

A need therefore exists for improved railway points operating apparatus.

Summary of the Disclosure

According to a first aspect of the present disclosure, there is provided railway points operating apparatus for a railway points arrangement comprising at least first and second pairs of longitudinally-extending, parallel-spaced static stock rails defining respectively a first route and a second route and a pair of switch rails movable between a first position to select the first route and a second position to select the second route, wherein the railway points operating apparatus comprises:

an actuator arrangement for moving the switch rails transversely and vertically about an arc between the first and second positions so that the switch rails are raised and lowered relative to the stock rails during said transverse movement; and

a locking arrangement for preventing transverse horizontal movement of the switch rails from the first and second positions.

According to a second aspect of the present disclosure, there is provided a railway points arrangement comprising:

at least first and second pairs of longitudinally-extending, parallel-spaced static stock rails defining respectively a first route and a second route;

a pair of longitudinally-extending switch rails movable between a first position to select the first route and a second position to select the second route; and

railway points operating apparatus comprising:

an actuator arrangement for moving the switch rails transversely and vertically about an arc between the first and second positions so that the switch rails are raised and lowered relative to the stock rails during said transverse movement; and

a locking arrangement for preventing transverse horizontal movement of the switch rails from the first and second positions.

The switch rails may be longitudinally-extending, parallel-spaced switch rails. The switch rails may be aligned with the first pair of stock rails when in the first position to thereby select the first route. The switch rails may be aligned with the second pair of stock rails when in the second position to thereby select the second route. The points arrangement may, thus, take the form of a stub switch.

The switch rails may alternatively be located between incoming stock rails. A free end of one of the switch rails may contact one of the incoming stock rails when the switch rails are in the first position to thereby select the first route. A free end of the other switch rail may contact the other incoming stock rail when the switch rails are in the second position to thereby select the second route. The points arrangement may, thus, take the form of traditional railway points.

According to a third aspect of the present disclosure, there is provided railway points operating apparatus for a railway points arrangement comprising at least first and second pairs of longitudinally-extending, parallel-spaced static stock rails defining respectively a first route and a second route and a pair of longitudinally-extending, parallel-spaced switch rails movable between a first position in alignment with the first pair of stock rails to select the first route and a second position in alignment with the second pair of stock rails to select the second route, wherein the railway points operating apparatus comprises:

an actuator arrangement for moving the switch rails transversely and vertically about an arc between the first and second positions so that the switch rails are raised and lowered relative to the stock rails during said transverse movement; and

a locking arrangement for preventing transverse horizontal movement of the switch rails from the first and second positions.

According to a fourth aspect of the present disclosure, there is provided a railway points arrangement comprising:

at least first and second pairs of longitudinally-extending, parallel-spaced static stock rails defining respectively a first route and a second route;

a pair of longitudinally-extending, parallel-spaced switch rails movable between a first position in alignment with the first pair of stock rails to select the first route and a second position in alignment with the second pair of stock rails to select the second route; and

railway points operating apparatus comprising:

an actuator arrangement for moving the switch rails transversely and vertically about an arc between the first and second positions so that the switch rails are raised and lowered relative to the stock rails during said transverse movement; and

a locking arrangement for preventing transverse horizontal movement of the switch rails from the first and second positions.

The railway points arrangement typically comprises a plurality of said railway points operating apparatus located at longitudinally spaced positions along the switch rails. The provision of a plurality of points operating apparatus is advantageous because it ensures that the switch rails are correctly supported and aligned along their length and that the necessary degree of redundancy is provided. Accordingly, if there is a failure of one of the points operating apparatus, for example a failure of any part of the actuator arrangement, it may still be possible to move the switch rails between the first and second positions by operating other points operating apparatus. In these circumstances, the railway points arrangement can remain in operation and the defective points operating apparatus can simply be replaced at a convenient time without requiring a track possession.

The redundancy capability is facilitated by the separate actuation and locking functions provided respectively by the actuator arrangement and the locking arrangement. For example, if there is a failure of any part of the actuator arrangement, the points operating apparatus with the failed actuator arrangement can still lock the switch rails in the first and second positions because locking is achieved passively, without any reliance on the actuator arrangement.

In the unlikely event of a failure of any part of the actuator arrangement of a points operating apparatus whilst the switch rails are in a transition state, between the first and second positions, and where other points operating apparatus are unable to move the switch rails to either the first or second positions, the points operating apparatus ensures that the railway points arrangement can never present a derailment risk to rolling stock executing a facing-point movement when the points arrangement is embodied as a stub switch or to rolling stock executing a trailing-point movement when the points arrangement is embodied as traditional railway points because the forces applied to the switch rails by approaching rolling stock allow the actuator arrangement to control the movement of the switch rails so that they safely move transversely and vertically about the aforesaid arc to either the first position or the second position. This is possible at least in part because, as explained above, the locking function is not provided by the actuator arrangement.

In traditional railway points, there is a need for supporting surfaces which allow low-friction horizontal sliding movement of the switch rails in the transverse direction and which at the same time provide adequate support for the loaded switch rails as rolling stock passes over them. These conflicting requirements are addressed by the present disclosure again due to the fact that the actuation and locking functions are separated. More particularly, the actuator arrangement may include bearing surfaces which can be configured to support the switch rails during movement about the arc between the first and second positions whilst the locking arrangement may include different bearing surfaces which can be configured to provide the necessary support for the loaded switch rails as rolling stock passes over them.

The actuator arrangement may be arranged to move the switch rails between the first and second positions about an arc which may be substantially semi-circular.

Because the switch rails are moved transversely and vertically about an arc between the first and second positions, contact, and hence friction, with supporting surfaces is minimised thereby increasing the reliability of the points operating apparatus. This is to be contrasted with conventional points operating apparatus where the switch rails slide across a supporting surface as explained above.

The points operating apparatus may include a support member which may have an upper surface on which the switch rails may be mounted in a predetermined spaced relationship. The actuator arrangement may be operable to move the support member about said arc to thereby move the switch rails between the first and second positions. Typically, the switch rails are removably secured to the upper surface of the support member, for example using suitable clips and mounts. This enables the points operating apparatus to be configured as a self-contained line replaceable unit which is readily attachable/detachable to/from the switch rails and therefore readily interchangeable in the event of failure of any part of the apparatus without requiring a track possession.

The support member may have a lower surface and a plurality of transversely spaced recesses may be provided on the lower surface. Each recess may include a bearing surface and each bearing surface may have a substantially semi-circular profile or an inverted substantially U-shaped profile. The recesses may be formed in a plate member mounted on the lower surface of the support member. The recesses could alternatively be formed in the lower surface of the support member.

The locking arrangement may include an upwardly extending locking projection which may locate in one of the transversely spaced recesses when the switch rails are in the first and second positions to prevent transverse horizontal movement of the support member. The cooperation between the locking projection and the transversely spaced recesses thus prevents transverse horizontal movement of the switch rails and holds them securely in the selected first or second position. It will, therefore, be appreciated that the locking projection and recesses are transversely positioned to ensure that when the locking projection is positioned in a recess, the switch rails are positioned to select either the first route or the second route, for example by virtue of alignment of the switch rails with either the first or second pair of stock rails.

The locking projection may have a bearing surface which cooperates with the bearing surface of each recess to transversely align the locking projection and recess about a vertical axis when the switch rails are in the first and second positions. The cooperation between the bearing surfaces advantageously guides the support member transversely and vertically in an arcuate motion (i.e. along a curved path) during movement between the first and second positions so that the switch rails are properly positioned to select either the first route or second route, for example by virtue of alignment of the switch rails with either the first or second pair of stock rails. The bearing surface of the locking projection typically has a substantially semi-circular profile or inverted U-shaped profile which may be complementary to the semi-circular profile or inverted U-shaped profile bearing surface of each recess.

The actuator arrangement may include an actuating member which may cooperate with the support member to move the support member, and hence the switch rails, about said arc.

The actuating member may cooperate with the transversely spaced recesses to move the support member, and thereby move the switch rails, about said arc. The recess with which the actuating member cooperates will depend on the starting position of the switch rails, e.g. whether they are being moved from the first position to the second position or from the second position to the first position.

In preferred embodiments, the actuating member is disengaged from the transversely spaced recesses when the switch rails are in the first and second positions. This ensures that the actuation and locking functions provided by the points operating apparatus are entirely separate. It also allows the actuating member to gain momentum prior to locating in the recess when movement of the support member, and hence the switch rails, is initiated, thereby overcoming any static friction.

The actuating member may comprise a rotatable cam member. The rotatable cam member may include a bearing surface which cooperates with the bearing surface of the recess during movement of the switch rails between the first and second positions.

The rotatable cam member may be mounted on a camshaft for rotation by the camshaft. The camshaft can be rotated to cause rotation of the cam member. It is this rotation which causes at least part of the cam member to engage and disengage the recesses.

The actuator arrangement may include a drivetrain for rotating the camshaft and the drivetrain may be backdrivable. This is advantageous because if any part of the actuator arrangement fails during movement of the switch rails between the first and second positions whilst the switch rails are in a transition state, the switch rails can move from the transition state to either the first position or the second position. As explained above, this movement could be effected by the actuator arrangements of other points operating apparatus located at longitudinally spaced positions along the switch rails or by forces applied to the switch rails by rolling stock passing the switch rails.

The drivetrain typically includes a motor and may include a gearbox arrangement.

The drivetrain may include a slip clutch which may have a predetermined slip torque. This may be advantageous, for example, in the unlikely event that the switch rails become stuck in a transition state between the first and second positions and cannot be moved to either the first or second positions by other points operating apparatus. In these circumstances, the forces applied to the switch rails by approaching rolling stock would generate a torque in the drivetrain which is greater than the predetermined slip torque thereby allowing the clutch to slip and the switch rails to move to either the first or second positions into a safe state in which the rolling stock can safely pass the points arrangement.

Brief Description of the Drawings

Figure 1 is a diagrammatic plan view of one possible form of points arrangement in the form of a stub switch and including a plurality of points operating apparatus according to the present disclosure;

Figure 2 is a detailed diagrammatic plan view of the points operating apparatus;

Figure 3 is a diagrammatic view similar to Figure 2 with the switch rails and support member for the switch rails omitted;

Figure 4 is a diagrammatic cross-sectional side view of the points operating apparatus of Figures 2 and 3 in a configuration in which it locates the switch rails in a first position;

Figures 5 to 8 illustrate the operation of the points operating apparatus as it moves the switch rails from the first position shown in Figure 4 to a second position shown in Figure 8;

Figure 9 is a diagrammatic cross-sectional side view of the points operating apparatus similar to Figure 4 but in a configuration in which it locates the switch rails in a third position;

Figure 10 is a diagrammatic plan view similar to Figure 3 of an alternative embodiment of a points operating apparatus; and

Figure 11 is a diagrammatic cross-sectional side view of the points operating apparatus shown in Figure 10.

Detailed Description of Embodiments

Embodiments of the present disclosure will now be described by way of example only and with reference to the accompanying drawings.

Figure 1 illustrates a railway points arrangement 10 for a railway track junction which enables different routes to be selected through the junction. The illustrated points arrangement 10 takes the form of a conventional stub switch and comprises first and second pairs of longitudinally-extending, parallel-spaced static stock rails 12, 14 mounted on fixed supports in the form of sleepers or bearers (not shown). The first pair of stock rails 12 defines a first route, in the illustrated arrangement straight route. The second pair of stock rails 14 defines a second route, in the illustrated arrangement a right turnout route. Although not shown in Figure 1, one or more further pairs of stock rails could be provided to define further diverging routes. For example, a pair of stock rails could be provided which define a third route in the form of a left turnout route.

The points arrangement 10 comprises a pair of longitudinally-extending, parallel-spaced switch rails 16 which can bend transversely about a generally fixed end 18 where the switch rails 16 are secured to plain line rails 20. In Figure 1, the switch rails 16 are shown in a first position with the free ends of the switch rails 16 aligned with the ends of the first pair of stock rails 12, thus enabling rolling stock to follow the first (straight) route through the railway track junction. The switch rails 16 can be moved between the illustrated first position and a second position in which the free ends of the switch rails 16 are aligned with the ends of the second pair of stock rails 14, thus enabling rolling stock to follow the second (right turnout) route through the railway track junction. Similarly, the switch rails 16 can be moved to other positions in which the free ends of the switch rails 12 are aligned with the ends of other pairs of stock rails thus enabling rolling stock to follow other diverging routes through the railway track junction, such as the third (left turnout) route mentioned above but not illustrated.

In order to move the switch rails 16 between different positions, for example between the first and second positions, and to ensure that the switch rails 16 are properly aligned with the first and second pairs of stock rails 12, 14 when they are in the first and second positions, a plurality of points operating apparatus 22 is provided. As shown in Figure 1, it is preferable that the points operating apparatus 22 are provided at longitudinally spaced positions along the switch rails 16 to ensure that the switch rails 16 are adequately supported and aligned along their length and to ensure that the necessary degree of redundancy is provided. Redundancy is desirable so that the points arrangement 10 can continue to operate in the event of failure of, for example, one of the points operating apparatus 22. Although three points operating apparatus 22 are shown in Figure 1, this is illustrative only and any suitable number of points operating apparatus can be provided.

Referring now to Figures 2 to 4, the points operating apparatus 22 comprises a housing 24 having a support member 26 in the form of a bearer which is positioned underneath the switch rails 16 and which forms the top of the housing 24. The switch rails 16 are removably secured, for example by suitable mounts 28, in a predetermined spaced relationship to the upper surface of the support member 26 and the support member 26 thus supports and moves the switch rails 16. The support member 26 has two pairs of longitudinally spaced plate members 30 on its lower surface. Each pair of plate members 30 is located at a position substantially beneath the switch rails 16 and has three transversely spaced and downward facing recesses 32. The recesses 32 each have a bearing surface 34 which has a substantially semi-circular or inverted U-shaped profile.

The points operating apparatus 22 comprises an actuator arrangement 35 which moves the support member 26, and hence the switch rails 16, between different positions, for example first, second and third positions, to select different routes through the railway track junction. Rather than moving the switch rails 16 in a transverse horizontal direction as is conventional in the prior art, the actuator arrangement 35 moves the support member 26, and hence the free ends of the switch rails 16, transversely and vertically about a semi-circular arc between different positions so that the free ends of the switch rails 16 are raised and lowered relative to the stock rails 12, 14 during the transverse switching movement. In practice, this transverse and vertical movement of the free ends of the switch rails 16 is achieved by bending the switch rails 16.

The actuator arrangement 35 comprises a drivetrain for rotating an actuating member in the form of a cam member 36 which can be selectively engaged in the recesses 32 to move the support member 26, and hence the switch rails 16, about the semi-circular arc between the first and second positions. The drivetrain comprises an electric motor 38 which is connected, by a backdrivable gearbox 40, to a primary driveshaft 42. Rotational motion is transmitted from the primary driveshaft 42 to a final driveshaft 44 by spur gears 46, 48 mounted respectively on each shaft 42, 44. One of the spur gears 46, 48 may include a slip clutch (not shown) having a predetermined slip torque. Rotational motion is transmitted from the final driveshaft 44 to cam shafts 50a, 50b by a crown and pinion gear arrangement 52a, 52b located at each end of the final driveshaft 44. Each cam shaft 50a, 50b carries two longitudinally spaced cam members 36. Each cam member 36 has a lobe which provides a bearing surface 54 which is complementary to the bearing surface 34 of each recess 32 and which cooperates with the bearing surface 34 of each recess 32 when the cam members 36 are engaged in the recesses 32.

The points operating apparatus 22 further comprises a locking arrangement 56 which securely retains the support member 26, and hence the switch rails 16, in a selected transverse position (such as the first, second or third position) and prevents movement of the support member 26 from the selected position in a transverse horizontal direction.

Movement of the support member 26, and hence the switch rails 16, from the selected position can be effected only when the support member 26 is urged to move by the actuator arrangement about the aforementioned semi-circular arc.

The locking arrangement 56 comprises two pairs of longitudinally spaced locking projections 58 which are fixed to, and extend upwardly from, a base of the housing 24. Each locking projection 58 has a bearing surface 60 with a substantially semi-circular or inverted U-shaped profile which is complementary to the bearing surfaces 34 of the recesses 32.

Figure 4 shows the points operating apparatus 22 in a first configuration in which the switch rails 16 are in a first, central, position aligned, for example, with the first pair of stock rails 12 illustrated in Figure 1 to select the straight route. Figure 8 shows the points operating apparatus 22 in a second configuration in which the switch rails 16 are in a second position aligned, for example, with the second pair of stock rails 14 illustrated in Figure 1 to select the right turnout route. It will be noted that when the points operating apparatus 22 is in either of these configurations or indeed similar configurations in with the switch rails 16 are set for any given route, the cam members 36 are disengaged from the recesses 32 whereas the locking projections 58 are fully engaged in the recesses 32. It will, therefore, be apparent that the actuator arrangement 35, in particular the cam members 36, plays no part in locking the support member 26, and hence the switch rails 16, in a selected position. This locking is achieved solely by virtue of the cooperation between the locking projections 58 and the recesses 32.

The operation of the points operating apparatus 22 will now be explained with reference to Figures 4 to 8 when the switch rails 16 are moved between the first and second positions.

The electric motor 38 is operated to rotate the primary driveshaft 42 via the gearbox 40. This in turn rotates the final driveshaft 44, via the spur gears 46, 48, thereby rotating the cam shafts 50a, 50b via the crown and pinion gear arrangements 52a, 52b. The cam members 36 are thus rotated in the clockwise direction into a position in which they engage the corresponding recesses 32 in the plate members 30 as shown in Figure 5. Continued clockwise rotation of the cam members 36 moves the support member 26, and hence the switch rails 16, upwardly and transversely towards the right to commence the semi-circular motion as shown in Figure 6. During this semi-circular motion, the locking projections 58 are progressively disengaged from the recesses 32, the cooperation between the bearing surfaces 34 and 60 facilitating this disengagement. Further clockwise rotation of the cam members 36 continues the semi-circular motion of the support member 26 and the switch rails 16, as shown in Figure 7. Once the support member 26 has reached the position shown in Figure 7, the inherent stiffness of the switch rails 16 (and possibly the mass of the switch rails 16 depending on their length) tends to urge them downwardly, along the semi-circular arc which is dictated by the rotational motion of the cam members 36 on the camshafts 50a, 50b. The support member 26 is, therefore, also urged downwardly along the same semi-circular arc and as the switch rails 16 approach the second position, the locking projections 58 progressively engage in the recesses 32, this engagement being facilitated by the cooperation between the bearing surfaces 34 and 60. Advantageously, the semi-circular profile of the bearing surfaces 34, 60 tends to align the support member 26 transversely as it completes its semi-circular motion and this helps to ensure that the switch rails 16 are correctly aligned with the stock rails 14 when the switch rails 16 are in the second position. As shown in Figure 8, rotation of the cam members 36 continues until the cam members 36 are completely disengaged from the recesses 32.

It will be understood that a different route, such as the left turnout route, can be selected in a similar manner, for example by operating the electric motor 38 to rotate the cam members 36 in the anti-clockwise direction to move the support member 26 and hence the switch rails 16 from the position shown in Figure 4 to the position shown in Figure 9.

It will be noted that the key components of the points operating apparatus 22 are all positioned inside the housing 24 and therefore protected from the external environment. This improves the reliability of the apparatus 22. In order to permit the support member 26 to follow the semi-circular path and at the same time maintain the sealed environment inside the housing 24, the apparatus 22 includes movable or flexible flap members 23 which can move upwardly and downwardly, as best shown in Figures 4 to 8, in concert with the movement of the support member 26.

Figures 10 and 11 illustrate an alternative embodiment of the points operating apparatus 122 which is similar to the points operating apparatus 22 shown in Figures 2 to 9 and in which corresponding components are identified using corresponding reference numerals.

The points operating apparatus 122 utilises a modified drivetrain based on a rack-and-pinion arrangement. In more detail, the electric motor 38 and gearbox 40 rotate a pinion gear 62 which cooperates with a transversely extending and transversely movable rack gear 64 to thereby move the rack gear 64. Each of the cam shafts 50a, 50b also carries a pinion gear 66a, 66b which cooperates with the rack gear 64. It will be apparent that upon movement of the rack gear 64 in the transverse direction, the pinion gears 66a, 66b are rotated thereby causing corresponding rotation of the camshafts 50a, 50b and the cam members 36. Although the points operating apparatus 122 utilises a modified drivetrain, it will be immediately apparent that the motion of the support member 26, and hence the motion of the switch rails 16, is the same as described above with reference to Figures 4 to 9. Accordingly, no further explanation is needed.

The points operating apparatus 22, 122 has been described in conjunction with a standard stub switch in which the free ends of the switch rails 16 do not cooperate with the ends of the stock rails 12, 14 when the switch rails 16 are in the first or second positions or indeed in any other position (such as a third position). In such conventional stub switches, there is no strict requirement to raise the switch rails 16 in order to effect transverse movement between different positions, such as the first, second and third positions, but this might be advantageous for the reasons mentioned earlier in this specification.

A points arrangement which is based on the standard stub switch but in which the free ends of the switch rails cooperate with the stock rails when the switch rails are in different positions, set for different routes, is described in a related co-pending patent application (application number GB 1322641.0) filed by the applicant on the same date as the present application and entitled “Railway Points”. In a preferred embodiment of the railway points arrangement described in this co-pending application, the free ends of the switch rails have to be raised to disengage them from the stock rails to enable the switch rails to be moved transversely between different positions, for example first, second and third positions, to select different routes. It will, therefore, be apparent that the points operating apparatus 22, 122 described in this specification is particularly, although not exclusively, suitable for use with the railway points arrangement described in the related co-pending application.

It should also be noted for completeness that the points operating apparatus 22, 122 is not exclusively intended for use with a points arrangement 10 in the form of a stub switch and that it can be used to move and lock the switch rails of a traditional points arrangement in which the switch rails are located between incoming stock rails and can move about a fixed end. In such a conventional points arrangement, the free ends of the switch rails can be moved transversely and vertically about an arc by the points operating apparatus 22, 122 between a first position in which the free end of one of the switch rails contacts one of the incoming stock rails to select the first route and a second position in which the free end of the other switch rail contacts the other incoming stock rail to select the second route.

Although exemplary embodiments have been described in the preceding paragraphs, it should be understood that various modifications may be made to those embodiments without departing from the scope of the appended claims. Thus, the breadth and scope of the claims should not be limited to the above-described exemplary embodiments. Each feature disclosed in the specification, including the claims and drawings, may be replaced by alternative features serving the same, equivalent or similar purposes, unless expressly stated otherwise.

For example, although three transversely-spaced recesses 32 are shown in the illustrated embodiments of the points operating apparatus 22, 122, it will be understood that this is illustrative only and that any suitable number of recesses 32 can be provided. In practice, it will be sufficient to provide one recess 32 per route. This means that if the points arrangement 10 comprises only two pairs of stock rails 12, 14 representing first and second routes, only two transversely-spaced recesses 32 will be needed because the switch rails 16 will only be required to move between two positions, namely a first position to select the first route and a second position to select the second route.

Unless the context clearly requires otherwise, throughout the description and the claims, the words “comprise”, “comprising”, and the like, are to be construed in an inclusive as opposed to an exclusive or exhaustive sense; that is to say, in the sense of “including, but not limited to”.

Any combination of the above-described features in all possible variations thereof is encompassed by the present invention unless otherwise indicated herein or otherwise clearly contradicted by context.

Claims

1. Railway points operating apparatus for a railway points arrangement comprising at least first and second pairs of longitudinally-extending, parallel-spaced static stock rails defining respectively a first route and a second route and a pair of longitudinally extending switch rails movable between a first position to select the first route and a second position to select the second route, wherein the railway points operating apparatus comprises:

an actuator arrangement for moving the switch rails transversely and vertically about an arc between the first and second positions so that the switch rails are raised and lowered relative to the stock rails during said transverse movement; and

a locking arrangement for preventing transverse horizontal movement of the switch rails from the first and second positions.

2. Points operating apparatus according to claim 1, wherein the arc is substantially semi-circular.

3. Points operating apparatus according to claim 1 or claim 2, wherein the points operating apparatus includes a support member having an upper surface on which the switch rails are mounted in a spaced relationship and the actuator arrangement is arranged to move the support member about said arc to move the switch rails between the first and second positions.

4. Points operating apparatus according to claim 3, wherein the support member has a lower surface and a plurality of transversely spaced recesses are provided on said lower surface.

5. Points operating apparatus according to claim 4, wherein each recess includes a bearing surface.

6. Points operating apparatus according to claim 4 or claim 5, wherein each recess has a substantially semi-circular profile.

7. Points operating apparatus according to any of claims 4 to 6, wherein the locking arrangement includes an upwardly extending locking projection which locates in one of said transversely spaced recesses when the switch rails are in the first and second positions to prevent transverse horizontal movement of the support member.

8. Points operating apparatus according to claim 7, wherein the locking projection has a bearing surface which cooperates with the bearing surface of one of said recesses to transversely align the projection and recess about a vertical axis when the switch rails are in the first and second positions.

9. Points operating apparatus according to claims 6 and 7 or claims 6, 7 and 8, wherein the locking projection has a substantially semi-circular profile which is complementary to the semi-circular profile of each recess.

10. Points operating apparatus according to any of claims 3 to 9, wherein the actuator arrangement includes an actuating member which cooperates with the support member to move the support member about said arc and thereby move the switch rails between the first and second positions.

11. Points operating apparatus according to claim 10 when dependent on any of claims 4 to 9, wherein the actuating member cooperates with the transversely spaced recesses to move the support member about said arc.

12. Points operating apparatus according to claim 11, wherein the actuating member is disengaged from the transversely spaced recesses when the switch rails are in the first and second positions.

13. Points operating apparatus according to claim 11 or claim 12, wherein the actuating member comprises a rotatable cam member.

14. Points operating apparatus according to claim 13, wherein the rotatable cam member includes a bearing surface which cooperates with the bearing surface of the recess during movement of the switch rails between the first and second positions.

15. Points operating apparatus according to claim 13 or claim 14, wherein the rotatable cam member is mounted on a camshaft and the actuator arrangement includes a backdrivable drivetrain for rotating the camshaft.

16. Points operating apparatus according to claim 15, wherein the drivetrain includes a motor and gearbox arrangement.

17. Points operating apparatus according to claim 16, wherein the drivetrain includes a slip clutch having a predetermined slip torque.

18. A railway points arrangement comprising:

at least first and second pairs of longitudinally-extending, parallel-spaced static stock rails defining respectively a first route and a second route;

a pair of longitudinally extending switch rails movable between a first position to select the first route and a second position to select the second route; and

railway points operating apparatus comprising:

an actuator arrangement for moving the switch rails transversely and vertically about an arc between the first and second positions so that the switch rails are raised and lowered relative to the stock rails during said transverse movement; and

a locking arrangement for preventing transverse horizontal movement of the switch rails from the first and second positions.

19. A railway points arrangement according to claim 18, wherein the points arrangement comprises a plurality of said railway points operating apparatus spaced longitudinally along the switch rails.

20. A railway points arrangement according to claim 18 or 19, wherein the railway points operating apparatus is as defined in any of claims 2 to 17.

21. A railway points arrangement according to any of claims 18 to 20, wherein the switch rails are longitudinally-extending, parallel-spaced switch rails, the switch rails being aligned with the first pair of stock rails when in the first position and with the second pair of stock rails when in the second position.

22. A railway points arrangement according to any of claims 18 to 20, wherein the points arrangement comprises a pair of incoming stock rails and the switch rails are located between incoming stock rails, and wherein a free end of one of the switch rails contacts one of the incoming stock rails when the switch rails are in the first position to thereby select the first route and a free end of the other switch rail contacts the other incoming stock rail when the switch rails are in the second position to thereby select the second route.

23. Railway points operating apparatus substantially as hereinbefore described and/or as shown in the accompanying drawings.

Intellectual Property Office

Application No:	GB1322660.0	**Examiner:**	Simon Rose
Claims searched:	1-23	**Date of search:**	6 August 2014

Patents Act 1977: Search Report under Section 17

Documents considered to be relevant:

Category	Relevant to claims	Identity of document and passage or figure of particular relevance
X	1, 18-19, 22	CH 684939 A5 (SIEMENS) See particularly Figures 1-5, rail 1, tongue 4, pivot 5, lock element 2, and WPI abstract accession number 1994-350677
X	1, 18-19, 22	DE 102008028862 A1 (DEUTSCHE BAHN) See particularly Figures 1-3 and 6, rail 8, tongue 7, lock piece 4, and WPI abstract accession number 2010-A17530
A	-	SU 1194939 A1 (ZHDANOVSKIJ) See particularly Figures 1, 6 and 7, stock rails 1, 2, tongues 3 4, rods 5, pivots 6, actuators 27, and WPI abstract accession number 1986-175226
A	-	EP 0922807 A (IMPRESA ANGELO MAZZI) See particularly Figures 1-6, tongue 3, inactive position 6, stock rail 4, and WPI abstract accession number 1999-339655
A	-	GB 191228636 A (CUMMING) See particularly Figures 1-6, oscillatable locking plate L, circular table C, junction tracks A^2, B^2, and abstract
A	-	GB 191115538 A (BROWN et al) See particularly Figures 1-7, stock rail 10, point blade 20, axis 24, and abstract
A	-	SU 1221268 A1 (ZHDANOVSKIJ) See particularly Figures 1-3, outer rail 1, inner rail 4, rotation supports 7, 8, and WPI abstract accession number 1986-317427

Categories:

X	Document indicating lack of novelty or inventive step	A	Document indicating technological background and/or state of the art.
Y	Document indicating lack of inventive step if combined with one or more other documents of same category.	P	Document published on or after the declared priority date but before the filing date of this invention.
&	Member of the same patent family	E	Patent document published on or after, but with priority date earlier than, the filing date of this application.

Field of Search:

Search of GB, EP, WO & US patent documents classified in the following areas of the UKC^X :

Worldwide search of patent documents classified in the following areas of the IPC

Intellectual Property Office

B61L; E01B

The following online and other databases have been used in the preparation of this search report

EPODOC, WPI

International Classification:

Subclass	Subgroup	Valid From
E01B	0007/02	01/01/2006
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B61L	0005/10	01/01/2006

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(56) Documents Cited:
GB 1470668 A
WO 1994/019542 A1
FR 002392168 A1
KR2010/0098098

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Other: **WPI, EPODOC**

(54) Title of the Invention: **Railway track crossing**
Abstract Title: **Railway track crossing**

(57) A railway track crossing (40, fig 2) comprises a fixed crossing nose 42 formed by a pair of diverging rails (44) and a pair of independently movable rails 45 each having a wing rail 46 provided on each side of the crossing nose. Each rail is movable transversely from a closed position, in which the wing rail contacts the crossing nose, to an open position, in which the wing rail is spaced from the crossing nose to form a groove 54 that allows the passage of a wheel flange 56a between the crossing nose and the wing rail. An actuator arrangement (60, fig. 11) is operable to move one of the movable rails from the closed position to the open position and each movable rail is arranged to adopt the closed position in the absence of any force applied to it by the actuator arrangement. Each movable rail includes a mating feature 78 which cooperates with a mating feature 82 to lock the movable rail in the closed position when the movable rail is loaded by the wheels 56 of rolling stock passing through the railway track crossing.

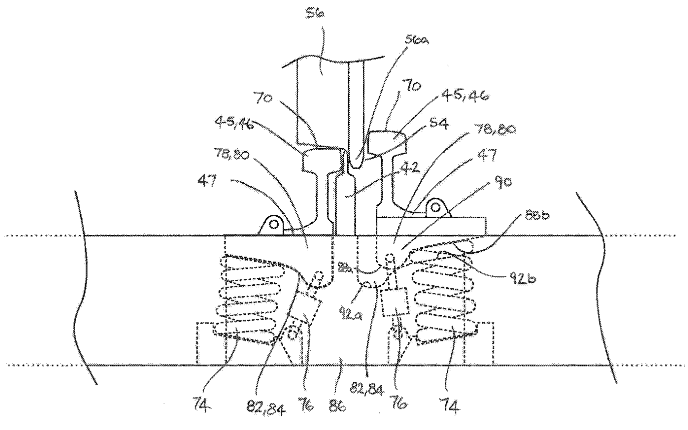

FIG. 10

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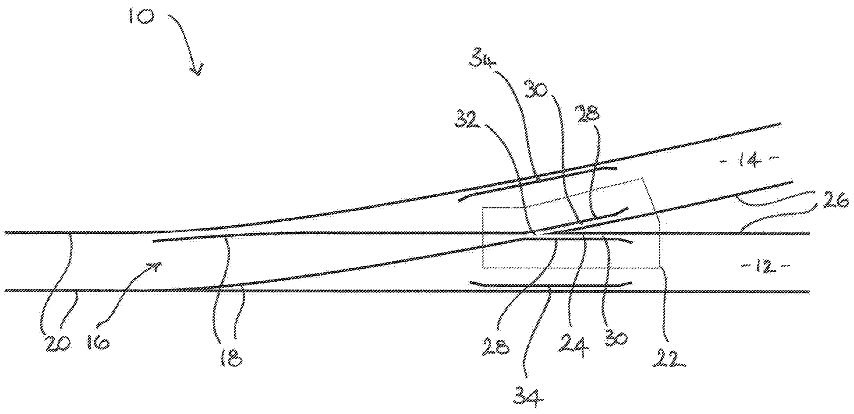


Fig. 1

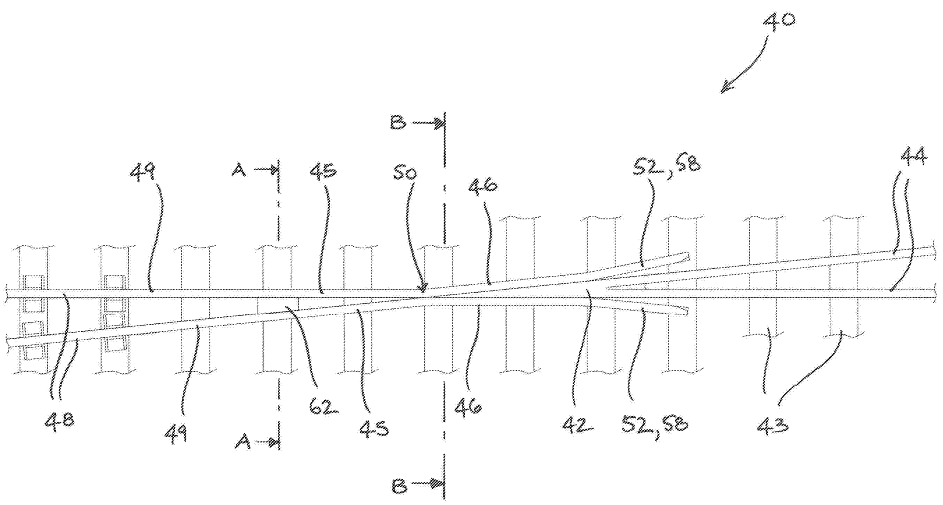


FIG. 2

2/12

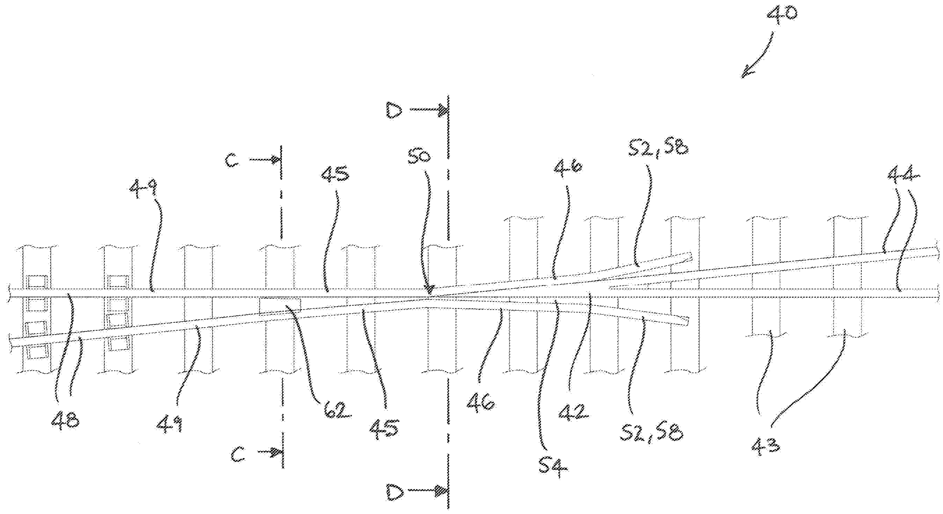


Fig. 3

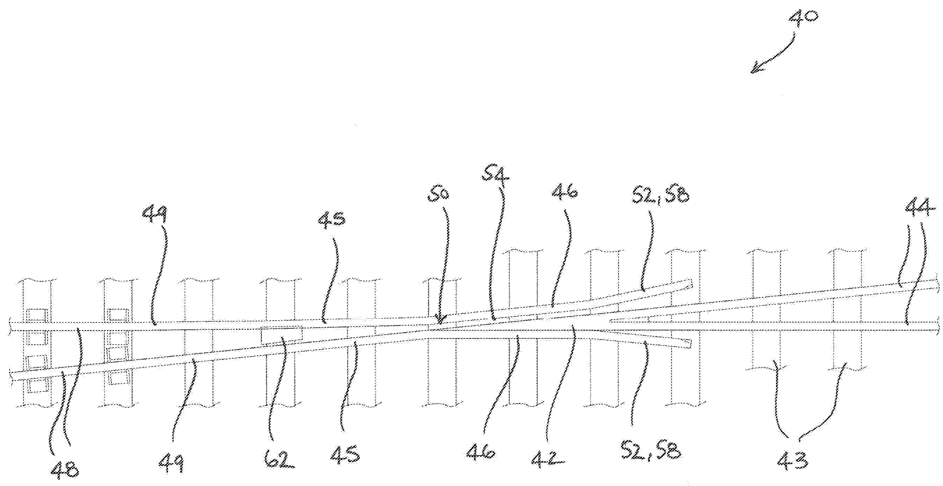
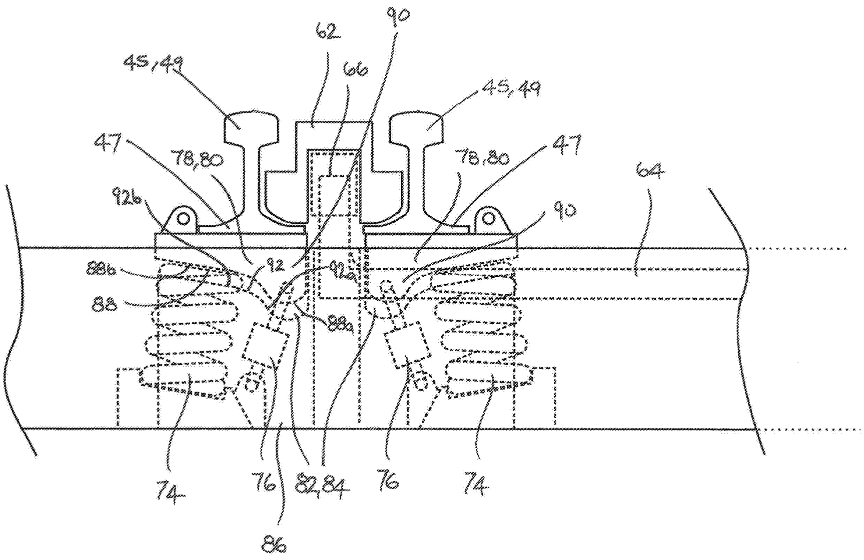


FIG. 4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78,80
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88b
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88a
74
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74
86

FIG. 5

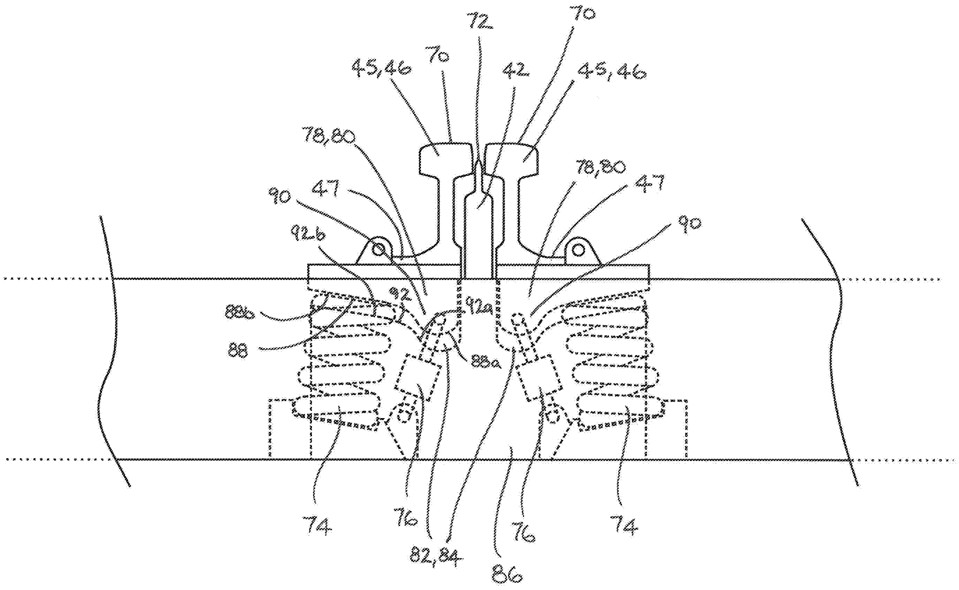
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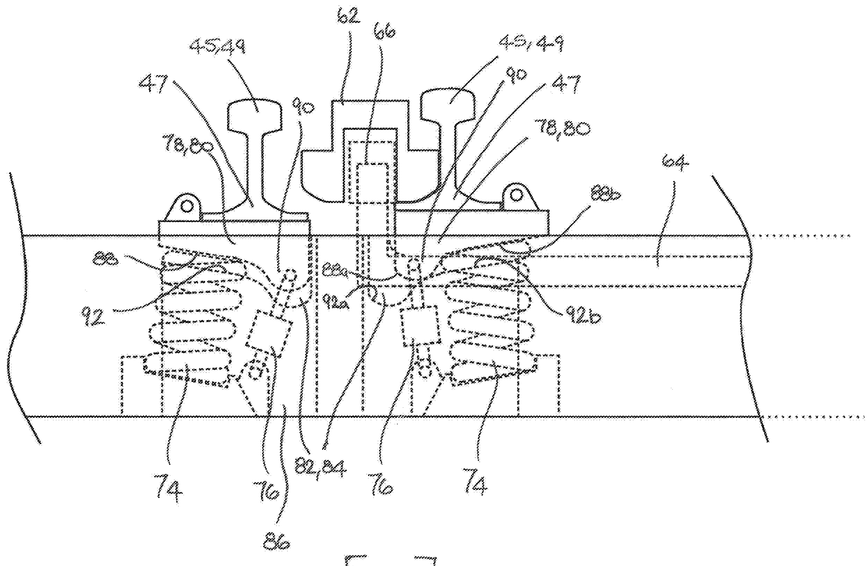
FIG. 6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82,84
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FIG. 7

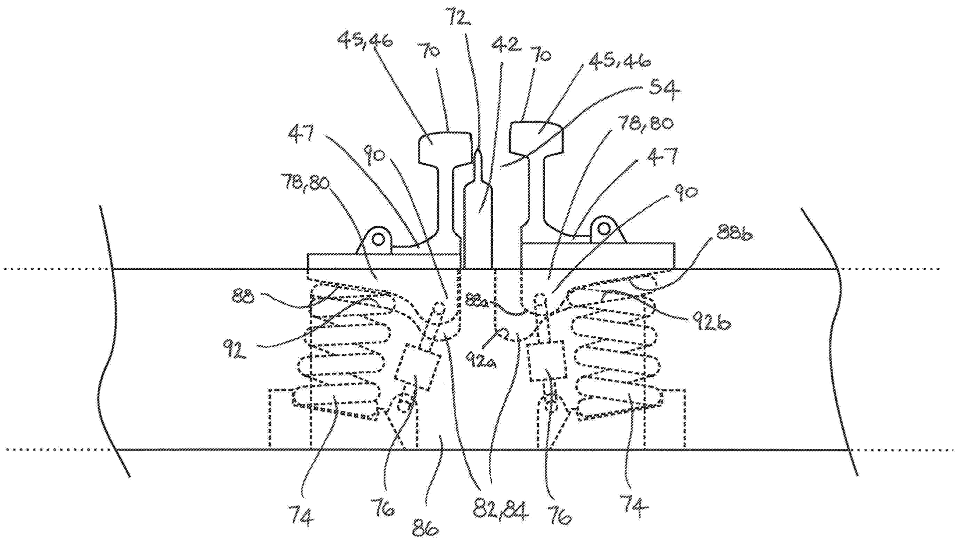
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FIG. 8

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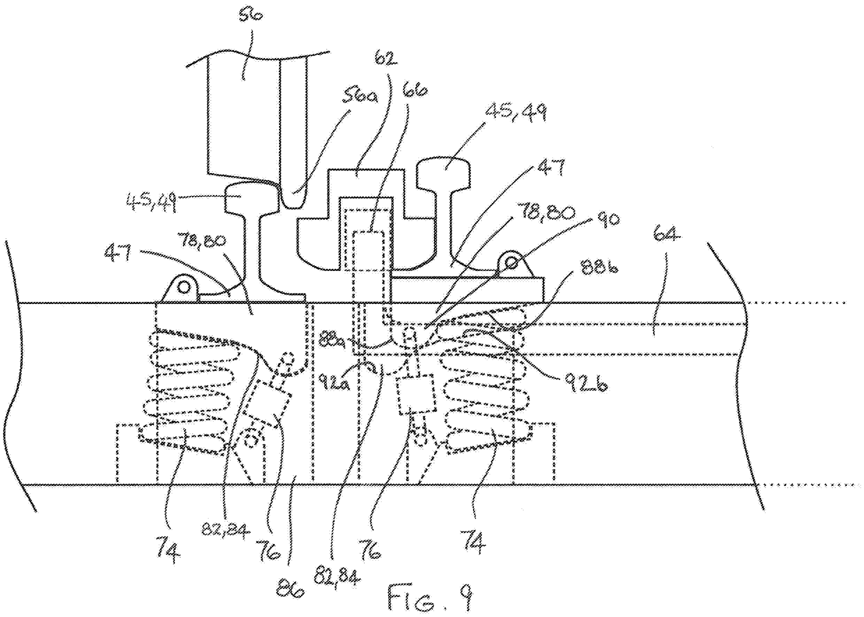
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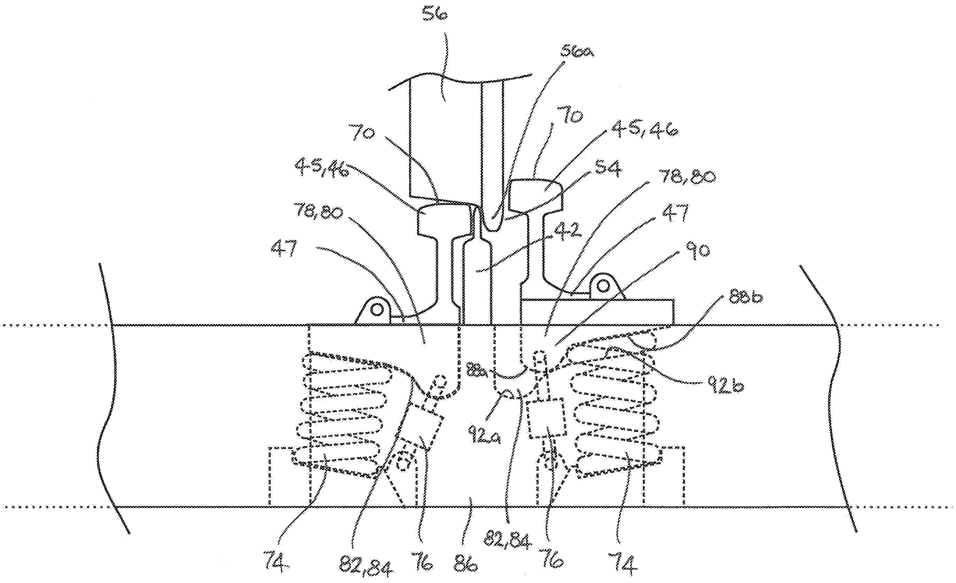
FIG. 9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78,80
78,80
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88a
92a
92b
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82,84
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82,84
76
74

FIG. 10

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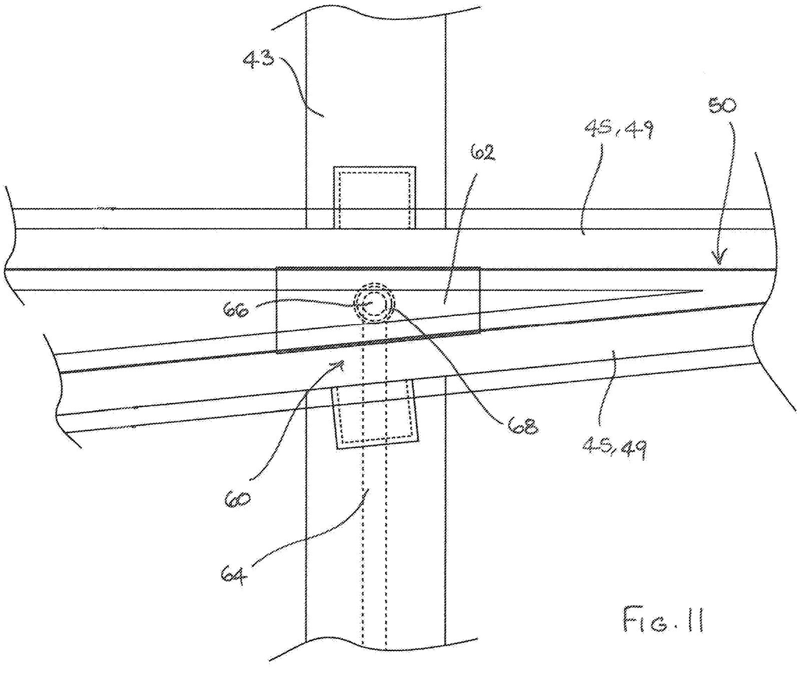

FIG. 11

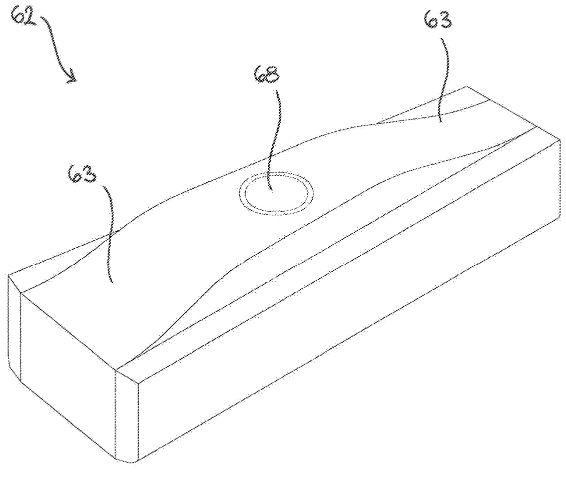

Fig. 12

RAILWAY TRACK CROSSING

Technical Field

The present disclosure relates generally to a railway track crossing at which the rails of two diverging railway tracks cross, for example defining a straight route and a turnout route. The diverging tracks are selectable in a conventional manner using a railway points arrangement so that rolling stock can travel along either the straight route or the turnout route.

Technical Background

A conventional railway track junction 10 which allows rolling stock to follow different routes through the rail network is illustrated in Figure 1. The railway track junction 10 includes a points arrangement 16, also known as a railway track switch, which enables different routes, for example a straight route 12 and a turnout route 14, to be selected through the railway track junction 10 by allowing rolling stock to transfer between different railway tracks. The points arrangement 16 illustrated in Figure 1 comprises a traditional set of railway points in which movable switch rails 18 are located between stock rails 20. The stock rails 20 are securely fixed to prevent movement and the free ends of the switch rails 18, which are linked via stretcher bars (not shown in Figure 1), slide transversely on suitable supports when commanded to move enabling either the straight route 12 or the turnout route 14 to be selected. In an alternative type of railway points, commonly known as a stub switch, the ends of a pair of movable switch rails are moved transversely between different positions into alignment with pairs of fixed stock rails to form a continuation of the main fixed rails on either side of the railway track junction.

The railway track junction 10 includes a railway track crossing 22 where the rails of one track (e.g. the straight track) cross the rails of the other track (e.g. the turnout track). Also known as a “common crossing” or “frog”, the railway track crossing 22 includes a v-section nose 24 which is formed by a pair of fixed diverging rails 26 (one of each track). A pair of wing rails 28 is located on either side of the nose 24 to strengthen the structure (transmit longitudinal stress) and to provide a smooth transfer of load.

In a “fixed” crossing such as that shown in Figure 1, which is the most common type of railway track crossing, the v-section nose 24 and wing rails 28 are fixed in position and the wing rails 28 are spaced apart from the v-section nose 24 by a small distance to form a groove 30 between each wing rail 28 and the nose 24 through which the wheel flanges of the rolling stock wheels can pass. Check rails 34 are provided to ensure that the wheels follow the correct route through the railway track crossing 22 and to ensure that the rolling stock does not derail. Before a wheel flange can engage in one of the grooves 30, the wheel must first traverse a gap 32 formed by the other groove 30 between the nose 24 and the other wing rail 28. The wheel is temporarily unsupported as it traverses this gap 32 and the impact between the wheel and the nose/wing rails results in both noise and an increased rate of wear of the nose 24 and the wing rails 28. In an attempt to address these problems, “swing nose” and “swing wing” crossings have been proposed.

In a swing nose crossing, the v-section nose 24 can move transversely so that it contacts one of the wing rails 28 and closes the gap 32 between the nose 24 and the wing rail 28 to provide a continuous length of rail for the wheels of the rolling stock. It will be appreciated that the position of the nose 24 (and hence which of the wing rails 28 it contacts) will vary according to the setting of the points arrangement 16 and, hence, whether the straight track or the turnout track needs to be selected. Swing nose crossings can either be “passive”, meaning that the v-section nose 24 is moved transversely by the wheels of rolling stock, or “active”, meaning that the v-section nose 24 is moved by an actuator arrangement. It should be noted that in a “passive” swing nose crossing, the v-section nose 24 is only moved transversely by the wheels of rolling stock when the rolling stock passes through the crossing in the trailing-point direction, i.e. the converging direction of the rails forming the v-section nose 24.

In a swing wing crossing, the v-section nose 24 is fixed and one or both of the wing rails 28 is movable. One example of a “passive” swing wing crossing is described in GB 1587042. In this passive arrangement, one of the wing rails is fixed whilst the other wing rail is flexible and can be moved transversely, from a closed position to an open position, by a passing wheel of rolling stock. In the closed position (set for the straight route), the flexible wing rail contacts the nose to provide a continuous running surface along the straight route for the rolling stock wheels. In the open position (set for the turnout route), the movable wing rail is pushed away from the nose by a passing wheel flange so that the rolling stock can travel along the turnout route. When following the turnout route, the wheels still have to traverse a gap between the fixed wing rail and the nose but this is not problematic if the turnout speed is quite low. In practice, there is an increasing demand for higher turnout speeds in order to increase network capacity. As a result, "active" swing wing crossings have been proposed in which an actuator arrangement is provided to move the wing rails transversely into and out of contact with the nose so that there are no gaps (i.e. a continuous running surface) when rolling stock travels along either the straight route or the turnout route.

Despite the obvious advantages of swing nose and swing wing crossings, including reduced wear of the v-section nose and wing rails, reduced noise and higher possible turnout speeds, they have seen limited use in the UK. This is because the aforementioned advantages are outweighed by disadvantages such as high cost, complexity and poor reliability. In fact, swing nose crossings are no longer fitted on the UK mainline rail network due to performance and reliability issues. There is, therefore, a need for a railway track crossing which overcomes these disadvantages.

Summary of the Disclosure

According to a first aspect of the present disclosure, there is provided a railway track crossing comprising:

a fixed crossing nose formed by a pair of diverging rails;

a pair of independently movable rails each having a wing rail section provided on each side of the fixed crossing nose, each rail being movable transversely from a closed position in which the wing rail section contacts the crossing nose to an open position in which the wing rail section is spaced from the crossing nose to form a groove that allows the passage of a wheel flange between the crossing nose and the wing rail section; and an actuator arrangement which is operable to move a selected one of the movable rails from the closed position to the open position, each movable rail being arranged to adopt the closed position in the absence of any force applied to it by the actuator arrangement;

wherein each movable rail includes a first mating feature which cooperates with a second mating feature to lock the movable rail in the closed position when the movable rail is loaded by the wheels of rolling stock passing through the railway track crossing.

The actuator arrangement moves a selected one of the movable rails from the closed position to the open position when rolling stock needs to travel along either the straight route or the turnout route. The other movable rail remains in the closed position, with its wing rail section in contact with the fixed crossing nose to provide a continuous running surface for the rolling stock wheels, and is positively locked in the closed position by the weight of passing rolling stock acting on the movable rail. The locking of each movable rail in the closed position is, therefore, achieved entirely passively by virtue of cooperation between the first and second mating features and does not rely on the actuator arrangement or other active locking mechanisms. The railway track crossing is consequently safer and more reliable than existing railway track crossings and can accommodate high turnout speeds because the wheels of passing rolling stock are fully supported throughout the crossing, in contrast to existing fixed crossings as discussed above.

Because the movable rails are arranged to adopt the closed position in the absence of any force applied by the actuator arrangement, the movable rails remain in the closed position at all times when the railway track crossing is not in use (i.e. when rolling stock is not passing through the railway track crossing). Accordingly, there is minimal risk of the movable rails becoming stuck in the open position, for example as a result of a blockage formed by debris becoming lodged in the groove between an open wing rail section and the crossing nose.

An additional advantage is that rolling stock can safely pass through the railway track crossing in any direction and along any route, irrespective of the route for which the movable rails are actually set. The railway track crossing does not, therefore, present a derailment risk.

Each movable rail may adopt a first position in which its wing rail section is elevated above the crossing nose when the movable rail is not loaded by the wheels of rolling stock and each movable rail may be arranged to move downwardly, to a second position, when loaded by the wheels of rolling stock passing through the railway track junction. The first and second mating features may be arranged to cooperate when the movable rail is loaded by the wheels of rolling stock and thereby moved to the second position. Accordingly, the simple loading of the movable rail by the passing rolling stock and the consequent downward movement of the movable rail causes the loaded movable rail to be locked in the closed position as a result of the cooperation between the first and second mating features.

A running surface of each wing rail section may be elevated above a running surface of the crossing nose when each movable rail is not loaded by the wheels of rolling stock and in the first position. The running surface of each wing rail section may be substantially level or substantially coplanar with the running surface of the crossing nose when the movable rail is loaded by the wheels of rolling stock and in the second position. This ensures that a continuous running surface is provided for the wheels of rolling stock passing through the railway track crossing.

The railway track crossing may include a plurality of biasing means. The biasing means may be arranged to bias each movable rail into the elevated first position when each movable rail is not loaded by the wheels of rolling stock. The biasing means thus support the movable rails in the longitudinal direction (i.e. along the running direction of the rails) and ensure that the movable rails adopt the elevated first position when they are not loaded by the wheels of passing rolling stock. The biasing means may be arranged to bias each movable rail into the closed position. The biasing means thus ensure that each movable rail adopts the closed position when each movable rail is not loaded by the wheels of rolling stock and when no force is applied by the actuator arrangement. The biasing means thus help to place the movable rails, and hence the railway track crossing, in a neutral, safe, state.

The railway track crossing may include a plurality of dampers. At least one of said dampers may be arranged to retard the movement of each movable rail from the second position to the first position and possibly from the open position to the closed position. The dampers ensure that each movable rail does not repeatedly spring upwardly from the second position to the elevated first position (under the action of the biasing means) as each wheelset passes through (there could be a few seconds between each wheelset passing). Additionally, should a wheelset pass through with the movable rails, and hence the wing rail sections, set incorrectly for the desired route, the dampers would prevent the unloaded movable rail trying to slam to the closed position immediately after each wheel flange passes through the groove between the wing rail section and the crossing nose. Although this is a somewhat unlikely occurrence, it could potentially prevent a lot of noise, vibration and wear as a large number of wheelsets (e.g. upwards of forty wheelsets) pass through per train.

The first and second mating features may comprise a concave profile section extending longitudinally along the running direction of the movable rails and a complementary convex profile section extending longitudinally along the running direction of the movable rails. The convex profile section may extend downwardly from a lower flange of each movable rail. The concave profile section may open upwardly to accommodate the convex profile section when the movable rail is in the second position.

The railway track crossing may include a locking element positioned beneath the movable rail in which the upwardly opening concave profile section may be formed. In one embodiment, a separate locking element may be positioned beneath each movable rail. In another embodiment, a single locking element may extend transversely between the movable rails and may include transversely spaced concave profile sections positioned beneath each movable rail.

The convex profile section and the concave profile section may each include a bearing surface which may be configured to guide each movable rail downwardly to the second position when the movable rail is loaded by the wheels of rolling stock passing through the railway track crossing. The bearing surfaces may be configured to guide each movable rail upwardly from the first position to a third position, elevated above the first position, when the movable rail is moved from the closed position to the open position by the actuator arrangement.

The actuator arrangement may include an actuating member which may be movable transversely to move a selected one of the movable rails from the closed position to the open position. The actuating member may be positioned between the movable rails. In some embodiments, each movable rail includes a converging rail section which converges between a fixed end and a constriction and the wing rail section diverges from the constriction on each side of the fixed crossing nose towards a free end. The actuating member may be positioned between the converging rail sections. The actuating member may be set to a neutral position out of contact with the movable rails, and in particular the converging rail sections, when the movable rails are in the closed position.

The actuating member may include a longitudinally extending contoured upper surface which may have ramp sections at longitudinally opposite ends thereof. The ramp sections advantageously help to guide and may possibly help to re-rail the wheels of rolling stock passing through the railway track junction in the extremely unlikely event that the movable rails, and hence the wing rail sections, are incorrectly set for the desired route.

The actuator arrangement may include a controllable drive mechanism which is selectively operable to transversely move the actuating member. The actuating member does not cooperate with the movable rails when they are in the closed position and can be moved into contact with only one of the movable rails at a time depending on the route that needs to be selected through the railway track crossing. The controllable drive mechanism may be backdrivable and may include a plurality of independent actuator drives, for example three actuator drives. The use of a plurality of independent actuator drives provides the required degree of redundancy.

Each wing rail section typically includes a flared section at its free end which is spaced from the crossing nose when the movable rail is in the closed position. This ensures that each wing rail section, and hence each movable rail, can be moved transversely by the wheel flanges of rolling stock executing a trailing-point movement in the converging direction of the rails forming the fixed crossing nose. As a result, the railway track crossing does not present a derailment risk to rolling stock executing such a movement even if the position of the movable rails, and hence the wing rail sections, is incorrectly set for the desired route, for example due to failure of the actuator arrangement.

Brief Description of the Drawings

Figure 1 is a plan view of a railway track junction including a set of railway points and a conventional “fixed” railway track crossing;

Figure 2 is a plan view of a railway track crossing according to the present disclosure in which each of the movable rails is in a closed position;

Figure 3 is a view similar to Figure 2 in which the railway track crossing is set for the straight route shown in Figure 1 with one of the movable rails in an open position;

Figure 4 is a view similar to Figures 2 and 3 in which the railway track crossing is set for the turnout route shown in Figure 1 with the other of the movable rails in an open position;

Figures 5 and 6 are cross-sectional views respectively along the lines A-A and B-B of Figure 2;

Figures 7 and 8 are cross-sectional views respectively along the lines C-C and D-D of Figure 3 showing the movable rail in the closed position in an unloaded state;

Figures 9 and 10 are cross-sectional views similar to Figures 7 and 8 showing the movable rail loaded by a wheel of passing rolling stock;

Figure 11 is an enlarged plan view of part of an actuator arrangement; and

Figure 12 is a perspective view of an actuating member.

Detailed Description of Embodiments

Embodiments of the present disclosure will now be described by way of example only and with reference to the accompanying drawings.

Figures 2 to 12 illustrate a railway track crossing 40 according to the present disclosure. The railway track crossing 40 forms part of a railway track junction 10 such as that shown in Figure 1 in place of the fixed railway track crossing 22.

Referring initially to Figures 2 to 4, the railway track crossing 40 includes a v-section fixed crossing nose 42, formed by a pair of diverging rails 44, and a pair of movable rails 45 each having a wing rail section 46 provided on each side of the fixed crossing nose 42. The diverging rails 44 and movable rails 45 are mounted in a conventional manner on fixed supports 43 in the form of sleepers or bearers. The movable rails 45 include converging rail sections 49 which converge from a fixed end 48 towards a constriction 50. The wing rail sections 46, which form a continuation of the converging rail sections 49, diverge from the constriction 50 on each side of the fixed crossing nose 42 towards a free end 52. Each of the movable rails 45 is independently movable between a closed position, shown in Figures 2, 5 and 6, in which its wing rail section 46 contacts the crossing nose 42, and an open position, shown in Figures 3, 4, 7, 8, 9 and 10, in which its wing rail section 46 is spaced from the crossing nose 42. When each movable rail 45 is in the open position, a groove 54 (Figures 3, 4 and 10) is provided between the crossing nose 42 and the wing rail section 46 to allow the passage of a wheel flange 56a. As can be clearly seen in Figure 2, each wing rail section 46 includes a flared section 58 at its free end 52 which is spaced from the crossing nose 42 when the movable rail 45 is in the closed position.

An actuator arrangement 60 (see Figure 11) is provided to move a selected one the movable rails 45 from the closed position to the open position by applying a transverse force to the selected movable rail 45. In the absence of any transverse force being applied to the movable rails 45 by the actuator arrangement 60, the movable rails 45 adopt the closed position shown in Figures 2 and 6 thereby placing the railway track crossing 40 in a neutral state. The actuator arrangement 60 includes an actuating member 62 located between the converging rail sections 49, at a position between the fixed ends 48 and the constriction 50.

The actuator arrangement 60 includes an actuator arm 64 which cooperates at one end with the actuating member 62 by virtue of engagement of an upwardly projecting leg 66 in a recess 68 formed in the actuating member 62. The other end of the actuator arm 64 cooperates with a trackside controllable drive mechanism (not shown), such as an actuator bank including a plurality of backdrivable independent actuator drives. The controllable drive mechanism can be operated in a conventional manner to displace the actuator arm 64, and hence the actuating member 62, transversely. The actuating member 62 can consequently be moved transversely into contact with a selected one of the movable rails 45, and in particular the converging rail sections 49, and can thereby displace the selected movable rail 45 transversely from the closed position to the open position.

When the movable rails 45 are in the closed position, they can move vertically between a first position, shown in Figures 5 and 6, and a second position, shown in Figures 9 and 10 (see the left movable rail 45). When the movable rails 45 are in the first position, the running surface 70 of the wing rail sections 46 is raised slightly above to the running surface 72 of the crossing nose 42. When the movable rails 45 are in the second position, the running surface 70 of the wing rail sections 46 is substantially coplanar with the running surface 72 of the crossing nose 42 thereby providing a continuous running surface for the wheels 56 of passing rolling stock.

The railway track crossing 40 includes a plurality of biasing means 74 in the form of compression springs which are spaced longitudinally along the running direction of each movable rail 45. The primary purpose of the biasing means 74 is to bias the movable rails 45 into the elevated first position shown in Figures 5 and 6 and to thereby prevent the movable rails 45 from moving to the second position under their own weight (i.e. from sagging). Due to the inclination of the biasing means 74 in the illustrated embodiment, it will be appreciated that the biasing means 74 also help to bias the movable rails 45 into the closed position, such that the wing rail sections 46 are in contact with the crossing nose 42. Referring to Figures 9 and 10, it will be seen that when a selected one of the movable rails 45 is in the closed position and is loaded by the wheels 56 of rolling stock passing through the railway track crossing 40 (the left movable rail in Figures 9 and 10), the load applied to the movable rail 45 displaces it from the elevated first position to the second position thereby compressing the biasing means 74. After rolling stock has passed through the railway track crossing 40, the movable rail 45 is biased upwardly to the elevated first position by the biasing means 74.

The railway track crossing includes a plurality of dampers 76 which, like the biasing means 74, are spaced longitudinally along the running direction of each movable rail 45. The dampers 76 retard the movement of the movable rails 45 in the upward direction, from the second position to the first position, and may also retard movement of the movable rails 45 from the open position to the closed position if the movable rails 45, and hence the wing rail sections 46, are incorrectly positioned for the desired route, as will be explained in further detail below.

Each movable rail 45 includes a first mating feature 78 in the form of a convex profile section 80 which extends longitudinally along the running direction of each movable rail 45. The convex profile section 80 projects downwardly from a lower flange 47 of each movable rail 46. The railway track crossing 10 also includes a second mating feature 82 in the form of an upwardly opening concave profile section 84 which extends longitudinally along the running direction of each movable rail 45. In the illustrated embodiment, a longitudinally extending locking element 86 is positioned beneath the movable rails 45 and the concave profile sections 84 are formed at transversely spaced positions in the locking element 86. As can be clearly seen in Figures 9 and 10, when the movable rail 45 which is in the closed position is loaded by the wheels 56 of rolling stock passing through the railway track crossing 40 so that it is moved to the second position, the convex profile section 80 engages the concave profile section 84. This engagement prevents any transverse movement of the movable rail 45, and hence the wing rail section 46, and ensures that the movable rail 45 is locked in the closed position, with the wing rail section 46 in contact with the crossing nose 42, whilst it is loaded by the wheels 56 of passing rolling stock.

Each convex profile section 80 includes a bearing surface 88 having a substantially semi-circular curved surface portion 88a provided by a shoulder 90 and a substantially linear surface portion 88b which is inclined upwardly away from the crossing nose 42 in the transverse direction. Each concave profile section 84 also includes a bearing surface 92 having a correspondingly shaped curved surface portion 92a and an upwardly inclined linear surface portion 92b. As will be clear from Figures 9 and 10, the various surface portions 88a, 88b, 92a, 92b of each bearing surface 88, 92 are in intimate contact when the movable rail 45 is in the second position. It is this intimate contact that locks the movable rail 45 in the closed position. When one of the movable rails 45 is moved from the closed position to the open position (i.e. the position adopted by the right hand movable rail 45 in Figures 7 to 10), the bearing surfaces 88, 92 cooperate to guide the movable rail 45 upwardly, from the first position to a third position which is elevated above the first position. More particularly, the curved surface portion 88a provided by the shoulder 90 contacts the curved surface portion 92a and the linear surface portion 92b thereby guiding the movable rail 45 upwardly.

The operation of the railway track crossing 40 will now be described with reference to the accompanying drawings.

When it is not intended that rolling stock should pass through the railway track crossing 40 and, therefore, when the railway track crossing 40 is not in use, the controllable drive mechanism is set so that the actuating member 62 adopts a neutral transverse position in which it does not apply any force to either of the movable rails 45. As a result both of the movable rails 45 adopt the closed position illustrated in Figures 2, 5 and 6. Furthermore, in the absence of any load applied to the movable rails 45 by rolling stock, the movable rails 45 are biased into the elevated first position by the biasing means 74 so that the running surfaces 70 of the wing rail sections 46 are elevated slightly above the running surface 72 of the crossing nose 42 (see Figure 6).

When it is intended that rolling stock should pass through the railway track crossing 40, a points arrangement is operated in a conventional manner to move switch blades to select a desired route for the rolling stock. At the same time, the controllable drive mechanism is operated to displace the actuator arm 64, and hence the actuating member 62, transversely to move the appropriate one of the movable rails 45 from the closed position to the open position. This is best seen in Figures 3, 7 and 8 which illustrates the movement of the appropriate movable rail 45 to allow rolling stock to follow the straight route 12 illustrated in Figure 1. The movement of the movable rail 45 opens a groove 54 between the wing rail section 46 and the crossing nose 42 through which the wheel flanges 56a of rolling stock wheels 56 can pass.

As rolling stock approaches the railway track crossing 40, the movable rail 45 that is in the closed position, and along which it is intended that rolling stock should travel, is gradually loaded by the wheels 56 of the approaching rolling stock and is thereby displaced downwardly from the elevated first position shown in Figures 7 and 8 to the second position shown in Figures 9 and 10. As the movable rail 45 is displaced downwardly from the elevated first position to the second position, the convex profile section 80 engages the concave profile section 84 as shown in Figures 9 and 10 and the movable rail 45 is thus locked in the closed position. As the wheelsets of rolling stock pass through the railway track crossing 40, the load applied to the locked movable rail 45 is intermittently reduced, typically for short periods of a few seconds each. During these short periods, the dampers 76 help to prevent the locked movable rail 45 from springing upwardly from the second position to the first position under the action of the biasing means 74.

After the rolling stock has passed through the railway track crossing 40 and load is no longer applied by the wheels 56 to the locked movable rail 45, the movable rail 45 is biased by the biasing means 74 back to the elevated first position shown in Figures 7 and 8. The movement of the movable rail 45 from the second position to the elevated first position is retarded by the dampers 76, thereby ensuring a controlled upward movement. Finally, the controllable drive mechanism is operated to displace the actuator arm 64, and hence the actuating member 62, transversely to a neutral position thereby allowing the displaced movable rail 45 to move from the open position shown in Figures 7 to 10 to the closed position shown in Figures 5 and 6 to thereby close the groove 54. The railway track crossing 40 is, thus, returned to the neutral state shown in Figures 2, 5 and 6. Movement of the displaced movable rail 45 from the open position to the closed position may occur due to the inherent stiffness and natural bend of the movable rail 45 and may be assisted by the biasing means 74. The dampers 76 may also help to retard the movement of the movable rail 45 from the open position to the closed position.

In the unlikely event that the railway track crossing 40 should fail when it is in the neutral state with both of the movable rails 45 in the closed position (for example due to failure of some part of the actuator arrangement 60), rolling stock can still safely pass through the crossing 40 without significantly increasing the derailment risk. In this mode of operation, the wing rail sections 46, and hence the movable rails 45, can be displaced transversely by the wheel flanges 56a of passing rolling stock. The railway track crossing 40 thus acts like a conventional “passive” swing wing crossing. The dampers 76 also help to prevent the movement of the movable rail 45 from the open position to the closed position after each wheel flange 56a has passed through the groove 54.

Although extremely unlikely, it is possible that the railway track crossing 40 could fail when set for a particular route but that rolling stock may need to pass through the railway track crossing 40 along the other route. For example, the railway track crossing 40 may be set for the straight route as shown in Figure 3 whereas rolling stock may need to follow the turnout route. As will now be explained, the railway track crossing 40 advantageously allows rolling stock to follow the correct route without derailment, albeit at much reduced speed, even when the crossing 40 is set for an incorrect route.

Referring again to Figure 3, when rolling stock is executing a trailing-point movement along the turnout route in the converging direction of the rails 44 forming the crossing nose 42, the wheel flanges 56a engage the flared section 58 of the closed wing rail section 46 and push it, and hence the movable rail 45, transversely to the open position.

There will, of course, be a gap between the crossing nose 42 and the other wing rail section 46, which has been displaced to the open position by the actuator arrangement 60, that will need to be traversed by the wheels 56. In extreme cases, the wheels 56 may fall to ground or onto a support 43. However, it will be seen from Figure 12 that the upper surface of the actuating member 62 includes ramp sections 63 at longitudinally opposite ends thereof. These ramp sections 63 help to re-rail the wheels 56 onto the movable rail 45 that has been displaced to the open position by the actuator arrangement 60 and with which the actuating member 62 is, therefore, in contact.

When rolling stock is travelling in the opposite direction and executing a facing-point movement along the turnout route in the diverging direction of the rails 44 forming the crossing nose 42, the wheels 56 derail and ride down the ramp section 63 of the actuating member 62 before the wheel flanges 56a are captured by the crossing nose 42 and re-lifted to follow the appropriate one of the diverging rails 44.

In all of the scenarios described above in which the railway track crossing 40 is incorrectly set to allow the passage of rolling stock along the desired route, it will be understood that the check rails 34 (see Figure 1) ensure that the rolling stock ultimately follows the correct route.

Although exemplary embodiments have been described in the preceding paragraphs, it should be understood that various modifications may be made to those embodiments without departing from the scope of the appended claims. Thus, the breadth and scope of the claims should not be limited to the above-described exemplary embodiments. Each feature disclosed in the specification, including the claims and drawings, may be replaced by alternative features serving the same, equivalent or similar purposes, unless expressly stated otherwise.

Unless the context clearly requires otherwise, throughout the description and the claims, the words “comprise”, “comprising”, and the like, are to be construed in an inclusive as opposed to an exclusive or exhaustive sense; that is to say, in the sense of “including, but not limited to”.

Any combination of the above-described features in all possible variations thereof is encompassed by the present invention unless otherwise indicated herein or otherwise clearly contradicted by context.

Claims

1. A railway track crossing comprising:

a fixed crossing nose formed by a pair of diverging rails;

a pair of independently movable rails each having a wing rail section provided on each side of the fixed crossing nose, each rail being movable transversely from a closed position in which the wing rail section contacts the crossing nose to an open position in which the wing rail section is spaced from the crossing nose to form a groove that allows the passage of a wheel flange between the crossing nose and the wing rail section; and

an actuator arrangement which is operable to move a selected one of the movable rails from the closed position to the open position, each movable rail being arranged to adopt the closed position in the absence of any force applied to it by the actuator arrangement;

wherein each movable rail includes a first mating feature which cooperates with a second mating feature to lock the movable rail in the closed position when the movable rail is loaded by the wheels of rolling stock passing through the railway track crossing.

2. A railway track crossing according to claim 1, wherein each movable rail adopts a first position in which the wing rail section is elevated above the crossing nose when the movable rail is unloaded and each movable rail is arranged to move downwardly to a second position when the movable rail is loaded by the wheels of rolling stock passing through the railway track junction, the first and second mating features being arranged to cooperate when the movable rail is loaded and thereby moved to the second position.

3. A railway track crossing according to claim 2, wherein a running surface of the wing rail section is substantially coplanar with a running surface of the crossing nose when the movable rail is loaded and in the second position.

4. A railway track crossing according to any preceding claim, wherein the railway track crossing includes a plurality of biasing means.

5. A railway track crossing according to claim 4 when dependent on claim 2 or claim 3, wherein the biasing means are arranged to bias each movable rail into the elevated first position when each movable rail is not loaded by the wheels of rolling stock.

6. A railway track crossing according to claim 4 or claim 5, wherein the biasing means are arranged to bias each movable rail into the closed position.

7. A railway track crossing according to any of claims 2 to 6, wherein the railway track crossing includes a plurality of dampers, at least one damper being arranged to retard the movement of each movable rail from the second position to the first position.

8. A railway track crossing according to claim 7, wherein the damper is arranged to retard the movement of the movable rail from the open position to the closed position.

9. A railway track crossing according to any preceding claim, wherein the first and second mating features comprise a longitudinally extending concave profile section and a complementary longitudinally extending convex profile section.

10. A railway track crossing according to claim 9, wherein the convex profile section extends downwardly from a lower flange of each movable rail and the concave profile section opens upwardly to accommodate the convex profile section when the movable rail is in the second position.

11. A railway track crossing according to claim 10, wherein the railway track crossing includes a locking element in which the upwardly opening concave profile section is formed.

12. A railway track crossing according to according to claim 11, wherein a separate locking element is positioned beneath each movable rail.

13. A railway track crossing according to claim 11, wherein a single locking element extends transversely between the movable rails and includes transversely spaced concave profile sections positioned beneath each movable rail.

14. A railway track crossing according to any of claims 9 to 13 when dependent on claim 2, wherein the convex profile section and the concave profile section each include a bearing surface configured to guide each movable rail downwardly to the second position when the movable rail is loaded by the wheels of rolling stock passing through the railway track crossing.

15. A railway track crossing according to claim 14, wherein the bearing surface is configured to guide each movable rail upwardly, from the first position to a third position that is elevated above the first position, when the movable rail is moved from the closed position to the open position.

16. A railway track crossing according to any preceding claim, wherein the actuator arrangement includes an actuating member positioned between the movable rails, the actuating member being movable transversely to move a selected one of the movable rails from the closed position to the open position.

17. A railway track crossing according to claim 16, wherein each movable rail includes a converging rail section which converges between a fixed end and a constriction, the wing rail section diverges from the constriction on each side of the fixed crossing nose towards a free end, and the actuating member is positioned between the converging rail sections.

18. A railway track crossing according to claim 16 or claim 17, wherein the actuating member includes a longitudinally extending contoured upper surface having ramp sections at longitudinally opposite ends thereof.

19. A railway track crossing according to any of claims 16 to 18, wherein the actuating member is set to a neutral position out of contact with the movable rails when the movable rails are in the closed position.

20. A railway track crossing according to any of claims 16 to 19, wherein the actuator arrangement includes a controllable drive mechanism which is selectively operable to transversely move the actuating member.

21. A railway track crossing according to any preceding claim, wherein each wing rail section includes a flared section at its free end which is spaced from the crossing nose when the movable rail is in the closed position.

22. A railway track crossing substantially as hereinbefore described and/or as shown in the accompanying drawings.

Intellectual Property Office

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Claims searched:	1-22	**Date of search:**	24 September 2014

Patents Act 1977: Search Report under Section 17

Documents considered to be relevant:

Category	Relevant to claims	Identity of document and passage or figure of particular relevance
A	-	FR 2392168 A1 (DIETRICH) See EPODOC abstract, WPI abstract accession number 1978-F1704A and figures.
A	-	WO 94/19542 A1 (BUTZBACHER) See EPODOC abstract, and WPI abstract accession number 1994-264830, and figures.
A	-	GB 1470668 A (JAPAN NATIONAL RAILWAY) See whole document.
A	-	KR2010/0098098 A (VOESTALPINE) See EPODOC abstract, WPI abstract accession number 2010-L82157 and figures.

Categories:

X	Document indicating lack of novelty or inventive step	A	Document indicating technological background and/or state of the art.
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Field of Search:

Search of GB, EP, WO & US patent documents classified in the following areas of the UKC^{X} :

Worldwide search of patent documents classified in the following areas of the IPC

E01B

The following online and other databases have been used in the preparation of this search report

WPI, EPODOC

International Classification:

Subclass	Subgroup	Valid From
E01B	0007/14	01/01/2006
E01B	0007/00	01/01/2006
E01B	0007/18	01/01/2006