**Systems Engineering - Railway Operators get it too!**

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Abstract

Systems Engineering techniques are increasingly applied with success in rail engineering design. Rail operating professionals, seeing the advantages have grasped the essentials with alacrity. This paper describes examples of such application, illustrating how time, cost and risk have been reduced and performance and operability improved, in ‘softer’ operational design of the rules, methods of working and competence management systems necessary to deliver the railway for customers. Examples over the last 15 years in the UK are referenced. The paper argues that System Engineering practitioners should view railway operations professionals as advocates, champions and co-practitioners and that System Engineering must embrace operational design in a systematic way rather than as an afterthought. The paper shows that use of System Engineering approaches by non-engineers is a successful model for others to adopt and provoke debate on practical steps that System Engineering practitioners should consider when developing new projects.

Purpose

The purpose of our paper is to:

- Show that Rail Operators are fully bought into System Engineering techniques and that the Operational Design philosophy espoused in this paper is complementary to and builds upon such techniques.
- Demonstrate that the use of Operational Concepts enables a common language to be used between engineers and operators in order to elicit operational requirements in a systematic and robust manner.
- Support the idea that the design of the railway should be operationally led with engineering requirements designed to support the overall Operational Design.
- Identify barriers and blockers; and hopefully some ways forward to overcome these.

Background

Systems Engineering has its roots outside the rail sector having spread from its original homeland in complex systems development in defence and aerospace. Given the imperative pre-occupations of real-time train service delivery, and the tendency for railway operators to be focused on the immediacy of safety and performance, it may be surprising to some that rail operating professionals were ‘early
adopters’ of Systems Engineering approaches. We hope to demonstrate that we have successfully tailored Systems Engineering to the non-engineered, operational elements of the whole system that makes up a railway. Indeed we shall show that such techniques have been applied to the rail operations domain for over a decade and a half.

Here we must be clear that in talking ‘operations’ we mean the safe and efficient management of train service delivery and its associated activities. We are not necessarily referring to ‘Concepts of Operation’ in the INCOSE sense. Rather we mean the non-engineered elements, the people, the rule books and other operational documents and processes they use to execute operational tasks. Rail operators use technology and equipment, underpinned by rules and competence to run the railway to a plan, and to anticipate and address perturbations and emergencies safely and efficiently.

INCOSE define ‘Operations’ in a process context as denoting: ‘a working method or a philosophy that focuses principally on cause and effect relationships (or stimulus/response, behaviour, etc) of specific interest to a particular domain at a particular point in time’ ¹

Within the European framework the 2008 Interoperability Directive defines railway operation as a functional sub-system covering: ‘the procedures and related equipment enabling a coherent operation of the different structural (or engineering) subsystems’. National operating rules and procedures provide the basis for human interaction with the sub-systems.

Put more simply: ‘Running the Railway’.

**Introduction to Operational Design**

All railways are technology-intensive undertakings. Increasingly some are almost entirely automated such that reliance on rules and procedures is abnormal, rare and inherently risky. To a greater or lesser extent though, all railways remain complex combinations and interactions of People, Technology and Rules (Procedures) that are required to integrate to deliver their functions.

![Diagram of People, Rules, Technology](Image)

**Figure 1** Railway Systems are comprised of three major sub-systems and their correct development and integration is mission-critical [With thanks to Simon Lane onetime CEO of Singapore NE Line].

These comprise:

1. INCOSE Systems Engineering Handbook V 3.3.2.(2011)

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• People (train drivers, signallers, station staff, maintainers and others);
• The rules or operational procedures they use (rule books, timetables, emergency plans and others, and;
• The technology they control (trains, control centres, communications, ticketing and other systems).

Even on highly-automated rail systems, these things remain true albeit that the functional allocations are different; with careful operational design for perturbed and degraded operation being vital, though much less so for normal operation.

One further thing that we should make clear, this is not about the development and application of a systematic Human Factors Integration Plan and user-centred design processes although these are complimentary and indeed essential approaches. Rather, this is about those elements of the operational railway delivery for which the functional allocation is to people who carry our procedures, rules, methods of operation.

As passengers, you may be blissfully unaware of the many operational people safely, quietly and efficiently delivering your service:

'We are the boys who make no noise'²

History of Systems Engineering in Operational Design

Non-engineers were early adopters in rail. The earliest traceable application of what we would recognise as formal Systems Engineering to operational development is found in the work undertaken in the Railtrack Network Management Centre project in 1997 and later in the West Coast Route Modernisation’s TCS developments in 1998.

Network Management Centres

The Operational Concept for Network Management Centres (NMC) was based upon a number of workshops held by the project with senior operators from both Railtrack (Infrastructure owner prior to Network Rail) and the Train Operating Companies. The workshops primarily were held to elicit the detailed operational requirements.

However, it soon became clear that expecting operators to stay focused on a large number of one line requirements statements would be impossible to deliver. Instead these senior operators required a narrative document illustrating how a Network Management Centre would or could contribute to a punctual and safe railway. Importantly, this included consideration of how the roles of the people would have to change, and how they would need to interrelate and communicate with each other and with the new systems functions that would be available. It became clear, for example, that the signaller would become more of a very short term planner and that the role of controller would be that of a more strategic planner, that is, the main difference between the roles would be time!

Once the narrative document was produced it became easier to relate to other industries such as National Grid and the privatised water companies (both industries are concerned, at some level, with the movement of product from ‘A’ to ‘B’ on time and safely) and then to use some of their techniques in the management of the train service.

To validate the Operational Concept, operational scenarios were created based on the ‘life of an operational train’ and these scenarios served:

² ‘I Tried to Run a Railway’: Gerard Fiennes (1967)
These scenarios were more akin to use cases and were built up to cover all aspects of operations including:

- Train preparation;
- Train Dispatch;
- Routing a train normally;
- Restrictions of speed;
- Terminating at destination.

Once these ‘normal working’ scenarios were created then a degraded mode analysis was applied to discover the relationship between the scenario and the Operational Concept. Lastly, engineering operations were applied since these are the ‘maintenance phase’ of the Operational Concept and cannot be considered as degraded. The Operational Scenarios were created using swim-line diagrams that showed how the actors involved within the operational process being delivered interacted with each other over time.

This approach ensured that stakeholders could clearly see how the NMC would be applied to the operational delivery of the railway, and to explore in a radical fashion such issues as job re-design, competence, roles and functions. If a systematic approach had not been taken it is unlikely that the overall value of the NMC would have been realised and would have jeopardised operational implementation.

Most of us know of course that NMC was not taken forward initially by Network Rail in the early 2000’s but now finds fresh momentum in the very similar Traffic Management System project, which is well under way, and builds, not least, on this early pioneering operational Systems Engineering work.

**Train Control System (TCS) (West Coast Route Modernisation Programme)**

A similar operational approach was taken with the scoping of the TCS from 1998 when the project became part of the West Coast Route Modernisation Programme following the review of Railtrack activities by management consultants McKinsey. TCS was intended to deliver ETCS Level 3 signalling to the West Coast Main line as part of the route upgrade.

A large number of operational scenarios were created to help elicit operational requirements as well as understanding key issues when the TCS railway interacted with the conventional railway. The scenarios were developed by professional operators and engineers working together creating swim-line diagrams (as with NMC). These swim-line diagrams enabled all contributors to converse using a common language and to drive out the high-level operational requirements for subsequent development. This process also revealed and clarified aspects of the ETCS ‘system’ which perhaps had not been determined and designed correctly to take account of operational needs; some of these issues remain problematic for ETCS implementations even today.

Much of the operational work carried out within this project was taken forward and help informed the subsequent National ERTMS Planning work and the Cambrian ERTMS Pilot project.

**Manchester South Capacity Improvement Project**

Concurrent with these projects Railtrack had already selected a novel (to the UK) signalling system for application on the Manchester South project. Much has been written and even more said about this

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3 INCOSE Systems Engineering Handbook V 3.2.2 (2011)
project, and the authors have deep personal experience of it from several perspectives. Given that neither the NMC nor West Coast TCS projects proceeded into service however, Manchester South was the first project where formal System Engineering focused on the operational elements successfully delivered ‘for real’.

It quickly became clear that the systems selected for the Manchester South project, were intended to be ‘lifted- and dropped’ from their native Italian rail domain into a ‘Mancunian’ domain; but that little formal thinking had been undertaken as to operational application.

The interfaces, equipment and operational routines which were integral to the Italian design had not been considered from a viewpoint of operational use in the UK. Remember that operational users in this case included people who regularly worked with Edwardian mechanical technology and were being asked to relate to 20th Century Italian technology. In defence terms this would be similar to leaping from flying a Sopwith Camel into a Eurofighter - and perhaps one optimised for the Italian Air Force at that.

Building on the experience with NMC, one of the authors, encouraged by the other, developed from scratch an Operational Concept to define what had gone undefined hitherto. It was proved too late to use this operational concept to re-define the engineering requirements for most of the system, already set. Instead focus had to be on defining requirements for operational re-design: training, competence management, operational routines and the supporting safety assessments to ensure proper integration.

![Diagram courtesy Mike Morua, Atkins](image)

Figure 2 Manchester South: Operational Systems Engineering

(Diagram courtesy Mike Morua, Atkins)

The Operational Concept went through several iterations concurrently with actual engineering implementation as the full functionality of the system was explored and the operational users got to understand its potential. Writing a clear conceptual document enabled users and stakeholders to see how the system would be used in language they could relate to. This was particularly vital in helping to define several aspects of implementation such as:
• Validating or correcting a host of assumptions that had been defined in the absence of clear evidence.
• Eliciting formal requirements for operational training, competence and operational rules; in turn these requirements could be formally validated and verified.
• Verifying that the Railway Safety Principles & Guidance⁴, the national rule book and operational rules could be applied without change of principle - up to that point this issue had gone unexplored.
• Determining that improvements to the method of route setting were needed for sound operational reasons rather than just for stated preference.
• Contributing to the demonstration of the safety case arguments - defining what was delivered and why it could be safely operated.

Certain aspects of the system were particularly ‘novel’ and operational scenarios written in workshops with end users explored how they would be used in the UK. In the case of one engineering sub-system these scenarios exposed that it had no direct application value at all for the project and it was de-scoped, offering a first cost saving as well as avoiding having undesired redundant functions available for use by the curious.

The Operational Concept also provided a basis against which the actual delivery of the operational requirements could be traced. As operational implementation progressed to deliver the defined requirements the project also developed a clear and simple process of operational readiness validation. While such an approach had been in use on LUL, validation of operational readiness had not, to the authors’ knowledge been formalised previously on the national network. Systematic formal testing and sign-off that the operational elements of the project were in place was undertaken, sampling and confirming evidence that operational requirements had been satisfied.

This approach of operational readiness validation, pioneered on the Manchester South project was subsequently adopted as standard for all West Coast Route Modernisation projects.

It should be noted that the availability of the Signaller’s Training simulator was of particular value, enabling:

• Training of the signallers.
• Evaluation of how effectively that training had been absorbed into competence.
• Testing of emergency and degraded scenarios in a low risk, non-operational environment.

The simulator has a high degree of fidelity to the main system.

Subsequent projects

Both authors were later involved in the development by Her Majesty’s Railway Inspectorate of the Railway Safety Publication ‘Safe Movement of Trains’ (2003, re-issued 2007)⁵, which provides information helpful to Railway Operators on the fundamental issues to address in operational design of operating rules. This publication adopted what might be termed ‘reverse - Systems Engineering’ approached by a working group de-composing the then current operational practices and rules, stripping away technology-specific attributes to expose what the fundamental higher level requirements were; hidden amongst nearly 200 years of evolution.

⁵ Now published by the Office of Rail Regulation

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Page 6 of 13
These techniques have also been employed over the last 10 years led by the authors to assist the implementation of axle counters (now Network Rail’s train detection of choice) in 2004, Proceed on Sight Authority (PoSA) in 2005, as well as the GSM-R (Global Standard for Mobile radio-Rail) Operational Design which is now being rolled out nationally.

The use of Operational Conceptual documents, operational scenarios and the elicitation of formal operational requirements have addressed aspects of overall design that had not been considered fully or formally by engineers working on these new technologies, or indeed by many operations personnel. Unaddressed, implementation would have been challenging, entailing rapid costly re-design and delay or worse, latent safety risks ready to trap users.

The GSM-R Operational Concept including the original Operational Scenarios (an appendix to the Operational Concept) have been recognised in 2006 by the RSSB Board as a Relevant Strategy for the purpose of Railway Group Standards, in effect putting operational design constraints on the engineering requirements included in Railway Group Standards. By having a formal Operational Concept many of the satisfaction arguments required by a System Engineering process can be obtained and also many of the conflicts that arise in the development and deployment of engineering requirements can be resolved at an early stage in the lifecycle.

The use of these techniques has become more commonplace within the rail industry with the Cambrian ERTMS Project (2007-2011) and the New Approach to the Rule Book (2009-onwards) being two further examples. This latter project was exclusively an operational project to re-design and re-structure the Rule Book and used a succinct Operational Concept document to engage with stakeholders whose views ranged from hesitancy through to suspicion. Engagement thus obtained made all downstream development more robust and enabled exposure of real issues which otherwise might have been ignored. It delivered this goal defined by INCOSE:

"A Primary Goal of a concept document is to capture, early in the system life cycle, an implementation-free understanding of stakeholders’ needs by defining what is needed, without addressing how to satisfy the need"\(^6\)

Towards the end of 2011, as part of the New Approach to the Rule Book, the RSSB Board supported the publication of the Operational Concept for the Main Line Railway which enables all projects to determine themselves whether their project requires changes to the Rule Book or not. This Operational Concept acts as the scope of the Rule Book and delivers the aim of the Operational Railway – The core aim of the fundamental operational principles is to enable the safe and timely delivery of people and goods to their destination – through nine fundamental operational principles. We have included these as an appendix to this paper as we would like to see them adopted and referenced in all future rail projects that affect operations (see Appendix A).

**Barriers and Blockers**

If one saying is seen as true by many on and off the railway it is: ‘that anyone can run a railway except those who run the railway’ however it is interesting to note that in an article in Modern Railways by Roger Ford the vast majority of industry leaders are ‘old school operators’\(^7\). The users of the system are traditionally the forgotten people in an innovative project whose engineering team may see them as a hangover from the past and only to be used as a last resort. Some, even in System Engineering, believe in the infallibility of their project to deliver functional engineering elegance relegating the user to

\(^{6}\) INCOSE Systems Engineering Handbook, V3.2.2 (2011)

\(^{7}\) Modern Railways April 2012
some kind of monitor of the system (a role not well suited to humans!) and then to have to suddenly jump in when the going gets tough and the machine switches off.

The main barrier to a robust Operational Design is the risk of taking a purist engineering approach. The solution to this is to engage professional operational input to projects from the outset, not only because ultimately rail systems will be used by operators (they are the customers), but also because they must be an intrinsic part of the systems engineering activities throughout the life-cycle if the system is to be optimised for its intended functions.

Of course it may not be easy to obtain Operational Design resources, most operating personnel are quite correctly required to keep our existing system moving, so this capability must be built into system engineering project teams so that operational requirements are developed, delivered, verified and validated throughout the project, not at the end of it.

Operational personnel have some movement to make also- they must develop the competence to think systematically about projects and develop skills as Systems Engineers. Fortunately we have proven that such a transformation is not only possible, but welcomed and valuable. Simple learning interventions have been part of our work on the projects we have mentioned, showing and explaining how a systematic approach brings benefits. We have not attempted to ‘sheep-dip’ everyone in the sophisticated and complex Systems Engineering techniques available, but brought fellow operators along through showing the value, benefits and outcomes available from such approaches. No-one exposed to this thinking has demurred and many, seeing the benefits, provide a valuable source for support to future projects.

Conclusions

If you have detected by now that we are advocates of this approach then we have attained one of our implicit aims in this paper. Jon Elphick and Duncan Kemp have attempted to define\(^8\) certain leadership styles in the kingdom of Systems Engineering. The authors would not claim to be Perfectionists and hopefully are not regarded as Pirates! But we believe in a systematic approach and this may make us Pragmatists or even Prophets!

We have demonstrated that rail operational professionals see the benefits of employing Systems Engineering approaches to conceive, design and deliver those elements of the ‘railway system’ that are delivered by non-engineered means. Systems are being used to deliver operational train services in Great Britain today where this work has helped assure success. Furthermore the approach has won stakeholder buy-in as being logical, clear, organised and comprehensive, but more so as being demonstrably valuable.

Operators (as end users) are only too aware of the need to have a functional, cost effective, and operable solutions resulting from engineering activities. We have successfully applied Systems Engineering approaches to the operational design of soft aspects of projects over 15 years, to the exploration and re-definition of requirements for hard engineering aspects of systems and to pure operational rules requirements and design as well.

Systems Engineering practitioners should view railway operations professionals as advocates, champions and co-practitioners for their profession, provided that the techniques are adapted and adaptable for the particular domain.

\(^{8}\) J Elphick and D Kemp: The One-eyed Systems Engineer – Pirate or Prophet? An analysis of the effectiveness of different systems engineering leadership styles: INCOSE (2012)
In exchange we urge System Engineers to embrace operational design in a systematic way throughout projects and indeed from their inception rather than, as occurs too often, the equipment and technology is designed built and tested only for the project to turn to the task of ‘ah now we need to write the operational instructions and rules for its use’.

The Royal Academy of Engineering suggests that engineers should consider the user (operator) in these terms:

*If someone who will be affected by the system were to be sitting beside you when you take design decisions, would he be happy with what you have done?*

What better than to have the rail operators actually sitting and working with you on those design decisions?

Our use of Systems Engineering approaches is a successful model for others to adopt and we hope that by illustrating how we have taken these real, live projects forward, it will provoke debate, and action on practical steps that Systems Engineering practitioners should consider when developing new rail projects, with the commitment and involvement of professional rail operators as allies.

References

5. Railway Safety Principles and Guidance (various chapters and dates) Published now by the Office of Rail Regulation.
7. Modern Railways (April 2012)

Biographies

Steve and Nigel's careers have seen them often work together on a range of rail operational projects and in different roles.

Nigel Murphy
is Principal Project Director for the Rail and Transit sector of Atkins North America based in Atlanta, Georgia. Nigel is a Professional Rail Operations and Safety Specialist who has been involved in the planning, development, assurance and approval of a wide range of rail systems and rolling stock projects over a career of 29 years. He has worked on assignments in Europe, the Asia-Pacific region and in Europe, as well as in the United Kingdom. On many of these projects he focused on the operational integration of new or complex systems to deliver enhancements and performance improvements to rail and transit networks. Nigel's earlier career experience was in front line, general management and policy/standards setting roles in heavy rail in the UK. He is not an engineer but values working with engineers to encourage systematic consideration of the users’ requirements, issues of operability and systems “mission” on the projects he works on.

With others, Nigel has also pioneered use of Systems Engineering approaches to ‘soft projects’ such as operations procedural requirements, design, integration and operational validation; and is currently preparing a Paper to explore these themes. Nigel is a Fellow and founding member of the Institution of Railway Operators, a member of INCOSE and currently co-chair of the Transportation Working Group and an Associate of the IRSE.

Steve Roberts
is Head of Traffic Operation and Management at the RSSB (Rail Safety and Standards Board). He railway career began in front-line train operations and he has therefore an excellent end-user’s perspective on rail systems and their operation. Steve worked for British Rail, Regional Railways and then with Railtrack HQ in an operational standards role. Steve progressed to lead the operational design work on the Network Management Centre project and West Coast TCS (Train Control System) projects, which pioneered the use of systems engineering to operational job and procedural design. UK. Latterly Steve's work as Head of New Systems, saw him - a non-engineer- leading the evolution of a range of new rail technologies for GB mainline operational application including GSM-R, Axle counters, and ETCS. This role included work in Europe on the Operations TSI and the development, simulation and testing of Operating Rules for ERTMS Level 2.

Appendix A - Operational Principles

Core Operational Aim

The core aim of the fundamental operational principles is to enable the safe and timely delivery of people and goods to their destination.

Fundamental Operational Principles

1. The method of signalling must maintain a space interval between trains that is safe.

Under normal operation, this underlies the ‘method of signalling’ in each set of block regulations. The concept of ‘one train in one section’ is an example of how this principle is delivered. The principle is equally relevant to variations from that concept, such as permissive working (when the safe distance through controlled means reduces to zero), and to abnormal and degraded operations when the space interval may be controlled by verbal instructions or by use of a Pilotman. The concept of maintaining a safe distance between trains also applies when an overlap is provided, or a constraint on movement.
applied, to ensure that following or converging movements, or trains approaching one another on a single line cannot come so close together that the effectiveness of any space interval is destroyed.

2. **Before a train is allowed to start or continue moving, it must have an authority to move that clearly indicates the limit of that authority.**

This principle is worded to apply to the issue of any authority to make a movement. It covers situations in which the movement may be made with or without any need for further clarification. Examples of this are when a signal is cleared, or an actual or electronic token indicates that a single line section can be occupied. It also applies when the extent of the authority has to be explained verbally or in writing, or when continuing confirmation that authority to move is given, as for example during a movement controlled by a shunter.

3. **Trains proceeding over any portion of line must not be obstructed in a way that threatens their safety.**

This principle covers two major potential operational situations in which a risk could arise. The first is at level crossings where road users might cause such a hazard. The second is when engineering work is to be carried out that makes a line unsafe for trains to pass. In that case, it must be possible to make any required movements in connection with that work safely, and that work must not expose trains to risk whilst they are passing on adjacent lines that are open to traffic.

4. **Trains must be prevented from proceeding onto a portion of line if it is known or suspected that it would not be safe for them to pass.**

The purpose of this principle is threefold. Firstly, information that a portion of railway is known, or believed to be, unsafe must be promptly and effectively communicated. Unsafe in this context might relate to any defect in track, signalling equipment, electrification equipment or structures, or to any type of obstruction, including any presented by a train or vehicle. Secondly, action must then be taken to prevent the approach of any trains. Thirdly, subsequent movement can only take place after it has been confirmed whether it is safe to permit any movement, and appropriate conditions have been established. This last includes making sure that all those involved are aware of what is required to happen.

5. **Trains must not be allowed to begin or continue their journeys until it is clear it is safe for them to do so.**

The scope of this principle is that prior to any type of train being allowed to start its journey all necessary preliminary activities have been completed. This includes confirmation that in all respects the train is able to run at its intended speed, or the permitted speed has
been reduced to overcome any deficiencies. It also requires that the train has been correctly formed up, coupled and marshalled, that traffic has been properly loaded and secured (and in the case of dangerous goods, identified and contained). Work on the train must have been completed, passengers have been safely loaded and doors closed, and that authority to move has been obtained. Although the complete range of activity is necessary before starting a journey from origin, at least some of these will be repeated at any subsequent stop en route where the train formation is altered, or passengers join and leave the train.

6. Trains must only be allowed to operate over any portion of line as long as the rolling stock is compatible with the infrastructure on that portion of line.

This principle relates to the requirements to confirm that any traction unit or rolling stock has authority to operate over any given route before doing so, in respect of features such as dimensions or axle loadings. This includes possession of a form RT3973 or other authority to operate subject to any conditions of travel, or restrictions on routing. A further example would be confirmation that the vehicle and container combination on a train conforms to dimensions that may pass over a specific route. Another issue would be a requirement to be equipped with particular equipment to operate over a specified route, such as train protection or electric traction equipment. It would also address situations in which compatibility can be achieved by applying a reduction in speed, as for example when the automatic brake power available may be insufficient to comply with the available braking requirements and signal spacing.

7. Trains must not continue to operate after they have been found to be unsafe in any respect, until measures have been taken to allow them to continue safely.

This is the equivalent of the principle 4 but referring to defective vehicles or on-train equipment that may prevent that train continuing normally without presenting a hazard. The controls relevant to fires on trains, dangerous goods incidents or displaced loads are also addressed. As with principle 4, the controls are threefold. Firstly, information that a train or vehicle is known, or believed to be, unsafe must be promptly and effectively communicated. Second, action must then be taken to prevent the approach of any trains if they would be put at risk, and finally, subsequent movement can only take place after it has been confirmed whether it is safe to permit any movement, and appropriate conditions have been established including making sure that all those involved are aware of what is required to happen.

8. People must be kept a safe distance from moving trains.

This single principle is designed to address the variety of situations in which personal safety can be at risk, including workforce activities ‘on or near the line’, the risks to members of the workforce who spend a small part of the working day in that environment (such as traincrew required to alight from a train), and ensuring that passengers at stations
are made aware by signage or warnings that they should keep well away from passing trains.

9. The workforce must be protected from the particular hazards associated with electrified railways.

In defining the scope of this principle it has been concluded that the operational controls against harm arising from electrified railways are almost exclusively directed at the workforce, as legitimate customers do not come into close proximity with hazardous equipment, and trespassers are excluded by physical barriers designed for that purpose and dissuaded by prohibitions.