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Railway Research
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Edited by Krzysztof Zboinski

RAILWAY RESEARCH - SELECTED TOPICS ON DEVELOPMENT, SAFETY AND TECHNOLOGY

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http://dx.doi.org/10.5772/59893
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First published in Croatia, 2015 by INTECH d.o.o.
eBook (PDF) Published by IN TECH d.o.o.
Place and year of publication of eBook (PDF): Rijeka, 2019.
IntechOpen is the global imprint of IN TECH d.o.o.
Printed in Croatia

Legal deposit, Croatia: National and University Library in Zagreb

Additional hard and PDF copies can be obtained from orders@intechopen.com

Railway Research - Selected Topics on Development, Safety and Technology
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p. cm.

ISBN 978-953-51-2235-7

eBook (PDF) ISBN 978-953-51-6648-1

Meet the editor

Krzysztof Zboinski is a Full Professor at the Faculty of Transport, Warsaw University of Technology, Poland. His general areas of interest are mechanical engineering and transport. His specialization is in vehicle dynamics. His specific area of research concerns railway vehicles. He is the author and coauthor of more than 200 publications and research elaborations, among which the most important and internationally known concern modeling rail vehicle dynamics, including multibody systems, computer methods, and curved track motion; stability in a curved track; dynamics in transition curves; and simulations of vehicle dynamics in general. These publications are subject to more than 150 international citations all over the world. He has been a leader of 33 collective and individual research projects and has 32 years of academic experience.

Contents

Preface

The railway serves people as a significant means of transport since the mid-19th century. Its development has passed through different stages, from intensive growth at the time of the Industrial Revolution, the role of dominating means of transport in the first half of the 20th century, certain collapse in the second half of the 20th century connected with effective competition from road transport, to characteristic renaissance in passenger transport, resulting from appearance of high-speed trains, and persevering tries to rebuild importance of the freight transport, e.g., through the introduction of multimodal transport, at the end of the 20th and the beginning of the 21st century.

In all these periods, engineers and researchers paid a lot of attention to improvement of effectiveness in broad terms, safety, comfort of travel, and unification of transport means and infrastructure. The imposed increase in traveling speed, by competition of air transport among others, put before designers very high and qualitatively new demands, both in terms of technical performance, particularly the speed, as well as safety and comfort. The realization of these objectives was possible to a high extent thanks to the intensive development of the technology in general and computer technology in particular, which includes both the hardware and the software and their contribution into our lives in the second half of the 20th century.

While talking about railways development, the economic issues cannot be ignored. The payback period of investment expenditure for the modern railway infrastructure, including the most modern traffic control and command systems, and also for the modern rolling stock is long. Besides, the benefits from investments in railway development are often difficult to determine precisely. Due to these reasons, only the developed countries can afford new investments. The other countries face difficulties in dealing with these issues and sometimes simultaneously even with maintaining what they already have. In spite of that, it has to be admitted that the present times are the good period for railways, when looking at it globally.

This book focuses on selected research problems of contemporary railways. The first chapter is devoted to the prediction of railways development in the nearest future. The particular areas of intensive development at specific geographic locations for them are defined. The next two chapters are focused on the problems of safety. The first of these chapters discusses the safety and security problem in general, precisely from the system point of view. In the second one, both the general approach and a particular case study of a critical incident with regard to railway safety are presented. In the fourth chapter, the question of railway infrastructure studies is presented, which is devoted to track superstructure. Both the experimental results and numerical calculations are of interest in the chapter. In the fifth chapter, the modern system for the technical condition monitoring of railway tracks is discussed. The compact on-board sensing device and the diagnosis software are presented. The last chapter focuses on modeling dynamics of the railway vehicle, taking the numerical approach. Also, two example research issues of the vehicle dynamics are resolved with the use of numerical simulation, where the dynamical models are exploited.

The content of the book comes mainly from offers for the book chapters received by the editor from the authors while organizing the book project under the working title "Railway" In fact, the influence of the editor on this content is negligible. The scope of this book is quite broad. Despite the eclectic content of the book and the limited number of chapters, the editor hopes that many readers will find this book interesting and useful.

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Railways in Renaissance — Review of Achievements and Reflection on Prospects

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Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/61273

Abstract

The authors introduce railway renaissance by considering the rail mode's inherent strengths, energy frugality, and developmental role. They address the research question: *Does a new post-renaissance normal now prevail?* The research progresses a multivariate design that they developed to a case study approach as proliferation of private railway operators as a consequence of renaissance has constrained access to formerly public information. The study examined four countries, Brazil, Russia, India, and China, and one region, the Gulf Cooperation Council States, whose railways have advanced substantially in recent years through implementation of high speed, heavy haul, heavy intermodal, and urban rail. It also examined the migration of countries from the previously identified Fortuitous and Insecure railways clusters to the Enlightened, Progressive, and Assertive clusters. It found advances in institutional learning with respect to design of interventions to achieve renaissance, ownership and funding, market structure, as well as networking and expanding strategic horizons. It concluded that countries that have embraced the railway renaissance have been able to reposition their railways to play a substantial role in their economies and societies, and that a new normal has emerged, with the rail mode now a formidable contender in high-speed, high-volume, heavy-traffic corridors.

Keywords: Energy, intervention design, new normal, strategic horizon, railway renaissance

1. Introduction

1.1. Manifestation of railway renaissance

From their origin in the Industrial Revolution, first-generation railways grew to dominate land transport, ultimately peaking in the late 1940s. Thereafter, they declined in the face of disruptive competition from other transport modes that had flourished on the momentum of the World War II technology boom. Why did rail not get onto the same bandwagon? By then most countries had either nationalised or regulated their railways, to restrain their monopolistic power, and they had become too unresponsive to technology and market opportunities to get in on the action.

Nevertheless, railways have experienced renaissance in an increasing number of countries in recent decades. The authors have researched the associated phenomena, and published their findings in [1–7]. This chapter continues that research stream, and addresses two additional considerations that have arisen since it started, namely, the transition from finite to renewable energy sources, and the revival of the rail mode's developmental role in economic geography. While the image of global railway renaissance originally appeared pixelated, every incremental investment in one of the four market spaces where railways can compete vigorously has increased the resolution and clarity to a level where it is appropriate to once again review achievements and reflect on prospects for the future.

Railways manifest renaissance by having exploited their three genetic technologies, supporting (the ability to carry heavy loads), guiding (the ability to travel at high speed), and coupling (the ability to connect many vehicles together), that set them apart from other transport modes. The three genetic technologies and the four market spaces that they support, namely high speed (passenger), heavy haul, heavy intermodal and urban rail, have been described in detail in [1–4, 6], so this chapter will only recapitulate as necessary to introduce its content. Together, they have turned railways around from grave decline and set them on new growth curves in each of the four market spaces mentioned. They have realised new opportunities by taking markets away from air over medium distances, from road and maritime transcontinental and intercontinental container movements, and created new markets in rampant urban rail.

1.2. Rail's inherent strengths

Rail's inherent strengths have been explained before in the references mentioned in subsection 1.1. What follows is, therefore, a brief recapitulation with emphasis on subsequent learning.

By comparison with other transport modes, such as air that offers three degrees of freedom of movement (longitudinal, lateral, and vertical) at relatively high cost, and road that offers two degrees of freedom of movement (longitudinal and lateral) at moderate cost, the rail mode is constrained to a single degree of freedom of movement (longitudinal) by its guideway, back and forth on a predetermined, inflexible route. To compete effectively against transport modes that take advantage of more degrees of freedom of movement to get closer to the ideal of ubiquitous access, railways must offer compensating advantages. Fortunately, a guideway endows railways with three genetic technologies that at once distinguish it from, and offer advantages over, all other transport modes. The rail mode's inherent competitiveness resides in its genetic technologies, and it must draw on them for competiveness and sustainability in the aggressive global logistics and mobility markets.

A pair of flanged wheels on an axle running on a pair of rails fixed to the ground precisely defines the spatial relation between rail and wheel. The three genetic technologies that stem from this relation are first, the supporting genetic technology, or the ability to carry heavy loads. The application path of the wheel load to the rail is precisely known and it is therefore possible to design the wheel-rail system to carry much heavier axle loads than can road vehicles. The highest heavy haul railway axle load in current operation is 40 tonnes in the Australian Pilbara, with aspirations to 42 tonnes. By contrast, vehicles on the rail mode's major land transport competitor, road, are driven autonomously; one cannot define the application path of the wheel load to the road precisely, but must design the entire road surface to accept the applied load. Consideration of economic relations among the amount of traffic and capital and maintenance expenditure has converged permissible road vehicle axle loads in the 8–9 tonne range around the world. Interestingly, where one can define the vehicle path more precisely and design the road structure accordingly, higher axle loads are possible: Thus, bus rapid transit axle loads can go as high as 12½ tonnes on specially designed runways. What about maritime transport, also a form of surface transport that can carry heavy loads? Vessels displace their own mass of water, hence their draught increases in proportion to their mass until buoyancy and deadweight forces are in equilibrium. Thus, while their cargo deadweight might be several times higher than the payload of a heavy haul train, they are nevertheless also subject to physical constraints such as limited draught, while hull drag in a medium more viscous than air incurs higher energy consumption than railways except at very low speeds, but more on that in the next section.

Second, the guiding genetic technology endows ability to travel at high speed. Once again, by contrast to its major land transport competitor, railway vehicles are precisely guided by wheel-rail forces, and can therefore safely attain much higher speeds than road vehicles that are still generally guided by humans exercising control through road-to-tyre friction forces. Freight and passenger vehicles are generally limited to no more than 120 km/h on public roads, whereas entry level on standard gauge track is 160 km/h with the ultimate maximum commercial service currently at 380 km/h. Railways can therefore generally service destinations faster and further than road, and at medium distances can also offer credible competition to aviation.

Third, the coupling genetic technology endows the ability to connect multiple individual vehicles to deliver high freight and/or passenger throughput capacity. The rail mode is therefore able to scale capacity to match demand within wide limits. For comparison, the number of trailers in Australia's commercial road trains is expressed by only a single digit; the number of barges in a single tow on the Mississippi river may be expressed by two digits; but no transport mode other than rail expresses its vehicle combinations by three digits, as for example South Africa's Sishen-Saldanha iron ore trains at 342 wagons, currently the longest in the world, and many other three-digit heavy haul train lengths around the world. For passenger traffic, coupling railway vehicles together essentially reduces the headway between them to zero. Thus, for example, single railway cars carrying say 200 passengers at two-minute headway would carry 6,000 passengers per hour per direction. Coupling ten of them together in a multiple unit train increases throughput to nearly[1] 60,000 passengers per hour per direction on the same infrastructure. Other modes do not support this magnitude of capacity scalability, while some modes do not scale at all, for example, aviation.

After a post World War II pessimistic interlude, during which sceptics questioned the rail mode's future and many stakeholders lost faith in it, optimism returned when appreciation of its genetic technologies stimulated vigorous new growth curves, in high-speed intercity starting in 1964 in Japan; heavy haul when mineral railways around the world recognised North American heavy freight standards in 1972; heavy intermodal or container double stacking when railroad deregulation in the United States released pent-up competitive forces in 1980;, and contemporary urban rail spontaneously around the world from the start of economic globalisation in 1989. These events are widely acknowledged as having launched a global railway renaissance that would position the mode as inherently competitive against other modes in high-volume corridors.

1.3. Energy's vital role

Although rail is known to be an energy-efficient transport mode, it is nevertheless valuable to contextualise this attribute to develop an appreciation of what role railways should fulfil in an energy-scarce future.

Rail's energy efficiency essentially spins off from its genetic technologies. The supporting genetic technology requires a strong wheel-to-guideway interface to sustain heavy axle loads, and rail's steel-on-steel system provides just that. The wheel and rail deflect minimally to develop a small contact patch between them, and steel-wheel-on-steel-rail rolling resistance and associated energy consumption, is therefore very low. By contrast, a rubber pneumatic tyre on a road deflects much more to develop a contact patch sufficiently large to sustain the load, which increases rolling resistance by comparison with rail and hence also the associated energy consumption.

The guiding genetic technology supports high speed, which in turn allows more potential energy to be converted to kinetic energy and vice versa by widening a train's actual speed range over undulating grades, thereby reducing both energy consumed during traction and energy dissipated during braking. High speed also reduces journey times, and hence reduces the period during which auxiliary services such as heating, ventilation, air conditioning, lighting, and catering must operate. Consequently, high speed passenger trains actually consume less energy per passenger for a given journey than conventional passenger trains [8].

The coupling genetic technology averages grades under a long train, thereby reducing traction energy input and braking energy dissipation by comparison with a short train, particularly for heavy freight trains that are limited to comparatively low speed, which in turn limits the acceptable speed variation range over crests and sags and hence also the quantum of kinetic energy that can be converted to potential energy and vice versa. Coupling also reduces aerodynamic resistance because the frontal area of a train in relation to its length is small compared to any other transport mode; for example, the ratio of the frontal area to vehicle length for a TGV Duplex train is one-tenth that of an Airbus 380 aircraft, both double deckers.

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1 Increasing the number of cars on a train increases its length, and hence the time it takes to clear signals for a following train. Capacity therefore scales at slightly less than in direct proportion to the number of cars.

The rail mode, therefore, occupies an energy consumption sweet spot that other transport modes cannot match. All other things being equal, propulsion energy consumption is a function of total resistance to motion, whether due to aerodynamic, hydrodynamic or mechanical phenomena, and speed. Railways essentially undercut the resistance to motion, expressed in Newtons per tonne, of all other transport modes. Relative to pipeline, railways have lower resistance from speeds higher than ≈3 km/h. Relative to maritime in displacement mode where resistance rises exponentially with speed, railways have lower resistance from speeds higher than ≈20 knots (≈40 km/h). In addition to being faster, railway routes can also be materially shorter, for example Beijing to Athens Piraeus is 8,500 km overland, but 16,000 km by sea. In the same way that high speed trains consume less energy because the journey time is shorter, freight trains consume less energy when the journey distance is shorter. Relative to road trucks, railways always have lower resistance, ≈50% at low speed, increasing to ≈80% at 100 km/h [9]. Relative to aviation, railways always have lower resistance, although it cannot match aviation's top speed. Nevertheless, railways can be attractive even on relatively long centre-city to centre-city journey times, e.g., the fastest current Beijing to Wuhan schedule averages 285 km/h over 1,229 km, a performance that aviation would be hard put to beat when accounting for time to commute to the airport, check in, check security, reclaim baggage, and commute to destination in addition to the scheduled flying time.

Relatively low braking and traction adhesion inhere in the rail mode's steel-wheel-on-steel-rail technology. Whereas contemporary high-performance passenger trains use a high proportion of motored axles and therefore accept comparatively steep grades despite low adhesion, exploiting the coupling genetic technology with locomotive-hauled trains, freight or passenger, results in heavy trailing loads that generally require comparatively flatter grades than rubber-on-road technology to balance braking or tractive effort against total resistance and gravity component. The flatter a ruling grade, the more long-wave topography influences it and the longer the distance between grade sign changes. Thus, in a given terrain, railway grades tend to be longer and flatter than road grades. Where the downgrade gravity component exceeds mechanical plus aerodynamic resistance, any vehicle generates instantaneously surplus energy, which needs to be dissipated or stored on board, or exported to where it can be consumed or stored. Road vehicles, singly or even in combination, have higher aerodynamic resistance than long trains, so on their comparatively short down grades they generate less instantaneously surplus energy to be stored, and hybrid road vehicles with on-board energy storage have become workable. However, current on-board storage technologies are totally inadequate for line-haul railways, particularly for heavy haul but also for heavy intermodal with its progressively higher rolling resistance: Therefore such trains need to dissipate instantaneously surplus energy on board, or conduct it off-board for consumption or storage elsewhere [5, 7].

Because railway rolling resistance is very low, its instantaneous traction and braking power requirements are largely determined by grade undulations. The resultant wide swings between demand and regeneration make it desirable to exchange energy in both directions with its environment. Railways and renewable energy are thus natural symbionts, particularly when railways are linked to a sizeable grid that can also store instantaneously surplus energy when necessary. Railways can then both consume and regenerate energy without restraint. For scale, locomotives and wind-turbines are of similar size, in the range of 2½–6 MW. While electrification infrastructure is an expensive way for railways to exchange energy with their environments, guided transport in general has the advantage that electrification need be confined only to routes defined by the guideway. Hence the emergence of inductive recharging of catenary-free light rail vehicle batteries or capacitors during dwell time halts.

It is common cause that railways are more energy efficient than other land transport modes, and at the higher speeds of which it is capable, it is also more energy efficient than waterborne transport. Nevertheless, since the first major oil crisis four decades ago, despite technological progress, potential for cost-effective energy efficiency improvements and policy efforts, the transport system has not fundamentally changed [10]. Nevertheless, recently published research has found that despite technological advances, there are still situations where freight railways do not achieve the best energy efficiency that they can [7]. Thus, while heavy freight baseline diesel traction uses comparatively expensive, but nevertheless available fuel, holds no systemic interaction surprises, and readily scales throughput, electric traction can decouple railways from on board power generation and facilitate access to other electricity generators and consumers. However, to realise its full potential, electric traction would require matching vertical alignment to locomotive performance characteristics: providing graduated release train braking; providing catenary, transformers, and feeder lines; providing high-capacity, low-latency, long-lived energy storage; and implementing net metering to render transactions transparent. Where a smart grid is within reach, the storage should come with that, and renewable energy would likely be available. There is still some way to go.

1.4. Rail's developmental role

When railways dominated land transport during their initial growth phase, they shaped the development of countries and continents, peaking in that role around mid-20th century. Thereafter, road and air transport together came to own the market until high speed railways commenced new growth in the 1960s, heavy haul in the 1970s, heavy intermodal or double stacking in the 1980s, and finally contemporary urban rail in the 1990s, thus establishing the four sub-modes of the railway renaissance. Railways in renaissance offer high capacity with high efficiency and low cost in well-defined high traffic volume corridors. After changing the economic geographies of Japan and France by means of high speed trains, developing remote regions throughout the world by means of pit-to-port heavy haul operations, shifting substantial traffic from road to rail in double-stack container trains, and supporting rapid urban rail growth in developed and developing countries, it is evident that the rail mode is once more stimulating widely dispersed economic and social development through each of its four new growth curves.

While the rail mode's initial growth phase spawned monolithic railways that introduced the first motorised transport ever with minimally differentiated offerings, renaissance has encouraged railways to do what they do best in particular market spaces in the face of strong competition from other modes. Renaissance rail is therefore always a high-capacity, high-performance transport mode in well defined corridors. Its initial investment is relatively expensive, and particularly, infrastructure needs therefore to be long lived. While it is possible to implement rail solutions in already highly developed settings, for example, deploying monorail in the air space above existing roadways as the only remaining option to introduce urban-guided transit, the rail's combination of high performance and low energy consumption are best exploited by positioning it as the foundation on which other transport modes should build to support integrated intermodal solutions. Thus, particular building-block solutions have emerged that spatial and transport planners can customise and assemble as required. Consider domestic and international airports connected to their catchment areas by urban, regional, and high speed rail; mixed-use, transit-oriented development that maximises both access to public transport and interchange with non-motorised transport; dedicated high-speed corridors that bring agglomeration benefits to otherwise disconnected communities and conurbations; logistics parks that add value to line-haul rail service through integration with intermodal facilities and distribution centres; dedicated heavy haul railways that link ore bodies with ports; and dedicated freight corridors that convey double-stacked containers from ports to their hinterland; all competitive, effective, and efficient solutions.

Renaissance rail's contemporary developmental role is nowhere more evident than in the BRIC (Brazil, Russia, India, China) countries, which are playing an increasingly influential role in the global economy [11], and who are positioning railways as the backbone of their transport systems in fulfilment of projections that they will, in due course, join the world's major economies. This chapter will examine them and the Gulf Cooperation Council States in more detail in Section 3.

2. The research approach

2.1. New research questions

One could hypothesise that, half a century after its launch, the railway renaissance might have completed its mission, and that for railways a new normal prevails. The hypothesis is important, because not all railways have experienced renaissance. What then is to become of the stragglers? The research stream underlying this chapter initially identified a suite of technologies that encouraged the rail mode to enter vigorous new growth curves in the high speed, heavy haul, heavy intermodal, and urban rail market spaces. The logical research question at this time must then be: *What outcome has the railway renaissance facilitated in countries that have purposefully embraced it*?

The research question then is: Does a new post-renaissance normal now prevail, and as a corollary, does there seem to be any viable alternative?

2.2. Recap of variables used

The following groups of variables, used to examine positioning of railways in relation to their setting, have been carried over from previous research [2, 4], with comment here on their continued relevance, and the need to introduce new ones to address the changed global setting in which railways now find themselves.

Business Group represents the way in which line haul railways deal with their task (variables: *Infrastructure Operator Diversity*, *Train Operator Diversity*, *Information Technology Leverage*, and *Total Road Network*, *Motorways* and *Paved Roads Percentage*).

Competitiveness Group represents the way in which railways position themselves to compete in their chosen or allotted market spaces (variables: *R&D Level*, *Relative Maximum Axle Load*, *Relative Maximum Speed*, *Distributed Power Presence*, *Heavy Haul Presence*, *High-speed Intercity Presence*, *Heavy Intermodal Presence*, *Motive Power Type*, and *Attitude to Competition*). Nowadays pre-competitive research is undertaken at the country or industry level, while competitive research is undertaken within industries, hence latest technologies are freely available in a global market and the R&D level has been deleted.

Contribution Group describes the railways' contribution to their host society (variables: *Network Coverage*, *Transport Task—Freight* and *Passenger Traffic Volume*, *Employment Created*, and *Initiative Source*, except that the latter has been redefined as *Initiative Direction*, with scale poles *Authority Initiative* and *Market Initiative*).

Networkability Group describes the extent and gauge of track, and the contiguous network beyond a country's borders (variables: *Narrow, Standard,* and *Broad Gauge; Networkability;* and *Strategic Horizon*).

Ownership Group describes the industry structure (variables: *Infrastructure-operations Separation, Infrastructure* and *Rolling Stock Ownership Locus*, and *Infrastructure* and *Rolling Stock Commitment Horizon*).

Society Group describes the railway setting (variables: *Country (Name)*, *Economic Freedom Index*, *Population*, *Gross National Income*, *Physical Size*, *Determinism*, and *Climate-change Position*, except that *Determinism* has been deleted in favour of the redefined *Initiative Direction*, and *Climate-change Position* has been superseded by the more comprehensive *Presence of Renewable Energy Sources*, *Ability to Regenerate Energy*, and *Availability of Smart Grids*).

Sustainability Group describes adaptation and fit (variables: Infrastructure and Rolling Stock Investment Capacity, Stakeholder Satisfaction Level, Service Reputation, Safety Reputation, and Subsidy Influence). Note, however, that subsidies and social obligations may be obscured to the public domain. It is therefore proposed that Subsidy Influence is no longer relevant, and that Infrastructure and Rolling Stock Investment Capacity are adequate proxy measures for sustainability. Likewise, Presence of Independent Railway Safety Regulator and Presence of Automatic Train Protection should supersede Safety Reputation.

Guided Urban Transit Group also describes adaptation and fit (variables *Metro Population*, *Population Growth*, *World Cities Score*, *Green Cities Index*, *Smart Card Application*; and in respect of each of the sub-modes Light Rail and Tram, Light Metro, Heavy Metro, Monorail, Automated Guided Transit, and Bus Rapid Transit: *Inaugural Year*, *Operators*, *Status of Project*, *Network Coverage*, *Rolling Stock Fleet*, *Passenger Journeys*, *Routes*, and *Stations* or *Stops*. In addition, driverless or automatic train operation, which maximises throughput capacity and minimises human shortcomings is gaining market share and should be recognised by the variable *Presence of Automatic Train Operation*).

Time Group represents passage of time, a prerequisite for longitudinal research (variable: *Calendar Year*).

2.3. Further research design

The country as basis for defining cases is still valid in most instances, but one needs to be sensitive to larger groupings. One example is Europe, where the tortuous passage of the Fourth Railway Package through the European Parliament illustrates that, despite significant shared interests, member states also have significant own interests. Another is the Community of Independent States (CIS), whose commercial behaviour reflects the broad gauge track that they share among themselves but not with their neighbours.

The authors originally followed a multivariate statistical approach. Not unexpectedly, renaissance has changed much of the global railway industry structure. Despite uncontested broad socio-economic benefits, increasing private sector participation has constrained the amount of commercially sensitive financial and operational performance data available to researchers in the public domain. Unsurprisingly, the railway operators' corpus in several countries now resembles that of other diversified and fragmented transport modes, with information dissemination restricted to legal minimum requirements. Thus, despite its limitations, a case study approach now appears to be more workable and has therefore been adopted in this chapter. The cases were selected by virtue of their extraordinary commitments to progress towards positioning railways as the backbone of their national or regional transport systems, in Brazil, Russia, India, China, and the Gulf Cooperation Council States, or of their urban transport systems in the world's cities-with-railways as a group.

As before, the authors used content analysis of trade periodicals and associated marker events to identify countries and market spaces in which positive shifts relative to their previous positioning have taken place. Notwithstanding adopting the case study approach, the authors' ultimate objective, the scientific method, rests on measurement and hypothesis testing. Hence this chapter will serve as a spinoff to identify additional variables intended to be used in a later round of statistical research.

3. The cases

3.1. Brazil

To revitalise its freight railways, Brazil initially implemented reform-led intervention through long-term concessions (30 years renewable for another 30 years) on its freight railways in the mid-1990s. This resulted in vertically integrated concessions over a total of twelve regional freight railways, which have since grown traffic by 117% [12]. Heavy haul operations on both broad and narrow gauge, as well as general freight on broad gauge networks have flourished, attaining creditable densities of 81 million tonne-km/route-km for Vale's dedicated heavy haul operations, and 37 million tonne-km/route-km in heavy general freight. However, Brazil's narrow gauge general freight railways achieve less than 2 million tonne-km/route-km [13]. It is therefore evident that the inherent competitiveness of Brazil's narrow gauge general freight railways is low and that their performance falls short by comparison with its BRIC peers reviewed in the next three sections.

Lease income from concessions and taxes on concessionaires have become a source of revenue for the Brazilian government. However, investment in rail services other than heavy haul has been meagre, and notwithstanding its economic upswing, high logistics costs characterise Brazil. They are estimated at ≈20% of the gross domestic product (GDP) and thus double the average in OECD countries. The high costs are attributed to regional differences in the state of infrastructure, even though the organisation of the Brazilian transport sector has improved substantially since the 1990s. The national rail network lacks investments and modernisation, while high harbour fees further contribute to high logistics costs. The logistics sector is highly dependent on the highway network, transporting 60% of total freight volume.

However, the network remains restricted, hindering economic growth. Although rail freight increased its logistics market share from 17% to 25% in 2013, the government would prefer a share above 50%. To achieve this, it envisages expanding the network from the present 30,000 km to 50,000–60,000 km [12]. Brazil, therefore, recently changed to an investment-led intervention, the Logistics Investment Program, a strategic project of the Brazilian State [14]. The primary intervention was to invest in railways, to raise their inherent competitiveness so that they can support economic development, and while elements of reform are still present, that is no longer the prime objective. It has connected its formerly isolated northern and southern broad gauge networks, albeit with breaks of gauge, by means of the new North-South Railway, which runs the length of the country. It is following up with two more priority freight rail projects of more than 1,000 km—the East-West line and the Trans-Northeastern Line—to open the interior of the country to development. Funding will partly be by public-private partnership (PPP), involving USD 121 billion over 30 years.

Importantly, Brazil is changing the way the new railways will operate to break monopolies in provision of rail services. Instead of awarding a single concession to operate and maintain a railway, a concessionaire will construct and maintain a line, as well as control train movements on it for a period of 35 years. State agency VALEC will manage the demand risk through the government guaranteeing to purchase the full capacity and then on-selling access to the whole new rail network to private rail freight operators, with an individual operator able to purchase up to 30% of the capacity of a particular line. This unique development in the railway world is something to follow closely. Thus far, observers feel that the significant sunk costs of building or improving a railway seem to have deterred more private investment. The federal government has filled the gap and observers expect that continued government investment in railroads is needed in the long term. Nevertheless, the World Bank considers that several steps could improve private investment in railways, among them enhancing interconnectivity between railways—Brazil operates on different track gauges, and the sheer lack of physical interconnectivity between the lines slows return on investment [15].

Brazil is working on a high speed railway in the Rio de Janeiro-São Paulo-Campinas corridor, to be implemented by PPP, although after two false starts, tendering has been postponed to give prospective bidders sufficient time to prepare. Rio de Janeiro-São Paulo is eighth on the list of the world's top 50 busiest passenger air routes. The envisaged concession period is 40 years, with commercial operation projected to start in 2020.

Brazil's cities have benefited from renaissance in urban rail: Since it started in 1989, heavy metro, light rail and monorail projects have been under construction or completed in Brasilia, Fortaleza, Porto Alegre, Recife, Rio de Janeiro, Salvador, Santos, and São Paulo [13].

Brazil has thus contemplated or implemented three of the four railway renaissance sub-modes, the outstanding one being heavy intermodal or double stacking. Loading gauge on some routes is restricted, and this state possibly reflects the concentration of heavy industry in the south and southeast of the country. Brazil is oil self-sufficient and insignificant routes are electrified outside urban areas.

3.2. Russia

The Russian Federation is the sole shareholder in Russian Railways (RZD). It exploits its strategic location to take full advantage of its key geographical position by fully integrating the Russian railway system into the Eurasian transport network [16]. RZD's strategy for developing rail transport up to 2030 envisages significant expansion of the rail network in two stages.

The first stage involves modernisation from 2008 to 2015 to ensure necessary capacity on key routes, fundamental renewal and upgrading of existing infrastructure, and the beginning of planning and surveying work for expansion, as well as starting construction of some high-priority lines. Among the company’s top priorities were reconstruction and technical enhancement of existing main lines along with construction of new lines to remove infrastructural limitations to Russia's economic growth. RZD already operates high speed passenger trains in the upgraded St Petersburg–Moscow–Nizhny Novgorod corridor. The next focus was on the Baikal-Amur Main Line as an investment in Russia's future that will substantially increase transportation of oil products and exports to the East, a more intensive development and exploitation of raw materials in its Far Eastern region, and an increase in the line’s share of East-West transit traffic. The latter's catchment area stretches from China, South Korea, and Vietnam in the East, and to Estonia, Finland, Germany, Hungary, Latvia, Lithuania, Poland, Romania, and Slovakia in the West. A further priority was the construction of dedicated freight lines to tap natural resources and develop new industrial zones in Western Siberia. Around 13,800 route-km were upgraded for heavy axle loads to reduce the cost of bulk freight shipments.

The second stage from 2016 to 2030 will involve large-scale expansion, creating infrastructure to develop new economic growth areas across Russia's vast territory, deploying world-class technology and improving the competitiveness of the country’s rail system on the global market [17]. This includes the North-South International Transport Corridor in strategic partnership with countries to the south, initially India and Iran, while Belarus, Kazakhstan, Oman and Tajikistan have subsequently opted in, and requests to join from Syria, Azerbaijan and Armenia are under consideration [18]. It also includes ambitions to build a 104-km tunnel under the Bering Strait to connect the Asian and North American continents. The recent Ukraine imbroglio has, however, dampened Russia's ability and aspirations to network railways on continental and intercontinental scale. Hot off the press, in March 2015, RZD called for tenders to undertake surveys, project development, and route planning for the proposed 770-km Moscow–Kazan dedicated high speed line. One of the benefits Russia attributes to this high speed line is simply an increase in the country's prestige, since in the modern world no economically developed country will remain without a system of high-speed railways in the coming years.

Because of limits on State funding, RZD is financing its investment programme through PPPs, in the ratio 46% generated by RZD, 30% met by the private sector, 19.5% provided by the Russian Federation, and 4.5% from regional governments. Raising outside capital is done in accordance with the company’s Loan Programme, which provides for various instruments to finance its operations, including syndicated and bilateral loans, rouble bonds and Euro bonds, as well as leasing and others. Key focus objectives for RZD are the interests of shareholders and partners, as well as increasing efficiency and speed of management decision-making and improving transparency of the group’s activities [19].

RZD was separated from ministry control in 2003 to become a public company responsible for operational and commercial functions. Separate daughter operating companies are being or have been set up for freight and passenger activities as a possible prelude to a sale of shares. It has commenced unbundling the former monolithic entity into, among others at time of writing, Eurosib, which runs container services linking Russia's ports with central Russia and Siberia; Federal Passenger Company, a subsidiary that manages long-distance passenger operations; Freight One, a subsidiary that offers cargo and intermodal shipment using its own fleet of hired wagons, and offers rolling stock leasing; Freight Two, a second freight subsidiary that will lease or acquire new and modernised wagons; Globaltrans, a rail freight operator and freight forwarder; JSC High Speed Rail Lines, a subsidiary to promote development of high speed lines including HSR1 from Moscow to St. Petersburg, and HSR2 from Moscow to Kazan and Yekaterinburg; RailTransAuto JSC that handles a range of commodities including finished motor vehicles [13].

RZD achieves line densities of 23.6 million tonne-km/route-km plus 1.6 million passenger-km/route-km in operations where block-load freight rather than dedicated heavy haul trains share the same infrastructure with passenger trains.

Russia has lagged its BRIC peers since urban rail renaissance started in 1989. Projects completed or under construction include only three metro lines in Chelyabinsk, Kazan, and Moscow, as well as metro extensions and a new monorail line in Moscow [13]. RZD owns and maintains infrastructure and rolling stock, which it leases to suburban companies, and receives a subsidy from the state for providing infrastructure services at a reduced rate. The primary institutional weakness is unprofitability due to ticket revenue failing to cover expenditure and insufficient compensation from state authorities. Thus, ageing and under-maintained rolling stock is gradually being withdrawn from service and not being replaced [20], to the extent that systems in two cities have ceased service.

Russia has, therefore, contemplated or implemented two of the four railway renaissance sub-modes, the outstanding two being heavy intermodal or double stacking, and urban rail. Russia's main east-west and north-south and railway routes, which among others, convey substantial amounts of container traffic are extensively but not completely electrified using 80% non-coal sources. The overhead contact wire would need to be raised to accommodate double-stacked container trains.

3.3. India

A railway budget presented to Parliament by the Railway Minister has traditionally funded Indian Railways (IR). The Ministry of Railways has a dedicated financing entity, Indian Railway Finance Corporation Ltd (IRFC), whose objective is to raise funds from the market to part finance the planned outlay of IR. Money so provided is used to acquire rolling stock and to meet other IR developmental needs. Rolling stock funded by IRFC is leased to the Ministry of Railways, which pays lease rentals to the corporation. IR also operates a Wagon Leasing Scheme to encourage shippers and private operators to invest in rolling stock, but it has continued to flounder. It appears that politicised relations between IR and the government, and the consequent apparent lack of strategic direction, deterred private participation. To overcome these obstacles in moving its railways into renaissance, IR has adopted the special purpose vehicles, described in the next two paragraphs.

First was the Dedicated Freight Corridor Corporation of India Ltd (DFCCIL) in 2006 under the Ministry of Railways administrative control, to plan, develop, fund, resource, construct, maintain, and operate Dedicated Freight Corridors (DFCs). Building DFCs across the country, to operate double stack container trains and/or heavy haul trains, marked a strategic inflexion point in IR's history, which has traditionally run mixed freight and passenger traffic across its network. DFCs will enable IR to improve customer orientation and meet market needs more effectively. Creation of rail infrastructure on such a scale—unprecedented in independent India—is expected to drive the establishment of industrial corridors and logistic parks along its alignment. Currently under construction, the Eastern DFC is being funded in three different ways: the Ludhiana-Mughalsarai section by the World Bank through an International Bank for Reconstruction and Development loan; the Mugalsarai-Sonnagar section by the Ministry of Railways directly; and the Sonnagar-Dankuni section by PPP. Also currently under construction, the Western DFC is funded through foreign direct investment by the Government of Japan who provided a Special Terms of Economic Partnership Loan to finance construction and procure locomotives. The Ministry of Railways will bear a remaining portion of the project construction cost as equity funding to the DFCCIL. Thereafter, construction of four more DFCs is slated to complete India's Golden Quadrilateral that connects Delhi, Kolkata, Chennai, and Mumbai, as well as its two diagonals.

Second was High Speed Rail Corporation of India Ltd in 2013, on directions of the Ministry of Railways to develop technical standards, undertake project-related studies, as well as prepare financial and implementation models. It appears that a 540-km dedicated high speed line between Mumbai and Ahmedabad could be first, followed by five other projects during the next ten years to connect major metropolitan centres Delhi-Amritsar, Delhi-Chennai, and Chennai-Mysore. Two of the projects are set to serve portions of the Delhi-Mumbai corridor, currently tenth on the list of the world's top 50 busiest passenger air routes. The recently elected government has implemented a fast track, investment-friendly and predicable PPP mechanism to modernise and revamp the railways and implement expensive projects such as high speed rails [21].

India's networking aspirations have, thus far, not pursued a strategic horizon much beyond the 1,676 mm broad gauge that it shares with neighbours Bangladesh and Pakistan, as well as Sri Lanka's island network. It is incompatible with the two other major track gauges in Asia, China's and Eurasia's standard gauge, and the CIS' 1,520 mm broad gauge, so it is beholden to transloading containers, bogie changing or gauge-changing, which would dampen networking enthusiasm unless there were major traffic flows at stake.

India's cities have also benefited from renaissance in urban rail. Since urban rail renaissance started in 1989, projects completed or under construction include 17 metro lines in Bangalore, Chennai, Delhi, Gurgaon, Hyderabad, Kolkata, Mumbai, and Navi Mumbai, as well as a monorail line in Mumbai [13]. Interestingly, Delhi's three Phase 1 lines are the same 1,676 mm broad gauge as its national network, while its four Phase 2 lines are standard gauge, to benefit from lower prices in the larger standard gauge market. This practice subsequently spread to metros in Bangalore, Chennai, Gurgaon, Hyderabad, Mumbai, and the planned metro in Pune.

India has in quick succession rolled out metro systems in major cities, started construction of dedicated freight corridors, and recently announced a cooperation agreement with China to develop a high speed network. It is a member of the International Heavy Haul Association, and already operates double-stacked container trains. IR achieves creditable overall line densities of 10.9 million tonne-km/route-km plus 16.6 million passenger-km/route-km in operations that at present include freight and passenger trains sharing the same infrastructure. Approximately 67% of freight and 50% of passenger traffic is hauled by electric traction [22]. It has positioned itself strongly in all four of the railway renaissance market spaces.

3.4. China

China's railway financing system is based on the government taking the leading role, diversified investment, and market orientation. Joint ventures are the major vehicles for new railway projects. By the end of 2008, RMB 300 billion had been committed from outside the Ministry of Transport. Major financing channels include the Railway Construction Fund, contributions from local governments and cooperative agreements between Ministry of Railways and 31 provincial governments, treasury bonds and budget from the central government, strategic investors such as power plants, coal mines, ports, insurance groups (either public or private), the Dedicated Construction Fund from operation revenue, restructuring railway assets to initial public offering, issue of Railway Construction Bonds, and domestic and foreign bank lending. Implementation rests on a clear vision, a good plan, an efficient implementation mechanism, and a creative financing system.

China recently opened its third heavy haul line, the 1,216-km public private partnership Shanxi South Central Railway from Watang in Xingxian County to the port of Rizhao in Shandong Province. It follows construction of the original 653-km Datong–Qinhuangdao coal railway completed in 1992 and the 1,040-km Shenmu–Huanghua Railway, all with nameplate capacity 200 million tonnes per year.

China Railways commenced high speed service as recently as 2007, and today operates the largest and most heavily used high-speed railway network in the world.

China's cities have benefited since urban rail renaissance started in 1989. Projects completed or currently under construction include 107 metro lines in Beijing, Changchun, Changsha, Chengdu, Chongqing, Dalian, Dongguan, Foshan, Fuzhou, Guangzhou, Guiyang, Hangzhou, Harbin, Hefei, Kunming, Lanzhou, Nanchang, Nanjing, Nanning, Ningbo, Qingdao, Shanghai, Shenyang, Shenzhen, Shijiazhuang, Suzhou, Taiyuan, Tianjin, Ürümqi, Wenzhou, Wuhan, Wuxi, Xi'an, Xiamen, Xuzhou, and Zhengzhou; nine light rail lines in Changchun, Nanjing, and Suzhou; six rubber- or steel-tyred automated light metro lines in Macau and Wuhan; two monorail lines in Chongqing; and two suburban lines in Wenzhou [13]. China also operates bus rapid transit systems. Its urban-guided transit catalogue thus includes the full range of three steel-tyred solutions, namely, heavy metro, automated light metro, and light rail; and three rubber-tyred solutions, namely, automated light metro, monorail, and bus rapid transit. It is therefore able to nuance solutions for particular city requirements.

China currently sets the world pace for railway expansion and performance. It achieves a creditable 26.9 million tonne-km/route-km plus 8.89 million passenger-km/route-km on a network that at present includes dedicated freight lines (heavy haul) and dedicated passenger lines (high speed), as well as extensive mixed traffic heritage infrastructure that has been progressively upgraded. It participates in all four of the railway renaissance market spaces, although the height of double-stacked containers is limited by overhead electrification, and has developed means to finance huge railway expansion in support of its rapid economic growth. It is a strong role model for driving railway renaissance through investment in inherently competitive railway technologies.

One aspect of China's railway development elevates it above its BRIC peers, and indeed all other railway countries of note, namely, its global railway network ambitions and the progress that it is making in this regard. Its Silk Road Economic Belt and Maritime Silk Road initiatives embrace countries situated on the original Silk Road through Central-, South-, Southeast- and West Asia, the Middle East, and Europe, as well as Oceania, and North and East Africa. They call for integration of the region into a cohesive economic area through building infrastructure, increasing cultural exchanges, and broadening trade [23]. China's railway strategic horizon thus reaches out from its 107,000-km standard gauge home network to surrounding and remote regions, e.g., the entire Asia, North America, Western Europe, and Africa. The following examples start from the north and proceed clockwise to show the magnitude of China's ambitions to open up transcontinental and intercontinental standard gauge trade routes.

- Connecting into broad-gauge Mongolia to support the latter's mineral exports.

- Strengthening linkages with Russia through additional border crossings, including lines from China's northern provinces to Russian ports Pos'et and Slavyanka on the Sea of Japan.
- Cooperating with Russia to build a 7,000 km high speed line from Beijing to Moscow.
- Reaching out to North America, together with Russia. Counter-intuitively, the great circle, i.e., shortest, route from, say, Chinese manufacturing city Chongqing to the western United States is not across the Pacific Ocean, but overland via the Bering Strait between the Asian- and North American continents.
- Routing rail traffic from standard-gauge North and South Korea through China to Europe, at present routed through Russia and Belarus.
- Connecting China's southern cities Nanning and Kunming to Vietnam, Laos, Thailand, and Myanmar, by re-gauging from narrow gauge to standard gauge in the countries mentioned, with ultimate vision to connect to Singapore through Malaysia.
- Connecting Xigaze railhead in Tibet over some 1,700 km along China's south-western border to Kashi railhead in Xinjiang Autonomous Region. This will springboard links among other to Bhutan, India, and Nepal under Mount Everest by 2020; through Pakistan to the Arabian Sea; and through Kyrgyzstan and Tajikistan to Herat in Afghanistan, soon to be the easternmost outpost of the Eurasian standard gauge network.
- Leveraging its existing connection with Kazakhstan's broad-gauge network via two border crossings west of Ürümqi, one to the northwest, and one to the southwest.
- Upgrading lines from the port of Piraeus in Greece through the Balkan states to Hungary, to access Western Europe.
- Promoting new standard gauge railways in several equatorial African countries: China has encouraged standard gauge ambitions and initiatives in Cameroon, Chad, Mali, Nigeria, Senegal, and others. This topic is addressed in more detail in sub-subsection 4.1.3 in respect of schemes that have already borne fruit.

To be fair, China is not having it all its own way. While its propositions may appear attractive, smaller countries, nevertheless, seem wary of a longer term agenda. Some would like to leverage China's overtures to their own benefit. Negotiations can take a long time. Several disputed territories mark its south-western border, so political challenges are likely to equal technical challenges. But ultimately, high performance rail has become the backbone of choice for integrated, multimodal freight and passenger transport in an energy-scarce world. Countries that cannot achieve that by their own means will likely eventually accept what is on offer.

3.5. The Gulf Cooperation Council States

The countries of the Cooperation Council for the Arab States of the Gulf, commonly called the GCC States, are arguably the world's current railway investment hotspot. The GCC comprises United Arab Emirates, the Kingdom of Bahrain, the Kingdom of Saudi Arabia, the Sultanate of Oman, Qatar, and Kuwait.

Saudi Arabia is a relative newcomer to railways, the first line having been built in 1951 to indirectly connect the port of Dammam on the Gulf of Persia with the capital Riyadh. A direct line followed in 1985. Saudi Railways Organization operates double-stack container and passenger trains on these lines. As the spectre of peak oil approached, Saudi Arabia established the Supreme Economic Council in 1999 to formulate and better coordinate economic development policies in order to accelerate institutional and industrial reform and diversify its economy beyond petroleum. Several key railway projects followed. First is the Saudi Landbridge, a 950-km, mixed traffic link from Riyadh to the port of Jeddah on the Red Sea to convey double-stack container trains at 120 km/h and passenger trains at 220 km/h. Scheduled for completion in 2021, the Public Investment Fund will finance it with operations contracted out. Second is the North-South Railway, a 1,400-km heavy haul route from mineral deposits in the north-western region to the Gulf port of Ras Az Zawr, completed in 2013. Saudi Railway Company, whose shares may put to subscription, administered construction, while Saudi Arabian Mining Company has a concession to operate the line. A 500-km link to Riyadh is under construction, to enable passenger and freight services to run between the capital and the Jordanian border. Third is the 320-km/h Haramain High Speed Rail linking Makkah, Jeddah, and Madinah, currently under construction. Fourth is the GCC railway, a new 2,177-km, 200-km/h double track international freight and passenger railway currently under construction to link the six abovementioned countries and integrate them with the railways of Saudi Arabia. It will follow the Gulf coast from Kuwait's border with Iraq to Salalah in southern Oman, with branches to Bahrain and Qatar, linking all six states and sharing the cost in proportion to the length of the main line in each country. The first phase was delivered in 2014 with completion expected in 2017. Fifth is Jeddah, with a joint venture of the Jeddah Municipality and the Jeddah Urban Development Company set to open three light metro lines in 2020. Sixth is Makkah, with an elevated metro to carry Hajj pilgrims opened in 2010 and four further regular metro lines approved in 2013. Seventh is Riyadh, with a university campus automated light metro opened in 2012, and an automated six-line metro, for which Arriyadh Development Authority has placed turnkey contracts for completion in 2018, and a monorail under construction to serve the financial district. Eighth is Dubai, which opened its first line in 2009, It currently operates two metro lines plus a tram line.

Saudi Arabia and its GCC fellow members have in around one decade moved from few or no railways to one of the world's most comprehensive systems. It includes all four of the railway renaissance sub-modes, high speed, heavy haul, heavy intermodal, and urban rail. The GCC example illustrates how quickly a committed authority can establish renaissance rail by selecting industry-leading practices in each of the previously mentioned sub-modes.

3.6. Urban rail

The following paragraphs are built on previously reported research [3, 4], including all urban-guided transit with the exception of bus rapid transit. Urban rail applications are too many to detail, therefore this section takes a necessarily highly aggregated view of the global urban rail and urban guided transit situation. The observations include all operations that qualify for inclusion in the Railway Directory's City Railways section, using the ten years spanned by the

2006 and 2015 issues [13]. Table 1 below presents their pertinent statistics in a way that brings out their significance.

During the nine years to 2015, the number of cities that have implemented urban rail or have it under construction has increased from 120 to 487 (32.7%). Of cities with existing urban rail, 47.7% increased their network size accounting for 23.3% of growth, which together with 13.4% growth in cities that previously had no urban rail of any description, resulted in 36.7% total network growth in nine years. This is exceptional growth by railway standards, and it is evident that urban railway renaissance has responded rapidly to the global megatrend migration of people to cities. Note that while the increased network size is mainly attributable to greenfield sites, there are a few brownfield sites where operations have been extended on existing, upgraded, or disused infrastructure of others, for example some tram-train projects.

Observations			Analysis							
Year	Cities, number	Global Net-work, km	Urban Rail Activity, number of cities				Global Network, km			
			Decrease	No change	Increase	New	Decrease	No change	Increase	New
2006	367	29457	36	156	175		-1589	27868	6859	
2015	487	38675				119				3948
Change, %	32.7	31.3	9.8	42.5	47.7	32.7	-5.4	94.6	23.3	13.4

Table 1. Analysis of global urban rail growth over time.

Two concurrent trends underlie the net change in global urban rail network size. The first is obviously the dominant expansive and new growth mentioned above. Notwithstanding that, 36 cities recorded an aggregate network decrease of 1,589 km. There are many reasons for this change including the ups and downs of economic growth; shifting relative economic and political power from country to country; population migrations; failure or inability to renew assets; the rise of alternative transport modes; changing social preferences; inappropriate institutional arrangements; redefined jurisdictions, usually by combining and sometimes by separating them; rationalising pre-existing networks as agglomerations develop; extending routes to tram-train applications on conventional networks; increasing intermodal integration among modes; and many others. This chapter reports on global shifts that generally favour rail, hence the foregoing phenomena are outside the present research scope and no grounded position is offered. They could justify substantial research in their own right.

Previous research has found that although Heavy Metro remains unchallenged in the highest capacity rail applications, rubber-tyred guided transit modes have challenged rail's former unquestioned status in the light-axle-load, low-speed market space [3]. One would therefore expect Light Rail and Light Metro to be more vulnerable to competition from rubber-tyred systems. Notwithstanding that potential weakness, their good green credentials attract smaller cities that value inherent environmental friendliness over the expediency of simply moving people under the weight of popular demand. Automated Guided Transit and Monorail nevertheless seem well-positioned to drive a wedge between the heavy and light poles of urban rail. Note, therefore, that Automated Light Metro, Automated Guided Transit, and Monorail are already present in 26 of the world's 487 cities with urban guided transit solutions.

4. Key results

4.1. Settling in of the renaissance

4.1.1. Selected country outcomes

The following comments on outcomes are confined to those countries that achieved significant positive repositioning relative to their baselines in the Insecure, Fortuitous, Enlightened, Progressive, and Assertive clusters published in 2008 [2], the countries being mentioned in the same order as in that publication. This chapter, therefore, records a parting of ways between countries that have embraced railway renaissance and those that have not yet. The strong entry of new countries that have recently built their first railways, such as most of the Gulf Cooperation Council states, has demonstrated the major impact that renaissance rail can make on the transport dispensation in a country or region. It also does not necessarily mean the end of the track for countries in the Insecure cluster. As mentioned under China in section 3.5, its expanding influence is also set to change the fortunes of several countries in that cluster.

4.1.2. The fortuitous cluster

Recall that that this cluster subsumed standard or broad gauge state railways, whose redeeming quality was an axle load sufficiently high to support a modicum of competitiveness [2]. In this cluster, Israel has undertaken substantial urban rail expansion and rolling stock procurement, including opening its new Jerusalem Light Rail Transit in 2011. Lithuania and Latvia, together with Estonia that is a member of the Enlightened and Progressive super cluster, are participating in Rail Baltica, a European Union (EU) sponsored project to integrate them into the European Union [24]. Landlocked Mongolia has recently started exploiting its mineral resources, connecting with consumer markets through China and Russia by means of heavy haul railways. Turkmenistan, together with Iran and Kazakhstan, has inaugurated a line linking all three countries. Azerbaijan and Georgia have joined forces with Turkey to complete missing links in a railway from Kars in Turkey to Baku on the Caspian Sea in Azerbaijan, to facilitate networkability [25]. Azerbaijan is also pursuing a north-south railway to leverage its position between Russia and Iran. Saudi Arabia is investing heavily in the full range of renaissance sub-modes, namely heavy haul, high speed, double stacking, and several variants of urban rail. Panama re-gauged its broad gauge Pacific Ocean–Gulf of Mexico line to standard gauge and now operates double-stack container trains under a 30-year concession. It also opened Panama City Metro in 2014. These countries are leveraging variables such as *Relative Maximum Axle Load*, *Relative Maximum Speed*, *Heavy Haul Presence*, *High-speed Intercity Presence*, *Heavy Intermodal Presence*, *Networkability*, *Climate-change Position*, *Market Initiative*, *Infrastructure* and *Rolling Stock Investment Capacity* to rise from the Fortuitous cluster.

4.1.3. The insecure cluster

This cluster subsumes predominantly narrow gauge railways that generally rated low on all variables [2]. The World Bank considers that Africa's many concessions perform poorly [26], not surprisingly because they are inherently uncompetitive. Insecure railways that aspire to elevate themselves therefore initiate interventions predictable from the factors *Positioning Passenger Rail*, *Exploiting Opportunities*, *Positioning Freight Rail*, *Exploring Horizons*, *Pursuing Competition*, *Aligning Assets*, *Greening the Image* and *Constraining Downside* identified in [2].

For example, Morocco is implementing a high speed line from Casablanca to Rabat, currently suspended due to expropriation issues. Iran has expanded its network to exploit its valuable geographic location to provide through routes to neighbouring countries, north-south between its Persian Gulf ports and Turkmenistan and Kazakhstan, as well as a planned route to Russia through Azerbaijan, and in the east between Herat in Afghanistan, and the rest of the Eurasian standard gauge network in the west. Jordan is set to replace its isolated narrow gauge railway with a standard gauge one that can network with the standard gauge railways of the Middle East. Ethiopia-Djibouti's and Kenya's new standard gauge railways are under construction, the latter as an element of a larger agreement that includes the other East African Community states Burundi, Rwanda, Tanzania, and Uganda with the prospect of South Sudan also linking up. Colombia has entered the bulk mineral business and is now the fifth largest coal exporter in the world [27]. Guinea is constructing a high-capacity standard gauge heavy haul railway to export iron ore from its Simandou deposit. Indonesia is seeking private investors to build standard gauge heavy haul coal export railways in Kalimantan and Sumatra. Southeast Asia has standard gauge initiatives in Laos, Malaysia, Myanmar, and Thailand's Legislative Assembly recently decided to proceed with a standard gauge railway from the Laotian border to the port of Rayong on the Gulf of Thailand, with a branch to Bangkok. A matching link through Laos to China is under negotiation. Peru has commenced operation on the entire Lima Metro Line 1, and has commenced construction on Line 2. Mozambique is opening up its minerals exporting potential, and has taken the first steps to upgrade some of its lines to convey export coal. Longest of these is the 910-km Nacala Logistics Corridor from mines at Moatize, a joint venture between Brazilian mining and logistics entity Vale and national rail and port operator CFM [28]. The Malaysian government has approved establishment of a state-backed project delivery company to manage Malaysia’s share in the Kuala Lumpur–Singapore high speed project.

These railways are leveraging variables such as *Relative Maximum Axle Load, Relative Maximum Speed, Heavy Haul Presence, High-speed Intercity Presence, Attitude to Competition, Network Coverage, Market Initiative, Networkability*, *Infrastructure-operations Separation*, *Infrastructure-* and *Rolling Stock Ownership Locus*, and *Climate-change Position* to lift themselves out of their inherent uncompetitiveness and hence to enjoy railway renaissance. The outlook for railways that remain in the Insecure cluster is bleak. Their significance is dwindling, e.g., narrow gauge freight tonne-km are down to less than 3% of the global total, while long-distance passenger services are generally moribund and, due to small market size, rolling stock has become more expensive than for standard gauge while its performance is inherently inferior.

4.1.4. The enlightened and progressive super cluster

All but five members of the Enlightened and Progressive clusters were either longstanding member states of the EU, joined during the 2002–2007 duration of data acquisition, or acceded after 2007, the last year included in the database. Norway, as member of the European Free Trade Association, is aligned in all pertinent respects with EU railways. Two more, Serbia and Turkey, are candidate countries. These clusters were neighbours in the icicle plot from which they were derived, and under the European Union's Regional Policy as well as its-railway specific directives, they can for the purpose of the present analysis be considered to have melded into one. The cluster includes only two non-European countries, Japan and the Republic of Korea, but despite geographic separation, their railways happen to be statistically aligned with those of the EU.

Developments in this super cluster have leveraged rail's inherent competitiveness in the high speed and urban rail market spaces. Its major challenge is that freight rail development has not followed economic development. The comparatively small size of Japan's linked islands opposes the heavy and/or long hauls that railways do well, and rail freight has therefore consistently declined over the last nine years [13]. Rail freight has similarly stagnated since railway reform in 2005 in South Korea [29], also a small country whose railways are currently politically constrained from networking with neighbours. However, while such constraints are absent in the EU, its rail freight performance is nevertheless cause for concern [30]. While railways in the EU rated highly on most variables, there is no evidence of them leveraging variables such as *Relative Maximum Axle Load*, *Heavy Haul Presence* and *Heavy Intermodal Presence*, which are fundamental to competitive and sustainable freight rail positioning. Note, however, that the recently completed EU-sponsored 1,500-m freight train Marathon project [31] has explored the value of *Distributed Power Presence* to support operation of long freight trains. This effort parallels that of other railways that are constrained by low axle load while high speed is not critical for business success. The only remaining genetic technology that can come to the rescue is coupling, which has led to commercial operation of trains conveying more than 300 wagons on Brazilian and South African narrow gauge heavy haul lines.

4.1.5. The assertive cluster

In line with expectations, members of this cluster have increased their commanding lead in several respects. Mexico follows North American practices and standards, so it is already strongly positioned in freight rail. In pursuing another of the railway renaissance growth curves, it awarded a contract for a 210-km high speed line from Mexico City to Querétaro in 2014, but subsequently cancelled the deal to maintain probity. It reopened bidding in January 2015, expecting to announce the preferred bidder in July 2015 [32]. Switzerland is exploiting its strategic location, having opened the 35-km Lötschberg Base Tunnel in 2007, and expecting to open the 57-km Gotthard Base Tunnel in 2016. Their objective is to increase total transport capacity across the Alps especially for transit freight between Germany and Italy, to shift freight from road to rail to reduce fatal accidents and environmental damage by ever-increasing numbers of trucks passing through Switzerland, and to cut passenger train journey times [33, 34]. Australia has taken the lead in heavy haul by increasing axle load on an iron ore export line in its Pilbara region to 40 tonnes, currently the world's highest. Canadian National, which despite its name is a private company, has from its traditional east–west Canadian transcontinental network extended its strategic horizon to the Gulf of Mexico through acquisition of

US north–south railroads. The United States has extended its across-the-board lead by commencing construction of the California High Speed Rail project that is set to link San Francisco with Los Angeles, with later extensions to Sacramento and San Diego.

Brazil, India, China, and Russia are making extraordinary progress in all or most of the four sub-modes of the railway renaissance, and have therefore been given special treatment in sections 3.1, 3.2, 3.3, and 3.4 respectively. No more will be said here. South Africa's Passenger Rail Agency in 2014 awarded the world's largest current order for electric multiple units, namely 3,600 cars. Its Transnet Freight Rail State-owned company also awarded orders for more than 1,000 locomotives in that year. However, noting that high speed and heavy intermodal (double-stacked containers) are not possible on narrow gauge, and that heavy haul needs standard gauge to maximise its performance, it will be interesting to follow its long-term sustainability.

These countries are generally leveraging variables such as *Relative Maximum Speed, High-speed Intercity Presence, Attitude to Competition, Network Coverage, Passenger Traffic Volume, Employment Created, Broad Gauge, Networkability, Strategic Horizon, Rolling Stock Ownership Locus*, and *Infrastructure* and *Rolling Stock Investment Capacity* to round out their already strong Assertive positioning.

4.2. Institutional learning

4.2.1. Interventions to achieve renaissance

Two railway revitalisation intervention mainstreams are evident in section 4.1, competition-led and investment-led. Although introducing competition to revitalise railways seems to enjoy top-of-mind awareness among many stakeholders, it is not appropriate in all settings. In developed countries, where standard or broad gauge track and adequate axle load, speed and train length parameters may already have made existing railways inherently competitive, introducing competition among service delivery functions may be desirable, and may indeed be the only available revitalisation lever. Thus, countries in the Enlightened and Progressive Railways super cluster have generally embraced competition to leverage maximum good from their investments in expensive long-lived railway assets.

However, competition alone is not the only remedy. For example, railways that operate, or contemplate operating, freight and passenger trains on the same network cannot concurrently optimise the train–infrastructure interface for both types. Thus, light-axle-load high-speed passenger trains require wide curves but tolerate steep gradients, while heavy-axle-load long freight trains require easy gradients, but tolerate tight curves. Optimising the interface for one train type unavoidably sub-optimises it for the other. Freight rail in the Enlightened and Progressive super-cluster (European Union plus Japan and the Republic of Korea) is a case in point. Its train–infrastructure interface is optimised for the dominant passenger traffic, thereby precluding concurrent optimisation for freight trains. Consequently, the latter are inherently uncompetitive and have, unsurprisingly, not responded positively to competition-led intervention, and currently face a bleak future.

Similarly, where inherent competitiveness is inadequate and new investment is required to make it good, it is futile to introduce competition and/or private sector participation only. Typically by way of operating concessions, such interventions risk reluctance to invest and even asset stripping as concessionaires find they need to subsist on stagnant or declining income. To illustrate, in Sub-Saharan Africa the World Bank found that few passenger train services cover above-rail operating costs, that few concessions generate significant profits for their operators and certainly not enough to fund long-term track renewals; and that government oversight of railway concessionaires is inconsistent with good business practices, which all result in expectations not being met [35]. Competition should, therefore, be introduced only in settings where inherent railway competitiveness is sufficient to sustain all operations that are present—freight and passenger.

4.2.2. Ownership and funding

Countries and railways that have participated in railway renaissance have of necessity invested in one or more of the Heavy Haul, High-speed Intercity, Double Stacking, and contemporary Urban Rail market spaces, to transition from the terminal decline phase of their first growth curve to new renaissance growth curves. Except for the privately-owned railways in the United States and Canada, as well as heavy haul railways around the world that mining houses have funded integrally with their mining investments, governments in many countries have traditionally led requisite railway investments. However, as contending claims on their funds have constrained the quantum available for railways, public and private sectors have increasingly come to share responsibility for railway investment, in such a way that each sector bears the risk for investments to achieve its objectives, developmental for the public sector, and productive for the private sector.

Opportunities for private sector participation in railways have stimulated a plethora of solutions. Outsourcing of routine maintenance work has been a mutually acceptable starting point that allows the two sectors to size one another up without deep commitment. However, the latter is required to establish the mutual respect and deeper trust that is the foundation of longer-term relationships.

It has been customary for private participation to fund moveable assets, which may be redeployed elsewhere if the project runs into difficulties. Rolling stock has traditionally filled that role. There are many opportunities, but they tend to start with special-purpose freight wagons that have limited redeployment opportunities. They are nevertheless a valuable way to cement a relationship, because they limit a customer's transport options, and signify strong commitment to rail with a high exit barrier. In recent years, it has become common to purchase multiple unit passenger stock with long term 30–35-year life cycle maintenance contracts that require a much deeper level of mutual understanding and commitment. Private participation in infrastructure has taken a long time because the exit barriers can be very high. That part of funding has, therefore, traditionally been left with the authority initiating the project. A tunnel in the ground has limited alternative deployment opportunities if a project runs into difficulties. Nevertheless, infrastructure is also slowly entering the private sector arena. Typically the authority needs to accept the demand risk for the asset, which can be done through it agreeing to purchase all the capacity over the life of the agreement, and then selling it to users. This has become a model for funding infrastructure, where a long route may be divided into portions funded by different agreements, as in the case of India's dedicated freight corridors. Initially, there was resistance to foreign participation, but there again India has broken ground on foreign direct investment, also on a dedicated freight corridor. In reality, long-term relationships bring stability by binding participants. Concessioning is frequently used for such schemes, where a concessioning authority owns an opportunity and needs market initiative to develop it.

Such interventions have stimulated a range of regulation models that reflect the developmental and socio-economic objectives of particular countries, as well as the quantum and diversity of funding sources that they can assemble. In the first instance, a railway economic regulatory function is required, either implicitly by way of coherent political will during the early stages of reform, or later explicitly by way of a statutory regulator, to ensure that railways are enabled and encouraged to contribute appropriately and fairly to the broad economic and social objectives of a country in a competitive setting. Thereafter, safety regulation also needs to be introduced in settings where multiple entities come to operate trains to ensure the establishment and maintenance of a safe operating environment.

4.2.3. Market structure

Railway systems may offer single or multiple routes between origin and destination. Multiple routes originated in the early days of railways, for example the railways of Britain prior to railway nationalisation and establishment of British Rail in 1948, the railways of the North American Free Trade Agreement that preserve alternative routings, and parallel railways from an ore body to the coast, as in the Australian Pilbara. Railway offerings can be competitive or monopolistic. This yields four quadrants. Notwithstanding the structure of an industry, many governments consider it desirable to preserve competition in all industries, even those that are essentially vertically integrated. Thus they tend to require regulated access by third parties, to ensure the presence of competitive operators.

Throughout the world, railway renaissance has been achieved only by investment in assets that have increased rail’s inherent competiveness against other transport modes. This is true for railways competing against other transport modes in domestic markets, or supporting competition against other countries in export markets, as well as for railways cooperating in intermodal alliances, particularly with road carriers. Appreciate that for freight, heavy intermodal goes beyond simply transferring a load unit (container or swap body) from one mode to another, such as between road and rail and vice-versa. When rail is involved, the axle load of container wagons needs to be increased to the heavy haul domain, by double stacking containers, to exploit the competitive strength of rail's heavy-axle-load genetic technology, supporting.

Regarding competition between rail and road, appreciate that logistics service providers and passengers incline naturally toward the more aggressive competitor, and will choose road until rail comes up with a superior offer, either alone or in cooperation with road carriers. Inherent competitiveness is thus an important element of railway positioning because as long as logistics service providers and passengers have a choice, rail is competing with road, either over the entire distance where it can offer such a service, or for the long-haul portion where customers want a door to door service and rail needs to complement its offer with feeder and/ or distribution service by another mode.

4.2.4. Networking and expanding strategic horizons

Consolidation of rail's strengths in the four renaissance market spaces foretells even greater rail significance in future national, international, continental, and intercontinental transport. The authors' earlier research identified networkability as a factor in positioning railways for competitiveness and sustainability [1], and several large-scale international initiatives have confirmed that finding. In transposing Metcalfe's Law, that network value increases as the square of the number of nodes [36], to the railway industry, the UN-led Trans-Asian Railway, mooted pre-renaissance in 1960, and the EU-led multilateral development of the Transport Corridor Europe-Caucasus-Asia in 1998 are examples. On the smaller-scale are Russian Railways' extensions eastward to North Korea (implemented) and westward to Vienna (planned), and the Bosphorus rail tunnel completed in 2009, Asia-Europe's first standard gauge connection. However, they progressed slowly until recently, primarily due to track gauge incompatibilities. Now Chinese rail ambitions have morphed earlier plans by others into wider strategic horizons, including freight services into Europe, a 7,000-km Beijing-Moscow high-speed line, and connection to North America under the Bering Strait. China's bold railway diplomacy is turning challenge into opportunity, with Premier Li promoting Chinese railway technologies around the world as advanced, secure, reliable, and cost-competitive [37]. The Jamestown Foundation [38] recommended the world should pay attention to a telling sign of things to come on global scale.

Great circle overland rail routes can be shorter and faster than maritime passages. For context, by weighting their latitude and longitude coordinates by their GDP, and calculating the weighted average, the author found the economic centre of Earth's top 100 cities by GDP to be in western Iran. All Europe, most of Asia, and much of Africa, lie within some 7,000–8,000 km radius thereof, less than the Trans-Siberian railway's 9,288 km benchmark. Note that this exercise excluded Australia, because it is more than 1,200 km from the nearest land (the island Java) that could conceivably link into a global railway network.

It seems axiomatic that political differences should be separated from traffic flows. Even the European Union has experienced push-back since publishing its first Council Directive on development of the Community's railways in 1991. Similar challenges have been experienced in consigning containers by rail from China through Kazakhstan, Russia, and Belarus into the European Union. Although they seem eventually all to be resolved, the time it takes allows other modes to entrench themselves at the expense of the rail mode.

4.3. Emergence of the new normal

Renaissance has passed. The first Japanese Series 0 Shinkansen train that started it all more than fifty years ago is already a display piece in the National Railway Museum in York, England. Railways have settled into a new dispensation. From a position of strength, their abilities stretch from heavy-duty urban transport across continents to distant strategic horizons.

The 14^{th}–17^{th} century Renaissance, or rebirth, provides a fitting archetype of the 1964–1989 quarter-century railway renaissance. Looking back to 1989, it is evident that the following quarter century to 2014 has been a period of settling railways into their four inherently competitive sub-modes high-speed intercity, heavy haul, heavy intermodal, and contemporary urban rail. The Enlightenment, the period that followed the Renaissance and exploited the intellectual freedom that it had let loose, has inspired this section.

The know-how of the railway renaissance has been captured in a myriad of publications and widely dispersed railway industry institutional knowledge. Now freely available, it is being applied to position railways for an energy-scarce future. Global consensus seems to be building around the year 2050 as the date by which the shift from a fossil-fuelled economy to a renewables-powered economy should be largely in place. The timing recognises the need to wear out the present fleet of transport vehicles—planes, ships, and trains—and to adapt, construct, or renew infrastructure and rolling stock. The exact year is not important. What is important is the form that transport systems will take at that time. The European Commission's [10] Transport White Paper, for example, provides valuable perspectives on that time by envisioning:

- An efficient core network for multimodal intercity travel and transport with greater use of buses and coaches, rail and air transport for passengers and, for freight, multimodal solutions relying on waterborne and rail modes for long-hauls.
- New transport patterns emerging, according to which larger volumes of freight and greater numbers of travellers are carried jointly to their destination by the most efficient (combination of) modes.
- A global level playing field for long-distance travel and intercontinental freight in which (high speed) rail should absorb much medium distance traffic.
- Clean urban transport and commuting where a higher share of travel is by collective transport, and the interface between long distance and last-mile freight transport is organised more efficiently.

The realisation of integrated, optimised, multi-nodal networks featuring urban rail within densely populated, commercialised, and industrialised areas, and regional rail within larger agglomerations and corridors, is already visible in several countries. Consider the example of Verkehrsverbund Rhein-Ruhr in Germany, serving a conurbation of eight million inhabitants in a 7,300 km^2 area. Formerly isolated light rail networks of individual local authorities have been connected to one another, going so far as to regauge some from metre gauge to standard gauge to promote networkability. This has in turn made acquisition of new 160 km/h regional trains sensible, to reduce journey times over longer distances. At national and international scale, long distance, high-speed passenger and heavy freight trains are common in Europe and North America, respectively. Dedicated freight and passenger corridors, where traffic volume is sufficient to separate freight and passenger trains, have been realised in China and India. China's One Belt, One Road framework takes rail-based corridor development to an unprecedented level. So the building blocks of the Railway Enlightenment or New Normal exist: What should now follow is expansion of application to countries that are earnest about road-to-rail shift to reduce congestion and the dependence on fossil fuels and the accompanying pollutant emissions.

4.4. Further research

Despite the difficulty of obtaining requisite data, the authors, nevertheless, continue seeking substitute sources that could support multivariate statistical analysis of post renaissance railway positioning. Substantial movement within the clusters is evident, so it is expected that changes in the composition of the variables used, and of course a different time period, could possibly identify new, more refined factors and clusters. Having established the benefits of achieving renaissance, it would now be useful to understand how to further optimise the role of railways in societies that are progressing well in their transition to an energy-scarce future.

5. Conclusions

For convenience, the research question repeated from section 2.1 is: *Does a new post-renaissance normal now prevail, and as a corollary, does there seem to be any viable alternative*?

Rail is to be observed doing the transport heavy lifting in countries that have embraced railway renaissance, as it should do by virtue of strong positioning in its inherently competitive market spaces and its comparative energy efficiency. Transcontinental and intercontinental hauls at higher speed and lower energy consumption than waterborne transport are emerging. Regional rail is expanding around the world, frequently with double-deck trains. High speed finds favour as an effective economic and social development intervention. Urban rail is standardising on standard gauge, even in non-standard gauge countries such as Brazil and India, to economically deliver high capacity in burgeoning cities. Urban guided transit scales capacity offerings from rubber-tyred light solutions for small cities to heavyweight metro solutions for densely populated cities. No solution other than heavy haul comes to mind to move large tonnages of bulk minerals over long distances. Double-stack container trains are able to wrest high-value, low-density goods from road hauliers. Overall, railway renaissance has aligned customers and suppliers around what works and what does not work in a global market, enabling suppliers to produce widely acceptable products and solutions at competitive prices.

It is now evident that the answer to the research question is that countries that have embraced railway renaissance have been able to reposition their railways to play a substantial role in their economies and societies. In the sense that the Enlightenment exploited the intellectual freedom that it had let loose, yes, that is happening today in the post railway renaissance period. In present colloquial language, the Enlightenment would more likely be called the New Normal. And that is just what has happened over the five decades since 1964. It is once again business as usual, the material difference being that the rail mode is a now a formidable contender in the High Speed, Heavy Haul, Heavy Intermodal and Urban Rail market spaces. The authors therefore argue that the hypothesis has not been disproved.

Regarding the corollary to the research question, there is no evidence of railways emerging from the Fortuitous an Insecure clusters other than by following one or more of the renaissance growth curves through appropriate investment.

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Chapter 2

A Systems View of Railway Safety and Security

Ali G. Hessami

Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/62080

Abstract

This chapter approaches the concerns over safety and security of modern mainline and light railways from a systems perspective. It addresses the two key concerns from the view point of systemic emergence arising from the interaction between all the principal constituents of the railway system, namely infrastructure, rolling stock, energy and human element comprising workers, passengers and the neighbours of the railways.

It presents a system level perspective on the requirements of the railways that impact on all design, development, operations, maintenance and upgrades. It offers a classification system for the requirements that includes safety and security concerns amongst in excess of twenty other requirement categories. The chapter subsequently covers a whole railway safety study carried out in the United Kingdom that is the only example of such analysis globally and will give an overview of the findings of this holistic safety study that may provide a reference for all international mainline railways.

Finally, the chapter reviews the trends in railway safety and security, and the impact of new control and command technologies on the safety performance of railways including a view of the emerging issues.

Keywords: Railway safety, Railway security, Railway system, Requirements, Emergence

1. Introduction

Modern railways have moved a long way from the slow, noisy, polluting and poor safety record of their earlier ancestors and offer speed, comfort, convenience and enhanced safety approaching those of air travel these days. This is largely driven by incorporation of many modern innovations into the infrastructure, rolling stock and operations comprising advanced computing on-board and track side, high-speed communications, energy efficient traction systems and new track materials. These evolutionary changes have rendered railways a highly attractive mode of transportation in today's world.

2. A Life-cycle Perspective

The systematic safety assurance of a product, system or process (PSP) requires the consideration of key activities at each phase of the development and deployment. This is referred to as the life-cycle perspective and constitutes the backbone of the most standards and codes of practice.

The generic PSP safety life-cycle comprises 12 phases as follows:

1. Concept Definition
2. Detailed Definition and Operational Context
3. Risk Analysis and Evaluation
4. Requirements (including Safety Requirements) Specification
5. Architecture and Apportionment
6. Design and Implementation
7. Manufacture/Production
8. System Integration
9. Validation
10. Acceptance
11. Operation, Maintenance and Performance Monitoring
12. Decommissioning.

The life-cycle concept constitutes the backbone of the systems engineering practice and the most system safety processes, standards and codes of practice. It exists in a variety of forms and detailed stages depending on the source. One old reference from railway safety standards [1,2] depicts this as a 12–14 phase process by separating many of the later stages such as monitoring and modification into distinct phases as depicted in Figure 1.

3. System Level Requirements and Classifications

The starting point of a comprehensive understanding of a desired or existing system is the so-called system level perspective. Once a level of interest in the hierarchy is stated, then the clear description of the system is the principal starting step.

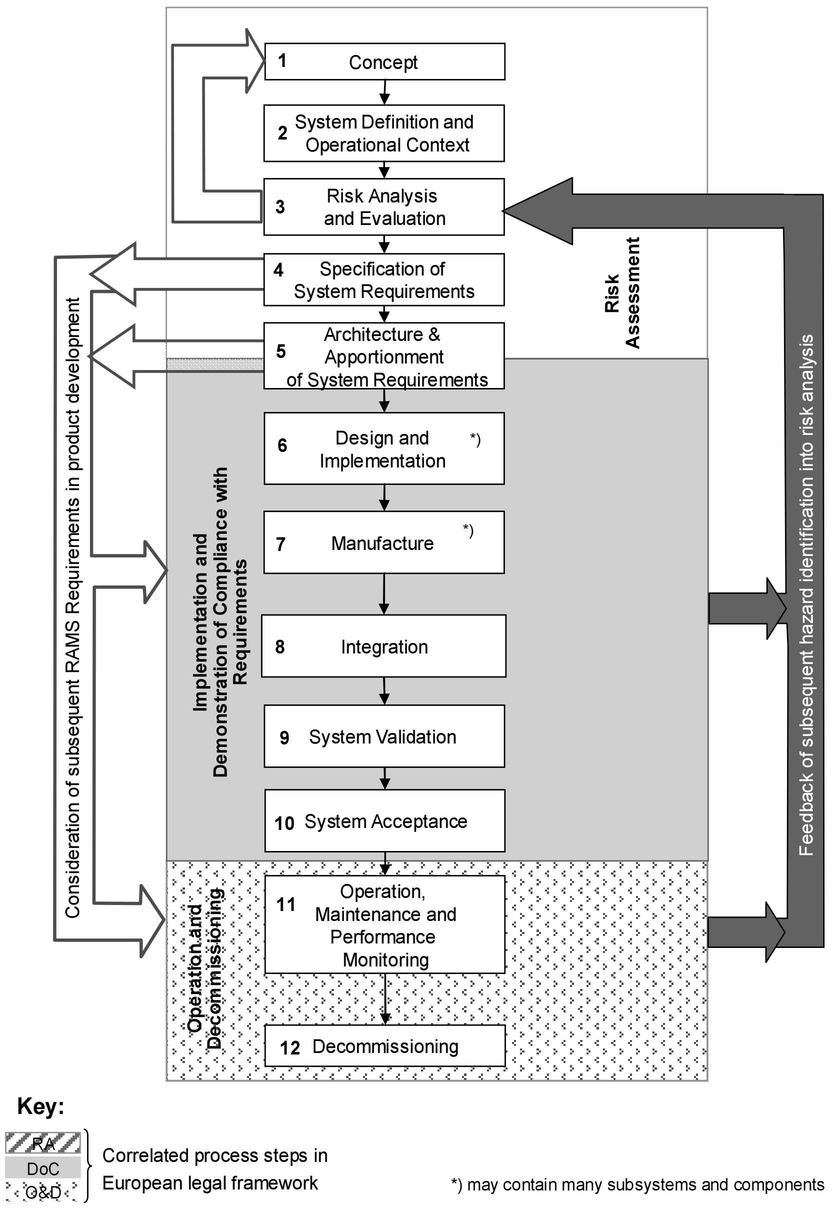

Figure 1. System Safety Life-cycle According to CENELEC Standards

3.1. System Level Perspective

The question of perspective and level is quite fundamental to understanding the system, its constituents, the topology, interfaces and dynamic behaviour. The so-called 'top-level' system perspective is a vision and representation that includes four classes of constituents, namely

a. People comprising users, operators, suppliers and the public (the latter category is relevant to the safety and security issues) that is sometimes referred to as stakeholders,

b. Control and automation system that performs functions based on embedded logic and algorithms in machines of mechanical, electro-mechanical or electronic nature,

c. The infrastructure that supports the functioning of the system. This includes supporting systems and the host environment that surrounds the system including the energy supply, major interfaces with neighbouring or supporting systems/sub-systems, etc.,

d. Processes and rules that govern the interactions between people, automation and the infrastructure. These are a broad range of operational, legal, commercial and emergency response conventions that create a common understanding for all system stakeholders. The socio-economic setting within which a system is realized and operated can also be considered as a part of the environmental rules and constraints that influence the functions and behaviours of the systems.

A general view of the broad system composition is depicted in Figure 2 as the so-called top-level system perspective.

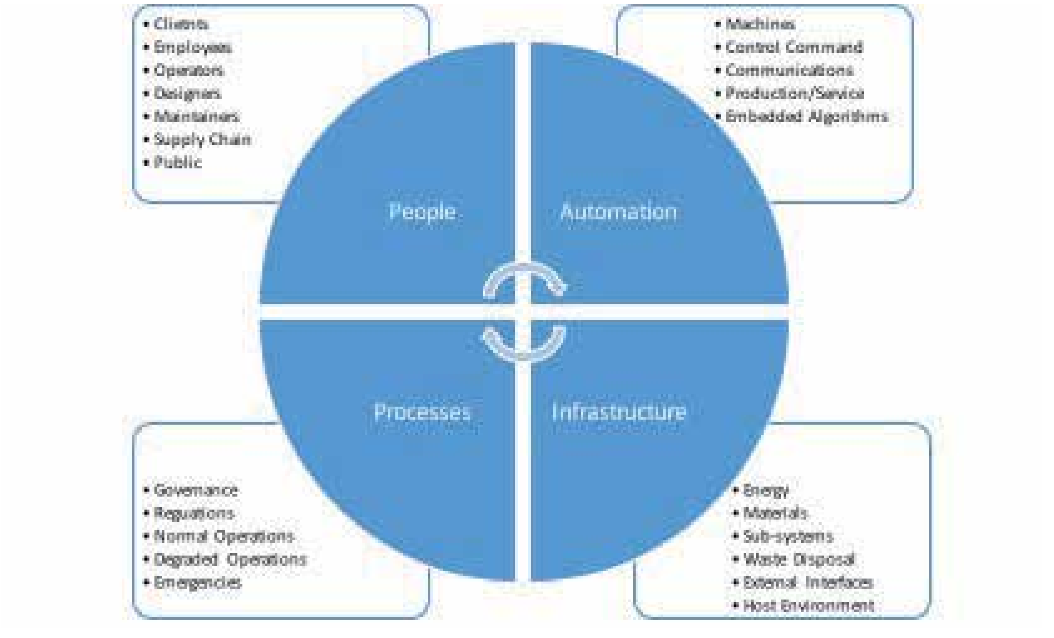

Figure 2. Top-level Railway System Constituents Perspective

The system of interest exists within such a setting and delivers a utility function or service as part of a larger natural or socio-economic system. However, the systematic study and analysis of the most systems requires the forms of conceptualisation, representation and formalisation that provides a backdrop for the study and understanding of the system properties.

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Most system studies start with a 'rich-picture' representation that places the system in its host environment and where possible, includes many of the four classes of information detailed above. One such illustration is given in Figure 3 for the safety study of a school within the proximity of a railway environment.

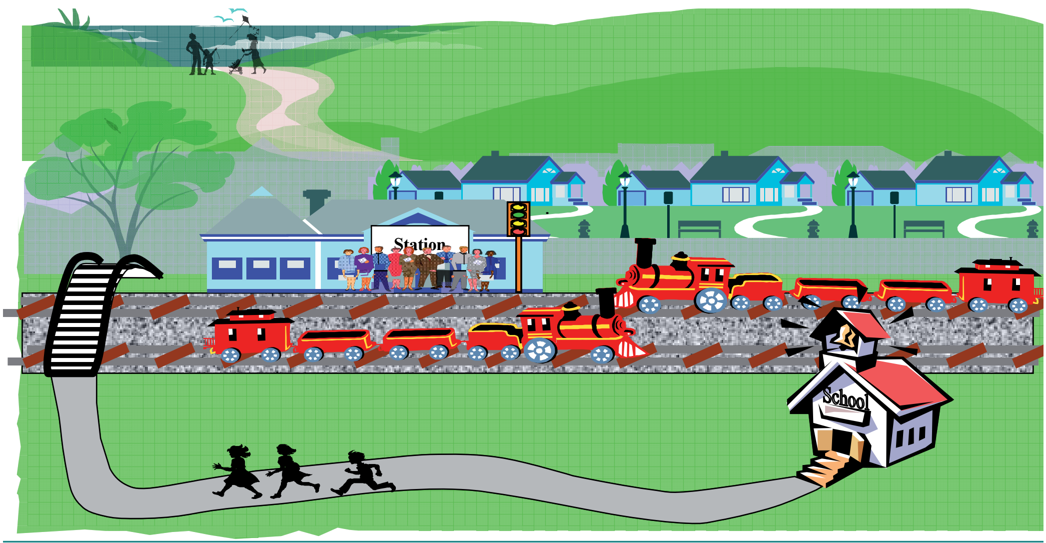

Figure 3. Rich-picture Representation of a Top-level System Perspective

The rich-picture representation and associated often pictorial forms of top-level system representation are largely employed in requirements capture and safety studies at the early phases of the life cycle.

3.2. System Level Requirements

In the life-cycle perspective, especially the one depicted in Figure 1 above, the specification of requirements including the safety requirements commence in phase 4 of the system life cycle. This in practice is unreal and untrue. Most system requirements and indeed some high-level safety requirements are known at the start of the life cycle. These are broadly derived from a number of sources comprising:

1. Past experience of similar or reference systems,
2. Customer and stakeholder expectations,
3. Contractual documents,
4. Operational principles known in the domain and derived or represented in the concept of operation (ConOps),
5. Regulations, standards, rules and codes of practice.

It is worth noting therefore that the system performance requirements are not strictly the matter for a specific time or phase in the life cycle and can predate the system. It is also an evolutionary and iterative process that gains more details the further development moves down the life-cycle phases. The derivation of system level requirements (SLR) is depicted in Figure 4.

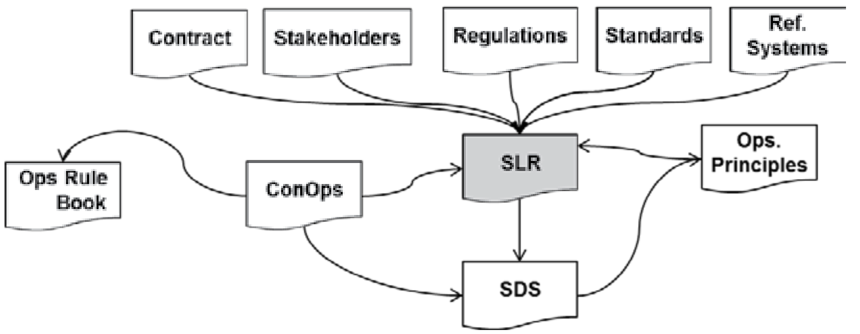

Figure 4. Derivation of System Level Requirements

The feedback loop from later phases of the life cycle such as the system integration phases back to the SLR is quite normal and in the same sense that system safety properties evolve in terms of understanding and detail, requirements, especially at system level may emerge much later than desired. This is a natural consequence of complexity of requirements, expected functions and behaviours as well as the evolving understanding or operational expectations of the client that may impose additional expectations on the system after the early phases of the life cycle.

3.2.1. Classification of SLR

Given the diversity of stakeholders and forms of requirements, it is constructive to classify a large list of requirements into distinct and verifiable classes. These classes are often chosen from performance point of view of stakeholder groupings to make reference and satisfaction arguments simpler and more efficient. The typical classes for such groupings of requirements within a railway context constitute a broad range as depicted in Table 1:

Item	Requirement Class	Scope and Observations
	Technical/functional	Throughput, speed, headway, energy usage, capacity, configurability, size, weight, features, gauge, ...
	Commercial/economic	Costs, finance, social benefit, return on investment,...
	Environmental	Temperature, humidity, vibration, shock, water ingress, rapid cycles, ...
	Integrity	Reliability, availability, maintainability and associated metrics

http://dx.doi.org/10.5772/62080

Item	Requirement Class	Scope and Observations
	Safety	The exposure of people especially clients, operators, service provider and the public to the harmful effects, system failures and accidents, expected level of safety, norms, ...
	Security	Immunity of the system to malicious intent in physical and cyber spaces including surveillance, espionage, attacks, contamination by CBRN,...
	Quality	Relating to system's materials, construction, assembly, installation, ambience, feel, appearance, comfort, ...
	Sustainability	Energy optimization, use of renewables, impact on emissions to the environment, use of rare materials, waste disposal, ...
	Service	Ease of use, alighting & egress, ride quality, HVAC, lighting levels, seating, standing support, passenger density, ...
	Operational	Operational modes, operational principles & rules that have to be observed, trains per hour, door operations, dispatching and station management, degraded operations, emergencies & evacuation, ...
	Usability	Accessibility issues for the elderly and disabled, lifts, support staff, ramps, steps, hand rails, ...
	Social	Scope of service, pricing, user affordability considerations, potential for suicides, ...
	Regulatory	The rules, regulations, targets and standards applicable to the design, development, installation, testing, commissioning and full passenger service, ...
	Temporal	The timing and speed of execution of the project, delivery in staged phases, operational constraints, dwell times, service periods, ...
	Contractual/legal	The obligations of the supply chain in delivering the requirements both legal as well as contractual, penalties and loss limitation, staged payments, operation and maintenance considerations, force majeure conditions, ...
	Performance monitoring	Proactive and reactive monitoring of system performance based on credible systemic predictors/indicators, identification of critical system states, avoidance of down times and accidents through intelligent supervisory systems, ...
	Human resource	The numbers, types and essential knowledge, experience and seniority of the human resources required to operate, monitor and maintain/upgrade the system including resources from the supply chain and temporary staff, organisational structure, reporting, health and safety issues, control and command, necessary licensing, ...

Item	Requirement Class	Scope and Observations
	Training and competencies	The initial training for the different classes of operators, maintainers, support and auxiliary staff to bring them to the minimum level of competence for operational readiness and continued maintenance of the knowledge in the event of system change and upgrades, ...
	Business continuity	Full consideration of maintaining a service level in the event of natural or manmade disasters and major disruptions, redundancy and operational contingencies in such circumstances, ...
	Operational readiness	Consideration of a minimal configuration of the system, supporting sub-systems, human resources, infrastructure, timing, time tabling and response arrangements that render a new system or one recovering from failure or degradation ready for full service operations, ...
	Expected life and life-extension	The client's expectation of the utility and continued functionality of the system in terms of normal operational life, obsolescence, necessary upgrades and maintenance activities and decision criteria for decommissioning and disposal of the system including safety and sustainability considerations, ...
	Special interest	Requests, needs and expectations of various social and formal groups who will be affected by the operation of the system including proximity, noise and vibration levels, EMC, disturbance, working hours, contingencies in the event of major accidents and catastrophes, ...

Table 1. Classification of System Level Requirements for a Railway Context

Any PSP may have an impact or specifically fit within one or more of the above classes. In this spirit and contrary to the immediate focus on a technical system, the classifications depicted in Table 1 should be used as a check-list to capture potential impact of any PSP on wider classes of requirements than mere technical and safety dimensions.

4. System Level Safety and Security Requirements

Safety is a system level emergent property and can best be understood and assured through a systems and high-level perspective. The highest level of perspective for the railways the so-called 'top-level' is the entire railway as a system comprising the constituents detailed in Section 3.1. Understanding of the total railway system safety performance requires a systematic study of the system level interactions between the system constituents and people exposed to the machinery, infrastructure and operations of the railway system. The CENELEC Technical Report TR50451 [3] developed to support EN50129 developed in 1998 details a perspective on the whole railway safety in which three key stakeholders collaborate to understand, analyse and communicate the principal requirements. The principal active stakeholders are the infrastructure manager (IM) and the railway undertakings (RU) who operate the services. The third key stakeholder involved is the safety regulator, often a government appointed entity. The proposed perspective is for the principal stakeholders who understand the operational railway, that is the RU and IM, to conduct safety analysis, identify system level hazards, conduct risk analysis and determine the tolerability level for the key system level hazards that they manage. This is referred to as the determination of the tolerable hazard rate (THR). The concept is depicted from CENELECTR50451 in Figure 5.

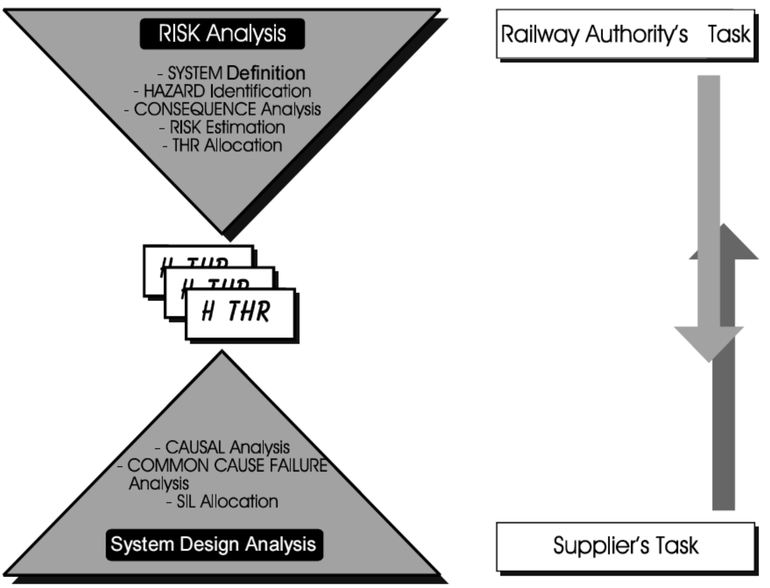

Figure 5. Collaborative Approach to Railway System Safety, Stakeholders and Responsibilities

The tolerable rate for a hazard (THR_H) and the derivation of safety integrity level (SIL) are presented in Figure 5 in the relative order and ownership.

The manufacturers, service providers and supply chain are expected to employ the published THRs to determine what hazards relate to their services/products and determine their share of the hazards affected and SIL applicable to their PSP/service. This is principally a collaborative approach to the achievement of system safety that is likely to render more benefits to the industry than the current disjointed and market driven approach.

4.1. Product Level Safety Requirements Specification

The system safety life cycle as depicted in Section 2 implies that the specification of the system requirements, especially the safety requirements for a PSP commences after system risk analysis, that is in phase 4 and well after the start of a project or programme. Whilst many of the detailed safety requirements emerge from the identification of the product/system behaviours that lead to hazardous states, in a similar manner to the general system requirements, many of the safety requirements are known at a high level of detail at the start of a project or programme. These come from a multiplicity of sources, standards, rules, reference products/systems, regulations, customer needs, existing operational safety performance data, existing operational principles, safety functions and finally, any industry level set of safety hazards. This is depicted in Figure 6. These are all recorded in the product/SLR as detailed in Table 1 and the system level safety requirements (SLSR) that constitute a subset.

In principle, if the national level safety data in terms of principal railway hazards and the THRs are known, then these can used together with a causal analysis and apportionment to derive the safety requirements for a complete PSP. Alas, in the absence of such desirable data, the process depicted here is the next best alternative solution to the identification of PSP safety requirements.

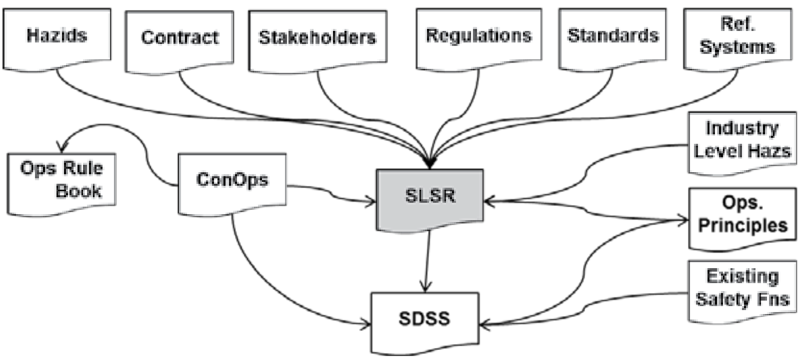

Figure 6. Derivation of System Level Safety Requirements for a PSP

It is also customary to initiate safety activities at the outset of a project or programme through conducting high-level hazard studies. The preliminary hazard studies that lead to an understanding of the potential system hazards are referred to as PHA. These often employ a system representation in the form of rich-picture or Process & Instrumentation Diagram (P&ID) and lead to the identification and capture of hazardous states arising from system composition, placement or the environment since at this stage, not much is known about the total system functionality or design. The PHA is then followed by IHA/OHA/SHA/SSHA at later stages of the life cycle as the design and development, integration and construction progresses.

The relationship between safety studies and the life-cycle phases is depicted in Table 2.

Item	LC Phase	Principal Safety Activity
1	Concept definition	· Hazid of system concept representations · Hazid of system composition, topology, placement, interfaces & Comms · Verify against industry hazards · Verify against ref system hazards

http://dx.doi.org/10.5772/62080

Item	LC Phase	Principal Safety Activity
		· Conduct PHA · Establish hazard log and capture all identified system level hazards
2	Detailed definition and operational context	· Evaluate past experience data for safety · Establish safety plan (overall) · Hazop of Ops Scenarios · Specify system functions and tag the safety related functions · Identify safety protection functions · Conduct SHA and develop core hazards · Conduct IHA &SSHA on the Comms and sub-systems · Hazard log capture
3	Risk analysis and evaluation	· Determine the risk acceptance principles and criteria · Perform system risk analysis based on core hazards · Perform risk evaluation · Determine THRs · Hazard log capture and update
4	Requirements (including Safety Requirements) Specification	· Specify top-level system safety requirements · Define safety acceptance criteria for the system · Define safety-related functional requirements · Determine SIL for safety functions · Establish safety validation plan · Hazard log capture and update
5	Architecture and apportionment	· Apportion system safety targets & requirements · Specify sub-system and component safety requirements · Allocate safety functions to sub-systems · Define sub-system and component safety acceptance criteria · Update safety plan and safety validation plan · Hazard log capture and update
6	Design and implementation	· Implement safety plan by review, analysis, testing and data assessment · Implement safety functions in line with relevant SIL guidelines in reference standards · Ensure hazard control and risk mitigation solutions are designed in · Justify safety-related design decisions · Undertake project control covering: · Safety management · Control of sub-contractors and suppliers · Develop test scripts · Prepare generic product safety case · Hazard log update with all hazard control options implemented
7	Manufacture/production	· Implement safety plan for production activities

Item	LC Phase	Principal Safety Activity
		· Hazard log update
8	System integration	· Verify safety functions and interfaces · Derive safety-related application conditions · Hazard log update
9	Validation	· Implement commissioning programme · Implement validation plan · Conduct Safety Validation tests, analysis · Prepare specific application safety case · Seek safety approvals · Hazard log update with test results, new hazards
10	Acceptance	· Assess specific application safety case · Detail all safety-related application conditions (SRACS) in the O&M Manuals · Close out all hazard-related actions · Ensure operational readiness · Hazard log update and handover
11	Operation and Maintenance& Performance Monitoring	· Undertake on-going safety centred maintenance · Assess the safety impact of any system upgrades and conduct risk analysis before implementation · Perform on going safety performance monitoring and hazard log maintenance · Implement SRACs · Collect, analyse, evaluate and use performance & safety statistics · Capture any emerging hazards in the hazard log
12	Decommissioning	· Establish Decommissioning Safety Plan (DSP) · Perform hazard analysis and risk assessment for decommissioning activities · Implement DSP

Table 2. LC Phase-related Principal Safety Activities

In principle, safety requirements of a composite system comprise functional and non-functional categories. The automation and control systems generally deliver algorithmic safety functions hence largely satisfy functional safety requirements (FSaR) even though any product, system, process/service may additionally have non-functional requirements that affect its safety performance.

The FSaR category is depicted in the class definition in Table 3.

The non-functional category largely relate to operating and environmental conditions, health and safety issues, materials, packaging and manufacturing aspects of a PSP and are not treated in this guidance. The non-functional safety requirements (NFSaR) are depicted in the class definition in Table 4.

Item	Class: Functional Safety Requirements (FSaR)
Attributes	· Is a positive statement of desirable safe performance to be achieved · Relates to ensuring the control or supervision of an undesirable system hazard to be avoided · Relates to a user/environment/operational need · Can be classed as Mandatory or Desirable · All Mandatory FSaRs shall be met by the design · Has a hierarchy from function to HW, SW and PW
Operations	· FSaRs translate into real algorithmic action/activity that has to be performed by SW, HW, PW or System · Has direct control/protection/supervisory role in system · Has varying risk control/protection capability · Has different levels of confidence defined by SIL · Satisfies one or more classes of Stakeholders · Is traceable to system level requirements (SLR and SLSR) · Has to be specified in a specific level of safety attainment to reduce costs of implementation

Table 3. Functional Safety Requirements Class

Item	Class: Non-Functional Safety Requirements
Attributes	Is a positive statement of desirable safety feature, e.g. electrical, EMC immunity etc. Relates to a user/environment/operational need Can be classed as Mandatory or Desirable All Mandatory NFSaRs shall be met
Operations	NFSaRs translate into features that need to be realised Has varying risk control/mitigation capability Satisfies one or more classes of Stakeholders Is traceable to system level requirements (SLR and SLSR) Influences environmental, safety, health and welfare, materials, packaging and manufacturing aspects

Table 4. Non-Functional Safety Requirements Class

It is also important to note that the apparent overlap between various hazard studies from PHA to SHA is matters of perspective and detail. What is identified at PHA is largely very high level and coarse issues akin to core hazard concept developed in the UK system level study and later adopted by ETCS, the European Train Control System. The more detailed hazards identified at the system and sub-system level often fit within these Core Hazard categories hence no repetition of the effort or waste of energies should occur in subsequent hazard studies.

5. System Level Safety Study–UK National Railways

To this date and since the initial publication of the CENELEC TR-50451 [3] initially published as R009-004 in 1999, only one system level study of the whole railway infrastructure and operations has been conducted in the United Kingdom, largely designed and implemented by the author and the supporting team at Railtrack plc in 1996.

The so-called risk profiling of UK Railways attempted to study the whole railway system from the view point of safety risks posed to three key groups, namely:

1. The Passengers,
2. The Workers and Employees,
3. The General Public and the railway Neighbours.

This national level study was scoped at the level of the whole UK national railway system and after three years resulted in identification, verification and publication of three hazard logs relating to the three groups studied and an integrated quantified safety and environmental risk model.

The idea of core hazard was devised to classify and group hazards with similar root, causation or synergy into larger classes and avoid dealing with many tens of detailed issues identified in the course of the national level study. The core hazards and the detailed hazards are the basis of determining the system level safety requirements (SLSR) for the entire railway. However, since the hazards and the requirements are system level properties that are heavily influenced by the national culture, it is not possible or indeed could be misleading to adopt the SLSR safety requirements from another country. In reality, each nation state needs to conduct their own studies to arrive at a current and culture sensitive nature of the safety risks of their national railways to the population.

The risk profiling of Railways project employed a detailed scenario-based scrutiny of the exposure of each group of people to the operational and infrastructure hazards of the national railway. The scenarios were themed around a 'Day in the Life of...' each group and took three years to complete. The hazards identified through the study were verified against a number of sources by a number of independent engineering safety consultancy organisations. After verification and checks for coverage and completeness, the identified hazards were modelled employing a systematic framework comprising causal, consequence and loss evaluation stages [4] in order to establish the risks and strive towards generating a safety risk profile for the national railways. The outcome was the first total railway system level integrated risk model that was capable of being employed to assess the impact of various changes, technologies and innovations on the safety performance of the national level railway or aspects of it. It also generated THRs for all the published groups of hazards for use in the supply chain. This study influenced TR-50451 [3] and the approach to collaboration in railway safety.

In principle, a national level railway Hazard Portfolio for each of the three affected groups, followed by determination of the risk tolerability level for the occurrence of these hazards is the only systematic approach to understanding system level safety issues and apportioning these products, systems and processes/services in a traceable, realistic and meaningful manner.

5.1. Passengers group

The national level safety study of the passenger group was planned and conducted over a number of workshops with diverse participants from many of the stakeholder groups. A series of pictographics and photos were taken and composed into 'A Day in the Life of a Railway Passenger' that covered most credible scenarios that a typical passenger would interact with the railways. This comprised entering a railway station, using the facilities, going to a platform, boarding a train, travelling, reaching their destination, alighting and eventually leaving the railway premises. The rich-picture representations were employed as the backdrop to a creative Hazop style process to identify all deviations from the normal behaviour that could result in a hazardous state to which a passenger was exposed to.

By the end of the national level workshops, 101 hazards had been identified [5] for the passenger group taking into account variations in age, conditions and luggage handling. The identified hazards were shared with the participants for offline verification and completeness checks. Through a further review, all hazards with common causality or synergy were grouped as a cluster under a core hazard. For the passenger group, each core hazard was tagged with a H for Hazard, P for Passenger and a unique number that represents the relative proximity of the hazard to an accident scenario. The core hazards for the passenger group, relating to the exposure scenarios throughout a railway journey are depicted as follows.

5.1.1. Core Hazard: HP500 – Abnormal or Criminal Behaviour

The HP500 addresses the range of abnormal and criminal behaviours that are known to take place within the railway infrastructure. This does not, however, address abnormal working practices of railway personnel, with the exception of train drivers and senior conductors. This cluster comprises a number of lower level hazards that were identified at the stakeholder workshops, namely

HP425 Irresponsible behaviour

HP426 Destructive behaviour (all forms)

HP427 Crossing line at station

5.1.2. Core Hazard: HP502 – Crowding

The causal model for HP502 represents the range of factors that potentially could cause a crowding situation to arise (e.g. a special event causing an increase in passengers, or an incident causing panic amongst an otherwise manageable number of passengers).

The consequence model for HP502 represents the development of a crowding situation to a level at which injuries or loss of balance (see HP506) could occur. This hazard cluster comprises:

HP502 *Crowding*

5.1.3. Core Hazard: HP503—Loss of Passenger Compartment Integrity During Movement

The scope of this core hazard includes the following:

- Doors opened early on stopping slam shut or CDL trains, potentially resulting in passengers and workers on the train falling out of the train or passengers and workers on the station platform being struck by open doors.
- Slam shut or CDL trains departing with a door open, potentially resulting in passengers and workers on the station platform being struck by the open door or the open door being struck by a passing train.
- Doors opened during train movement, potentially resulting in passengers or workers falling out of the train.
- Doors on the wrong side of the platform unlocked (on trains with sliding or CDL doors) or opened (on trains with slam shut doors), potentially leading to passengers or workers getting off the train on the wrong side, or falling out of the train onto the track. Also included here are incidents where doors which are on the same side of the train as the platform but which are not adjacent to the platform (e.g. when a train is longer than the platform) are unlocked or opened and passenger or worker leaves or falls out of the train.
- Train carriage decoupling during movement, potentially leading to passengers or workers falling off the train.
- Doors failing to open at a station are included within this core hazard in the causal analysis for consistency with earlier work but consequence barriers are not modelled as it is considered that there are no safety implications within the scope of this core hazard associated with doors failing to open. Train doors are barriers to consequence escalation for other core hazards, for example HP507 'Onset of fire/explosion', but failure of train doors to open does not in itself present a hazard. This cluster comprises:

HP503 *Loss of passenger compartment integrity during movement*

5.1.4. Core Hazard: HP504—Passengers in Path of Closing Train Doors

This hazard encompasses 'passenger in path of closing train door' (HP504) and 'worker in path of closing train' (HW503). The scope of this core hazard includes

- Passenger or worker hit by closing door.
- Passenger or worker caught in door of stationary train, potentially leading to the train moving off, dragging the person along the platform.
- Passenger or worker trying to board a moving train, potentially leading to apparel being caught on the door and dragged along the platform or opening the door then falling and being hit by the door or caught up in the door.

The cluster comprises;

HP504HP504 passenger/apparel in path of closing train door

5.1.5. Core Hazard: HP506—Loss of Balance

We have excluded from this core hazard falls to trespassers and falls occurring on level crossings. The scope of passengers has been enlarged to include all persons in a railway station. We also excluded a few falls that were suicide attempts, but included some where there was no clear determination. We have excluded passengers falling as a result of trying to enter or leave the train, while it is still moving. This cluster comprises

HP413 Loss of balance on the ground

HP414 Loss of balance on stairs and escalators

HP415 Loss of balance getting on and off trains

HP416 Loss of balance whilst in a train

5.1.6. Core Hazard: HP509—Inappropriate Separation between Running Railways and Passengers

The HP509 Core Hazard for inappropriate separation between running rail and passengers has been developed to include those situations where the distance between the running rail and people is not sufficient to ensure the safety of passengers.

This core hazard does not include Core Hazard HN501 failure of level crossing to protect the public from passing trains. This model also does not include incidents of inappropriate separation between running rail and passengers resulting from suicide. Finally, this model does not include incidents of inappropriate separation between running rail and people caused by derailment. This cluster comprises:

HP509Inappropriate separation between rail & passengers

5.1.7. Core Hazard: HP510—Inappropriate Separation between Un-insulated Live Conductors and Passengers

The scope of 'Inappropriate separation between un-insulated live conductors and passengers' includes the following:

HP417 Occurrence of DC power arc

HP418 Existence of touch potential

HP419 Inappropriate separation from DC conductor rail

HP420 Structure in contact with live conductor rail

HP421 Inappropriate separation from OHL

HP422 Structure in contact with OHL

HP423 Occurrence of AC power arc

HP424 Inappropriate separation from OHL induced voltage

5.1.8. Core Hazard: HP512—Passenger Protruding Beyond Train Gauge During Movement

Core Hazards HP512, passenger protruding beyond train gauge during movement, have been developed to include all situations in which a person is protruding outside the gauge of a moving train.

The model excludes incidents resulting from suicide or attempted suicide— these are assumed to be covered under HP500 Abnormal or Criminal Behaviour. The cluster comprises

HP512 Passenger protruding beyond train gauge

5.1.9. Core Hazard: HP513—Unsecured Objects at Height

This core hazard falls within the generic grouping of 'Objects Falling from Height' affecting passengers (HP513) which includes the following:

- Objects falling from height within stations (HP513, HP512) as a result of degradation (e.g. falling glass) or maintenance or construction work.
- Objects thrown at trains (HP513, HW512).
- Falling luggage stored at height on trains and falling train furniture (HP513).
- Dropped crane loads (HW512).

The cluster comprises

HP513 Unsecured objects falling from height

5.1.10. Core Hazard: HP515—Inappropriate Separation between Passengers and Moving Vehicle (Other Than Rail Vehicle)

The scope of this core hazard is concerned with inappropriate separation between passengers (HP515) and moving vehicles (not rail vehicles). This encompasses the following:

- Accidents involving road vehicles in collision with pedestrians, other vehicles or structures in the vicinity of stations and work sites (including workers at level crossings in local control mode).
- Accidents involving non-road motorised vehicles, push trolleys and catering trolleys.
- Accidents involving overturned machinery and inadequate control of wheel set movements.

The cluster comprises:

HP515 inappropriate separation between passenger and moving vehicle (non-rail)

5.1.11. Core Hazard: HP516— Handling Heavy Loads

The hazard is defined to assume some error had occurred in handling a heavy load since otherwise the estimated number of incidents would be so high to be meaningless as a hazard. Various scenarios were identified, including strain injuries from carrying and lifting luggage,

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luggage falling on to other passengers usually inside trains and cases of luggage falling down escalators and stairs.

The cluster comprises:

HP516 Error in handling heavy load

5.1.12. Core Hazard: HP517—Incompatibility of Train and Structure Gauge

The HP517 (incompatibility of train and structure gauge) have been developed to include those situations where the clearances between trains and infrastructure have been compromised. This hazard includes events where the train or its load extend beyond the specified gauge due to errors in loading, equipment failures or damage; movement errors leading to the train going onto the wrong route; track defects/misalignment; failures or damage leading to civil structures compromising the clearance. This core hazard does not consider events which have resulted in objects on the line (HP511), railway construction/ maintenance works, unsound structures (HP514) or unsecured objects at height (HP513). The cluster comprises

HP517 incompatibility of train and structure gauge

5.1.13. Core Hazard: HP600—Abnormal Deceleration

The risk model for HP600 'Abnormal deceleration' has been developed to strictly model only those instances of a train's slowing sharply when not actually as a part of a derailment or collision scenario. The consequences of the abnormal deceleration part of derailment and collision scenarios are assumed to be included in the loss estimation for those events. The cluster comprises

HP600 Abnormal Deceleration (super-set of HP518 &HW516)

5.1.14. Core Hazard: HP601—Uncontrolled Approach to Buffer

In the causal model, malicious or reckless behaviour on the part of the driver of the relevant train has been assumed to have been included in the data for 'Driver error'. The causal model has been populated using the SMIS database and data from Health and Safety Executive (HSE) reports.

The consequences of this hazard have been taken forward only to the point of the accident's occurring, that beyond is assumed to be calculated by loss modelling. Therefore, the incidence of fire due to buffer-stop collision has not been separately developed in the consequence model. The consequences have been assumed to fall into three bands: collisions at speeds at or below that for which the buffers have been designed; collisions at speeds greater than that for which the buffers have been designed; and collisions with siding buffer-stops. The effects of TPWS and ATP have been ignored, as they were fitted in only a small minority of cases at the time. The consequence model has been populated using expert judgement. The cluster comprises

HP601 Uncontrolled approach to buffer (HP501 &HW501)

5.1.15. Core Hazard: HP602—Loss of Train Guidance (Passenger Trains)

The risk model for HP602 'Loss of train guidance (Passenger Train)' has been developed to strictly model only those instances where a derailment actually occurs. The losses associated with this model include those occurring before the derailment due to abnormal deceleration, if there are any. However, where such deceleration avoids a derailment, the consequences are included in the 'Abnormal Deceleration' model. The cluster comprises

HP602 Loss of train guidance (Passenger Train) (HP412, HW409 &HN402)

5.1.16. Core Hazard: HP603—Loss of Train Guidance (Freight Trains)

The risk model for HP603 'Loss of train guidance (Freight Train)' has been developed to strictly model only those instances where a derailment actually occurs. The losses associated with this model include those occurring before the derailment due to abnormal deceleration, if there are any. However, where such deceleration avoids a derailment, the consequences are included in the 'Abnormal Deceleration' model. The cluster comprises

HP603 Loss of train guidance (Freight Train) (HP411, HW408 &HN401)

5.1.17. Core Hazard: HP604—Objects/Animals on the Line

The risk model for HP604 'Objects/Animals on the line' has been developed to model only the instances of animals or objects being on the running railway and having some effect thereon. There may be many instances of animals entering and leaving the railway having no effect at all and being entirely unnoticed. These scenarios are not modelled, neither are those in which other objects, such as litter, come to rest on the railway, but do not affect the system at all. Instances of objects and animals on the line causing fires are captured in the fire models and not within this model. This model also specifically excludes all causes and consequences arising from the Core Hazard HN501 'Crossing running railway at a Level Crossing'. The cluster comprises

HP604 Object/animals on line (HP511, HW510 &HN514)

5.1.18. Core Hazard: HP605—Inappropriate Separation between Trains

The risk model for HP605 'Inappropriate separation between trains' has been developed to address only the scenarios in which the separation between trains, normally provided by the signalling system, has broken down. This hazard is defined such that there is no interface between it and the 'Loss of Balance' core hazards. The cluster comprises:

HP605 Inappropriate separation between trains (HP505, HW504, HN505)

5.1.19. Core Hazard: HP606—Onset of Fire/Explosion

Core Hazard HP507 onset of fire/explosion for passengers has been developed to include those situations where fire is a spontaneous event, however, the situations where fire is a secondary consequence of a train collision or derailment are excluded. Noxious fumes are included when the cause is fire related.

Consideration has been given to the interface of his Core Hazard with Core Hazard HP500 / HW500 / HN500 abnormal or criminal behaviour. The cluster comprises:

HN400 Fire at line side

HP400 Fire inside passenger carriage

HP401 fire outside passenger electric train

HP402 fire outside diesel passenger train

HP403 Fire at station

HW400 fire on electric freight train

HW401 fire on diesel freight train

5.1.20. Core Hazard: HP607—Unsound/Unsecured Structures

The HP514 Core Hazard for Unsound/Unsecured Structure has been developed to include those situations where structures are unstable creating a threat to passengers or neighbours. This core hazard shall not include instability of trains or the movement of materials on trains. Consideration has been given to the interface of this core hazard with the core hazards object on line and inappropriate separation between trains.

All structures going beyond the railway boundary are covered here and not in HP509, inappropriate separation between running rail and passenger.

Neither the causal nor the consequence models refer to situations where structures are unstable creating a threat to workers. This is a part of Core Hazard HW512 Unsecured Objects at Height and Core Hazard HW517 Collapsing Machinery/Materials/ Structures. The cluster comprises

HP404 Unsound/Unsecured Tree

HP405 Unsound/Unsecured Tunnel

HP406 Unsound/Unsecured Under-bridge / Culvert

HP407 Unsound/Unsecured over-bridge

HP408 Unsound/Unsecured Station

HP409 Unsound/Unsecured Signalling Structure

HP410 Unsound/Unsecured Electrification Structure

5.2. Workers Group

The national level safety study of the railway workers group was planned and conducted over a number of workshops with diverse participants from many of the stakeholder groups. A similar set of prompts and photos focused on this group were taken and composed into 'A Day in the Life of a Railway Worker' that covered most credible scenarios that employees/ workers interact with the railways. This comprised planning, operating, station duties, maintenance and driving of trains. The pictorial scenarios were likewise employed as the backdrop to a creative Hazop style process to identify all circumstances where railway employees/workers were potentially exposed to hazardous states.

By the end of the national level workshops, 119 hazards had been identified [5] for the workers group. Through a further review, all hazards with common causality or synergy were grouped as a cluster under a core hazard. For the passenger group, each core hazard was tagged with a H for hazard, W for workers and a unique number that represents the relative proximity of the hazard to an accident scenario. The core hazards for the workers group, relating to the exposure scenarios are depicted as follows.

5.2.1. Core Hazard: HW500—Abnormal or Criminal Behaviour

The model developed for HW500 addresses the range of abnormal and criminal behaviours that are known to be performed within the railway infrastructure. They do not, however, address abnormal working practices of railway personnel, with the exception of train drivers and senior conductors. This was agreed with the experts at the start of the modelling process. The cluster comprises

HW426 Irresponsible behaviour

HW427 Destructive behaviour

HW428 Crossing line at station

5.2.2. Core Hazard: HW502—Loss of Passenger Compartment Integrity During Movement

The scope of this core hazard includes the following:

- Doors opened early on stopping slam shut or CDL trains, potentially resulting in workers on the train falling out of the train or workers on the station platform being struck by open doors.
- Slam shut or CDL trains departing with a door open, potentially resulting in workers on the station platform being struck by the open door or the open door being struck by a passing train.
- Doors opened during train movement, potentially resulting in workers falling out of the train.
- Doors on the wrong side of the platform unlocked (on trains with sliding or CDL doors) or opened (on trains with slam shut doors), potentially leading to workers getting off the train on the wrong side, or falling out of the train onto the track. Also included here are incidents where doors which are on the same side of the train as the platform but which are not adjacent to the platform (e.g. when a train is longer than the platform) are unlocked or opened and passenger or worker leaves or falls out of the train.

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- Train carriage decoupling during movement, potentially leading to workers falling off the train.
- Doors failing to open at a station are included within this core hazard in the causal analysis for consistency with earlier work but consequence barriers are not modelled as it is considered that there are no safety implications within the scope of this core hazard associated with doors failing to open. Train doors are barriers to consequence escalation for other core hazards, for example HP507 'Onset of fire/explosion', but failure of train doors to open does not in itself present a hazard.

The cluster comprises

HW502 Loss of passenger compartment integrity during movement

5.2.3. Core Hazard: HW503—Worker in Path of Closing Train Doors

This hazard encompasses workers in path of closing train (HW503). The scope of this core hazard includes

- Worker hit by closing door.
- Worker caught in door of stationary train, potentially leading to the train moving off, dragging the person along the platform.
- Worker trying to board a moving train, potentially leading to apparel being caught on the door and dragged along the platform or opening the door then falling and being hit by the door or caught up in the door.

The cluster comprises

HW503 HW503 worker/apparel in path of closing train door

5.2.4. Core Hazard: HW505—Loss of Balance

We have excluded from this core hazard any falls occurring on level crossings, although works crossings were included. There is some overlap at the consequence side with HW508. We have included falls getting on and off trains by drivers and cleaning staff who often have to negotiate steps and gaps which would not be encountered by passengers. The cluster comprises

HW410 Loss of balance on the ground

HW411 Loss of balance on stairs and escalators

HW412 Loss of balance getting on and off trains

HW413 Loss of balance whilst in a train

HW414 Loss of balance when working at height

5.2.5. Core Hazard: HW508—Inappropriate Separation between Running Railways and Workers

The HW508 Core Hazard for inappropriate separation between running rail and workers has been developed to include those situations where the distance between the running rail and people is not sufficient to ensure the safety of workers.

This core hazard does not include Core Hazard HN501 failure of level crossing to protect the public from passing trains. This model also does not include incidents of inappropriate separation between running rail and workers resulting from suicides. Finally, this model does not include incidents of inappropriate separation between running rail and people caused by derailment. The cluster comprises

HW402 Red zone working

HW403 Green zone working

5.2.6. Core Hazard: HW509—Inappropriate Separation between Un-insulated Live Conductors and Workers

The scope of 'Inappropriate separation between un-insulated live conductors and workers' includes the following:

HW415 Occurrence of DC power arc

HW416 Existence of touch potential

HW417 Structure exposed to leakage current [DC]

HW418 Inappropriate separation from conductor rail

HW419 Structure in contact with live conductor rail

HW420 Inappropriate separation from OHL

HW421 Structure in contact with live OHL

HW422 Inappropriate separation from OHL induced voltage

HW423 Inappropriate separation from ground potential

HW424 Occurrence of AC power arc

HW425 Structure exposed to current leakage [AC]

5.2.7. Core Hazard: HW511—Worker Protruding Beyond Train Gauge During Movement

Core Hazard HW511, worker protruding beyond train gauge during movement, have been developed to include all situations in which a person is protruding outside the gauge of a moving train.

The model developed excludes incidents resulting from suicide or attempted suicide—these are assumed to be covered under HHW500 abnormal or criminal behaviour. The cluster comprises

HW511 Worker protruding beyond train gauge

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5.2.8. Core Hazard: HW512—Unsecured Objects at Height

This core hazard falls within the generic grouping of 'Objects Falling from Height' affecting workers (HW512) that includes the following:

- Objects falling from height within stations (HP513, HP512) as a result of degradation (e.g. falling glass) or maintenance or construction work.
- Objects thrown at trains (HP513, HW512) or hung in front of trains (HW512).
- Falling luggage stored at height on trains and falling train furniture (HP513, HW512).
- Dropped crane loads (HW512).
- Falling objects from the infrastructure (HW512, HN512).

The cluster comprises:

HW512 Unsecured objects at height

5.2.9. Core Hazard: HW513—Inappropriate Separation between Workers and Moving Vehicle (Other Than Rail Vehicle)

The scope of this core hazard is concerned with inappropriate separation between the workers (HW513) and moving vehicles (not rail vehicles). This encompasses the following:

- Accidents involving road vehicles in collision with pedestrians, other vehicles or structures in the vicinity of stations and work sites (including workers at level crossings in local control mode).
- Accidents involving non-road motorised vehicles, push trolleys and catering trolleys.
- Accidents involving overturned machinery and inadequate control of wheel set movements.

The cluster comprises:

HW513 inappropriate separation between workers and vehicles

5.2.10. Core Hazard: HW514—Handling Heavy Loads

The core hazard was defined to assume some error had occurred in handling a heavy load since otherwise the estimated number of incidents could be so high to be meaningless as a hazard. We scoped the hazard to cover manual handling of loads, including unloading from vehicles.

We did not formulate a definition of a heavy load as a specific weight but considered any incident where the handling of a load caused some loss and where the weight of the load was a factor. We followed the general approach of HP516 of dividing the hazard into problems with lifting, carrying or stacking a load. The cluster comprises

HW514 Improper manual handling of heavy load

5.2.11. Core Hazard: HW517—Unsound/Unsecured Machinery/Materials or Structures

The scope of this core hazard includes the following:

- Crane and rail crane collapse potentially leading to a worker being crushed.
- Collapse of stacked materials potentially leading to a worker being crushed.
- Inadequate protection for working at height potentially leading to a worker falling whilst working at height.
- Misuse or inadequate maintenance of tools causing worker injury.

The cluster comprises

HW517 unsound/unsecured machinery/materials/structures

5.2.12. Core Hazard: HW518—Work in Confined Spaces

We kept the scope of this hazard quite large to include events where workers are in spaces such as offices and drivers in cabs and are exposed to hazards such as fumes from batteries. There is probably some overlap with core hazard area HW512 in the consequences relating to workers in a confined space being affected by toxic or hazardous fumes. We have excluded shunting incidents since these are being dealt with under Core Hazard area HW508.

The cluster comprises:

HW518 Work taking place in confined space

5.2.13. Core Hazard: HW519—Contaminated Water and/or Land

The core hazards for contaminated water and/or land for workers and neighbourhood (HW519 and HN502, respectively) have been defined as the release of harmful substances likely to cause contamination of the environment. This allows the consideration of detection, mitigation and remediation barriers in the consequence domain. The release of toxic gases likely to cause harm to workers or neighbours has also been considered under this core hazard.

This core hazard considers harm to workers or neighbours as a result of coming into contact with land, water or air contaminated with harmful substances, rather than coming into contact with the harmful substances themselves although the toxicology is similar, the frequency and dispersion will differ. Core Hazard HW521, workers in proximity to harmful substances covers the case where water or land contamination is not an issue.

The cluster comprises:

HW519 Release of hazardous substances

5.2.14. Core Hazard: HW520—Inappropriate Working Methods/Environment

The scope of this hazard was defined to include most 'occupational' accidents where typically a single worker is affected. We also included the case of crane loads and other mechanical

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equipment fouling trains passing nearby as this was always due to operator error. Any particular scenario where an inappropriate working method was applied to result in an incident which was also covered by another core hazard was excluded. For example, if an inappropriate lifting technique was applied to a task involving a heavy object, we did not consider this part of this core hazard but dealt with it under HW514.

The cluster comprises

HW520 Inappropriate working methods/environment

5.2.15. Core Hazard: HW521—Workers in Proximity to Harmful Substances

The Core Hazards Workers in Proximity to Harmful Substances (HW521) have been defined as the hazard presented to workers when in proximity to uncontrolled harmful substances. This includes those harmful substances carried by the railway (dangerous goods) as well as harmful substances routinely used in the running and maintenance of the railway (fuel oils, caustics, etc.). It does not include substances which are harmful only due to their physical state, for example boiling water or hot food, or indeed, railway food in general.

The case where workers come into proximity to harmful substances through contaminated water or land is not considered in this report as that case is covered under Core Hazard HW519 contaminated water and/or land. The cluster comprises

HW521 Workers in proximity to harmful substances

5.2.16. Core Hazard: HW522—Road Vehicle Accidents

Core Hazard HW522, road vehicle accidents covers accidents to workers in road vehicles whilst on railway business, but on the public highway. The model excludes incidents on Railtrack property and controlled infrastructure—these are covered under Core Hazards HW513/HP515 inappropriate separation between workers/passengers and Moving Vehicle (other than Rail Vehicle).The cluster comprises:

HW522 Road Vehicle Accident

5.2.17. Core Hazard: HW523—Objects Thrown or Falling from Train

The core hazard considered in this report considers the impact on workers of 'Objects Thrown or Falling from Train'. The impact on neighbours of objects thrown or falling from trains is included in the work scope for HN511 and is not included in the scope of work reported here. The work scope for HW523 includes the following:

- Objects deliberately thrown from trains.
- Objects falling off trains, for example shattered brake disk.
- Loads falling from freight trains, including ballast.

The cluster comprises:

HW523 Object thrown or falls from train

5.3. Neighbours group

The national level safety study of the railway neighbours group was planned and conducted over a number of workshops with diverse participants from many of the stakeholder groups. Neighbours are those who live within proximity of the railway environment and cross the line at level crossings. A similar set of prompts and photos focused on this group were taken and composed into 'A Day in the Life of a Railway Neighbour' that covered most credible scenarios that neighbours of the railways get exposed to generally involuntarily. The pictorial scenarios were employed as the backdrop to a creative Hazop style process to identify all circumstances where railway neighbours were potentially exposed to hazardous states.

By the end of the national level workshops, 64 hazards had been identified [5] for the neighbours group. In a similar manner, Core Hazards were developed for the neighbour group; each Core Hazard was tagged with a H for Hazard, N for Neighbour and a unique number that represents the relative proximity of the hazard to an accident scenario. The core hazards for the neighbour group, relating to the exposure scenarios are depicted as follows.

5.3.1. Core Hazard: HN500—Abnormal or Criminal Behaviour

The models for HP500, HW500 and HN500 address the range of abnormal and criminal behaviours that are known to be performed within the railway infrastructure. They do not, however, address abnormal working practices of railway personnel, with the exception of train drivers and senior conductors. This was agreed between Human Engineering and Railtrack at the start of the modelling process. The cluster comprises

HN416 Suicide attempt

HN417 Trespass

HN418 Abnormal behaviour at special events

5.3.2. Core Hazard: HN501—Crossing Running Railway at Level Crossing

Core Hazard HN501, crossing running railway at a level crossing, has been developed to include all situations in which a user (i.e. a Neighbour) is present on a level crossing without the intended degree of protection from trains. This may arise from intentional or inadvertent misuse of the crossing by the neighbour as well as from failures and errors in railway equipment and procedures.

The definition excludes situations in which harm may arise when using a level crossing as intended, for example if a user falls and injures themselves on a crossing but is still able to cross within the design time limit. Such occurrences are assumed to be subsumed within Core Hazard HN506, loss of balance.

The model excludes incidents at level crossings resulting from suicide or attempted suicide—these are assumed to be covered under HN500 abnormal or criminal behaviour

The model is limited to neighbour hazards and thus does not consider hazards at worker crossings provided within stations, depots, sidings etc. Un-authorised neighbour use of such

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crossings should be regarded as abnormal or criminal behaviour (HN500), being a form of trespass. (Unauthorised passenger use is covered in Core Hazards HP509 inappropriate separation between running railway and workers/ passengers.)

It should be noted that HN509, inappropriate separation between running railway and neighbourhood, did not consider level crossing hazards. HN501 and HN509 are thus taken to be mutually exclusive.). The cluster comprises

HN480 crossing running railway at a manual level crossing

HN481 crossing running railway at an automatic level crossing

HN482 crossing running railway at user worked level crossing

HN484 crossing running railway at a level crossing

5.3.3. Core Hazard: HN502—Contaminated Water and/or Land

The core hazards for contaminated water and/or land for neighbours have been defined as the release of harmful substances likely to cause contamination of the environment. This allows the consideration of detection, mitigation and remediation barriers in the consequence domain. The release of toxic gases likely to cause harm to workers or neighbours has also been considered under this core hazard.

This core hazard considers harm to workers or neighbours as a result of coming into contact with land, water or air contaminated with harmful substances, rather than coming into contact with the harmful substances themselves—although the toxicology is similar, the frequency and dispersion will differ. The cluster comprises

HN502 Contaminated Water and/or Land

5.3.4. Core Hazard: HN503—Electro-Magnetic Interference (EMI) Caused to by Railway Operations

EMI caused by railway operations to businesses, general public, adjacent buildings, hospitals, HN503 has been developed to include those situations where EMI from the infrastructure or rolling stock could affect the safety of neighbours directly. This core hazard does not include EMI caused by infrastructure or rolling stock to signalling and track circuits, or interference between the rolling stock and infrastructure. Such interference could be considered part of the base event frequencies for other core hazards. Interference caused by radio systems is not explicitly examined, it is considered to be subsumed into the frequencies of the initiating events identified and would be subject to the same design controls and regulations. In addition, this core hazard does not consider the effects of earth leakage currents causing corrosion of steel pipelines or structures. Thus issues such as HN30 (corrosion of structures from dc rail systems) are covered under HN510. That core hazard also covers the possibility of electrocution due to inductive pickup in cables running adjacent to the AC electrified lines. The cluster comprises

HN503 EMI impact on neighbourhood

5.3.5. Core Hazard: HN504—Impact from Railway Construction/Maintenance Works

The scope of 'impact from railway construction and maintenance works' includes the following:

- Inappropriate construction and maintenance practices' not included under other core hazards
- Dumping heavy loads onto roads, buildings and property of neighbours

Release of flammable materials (other than gas mains) and damage to electrical cabling and gas mains

The cluster comprises

HN504 Impact from railway construction/maintenance works

5.3.6. Core Hazard: HN506—Loss of Balance

We have excluded from this core hazard falls to trespassers and falls occurring on level crossings. As all persons on stations are regarded as passengers for the purpose of this project, the relevant neighbours for this core hazard are basically those persons using footpaths and footbridges which form part of the railway infrastructure. Footpaths alongside public roads are part of the public highway and are excluded. The cluster comprises

HN403 Loss of balance on the ground

HN404 Loss of balance on stairs

5.3.7. Core Hazard: HN509—Inappropriate Separation between Running Railway and Neighbourhood

The HN509 Core Hazard for inappropriate separation between running rail and neighbours have been developed to include those situations where the distance between the running rail and people is not sufficient to ensure the safety of passengers, workers or neighbourhood.

This core hazard does not include Core Hazard HN501 failure of level crossing to protect the public from passing trains. This model also does not include incidents of inappropriate separation between running rail and neighbourhood resulting from suicide. Finally, this model does not include incidents of inappropriate separation between running rail and people caused by Derailment. The cluster comprises

HN509 Inappropriate separation between rail &neighbours

5.3.8. Core Hazard: HN510—Inappropriate Separation between Un-insulated Live Conductors and the Public

The scope of 'inappropriate separation between un-insulated live conductors and the public' includes the following:

HN405 Occurrence of DC power arc

HN406 Existence of touch potential

HN407 Structure exposed to leakage current [DC]

HN408 Inappropriate separation from DC conductor rail

HN409 Structure in contact with live conductor rail

HN410 Inappropriate separation from OHL live conductor

HN411 Structure in contact with live OHL

HN412 Inappropriate separation from OHL induced voltage

HN413 Inappropriate separation from ground potential

HN414 Occurrence of AC power arc

HN415 Structure exposed to leakage current [AC]

5.3.9. Core Hazard: HN511—Flying Debris from Moving Train and Objects Falling from Trains

HN511 Core Hazard for flying debris from moving trains and objects falling from trains has been developed to include those situations where parts of the train and objects carried on the train are separated from the moving train and are a potential hazard to neighbours.

This core hazard does not include things falling from bridges into the surrounding neighbourhood. These incidents are covered in the Core Hazard HN512 unsecured objects at height.

Neither the causal nor the consequence models refer to situations where parts of the train and objects carried on the train are separated from the moving train and are a potential hazard to passengers or workers. The cluster comprises

HN511 Flying debris / objects falling from trains

5.3.10. Core Hazard: HN512—Unsecured Objects at Height

This core hazard falls within the generic grouping of 'Objects Falling from Height' affecting neighbours (HN512) which includes the following:

- Objects falling from height within stations (HP513, HP512) as a result of degradation (e.g. falling glass) or maintenance or construction work.
- Objects thrown at trains (HP513, HW512) or hung in front of trains (HW512).
- Falling luggage stored at height on trains and falling train furniture (HP513, HW512).
- Dropped crane loads (HW512).

Falling objects from the infrastructure (HW512, HN512).

The cluster comprises

HN512 Unsecured objects falling from height

6. System Level Security Issues

The transportation network constitutes the artery of economic activity and growth in modern economies. Whilst challenged by telecommunications and internet technologies, the movement of goods and people is still an indispensable aspect of social and economic life contributing around one tenth of the GDP in the developed world[1]. It is not surprising therefore to find transportation on the social and political agenda and any faults, failures and consequent accident, being given a high degree of publicity and exposure. Traditionally, the key mantra in transportation has been safety followed by reliability, punctuality, cost, journey time and quality of travel. This has held true so far for the most modes of transport until recently when malicious intent with the aim of disrupting the network, victimising its customers and inflicting large economic losses has added a new ingredient to the traditional concerns of the industry. The malicious intent broadly falls into the following categories:

- Antisocial Behaviour and Vandalism
- IP Espionage/Violations
- Theft, Extortion, and Fraud
- Robberies, Assaults
- Sabotage
- Terrorism and CBRN Attacks

Whilst vandalism is of limited consequence and often related to adventure seeking youth, the other categories of concern specifically terrorism pose a largely new sinister development often beyond the powers of transportation authorities to predict, prevent or contain. This is where the power of scientific structured approaches and methodologies principally applied in safety engineering can be exploited to render assurance in transportation security in road, rail, shipping and aviation transport hubs.

The proficient assessment, control and mitigation of safety and security risks demand a systematic and objective approach to understanding and proactive management of response processes. However, the traditional focus of security relating to the physical infrastructure and systems is now extended to cyber systems in view of the extensive deployment of modern communications and computing in the railways. A systematic approach to system level security should consider physical and cyber threats and vulnerabilities to assure adequate security throughout the life cycle of the product, process, system or undertaking.

Many facets of a system's performance are inter-related and overall optimisation requires a reasonable insight into the desirable system properties and performance profile. This is equally applicable to the transportation and railways where the provision of service is nowadays taking place within a commercial and cost/performance conscious environment.

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1 U.S. Department of Commerce, Bureau of Economic Analysis

http://dx.doi.org/10.5772/62080

Adoption of a systemic and numerate approach to safety and security assurance within an integrated systems framework yields a more inclusive understanding of key facets of performance and the inevitable trade-offs between cost, reliability, quality, safety, security and capacity, journey time/punctuality in the railway context. It also generates rational criteria in support of decision making thus reducing the dependency upon opinion-based subjectivity, lengthy processes and less-informed costly choices. The enhanced objectivity and transparency would result in streamlined decision making and more efficient/responsive processes thus saving time and cost and fostering progress. Additionally, it generates major economic benefits by arriving at a right solution first time. In short, a more objective and numerate approach could help to avoid the subjectivity which be-devils much of the current approach to safety and security management.

Finally, an integrated approach to safety and security assurance that is based on a generic accident model is intuitively more pertinent than one based on anecdotal observation and view of available technologies. It rebalances focus on risks that arise during design, installation, operation, maintenance and retrofitting. It cuts across organisational boundaries, roles, responsibilities and requisite competences that, in the system life-cycle approach, tend to be overlooked thus constraining our perception of risks.

In view of the increasing concerns over security of the transportation systems, the advanced processes and methodologies principally developed and applied in safety critical industries such as nuclear, transportation, oil and gas industries should be extended to the prognosis of transportation vulnerabilities to malicious intent[2]. The new framework is intended to principally harness the significant overlaps between safety and security landscape to offer:

- Systematic and scientific study of transportation networks with a view to identify vulnerabilities to malicious intent in a multi-modal environment whilst also identifying safety and environmental issues.
- Assessment of the risks associated with significant hazards, vulnerabilities or threats.
- Identification of principal elimination, control and mitigation measures.
- Cost-benefit studies to provide technical, procedural and organisational risk elimination/control/mitigation measures with highest potential impact.
- Transportation threat/vulnerability log to keep key stakeholders informed and engaged in the overall assurance process.
- Transportation surety cases to capture the system, safety and security issues (hazards, threats and vulnerabilities), control and mitigation measures and the rationale for the continued vigilance and continual improvement.
- Safety and security (Surety) management systems to provide a framework for continued control and fulfilment of the obligations by the duty holders.

2 UITP-UIC Press Release June 2004

The key benefits will accrue from a structured and cost-effective and high-performance approach to the integrated safety and security assurance of products, systems and services hence surety. In view of the generic nature of the process, these capabilities can be extended to provide the integrated services beyond transportation.

Integrated framework for assurance of safety and security is highly pertinent to the emerging profile of the railways in that, whilst safety is subject to an impressive record of improvement, security is a largely unknown and poses the bigger challenge in the overall assurance landscape.

The risk profiling of the national railways depicted in Section 5 did not take security threats and system level vulnerabilities into account. This was largely driven by the concerns over network safety at the time and lack of immediate security threats to the railways. Ever-since, railways and mass transit systems in the European mainland and indeed in Asia have been targets of attacks and terrorism highlighting the need for a consistent, comprehensive and effective approach to security assurance alongside that of safety.

7. Safety Roles and Competences

The safety performance of the various transportation modes is on the steady improvement largely driven by better regulation, improved deployment of communications and computing technologies in spite of rising speeds and passenger numbers. Many countries in North West Europe outperform the European average for passenger and workforce fatalities with Denmark, United Kingdom and Netherlands in the top three best performing countries that have performance an order of magnitude below the European average.

The European Railway Agency (ERA) has published indicative statistics on the relative safety of various transportation modes that indicates railways are approaching aviation levels of safety on a normalised (per billion kilometre of passenger travel) basis (Table 5).

Transport mode	Fatality risk (2008–2010) Fatalities/billion passenger kilometres
Airline passenger	0.101
Bus/coach occupant	0.433
Car occupant	4.45
Powered two-wheelers	52.593
Railway passenger	0.156

Table 5. Relative Safety of Transportation Modes (Source ERA)

Taking the top level system's constituents perspective as depicted in Figure 2, we postulate that whilst advancing technology has made significant contributions to the reliability and

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integrity of the automation and infrastructure, the human (people and process) aspects have lagged behind in the relative scale of improvement. The principal aspects relating to people's influence on the safety performance relate to their competence and the collective values/ behaviours referred to as safety culture. The rules, codes of practice and standards constitute the other key contributory facet of overall system safety framework. The desired improvements in rules and standards as well as understanding and improving collective safety culture are beyond the scope of the current discussion. Here, we concentrate on the systematic characterisation, evaluation, assessment and management of safety competences as a key aspect of the human dimension in safety performance.

7.1. Competence

The European Guide to good practice in knowledge management [6] defines competence as an appropriate blend of knowledge, experience and motivational factors that enables a person to perform a task successfully. In this context, competence is the ability to perform a task correctly, efficiently and consistently to a high quality, under varying conditions, to the satisfaction of the end client. This is a much more demanding portfolio of talents and capabilities than successful application of knowledge. So a competent person is much more than and knowledge worker [20]. Competency may also be attributed to a group or a team when a task is performed by more than one person in view of the multi-disciplinary nature, complexity or the scale. A competent person or team requires a number of requisite qualities and capabilities, namely

1. The domain knowledge empirical, scientific or a blend of both.

2. The experience of application (knowing what works) in different contexts and the requisite skills.

3. The drive, motivation to achieve the goals and strive for betterment/excellence as well as appropriate behaviours such as team work, leadership, compliance with professional codes etc.

4. The ability to adapt to changing circumstances and demands by creating new know-how.

5. The ability to perform the requisite tasks efficiently and minimise wastage of physical and virtual resources.

6. The ability to sense what is desired and consistently delivers a high quality to the satisfaction of the end client(s).

The right blend of these abilities renders a person or group of people (a team) competent in that they would achieve the desired outcomes consistently, efficiently, every time or more often than not satisfying or exceeding the expectations of the clients over varying circumstances. Such persons/groups will be recognised for their mastery of the discipline and not just considered a fount of relevant knowledge often characterised by qualifications. In this spirit, competence is the ability to generate success, satisfaction, value and excellence from the application of knowledge and knowhow.

The Business Dictionary [7] defines competence as a cluster of related abilities, commitments, knowledge and skills that enable a person (or an organisation) to act effectively in a job or situation. It further states that competence indicates sufficiency of knowledge and skills that enable someone to act in a wide variety of situations. Because each level of responsibility has its own requirements, competence can occur in any period of a person's life or at any stage of his or her career. With reference to the legal profession, the dictionary defines competence as the capacity of a person to understand a situation and to act reasonably. The disputes regarding the competence of an individual are settled by a judge and not by a professional (such as a doctor or a psychiatrist) although the judge may seek expert opinion before delivering at a judgment.

In the context of UK's Managing Health and Safety in Construction (CDM Regulations), [8] the HSE elaborates on the necessity for competence as follows.

To be competent an organisation or individual must have:

- Sufficient knowledge of the tasks to be undertaken and the risks involved.
- The experience and ability to carry out their duties in relation to the project, to recognise their limitations and take appropriate action to prevent harm to those carrying out construction work, or those affected by the work.

The HSE [9] further maintain that competence develops over time. Individuals develop their competence through a mix of initial training, on-the-job learning, instruction, assessment and formal qualification. In the early stages of training and experience, individuals should be closely supervised. As competence develops, the need for direct supervision should be reduced. If you are engaging a person or organisation to carry out construction work for you, then you need to make a reasonable judgement of their competence based on evidence. The evidence will usually be supplied to you by the person or organisation quoting or bidding for the work. There are many industry card schemes which can help in judging competence. However, the possession of a card by an individual is only one indication of competence. You are expected to make efforts to establish what qualifications and experience the cardholder has.

7.2. Recent Developments

The matters of competence and relevance of the deployed human resource to the requirements of mission and safety critical tasks have always been recognised but not been explicitly formalised until recently. The European Standard for Safety Critical Software [11] in the rail sector is potentially the first to recognise and formalise human competence requirements in the context of high-integrity software development for railway applications. The tables in Annex B of the standard have ten normative role specifications in the development of high-integrity software for safety applications, namely

B.1: Software Requirements Manager

B.2: Software Designer

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B.3: Software Implementer

B.4: Software Tester

B.5: Software Verifier

B.6: Software Integrator

B.7: Software Validator

B.8: Software Assessor

B.9: Software Project Manager

B.10: Software Configuration Manager.

For each one of the above roles, a template based on the UML Class for the role is developed to describe the minimum essential competence requirements in terms of attributes (qualities) and operations (key activities and responsibilities) in the development and deployment of safety critical software. Whilst these appear simplistic and potentially inadequate, the significance of recognising and incorporating human characteristics in a traditional process only standard cannot be under-stated. In this respect, the competence requirements in the safety critical software standard are just a start and a foundation for more elaborations!

In principle, many of the normative software roles are generic and can be modified and applied to hardware, sub-system and system aspects. In a complex and safety critical project, it is beneficial if not necessary to adopt a systematic approach to characterising, assessing and managing competence in the key roles since as a minimum; these will be required for sub-system and system level software developers where a fair proportion of the change will originate from. To this end, a Competence Assessment and Management System is an essential aspect of a credible strategy within the context of a safety critical programme.

7.3. Competence Assessment and Management, a Systems Approach

Given the six facets of competence elaborated earlier under 7.1, the acquisition, assessment, development and management of competence poses a challenge beyond the traditional education and curriculum vitae. Whilst a blend of all six facets is a pre-requisite for competency and mastery in a given discipline, the significance of each is highly dependent on the context and requirements of a given domain. Whilst theoretical knowledge plays a more significant role in abstract scenarios, experience of application, adaptability and creativity may become more prominent in other domains. Whatever the domain, however, a systems framework for the evaluation, development and enhancement of competence is called for. This by necessity comprises two inter-dependent framework one focused on evaluation and assessment and the other on the management of competence.

7.3.1. Assessment of Competence

The competence assessment framework provides an integrated perspective on competence in a given context whilst additionally empowering the duty holders or the organisation to benchmark each aspect, measure, assess and where necessary take actions to enhance various elements in the framework. [20] This is illustrated in the Weighted Factors Analysis (WeFA) schema of Figure 7. The latter aspects of benchmarking, evaluating, assessing and potentially enhancing competence are inherent in the underpinning WeFA methodology [12] and not elaborated here. The Schema details are omitted and elaborated in the subsequent section.

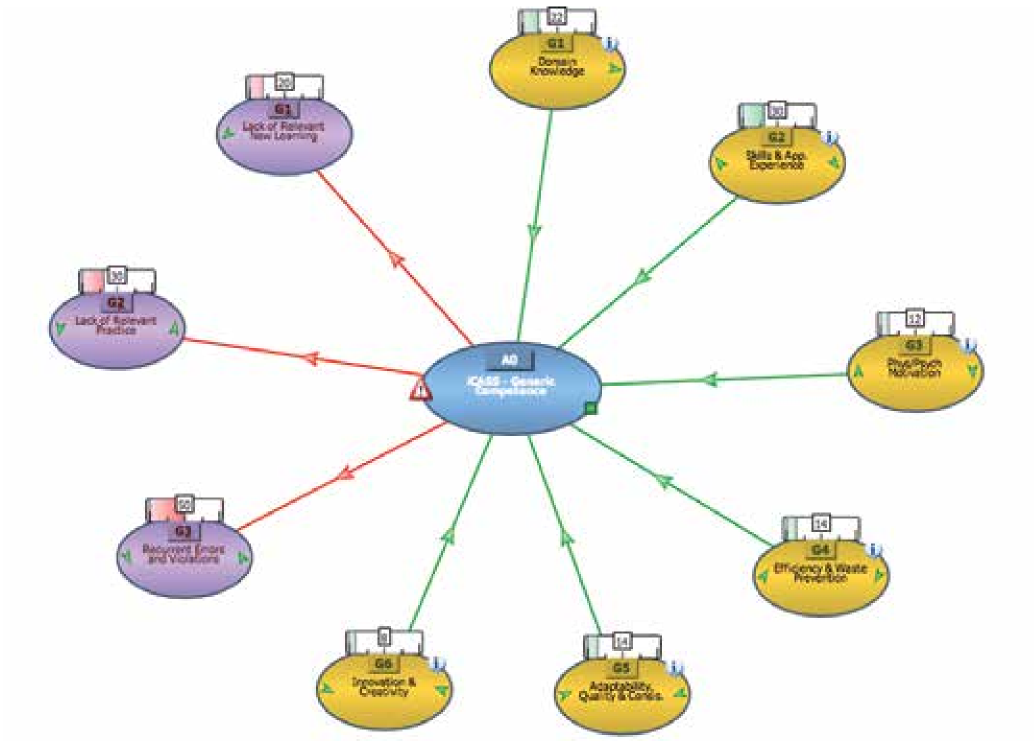

Figure 7. The Systemic Competence Assessment Framework

The determination, benchmarking, evaluation and quantified performance assessment of six drivers and three inhibitor Goals in the above WeFA schema is carried out as follows

7.3.1.1. Driver Goals

The requisite 'domain knowledge and understanding' in a given context as depicted in the driver Goal 1 (G1) is broadly supported by relevant industry's skill/competence frameworks. There are a number of such frameworks in use largely within various engineering disciplines in the United Kingdom, for example OSCEng, [13] IRSE [14] and IET [15]. Given the poor state of attention to competence and systematic approaches to its recognition, evaluation and assessment internationally, United Kingdom appears amongst the leading proponents globally [16].

http://dx.doi.org/10.5772/62080

The composition and extent of 'skill and relevant experience' in a given context as depicted in the driver Goal 2 (G2) in the assessment framework is supported by subsequent decomposition of G2 into lower-level WeFA structures, the so-called Level 2 and Level 3 goals. This principally helps determine the driver and inhibitor goals for the higher-level goal, the domain experience.

The requisite 'psycho-physical factors and behaviours' in a given context as depicted in the driver Goal 3 (G3) in the framework is supported by subsequent decomposition of G3 into lower-level WeFA structures in WeFA. This principally helps determine the driver and inhibitor goals for motivational, behavioural and drive aspects.

The essential determinants of 'efficiency and waste minimisation' in carrying out tasks in a given context as depicted in the driver Goal 4 (G4) in the framework is supported by subsequent decomposition of G4 into lower-level WeFA structures that drive or inhibit this goal.

The key determinants of 'quality, excellence and consistency' in carrying out tasks in a given context as depicted in the driver Goal 5 (G5) in the framework is supported by subsequent decomposition of G5 into lower-level WeFA structures, drivers and inhibitors, respectively.

Finally, the degree of 'adaptability, innovation and creativity' in a given context as depicted in the driver Goal 6 (G6) in the framework is supported by subsequent decomposition into lower-level factors relevant to this focus.

Given the hierarchical nature of WeFA schema, the so-called level 1 goals in the proposed individual competence assurance system are generic and universal. The decomposition of these goals into appropriate drivers and inhibitors in levels 2 and beyond will help tailor the generic model towards specific requirements of a given role in a given context. The driver and inhibitor goals in levels 2 and below in a competence role schema denote the specific measurable predictors for generic level 1 goals such as knowledge, experience.

Once a role is completely characterised through decomposition of the generic model (level 1) into a number of predictors (levels 2 and below), the schema is subsequently weighted by the same expert panel that have helped with the development of the schema. This assigns relative significance to the factors in the schema thus rendering it compatible with the values, preferences and possibly culturally driven norms within the application environment. A calibrated schema is then reviewed, enhanced and validated for general application within the context of use. In an automated environment, a validated/authorised schema can be assigned to every member of staff in a given role, enabling them to evaluate themselves against the criteria and develop a competence profile to establish the areas in need of further development.

7.3.1.2. Inhibitor Goals

The key aspects and the extent of 'lack or inadequacy of relevant new learning' in a given context of application as depicted in the inhibitor Goal 1 (G1) in the proposed framework is supported by subsequent decomposition into lower-level WeFA structures, the so-called Level 2 and Level 3 drivers and inhibitors.

The key predictors and the extent of the 'absence or inadequacy of relevant practice' in a given context as depicted in the inhibitor Goal 2 (G2) in the framework is supported by subsequent decomposition into lower-level WeFA structures.

Finally, the degree of 'recurrent errors and violations' in a given context as depicted in the inhibitor Goal 3 (G3) in the framework is supported by subsequent decomposition into specific predictors of these behaviours and outcomes in the schema.

A suitably developed and validated WeFA schema for competence assessment in a given role, context/domain additionally requires a measurement scale for each goal (driver or inhibitor) as well the weights, that is the strengths of influence(s) from each goal, on higher-level goals. Once established, the weighted framework lends itself to application for assessment and management of individual's or groups' competence in fulfilling tasks in the particular context as depicted by the framework. This would render a number of advanced features and benefits, namely

- Up to five levels of competence comprising apprentice, technician, practitioner, expert, leader in a given role/domain;
- Identification of the gaps and training/experience/mentoring requirements;
- A consistent and systematic regime for continual assessment and enhancement.

It should be noted that assessment here is devised and intended as a tool in the service of systematic approach to staff development and should not be misconstrued as an adversarial instrument for classification of people's contributions to the organisation.

7.3.2. Management of Competence

The deliverables of the engineering process applied to the creation and realization of parts, products, systems or processes often follow a life cycle from concept to decommissioning as popularised by engineering standards as detailed in Section 2.

In this spirit, the human resource involvement/employment within an engineering environment, organisation or project likewise follows a life-cycle comprising seven key phases essential to the systematic and focused management of knowledge, [20] namely

Proactivity comprises corporate policy, leadership, mission, objectives, planning, quality assurance and commitments to competency and service delivery for the whole organisation;

Architecting and profiling which comprises specification and development of a corporate structure aligned with the strategy and policy objectives together with the definition of roles and capabilities to fulfil these;

Placement which essentially involves advertising and attracting candidates matching the role profiles/requirements involving search, selection and induction. Selection relates to deriving role focused criteria and relevant tests to assist with the systematic assessment, scoring and appointment tasks. Induction involves a period of briefing, familiarisation and possibly training the extent of which is determined by the familiarity and competence of the individual concerned and the complexity and novelty of the role;

http://dx.doi.org/10.5772/62080

Deployment and empowerment which involves a holistic description depicting the scope of the responsibility, accountability and technical/managerial tasks associated with a specific role and empowering the individual to fulfil the demands of the role. This would include training, supervision, coaching, resourcing, delineation of requisite authority and accountabilities, mentoring and potential certification as means to empowerment for achievement and development;

Appraisal which involves the planning and setting performance objectives, and identification of the performance indicators/predictors synergistic to the demands of a role and the individual's domain knowledge, aimed at ensuring all relevant and periphery aspects of the role are adequately addressed and the necessary provisions are made for learning where a need is identified. The evaluation and appraisal provides the necessary feedback on compliance with individual and organisational objectives and achievement, enabling the organisation to identify and reward good performance and develop remedial solutions where necessary;

Organisation and culture which involves clarification of role relationships and communications, support, reward and motivational aspects for competency development including requisite resources and learning processes for attaining the policy objectives. This is intended to develop and foster a caring and sensitive approach/culture nurturing talents and paving the way towards an innovating organisation;

Continual development and progression: this comprises identifying the synergistic aspects which may serve as a complementary and rewarding extension to individuals'/teams' specific roles. Development may involve managerial, technical, support functions or an appropriate blend of duties at the whole life-cycle level or extensions to the role-specific activities and vision/ career paths above an existing role into other parts of an organisation and even beyond. The review and assessment of success in all the principles inherent in the framework also fall within the continual development principle.

The seven focal areas/principles constitute a systematic competency management framework. It is worth noting, however, that employment and project/product life cycles are orthogonal in that securing the requisite human resource and competence for any phase of an engineering production activity would potentially involve all the seven phases of the competence management.

The traditional process-based prescriptive rules and standards [4] have served the industry over a century where product and system complexities were generally low permitting good design and sufficient testing to ensure integrity of products, processes and systems. The pervasive complexities arising from adoption of new ICT technologies have necessitated a continuous approach to assurance throughout the life cycle as advocated by modern standards. This is now the accepted norm in the most safety and mission critical applications and industries.

Alas, the significance and role of the human agent has been largely ignored so far on the unfounded assumption that a recipe given to any capable and qualified person will ensure quality and integrity of the outcomes. With the ever increasing embedded knowledge contents in most products, processes and systems, the necessity to focus on the humans as the source of such creation, and their fitness for the task in hand is now gaining momentum. In the face of such realisation and demands, our capacity to understand, characterise and evaluate human capabilities and latent potential has lagged significantly behind other technological advances.

We posit that human competence should be regarded as an integral facet of assuring designs, products and services, especially those with safety, security, sustainability or mission critical profile. The continual assurance processes advocated by modern standards need to complemented with focus on human competence to face the modern challenges of high risks and ever increasing complexity. The framework offered uses systems thinking to address assessment and management of competence within a coherent solution for enhancing quality, safety, reliability and assuring integrity.

8. General Trends and Emerging Issues

The statistics published by the Office of Rail Regulation (ORR) in the United Kingdom [17] is a timely reminder of the rise in passenger demand over the recent past that seems to illustrate a rising trend of roughly 50% per decade (Figure 8).

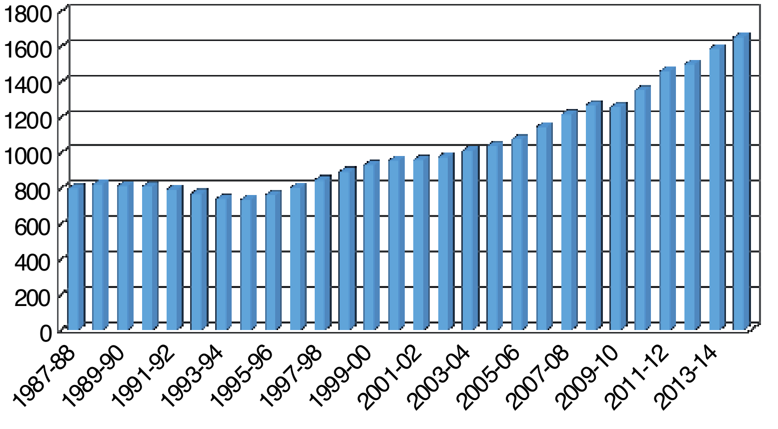

Figure 8. Rise in UK Railway Passenger Demand (ORR data)

Data from the World Bank relating to a rather similar period [18] seem to pint to a rising trend especially in the developing economies (Figure 9).

Overall, rise in global demand for rail transportation needs to be matched by increasing infrastructure investment, technology development and rising consciousness about the carbon foot print and global warming impact of transportation. Given the highly advantageous position of rail transportation with respect to sustainability, energy efficiency, carbon footprint, convenience and the increasing speeds, this is a growth industry on a competition course with the airlines.

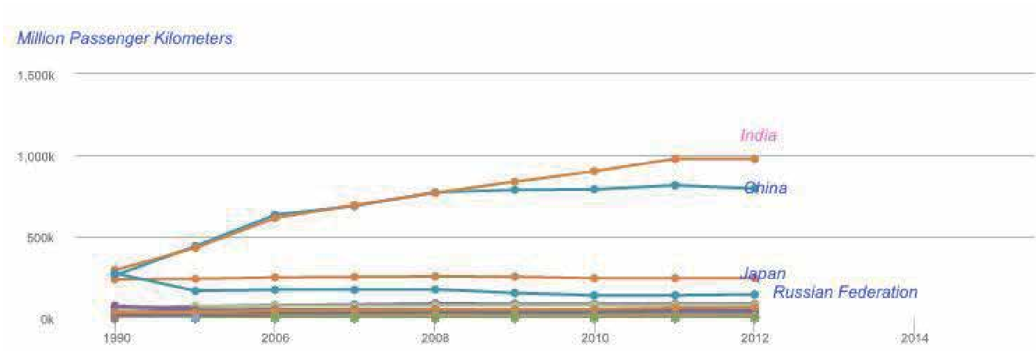

Figure 9. Rise in Global Railway Passenger Demand (World Bank Databank)

With the advancing technology, increasing automation, land speeds and demand for higher levels of safety, the key issues facing the industry from a safety and security perspective will be

i. Safety and security assurance of complex communications, supervisory and control systems comprising advanced hardware, hugely intricate heterogeneous software including some COTS components and vast amount of data.

ii. Integration of diverse multi-sourced inter-operable systems into a safe operational railway system.

iii. Understanding, addressing and monitoring of organisational and culture aspects of the human dimension.

iv. Developing and adopting advanced evidence driven scientific frameworks for evaluation, assessment and certification of railway products, services and systems.

v. Integration of safety and security assessment and management frameworks [19] for enhanced effectiveness, efficiency and cost reduction.

vi. Standardisation and harmonisation of operational rules across international borders.

vii. Developing common methods and metrics for the evaluation and assessment of safety and security.

Finally, with the maturity of the ICT technologies employed and improvement of safety performance, the concern will shift towards security as a more likely cause for incidents and accidents than the traditional concern over safety. Increasing levels of automation in train driving, traffic management and control would expose the future railway environment to a range of security threats that may take the operators, IMs and the authorities by surprise unless security, alongside safety is taken into account throughout the life cycle of products, systems and processes.

To this end, a similar reference portfolio as developed for the UK national railway's safety hazards is required to address security threats and vulnerabilities at railway system level. This will provide a rational, systematic and consistent support to the operators and the supply chain in the industry empowering them to effectively address the security requirements pertinent to the scope of their services, products, systems and processes.

9. Abbreviations

CBRN Chemical, Biological, Radiological and Nuclear (attacks)

CDL Central Door Locking

CDM Construction, Design and Management (regulations)

Comms Communications

ConOps Concept of Operations

COTS Commercial-Off-the-Shelf

CRS Customer Requirements Specification

CSC Certificate of Safety Conformity

DRACAS Data Reporting and Corrective Action System

EMC Electro-Magnetic Compatibility

FMECA Failure Mode Effects and Criticality Analysis

FRACAS Failure Reporting and Corrective Actions System

FSaR Functional Safety Requirements

GDP Gross Domestic Product

HAZAN Hazard Analysis

Hazid Hazard Identification

HAZOP Hazard And Operability Study

HRC Human Resource Competence

HSE Health and Safety Executive (UK)

HW Hardware

IHA Interface Hazard Analysis

IP Intellectual Property

ISA Independent Safety Assessor

IT Information Technology

http://dx.doi.org/10.5772/62080

O&M Operation and Maintenance

OHA Operational Hazard Analysis

OHL Over-Head Line

Ops Operations

OPSEC Operational Scenarios

OSHA Operation and System Hazard Analysis

PHA Preliminary Hazard Analysis

PSP Product, System or Process

PW People-ware, the human element in a control system

QMS Quality Management System

RAM Reliability, Availability, Maintainability

SDS System Design Specification

SDSS System Design Safety Specification

SHA System Hazard Analysis

SSHA Sub-system Hazard Analysis

SIL Safety Integrity Level

SLSR Railway System Level Safety Requirements

SMS Safety Management System

SMIS An old UK Safety Management Information System data base

SRS System Requirements Specification

SSHA Subsystem Hazard Analysis

SSRS Subsystem Requirements Specification

SW Software

THR Tolerable Hazard Rate

UML Unified Modelling Language

V&V Verification & Validation

VTR Validation Test Report

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Application of Cognitive Systems Engineering Approach to Railway Systems (System for Investigation of Railway Interfaces)

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Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/61527

Abstract

This chapter presents the results of a cognitive systems engineering approach applied to railway systems. This application is through the methodology of 'System for Investigation of Railway Interfaces – SIRI'. The utility of the chapter lies in highlighting errors in the current approaches to safety risk management.

Keywords: Cognitive systems Engineering, Systems safety engineeering, Human factors engineering, Risk and Decision Making

1. Introduction

This chapter presents the results of a cognitive systems engineering approach to safety, 'System for Investigation of Railway Interfaces – SIRI'. The objectives of the application are to show:

a. How current methods to model, analyse, and manage safety risk do not facilitate learning lessons from past accidents;

b. How the use of heuristics by decision makers induce biases into the Committee-based decision-making process;

c. How failure of understanding amongst railway practitioners manifests when the attributes of reliability, availability, maintainability, and safety (RAMS) are treated as independent parameters of a signalling system.

The above failings are demonstrated by means of a case study of Cambrian European Railway Train Management System – ERTMS – level crossing incident investigated by UK's Rail Accident Investigation Board(RAIB) in Jan 2012.

RAIB noted that a deviation to a safety critical requirement to interlock the function of the barriers with the function of train protection (braking system) was granted by the Signalling Standards Committee to the duty – holder organisation – Network Rail, without asking for a human factors analysis or risk assessment to support the deviation request. This incident occurred at the automatic barrier locally monitored type level crossing (ABCL). This chapter provides the causal factors behind the decision to grant a deviation to safety critical requirements.

This chapter draws upon author's papers peer reviewed and published in the proceedings of the IET International System Safety Conferences since 2006, and publicly available literature [2, 3, 4, 7, 9, 11, 12].

The rest of the chapter is organised in this way: Section 1 provides the abstract of the chapter; Section 2 shows why wrong-but-popular approaches to safety risk management persist in the railway domain; Section 3 presents a case study using the SIRI methodology to help understand its application; Section 4 provides conclusions on subject matter of the chapter. Section 5 provides acknowledgements. Section 6 provides the references.

2. Explanation for persistence of wrong-but–popular approaches to safety risk management: Doing the wrong thing right

> OM. What instructions did the Blessed Lord give: Be compassionate. Be controlled. Be charitable.
>
> Sri Adi Śhankarāchārya, 8th Century AD, Brihadaranyaka Upanishad
>
> Translated by Prof V. Roebuck [79]
>
> Everything is fine today that is our illusion.
>
> Voltaire, quoted by Douglass W. Hubbard [29]
>
> We have inherited the neural mechanisms that evolved to provide ongoing assessment of threat level, and they have not been turned off. Situations are constantly evaluated as good or bad, requiring escaping or permitting approach. Good mood and cognitive ease are the human equivalents of assessments of safety and familiarity.
>
> Nobel laureate and psychologist, Prof Daniel Kahneman (pp. 90) [36]

OM is the sacred symbol to denote Brahman in the Hindu religious literature. More information can be gained about the nature and meaning of the symbol from reading Prof Roebuck's writings [79]. Prof Charles Perrow, originator of Normal Accident Theory, recounted the abnormal blessings he had received from his co-researchers in his preface to second edition of his book. Author speculates that Prof Charles Perrow did not know the source of abnormal blessings for the success of Normal Accident Theory as he may have thought he had not prayed for its success [49, 79]. In his survey of risk assessment theories and practices, Charles Perrow did recognise the work of cognitive systems engineering experts and various kinds of rationalities but opinied that these view points did not recognise the role of power in and of organisations (pp. 379) [79]. Interpretating the reality of accident causal factors and represent them by means of fault free fault tree analytical representation to show errors in the systems engineering steps, in the professional opinion of the author, helps mitigate the problem of discounting power of subject matter experts, and risk assessors in generating biased risk information in producer and client, systems engineering and regulatory organisations (pp.65) [52].

From the vast literature on risk on the perspective of risk rationality in human affairs, it is easy to think of four types of rationalities: omniscient rationality, which is enjoyed by political economists like Nobel laureate Gary S. Baker, "bounded" or limited rationality advanced by organisational decision scientist is and some risk assessors like Nobel laureate Herbert A. Simon, irrationality as advocated by behavorial economists like Noble laureate Daniel Kahneman, reluctant rationality of participants in making choices and displaying regret after the fact who may regard false negative alarms (near miss incidents) as reliablity events [36, 62]. Typical example being NASA managerial judgements on the Challenger launch decision.

Neuro-scientists have identified human brain regions associated with emotional and cognitive side of information processing activity when an individual processes a risky stimulus [36, 50]. Studies cited by Nobel laureate Daniel Kahneman, Peter N.C. Mohr, and his co-workers draw attention to the fact that decision maker(s) when engaged in the tasks of revealing preferences or answering queries on uncertain situations such as questions on lottery, risk assessment, and risk management do consult their emotions, and these decisions can be called decisions under risk. Decision theorists like psychologists, philosophers, statisticians, and economists approach decision making in a mathematical manner and are not prone to emotions and framing effects felt in the case of non-decision scientist(s) asserted in these research papers. The idea of risk as a rare event with odds of 1 in 400 or more with a consequence probability of 0.249% is possible is acknowedged by Prof David Hand, an expert statistician [26]. In other words, definition of rare events and estimation of the odds of their occurrence by expert statisticians may be prone to error is the thesis advanced by Prof David Hand. Evidence for this thesis is drawn by Prof David Hand from the case study of Sudden Infant Death Syndrome. Sir Roy Meadow's expert evidence led to erroneous legal prosecution of Sally Clarke. Rare event of train and vehicle collision on the Great Britain railway track was experienced by the members of the same family in the UK within a span of 15 years is cited as well [26]. The mean expected rate for such random events to occur as per Poisson's distribution is 0.741%. It is tempting to arrive at a conclusion that operational reliability of the railway is very high, i.e. 99.25% based upon the foregoing metric. Most pre–university students learn about stastitical distributions in their final year of secondary school leaving stage. Students of risk management can easily be laid into error if they are not careful in their thinking when making risk judgements that involve casual inferences (pp. 166–67) [36]. The litmus test for any student of decision making and risk management is the case of NASA Space Shuttle Accident in 1986. This case study alone poses challenge to statistical and rational decision theory, learning from past failure incidents, theories of control, system safety, and risk management [5, 36, 49]. The signal of less than adequate design shuttle vehicle flown by NASA and supported by its supplier, Morton Thiokol, till the pre-launch decision was obscured or buried under the noise generated by the hindsight observations of NASA manager's pre-launch decision [5]. To its credit, NASA, Langley Research News hosts the book on its website written by former Morton Thikol engineering director, Allan Madonald, who had a change of heart without any apparent reason on the pre-launch decision day and went along with engineer Roger Boisjoly who was opposed to the launch decision [5], [55]. Risk management expert Douglass Hubbard is of the view that Bayesian risk analysis may have helped in the case of NASA Challenger decision situation where the failure data was scanty [29]. Bayesian risk analysis can certainly help if prior information of categorial variables is available in the odds form and likelihood ratio of positive and negative rates are known as well. But we 've bear in mind Prof James Reason's thesis that most of us are not intutive bayesians [55]. Once Johann Wolfgang von Goethe observed that it is much easier to recognize error than to find truth; the former lies on the surface, this is quite manageable; the latter resides in depth, and this quest is not everyone's business. No accident researcher has the luxury of verifying correspondence between ideas of managerial oversight and risk seeking behavior apart from relying upon lessons learn from behavioral science risk literature (pp. 228) [53, 54].

The thesis advanced in the research papers in the area of cognitive psychology is that people who resist intutive responses to following bat–ball question do not need to reflect on the question again. The bat-–ball puzzle is as under. This question is to be answered in an intutive manner without solving it on a paper.

A bat and ball costs £1.10.

The bat costs one dollar more than the ball.

How much does the ball cost?

The intutive answer is 10 cents. Many thousands of university students have answered the bat–ball question. More than half of the undergraduate students at Harvard, MIT, Princeton gave the intutive–incorrect –answer.

The failure rate at other American universities is even more higher at 80% (pp. 44–45) [36]. The correct answer is 5 cents. Perhaps, a distinction between intelligence and rationality is needed is the suggestion made by these researchers (pp. 49) [36].

The author observes that intutive errors in decisions made by these undergraduate students cannot be explained by saying that these students are not skilled mathematicians. The author speculates that the psychological mechanisms involved in the perceptual and cognitive decision process by experimental subjects are as follows; mentally formulating the equations to represent the quantities of prices involved, and then subtracting the equations to identify one of the single unknown and arrive at its value by halving it. The difference between those who get the right and wrong answers is simply this: failure to divide in the final equation.

These errors are attributed by cognitive psychologists to the property of overconfidence of subjects who answer the question as 10 cents. From the science of cybernetics perspective, the purpose of the bat–ball question is to trigger thinking activity on decisions on safety-related control systems where the safe state of the system cannot be perceived by sight and failures in risk management and safety assurance process are likely [12, 28, 44, 57].

When author compares and evaluates the foregoing behavorial science research findings against the research findings published within system safety research domain, then another type of culture of decision-making emerges. Complexity of a socio-technical system became the focus of attention of system safety researchers during the 1980s. Prof Charles Perrow (1984) argued that complexity of organisations and tight-coupling of systems render it difficult to foresee how rare accidents can occur. The problem of complexity poses serious challenge to formal system safety management processes. Evidence is available to show that the counter thesis of Normal Accident Theory namely, High Reliable Organisations, is negated by John Bushby's case study of two British railway accidents [16]. James Reason (1990) whilst advancing a general view of accident causation in complex systems in the form of Swiss Cheese Model observed that system (normal) accidents have their origin in latent failures (fallible decisions) in supervisory control systems made at the corporate management, designer(s), and line management levels. He noted that identifying latent errors is a challenge faced by human factors researchers concerned with preserving the safety of complex, high-risk systems (pp. 199–216) [55]. Further, the author accepts Prof James Reason's idea of latent error that it is intimately bound up with the character of technology and accepts that tackling latent errors by identifying resident pathogens is the most effective way to improve the safety of complex systems (pp. 174) [55]. Prof Jens Rasmussen (1994) and his co-workers raised the question: are managers willing to spend the effort required for effective risk management? They argued senior managers like chief executive officers (CEOs) may not possess competence to deal with discipline of system safety management as they are usually drawn from finance or legal background (pp.159) [52]. System safety practitioners are to be found at lower levels in organisation in situations where the mean time between fatal accidents is large and the tenure of CEOs is short. In other words, CEOs do not get feedback on their performance in the field of system safety risk management. Further, they argued that Prof James Reason's approach will encounter problems if large number of 'less than adequate' conditions or decisions are identified from the past accidents using causal trees included in the Management Oversight and Risk Tree by William Johnson. However, applicant shows how the problem of representing various less than adequate latent failures by way of fault tree representation, taking into account the less-than-adequate decisions, is shown by the case study later on. This will show where interventions may be necessary.

It is common to observe three strategies to manage risks of fatal accidents [2, 52]. The strategy of emperical safety control used in the traffic and work domain is based upon 'safety on the average' for high-frequency and low-consequence traffic accidents. The problem with the strategy is that these measures may be degraded if the organisation is under economic pressure. Author finds that Network Rail's approach to change the specification of a signalling cable without checking for unsafe conditions that may be generated during operations is one example from the railway domain of this tendency to buckle under economic pressure as it was done in 2011. Risk management strategy of making design improvements after learning lessons from investigation of medium size, infrequent accidents is practised within the railway and aircraft domains. The third, risk management strategy followed is through the control of hazards based upon use of multiple barriers or defences as in the nuclear domain based upon predictive risk analysis (pp. 35–159), [52]. Prof Trevor Kletz argued that organisations suffer from lack of memory in 2003 [38]. An UK Health & Safety Executive (HSE) Publication HSG 238 argued that safety-related control systems are bound to fail if the errors in the specification, design, testing, commissioning phases (lifecycle factors) of control systems are not checked and corrected [72, 73 ,74, 75]. Prof Nancy Leveson presented a new control systems engineering method, named STAMP, for accident analysis, which included representations of legal, socio-technical systems as well [40]. Knut Rygh, Chief System Safety Engineer, Accident Investigation Board, Norway, stated in 2005 publication that it is an establised fact that a systematic safety assessment is an accident investigation before the accident occurs (pp. 90–108) [63]. It follows from the foregoing research facts that an occurrence of incident or an accident implies that system safety case which documents the results of potential accident has either failed to investigate the potential hazard in a thorough manner or system case documentation ignored the hazard that could occur in the operations or lessons learnt from past accidents were forgotten or unknown dangerous unforeseen mode of operation has occurred or incident reporting system has failed or failures in risk management process were ignored or the independent safety analysts organisation has used the safety target of Mean Time to Unsafe Failure for safety case without using HAZOP + Fault Tree Analysis in the safety analysis of complex systems [29, 33, 34]. Prof Derek Hitchins (2007) stated that systems engineering cannot be carried out by the method discovered by Rene Descartes; dividing the problem space into its parts to analyse the parts and a holistic method as a frame of reference is necessary [28]. Following the financial crisis in 2007/2008, the idea of Black Swan event was popularised by Prof Nicholas Taleb [36]. Prof John Adams (2009) argued that economics of safety is a debate that is not settled as moral attitudes towards risk management are not stable; they depend upon the individual or social cultural perspective invovled in the debate [1]. Nobel laureate Daniel Kahneman (2011) argued that senior executives lack robust decision-making process and are prone to committing same errors like others as well [36]. Further, most railway, household kitchen, and weapons system projects fail to attain their objective due to planning fallacy as noted by him drawing upon the evidence of 2005 Oxford study. Prof David Hand (2015) argued using the evidence of 2008 financial crisis that risk inherent in the finance operations is better handled by Cauchy distribution as the decision-making framework of Gaussian means and variance leads to under-estimation of fat-tail risk events. During the financial crisis in 2008, it was revealed that Goldman Sachs's Chief Financial Officer (CFO) reported 25 standard deviation events occuring in a row in their operations [26]. Readers may wish to look up the probability of 25 Sigma event on the freely available online website – Wolfram Computational Engine. This works out to be 6.113 E-10^{-138} or a chance event of obtainning a head in all tosses of 456 fair coins. These rare events have occurred several times during the course of the past two decades. This failure in understanding risk is labelled in the safety risk literature as latent error. If latent errors are not cognised, then there is no way to address them. Therefore, switch to Bayesian risk management is required. However, Prof David Hand's work illustrates how abuse of statistics can occur [26].

The following are the definitions for latent and active errors.

Definition: Active errors are human errors, whose effects are felt almost immediately. For example, a road user may enter a level crossing space when it is not safe to do so due to wrong-side failure of the level crossing as in the case of the Herefordshire level crossing accident in 2011 [2, 11].

Definition: Latent errors are human errors whose adverse consequences may lie dormant within the system for a long time, only becoming evident when they combine with other factors to breach system (production) defences. For example, wrong-side failure event of the level crossing caused by the signaller who raised the barrier needed a conjuction of events of lack of approach locking and a road user entering the crossing space simultaneously to manifest the Herefordshire level crossing accident in 2011 [2, 11]. The independent accident investigating organisation, RAIB, reasoned, by way of counter-factual reasoning, that if the level crossing were to be fitted with approach locking facility, then the signaller would have been prevented from raising the road barriers, after they have been lowered. The causal statement was accepted by all organisations invovled in the situation according to the intutive frame of reference in the language of Prof Jens Rasmussen. Rather than questioning the scenario as to why the train did not stop at the level crossing signal fitted with Train Protection Warning System (TPWS) when stop signal was replaced, RAIB remained satisfied with the answer they found [2]. Based upon behavorial research discussed earlier, lack of cognitive reflection is implied and author concludes that this is a sign of irrationality. In human error terms, this act of omission can be called violation by element and duty holder as well.

Now, let us look at the other reasons for failures to recognise latent errors. First, lack of familiarty with the cognitive system engineering approach advocated by Prof Jen Rasmussen and his co-authors in the railway domain signalling and telegraph, human factors, safety and risk experts [52, 54]. Consequence of the lack of familiarity is the exclusion of certain stakeholders organisations' contribution to risk. Prof Jens Rasemussen's approach demands that cognitive system analysis shall include all stakeholder organisations and their contribution (positive or negative) towards system safety performance must be represented. These contributions are captured by way of a graphical representation in the form of Accimap [32, 52, 54]. Evidence for the lack of familiarity of contribution of human errors in management field can be seen in the case of the popular quantitative risk assessments made up of fault and event tree model. These representations are used by industrial practitioners for identifying accident precursors to safety risk, but do not include latent errors [24, 56]. The latent errors are errors committed in the areas of risk policy, domain-specific safety standards, which are industry consensus standards, and ignore errors in system design, risk assessments, independent safety assessments and reviews, and risk management that lead to less than sub-optimal diagnosis of potential or actual hazards. And as a result, risk assessors and managers pay less attention to less than adequate barriers for controlling hazards can be seen from the documentation on hazard analysis, modelling, risk analysis, and management of individual and societal risk concerns [17, 24, 60, 61, 72, 74, 75, 77]. Recommendations from the UK HSE Guidance on safety relevant control systems are not followed in these documents [73, 74]. When accidents do occur, front-line staff or members of public get blamed for less than adequate designs with which these actors have to grapple as it can be seen in the case of assertion made in the publication by a team of railway signalling and train driving managers and this blame culture was investigated as well [25, 80].

All psychologists hold the thesis that human mind cannot estimate the probabilities or likelihood of rare events which lie between the interval of zero to one percentile and ninety-nine percentile of distribution of probabilities and errors in judgements arise due to basic inability in human thinking (pp. 315) [36]. Misconceptions of chances and lack of recognition of co-variation do occur in the railway industry is asserted by the author following Prof James Reason's work. For example, collision of a train with a vehicle on the track was regarded as once-in-a million kind of chance event by a member of public is cited by Prof David Hand [26]. The author found that the probability of Hixon level crossing accident was reckoned by S. Hall, a British Rail signalling expert (1991)to be one in a million kind of chance event [2, 11]. However, the RSSB (formerly Rail Safety and Standards Board) Report tells a different story of high likelihood of more than ten collisions events per year [59]. If readers think that progress may have been made since 1990s, then they will be disappointed to read that errors in risk modelling by Network Rail/RSSB All Level Crossings Risk Model were reported in the UK House of Commons Report in 2014 [71]. Combining two pieces of information such as RSSB's statistical data with the causes identified in the RAIB accident reports poses a problem of inferrring causes of level crossing accidents. This problem is logically equivalent to the problem of applying Bayes rule to the taxi-cab problem cited in the risk literature (pp. 166–167) [36].

Second explanation is that the majority of railway domain experts, i.e. engineers and managers, are not aware of errors in their statistical, economical, logical, ontological, and cosmological reasonings of railway accidents [26, 32, 36, 42, 50, 55, 67].

For example, if reliability, availability, maintainability, and safety properties of systems and human actors forming part of a given social-technical system are considered in an unified manner, then it is clear they are not to be treated as independent parameters as it is assumed in classical economical theories is demonstrated by sociologist Prof Charles Perrow and system safety theorist Prof Nancy Leveson as well [40, 49]. Prof Charles Perrow argued that errors in sub-systems in the system lifecycle factors may interact in unforseen ways; and as a result of these unwanted interactions, risk of an accident cannot be foreseen and pre-determined. Therefore, some high-risk technologies like nuclear plants that are prone to acccidents should be avoided. Rare events like nuclear power accidents require more time to manifest not withstanding the claims of risk assessors and managers to the contrary [13, 17, 49, 57]. The author found this reasoning to be true in the cases of NASA Space Shuttle Challenger and Japanense Nuclear accidents where errors in risk assessment led to under-estimating of fatal risk in terms of its likelihood [5, 6]. RSSB does not apply the requirements in the risk guidance from cognitive perspective issued to the industry to itself and fails to identify risk in its management systems are shown by the case study in the paper [58, 59, 60, 61].

The author is led to the insight on human and scoial cognition, drawn from works of Nobel laureates Herbert A. Simon, Daniel Mcfadden, and Daniel Kahneman, that cognitive errors in information processing activity do exist [36, 42, 55, 67]. Insight drawn from the work of Nobel laureate, Herbert Simon (1978), is that the fundamental limitation of human cognition

http://dx.doi.org/10.5772/61527

in organisational context gives rise to *satisficing behaviour*: tendency to settle for satisfactory rather than optimal courses of action; this is discussed in the text on the topic of bounded rationality in Section 3.3.1 of the Chapter 2 on cognitive science tradition by James Reason [55]. In the same text, Reason observed that this is true for both individual and collective decision making and cites Cyert and March (1963) who demonstrated organisational planners are inclined to compromise their goal setting by choosing minimal objectives rather than those likely to lead to best outcome. Organisational behaviour needs to become the focus of attention [15]. Two examples of the necessity to focus on this social tendency to compromise goals can be read from the evidence of failure of the High Speed 2 Business Case in the UK House of Lords Economics Affairs Committee Report and failure in the case of Chinese ERTMS Train Crash [14, 68].

Third, Prof James Reason advanced the idea of controlling safer operations by identifying the pathogens hidden in the senior and line management decisions and practices that feed into psychological precursors of unsafe acts is the best way of controlling safer operations [55]. These hidden pathogens are best discovered, as per the author's knowledge, by using the Management Oversight and Risk Tree to include human failings in risk assessment, risk management, engineering management, and investment management. This idea is supported byProf Jens Rasmussen as well. The problem of determining the risk in a qualitative or quantitaive manner is subject to professional biases is noted by Prof David Ball in the UK HSE Research Report 034 on how to understand and respond to the societal concerns. He observed that a risk management strategy cannot be promoted without a belief that one way of life, or one way of sharing risks and costs, is better than another [73]. Questions of will to impose harm on others and acting under ignorance are philosophical questions if we disregard the legal and bounded rationality perspective for a moment [66, 67]. Acting upon information generated by FN curves by means of RSSB's Safety Risk Model or FN curve data analysis without taking into account decision-making under uncertainty is an error is noted by Prof Andrew Evans in his study of transport accidents. The literaruture by Prof Andrew Evans shows how FN curves are constructed [76].

The HSE Report 034 had emphasised the need to incorporate plural views into decision making, while acknowledging that these will be based substantially on beliefs, values and ways of categorising the world, rather than upon objective information [73]. Role culture plays an important role is shown by Prof John Adams as well. In other words, bias will unavoidably be encountered, and ultimately the question may well come down to choosing one form of bias over another. Further, the following features characterise risk-based decision-making:

- not all values are equal – some can be more thoroughly justified than others (moral philosophy) and some – when applied – produce better practical results than others
- a risk management strategy cannot be promoted without having an opinion that one way of life is better than another.
- risk management is essentially political – the only honest and open way forward is to admit this and embrace it

The Skills-Rules-Knowledge taxonomy advanced by Prof Jens Rasmussen is applicable to the co-operative archictecture of work which is applicable to the current regime of risk management within the Europe as well [53, 54, 55]. Duty of co-operation is mandated by the UK Rail Regulator as well [46]. Contrary to the advice that emerges from reading the management literature that safety and production planning should not be placed lower than finance and planning activity in the hierarchy of management concerns, it is common place to find economic concerns being prioritsed ahead of the safety concerns in the industrial context. From cognitive science perspective, this act of compromising safety is a violation (pp. 206), [55].

The cognitive biases and information processing flaws were identifed by Prof Andrew.P. Sage as well. These flaws affect information formulation for acquisition, analysis, and interpretation. These can be read from the works of Prof Andrew P. Sage [47]. These flaws are based on those identified in the works of 1974 Daniel Kahneman and Amos Tversky's paper [36].

The following are the biases that have come to the author's attention as a result of his own research on system risk assessment and management.

1. *Incomplete data*. Failure to include uncertainty in the scientific estimates of reliability, availability, and maintainability of digital signalling systems including communication systems as a whole. I know the report is damning, and it may be based upon solid evidence, but how sure are we? We must allow for that uncertainty in our thinking.

2. *Defence-in-depth fallacy*. Fallacy on the part of computing science experts who entertain the idea that graceful degradation of automated information processes (fault tolerant architecture) shall be fail safe as the automated system is designed to stop the process under control if in doubt over the data (how the computer will doubt its input data, its own logic, and the outputs it generated if it has no access to real world like human beings is not questioned?);

3. *Affect Heuristic and/or planning fallacy*. The transport programme has large benefits and no major costs. I suspect the affect heuristic. No one pays attention to the fact of failure of 90% of the large railway projects to attain the cost, and passenger targets has been cited in a 2005 study. The great and good in the company are agreed with the programme mission and they like their plans. I suspect *Affect* and *satisficing heuristic and planning fallacy* [36].

4. *Narrative fallacy*. The consulting engineer is learning too much from the recent £1 billion project success, which is too tidy. The engineer has fallen for a *narrative fallacy.*

5. *Out of mind out of sight bias*. The fault tree and event tree analysis of the train crashes do not show any management and technical errors. I suspect '*out of mind out of sight bias'.*

6. *Blame Game.* The train failed in the tunnel. The communcation between the trackside and train-based equipment did not take place in the degraded scenario due to operator error. The computer simulation did not test this scenario. I smell the 'blame game'.

7. *Gambler's fallacy*. Clear-cut information about the probablity of an event is not taken into account because people believe that chance is a self-correcting process, such that a deviation in one direction will necessarily be followed by a deviation in the opposite direction. 'The shares have been falling for the railway firm, it is time to buy as the trend will reverse'. Gambler's fallacy can be seen as a factor in the explanation of Saint Petersburg paradox described in the literature.

The expected value of the game as a sum of the product of probability of loss or gain multiplied by the values of the outcomes considered by the decision maker(s) or taker(s) is poor psychology is noted by Nobel Laureate, Daniel Kahneman. These type of erroneous arguments can be seen in the case of level crossings [25].

8. *Illusion of Invincibility bias*. The supplier has announced a new train protection system which is designed to be fail safe and uses mutliple but redundant channels for information processing. Full moon effect on information processing is not recognized. I suspect 'Illusion of invincibility bias'.

9. *Expert's Subjective Risk Bias*. The supplier has furnished us the risk register for the anticipated risks. The hazard mitigation method is noted by the domain experts, but the method of hazard control is insufficent for the risk. I suspect 'Expert's Subjective Bias'.

Allais paradox: Norms of Expected Utility Theory and axioms of Rational Choice were violated due to certainty effect by expert statisticians and future Laureates in Economics in the following decision situation is cited by Laureate economist Daniel Kahneman (pp. 310–321) [36], (pp. 39) [55].

Decision I: choose 61% of £520,000 or 63% of £500,000

Decision II: choose 98% of £520,000 and 100% of £500,000

10. *Railway Senior Managers's Fallacy.* The train driver has the ultimate responsibility for the safety of the train and passengers and has to comply with signal commands. We have robust systems for recruiting, training, developing, and certifying the train staff. Our operating rules and regulations are robust. The train drivers can handle the emergency and normal situations with cognitive work load.

11. Our experience has shown that signalling systems are functioning correctly after the accident. I suspect 'Senior Manager's Fallacy'.

12. *Railway Engineer's fallacy*. Human intuitions are prone to errors and mistakes. Train driver's response is too slow for attaining productivity target. Let us automate the train driving task. I suspect 'Engineer's fallacy'.

13. *Instrumentalism Fallacy.* Give a small boy a hammer, and he will find that everything he encounters needs pounding. I suspect instrumental fallacy.

14. *Geometer's Fallacy.* Noble laureate and a physicist, Albert Einstein, in his phenomenalogical experience wrote that old geometers like Euclid dealt with conceptual objects (straight line, point, surface) but not really with space, such as was done later in Descartes's analytical geometry [20]. We must be careful of the lack of connection between geometry and physics. I suspect Geometer 'Engineer's fallacy'.

15. *Measurement Fallacy.* Risk not measured is not managed. Let us quantify the risk of rare events according to Poisson method and justify that it is acceptable as the greater good of the society is served by ignoring so-called wider human factors. I suspect Measurement Fallacy.

16. *Concrete Jungle Fallacy.* European and American city dwellers have a much higher percentage of rectangularity in their environments than non-Europeans and so are more susceptible to Muller-lyer illusion. Muller-lyer illusion occurs when two lines of equally long parallel lines with arrow tails placed at the end visually appear longer.

17. *Coherence Bias.* The plan to implement the requirements as a decision rule has been agreed by domain experts. But this plan fails to meet the decision criteria for cognitive adequacy and safety requirements. Warnings about the inadequacy are dismissed as soon as raised. The operator's inattention due to distractions in the environment to execute the task is ignored. I suspect group–think bias [4, 36].

18. *Fault and event tree analysis bias.* Goldman Sach's (error cited earlier) bug is not acknowledged by mechanical approach to change management in organisations without paying attention to the nature and behaviour of organisations and blindly relying upon methods like fault and event trees are prone to error [13, 16, 17, 25, 55, 65, 78].

Some of the above latent human factors that may contribute to any of the potential ERTMS accident was noted by Sanjeev Appicharla in 2013 [6, 8]. The author refers the reader(s) to an excellent online 2010 report by Felix Redmill in the computing science domain on how to judge if the safety risks are ALARP via a decision-making process [57]. There is no unanimous agreement on the use of ALARP principle as per the UK House of Lords Report [77]. However, the Redmill's 2010 Report does not take into account all errors in information processing of choices revealed to us by economists and psychologists in general and Nobel laureates, Herbert A. Simon, Daniel Mcfadden, and Daniel Kahneman in particular [36, 42, 67]. The author does not subscribe to the idea automated risk assessement tools such as genetic alogrithms are of help. Readers may note that SIRI methodology is a engineering methodology to assist system and safety analysis of engineered systems by taking into account success and failure scenarios and based upon the theory of decision-making under uncertainty in the data and decision-making process [35, 37]. The challenges posed by problems of complexity, causality, overconfidence, human error, hindsight and outcome biases, bounded rationality, economic choices, cognitive limitations, out of sight out of mind bias, halo effect, omissions and oversight has to be met by any methodology to be used for decision making for the assurance of system safety risk management of complex engineered systems [55].

In this section, idea as to why some wrong approaches to safety risk management relying upon risk-benefit analysis or fault and event tree analysis or reactive risk management persist was discussed.

In the next section, the case study of ERTMS Cambrian Safety Critical Incident is taken up to show how the foregoing concepts are logically demonstrated in the case study of Cambrian ERTMS Safety Critical Incident.

3. Analysis and modelling of cambrian ERTMS safety critical incident

To manage the hazardous (potential or actual) situations, the different steps followed in the system and safety analysis as per SIRI methodology are as follows [3].

a. Developing description of an operational railway (system modelling process through architecture context diagrams, operational process diagrams, parameters diagram, and/or event causal flow analysis and agree emergent properties). This activity is usually carried out within a team and process is used to elicit domain knowledge through representation of diagrams such that a validated design or concept diagram is taken as input to the next stage of the SIRI methodology;

b. Identifying hazards (hazards identification process through hazard and operability (HAZOP) study, a team-based acitivity by HAZOP Chair);

c. Modelling accident scenarios (causal analysis process through Energy and Barrier Trace Analysis to identify harmful energy sources, victims, and barriers; failures of barriers detected through the application of Management Oversight and Risk Tree questionnaire and compare results with Skills–Rules–Knowledge Framework and Swiss Cheese Model to identify latent errors and develop the Hazard and Causal Factors Analysis Report. These tasks are to be carried by HAZOP Chair and Secretary)

d. Performing risk assessment and developing countermeasures (risk assessment process through Bayesian risk analysis and/or binomial distributions or Cauchy distributions to work out base rates, these results may be needed to be incorporated with MORT Analysis. Risk analyst and HAZOP Chair)

e. Preparation of impact assessment and documentation of results and release for stakeholders' consultation or peer review (impact assessment process, HAZOP Chair and MORT Analyst)

The last three steps may involve iterative process between them; processing of developing understanding may require intermediate stages to store the results on a draft version to revisit the branches of Management Oversight and Risk Tree (MORT) questions from engineering and risk management perspectives. A red, green, amber light marking system may be needed as each sequence of energy transfer process may need to be revisited. Further, as the original Management Oversight and Risk Tree in 1974 was developed with an understanding that at the design phase engineers and their managers will be able to perceive, concieve, and act upon the identified hazards before the close out of the design process [35, 37]. However, as the railway domain does not use the concept of affordance of harm from the system as a design criterion as required by human factors engineering process, it is necessary to consider various heuristics used by designers and operators and resulting biases that may arise at the design as well as operational time in the risk assessment, safety verification, and valdiation phases [5, 6].

It is assumed that HAZOP Chair and Risk Analyst roles will be performed by competent persons. In terms of meeting systems engineeering and safety standards set by engineering institutions such as Institution of Electrical and Electronic Engineers – IEEE std 1220 or International Electro-technical Commission – IEC 61508 or sector-specific European Committee for Electro-technical Standardisation – CENELEC 50126, the two stage processes of system and safety analysis can be complied and implemented with the help of SIRI methodology [6].

To produce a model of an operational railway, the model should be able to reflect the real world closely. The operational railway includes several interfaces in all operational circumstances:

a. Man–machine interface (driver–line signals, signaller–automatic route setting, driver–train, etc.)

b. Machine–machine interface (interlocking – lineside signals, ATP-train brake, ERTMS-interlocking, ERTMS-fixed and mobile telephony, mobile telephony to ETCS, etc.)

c. Man procedures (operational procedures, work instructions, etc.)

d. Organisational interfaces (safety standards, failure management, hazard control between duty holders, between duty holders and industry bodies, between various types of organisations)

However, the present modelling languages suffer from a disadvantage in the sense that they tend to superimpose their own order on existing systems and fail to capture the rich partial order present in the system.

The application of the SIRI methodology to the incident situation under study is described. The RAIB Accident Investigation Report is used as the input document alongside the MORT (2002) questionnaire.

The RAIB Summary is reproduced here.

Shortly before 22:00 hrs on Sunday, 19 June 2011, a passenger train, travelling from Aberystwyth to Machynlleth, ran onto the level crossing at Llanbadarn while the barriers at the crossing were raised, and came to a stop with the front of the train about 31 metres beyond the crossing. There were no road vehicles or pedestrians on the crossing at the time. The immediate cause of the incident was that the train driver did not notice that the indicator close to the crossing was flashing red until it was too late for him to stop the train before it reached the crossing. Factors behind this included the driver's 'Increased work load' (his need to observe a screen in the cab at the same time as he should also be observing a lineside indicator), the design of the equipment associated with the operation of the level crossing, and the re-setting of the signalling system on board the train before it could depart from Aberystwyth. An underlying cause of the incident was that the signalling system now in use on the lines from Shrewsbury to Aberystwyth and Pwllheli does not interface with the automatic level crossings on these routes.

The RAIB has made six recommendations, three directed to Network Rail, two to Arriva Trains Wales, and one to the Rail Safety and Standards Board. These cover the development of engineering solutions to mitigate the risk of trains passing over automatic crossings which have not operated correctly; changes to the operating equipment of Llanbadarn crossing; the processes used by railway operators to request permission to deviate from published standards; the operational requirements of drivers as trains depart from Aberystwyth; and the way in which drivers interact with the information screens of the cab signalling used on the Cambrian lines.

3.1. System analysis diagram

To enable, visualise, and reason about risk manager behaviour in general operating situation within the real world, the author has prepared an adapted version of diagram of Prof Jens Rasmussen's Skills-Rules-Knowledge Framework within Cognitive Science tradition. The diagram does not show actual mental world of an individual, but it is a model or a representation to be used by SIRI Analyst to reason about certain behaviour in philosophical, teleological, cultural, and scentific traditions of thinking and reasoning reflected in the literature on risk. However, it should be noted that this model does not reflect real truths. As Prof David Hand has written, one must revert to religion or pure mathematics for learning absolute truths [26]. It only shows a frame to reason about heuristics which allows response (automatic or reasoned) to the questions on risks or operator's actions in the real danger situation as well as shortfalls in risk or investment actions reasoned in the mangerial thinking.

To enable easy comprehension of the context of the UK railway industry operations, a system diagram is prepared. This is shown in Figure 1. This is an architectural context diagram (ACD) showing stakeholder organisations involved in the context of the Cambrian ERTMS Incident. From a systems engineering perspective, organisations forming part of the railway system are Network Rail and Passenger or Freight operating (not shown in the figure) companies, European Railway Agency, RSSB, RAIB are system supporting organisations whereas Department of Transport is the ultimate owner of the UK Railway System. Office of Rail Regulator, ORR, is a regulatory organisation. Element organisations like Alstom, Siemens, Ansaldo, Bombardier, Invensys, and Thales that supply signalling solutions are represented as contractors. Professional engineering societies which train, license, and certify individuals to meet the railway industrial needs are not represented in the diagram, but are recognised as institutions contributing to human capital development and as consequence to risk management as per Noble laureate and economist, Gary Becker's perspective [62]. Notified bodies or project safety organisations are treated as entities acting as contractors providing safety auditing, assessment, advice, and accreditation. The brief details of European Process validation and certification process is defined in the Section 5.5.3 of the uic Compendium on ERTMS [81].

From system analytical perspective, the definition of an organisation offered by Nobel Herbert Simon that organisations are adaptable systems made up of physical, technical, and human resources and exhibit what is known as 'satisficing behaviour' is accepted in this chapter [67]. The solid red lines in the above figure indicate safety critical interfaces and functions and dotted red line indicates influences emerging from accident investigations. Symbol 1 indicates ORR is legally independent of the Secretary of State. Symbol 2 indicates Passenger Focus is an independent body set up by the UK Government to protect the interests of passengers.

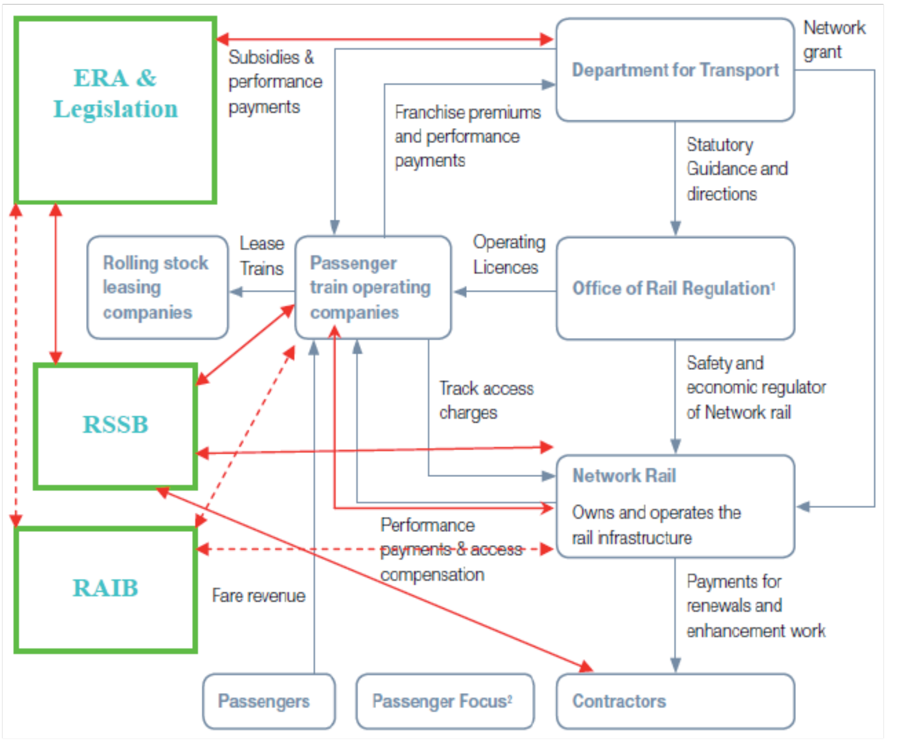

Figure 1. Architecture Context Diagram of the Railway Industry. Adapted from the UK National Audit Office Report (The UK National Audit Office 2010).

3.2. Hypothetical HAZOP study

The description of hazard identification and analytical methods used in the SIRI methodology is available in the published liteature. It is a hazard identification technique promoted by the UK Intuition of Chemical Industry in the early 1970s [17].

From the information gathered from the summary section, paragraph 95 and 177 of the RAIB Report, the critical interface between stakeholder organisations, Network Rail, the owner of the rail infrastructure and Arriva Trains Wales (ATW), the passenger train operating company at the operational time is the interface between driver's eye ball and the driver crossing indicator [51]. This is identified as Driver_ Perception of the Driver Crossing Indicator (DCI) and is the emergent property to be conserved in this study and operations as well.

The indicator was flashing red giving dynamic information to the train driver, but driver's response was delayed and the train did not stop ahead of the level crossing, indicating a safety critical deviation. From the SIRI methodological perspective, after Driver_ Perception is a safety critical deviation as the event of driver perception occurred after the braking point despite stopping ahead of the crossing space. Reading of the para 100 and subsequent text of RAIB Report suggests that signaller made mistake in setting the routes which led to a timing sequence problem, leading to the event of the opening of the barriers prior to the event of train passing over the crossing space. The chain of events leading from this pre-cursor event is not discussed as the parameter of interest in the hypothetical HAZOP study is Driver_ Perception of the Driver Crossing Indicator in the sequence of events desired and its late occurrence. Suffices to note that signaller's error is a latent error and it is clear that human factor analysis of the signaller's task post implementation was not carried out. This is a latent error from the Common Safety Method's perspective as well [11].

Moreover, the design intent of ERTMS signalling automatic train protection (ATP) system is to provide the signal to programmable electronic system giving information on safe speeds and stopping points in Full Supervision (FS) Mode [82]. Thus, from the ERTMS signalling system function perspective, the emergent property which is to be conserved by trackside sub-system to on-board train system critical interface is Provide_ Signal.

But the national signalling infrastructure and human factors are excluded from the scope of Signalling Supplier's Consortium's (UNISIG) safety analysis. Further, the Compendium on ERTMS notes in Section 8.3.2 that the Index 47 document contained in the Chapter 6, risk analysis performed by two member states resulted in different interpretations of the hazard lists [82]. Given the fact that certain signalling entities and human factors are excluded, then the questions on the purpose of the European Train Control System(ETCS) *to provide the train driver with information to enable drive the train safely and to enforce respect for this information is* not satisfied if Driver _Perception _ Crossing Indicator is not included in the movement authority information. This discovery should provoke thoughts on the requirements management process used in the programme management of ETCS programes. This incident has shown that the design intent as per RGS GE/RT 8026 was not met [51].

The sample HAZOP worksheet for automatic train protection system adapted from the IEC 61822 standard for HAZOP study is shown in Figure 2. From reading the text in the para of the RAIB investigation, para 157 it is clear that the movement authority across the crossing was issued without stopping information ie No _ Provide_ Signal [51]. From this hypothetical HAZOP study and RAIB information, it is clear that trackside sub-system was not configured for the emergent property Provide_ Signal at the ABCL Level Crossings. If a real HAZOP study were to be conducted, then this failure may provoke thinking about the adequacy of study of failure scenarios and barriers as well.

Absence of the road user at the crossing space averted the potential accident. The real accident, if it had occurred, may have led to a range of outcomes with the loss of life as well as public and media outrage, if too many fatalities had resulted from it.

Figure 3 shows the schematic diagram of Llanbadarn ABCL facility. This figure may have to be zoomed to 180% or above to gain visual clarity. At the minimum, actions as planned under the risky scenario of raised barriers and stopping train front stopping 31 metres beyond the crossing space would have certainly resulted in a collision between the road and the rail vehicle, given the present understanding of laws of physics [48].

The absence of road user at the same time when the train passed the ABCL crossing space in error is judged by the SIRI analyst to be an 'act of God', as the intention of all stakeholder organisations such as regulating, specifying, developing, designing, manufacturing, supply-

STUDY TITLE: AUTOMATIC TRAIN PROTECTION SYSTEM									SHEET: 1 of 2	
REFERENCE DRAWING No.: ATP BLOCK DIAGRAM					REVISION No.: 1				DATE:	
TEAM COMPOSITION: DJ, JB, BA									MEETING DATE:	
PART CONSIDERED:				INPUT FROM TRACKSIDE EQUIPMENT						
DESIGN INTENT:				TO PROVIDE SIGNAL TO PES VIA ANTENNAE GIVING INFORMATION ON SAFE SPEEDS AND STOPPING POINTS						
No.	Element	Characteristic	Guide word	Deviation	Possible causes	Consequences	Safeguards	Comments	Actions required	Action allocated to
1	Input signal	Amplitude	NO	No signal detected	Transmitter failure	Considered in separate study of trackside equipment			Review output from trackside equipment study	DJ
2	Input signal	Amplitude	MORE	Greater than design amplitude	Transmitter mounted too close to rail	May damage equipment	Checks to be carried out during installation		Add check to installation procedure	DJ
3	Input signal	Amplitude	LESS	Smaller than design amplitude	Transmitter mounted too far from rail	Signal may be missed	As above		Add check to installation procedure	DJ
4	Input signal	Frequency	OTHER THAN	Different frequency detected	Pick up of a signal from adjacent track	Incorrect value passed to processor	Currently none		Check if action is needed to protect against this	DJ
5	Antennae	Position	OTHER THAN	Antennae is in other than the correct location	Failure of mountings	Could hit track and be destroyed	Cable should provide secondary support		Ensure that cable will keep antennae clear of track	JB
6	Antennae	Voltage	MORE	Greater voltage than expected	Antennae short to live rail	Antennae and other equipment become electrically live			Check if there is any protection against this occurring	DJ

Figure 2. Sample HAZOP worksheet for ATP system.

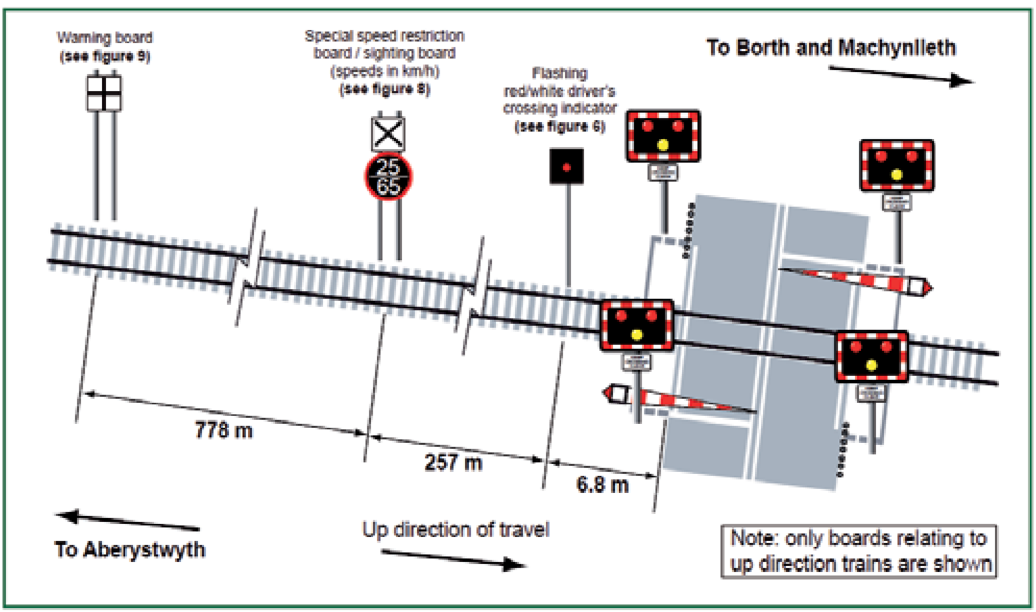

Figure 3. Schematic diagram of Llanbadarn ABCL.

ing, utilising, and maintaining the ABCL design is to allow road users (without committing an error) to pass through the crossing space when barriers are raised.

Non-provision of engineered safety feature in the contemporary ABCL design is a signalling engineering induced (latent) error at the RSSB Standards Committee Level whereas driver's delay in departing and arriving at the strike in point may be signaller (active) induced error.

The SIRI methodology adopts a system-induced error approach; and therefore, it is necessary to look at errors from a holistic perspective. The lack of compatability of requirements between Railway Group Safety Standard GE/RT 8026 and European Norm for ERTMS/ETCS System is a glaring omission in the area of railway safety risk management [46]. It shows intelligence failure on the part of all organisations. This type of failure was investigated in the GB Railway domain in 1976 by Barry A. Turner as well [78].

3.3. System safety analysis: Application of Energy Barrier Trace Analysis – EBTA, Skills–Rules–Knowledge (SRK) and Management and Oversight and Risk Tree (MORT) methods

Management and Oversight and Risk Tree (MORT) is an analytical technique for identifying safety-related oversights, errors, and/or omissions, or assumed risks that lead to occurence of an incident or accident [17, 35]. The MORT diagram uses of the logic of fault tree. It contains two main branches. One related to control of technical factors denoted by letters SB, SD, etc., which are leaves of the causal tree and representing system life-cycle factors. Another branch relates to management branch denoted by letters such MA, MB. Leaves within these branches are noted by lower case letters a1, b2, etc., which relate these events to questions listed in the MORT User Manual [17, 35].

The MORT Report contains following acronyms:

LTA: less than adequate

DN: did not

FT: failed to

HAP: hazard analysis process

The description of the concept of operations is drawn from the ORR documentation, RSSB Railway Group Standards, and is based upon the author's past experience of chairing HAZOP study at RSSB for generic ABCL facility and described using the generic Event Causal Factors (ECFA) analysis chart. This is shown in Figure 4. This may be required to enlarge till 180% to gain visual clarity on the computer screen.

The description of the expected event sequence to form a coherent description uses a particular notation of ECF analysis. The criteria to be used to read the event sequence diagram follows.

- Events must describe an occurrence, not a condition,
- Events must be described with at least one noun or verb,
- Occurrences must be precisely described,
- Events must describe one discrete action,
- Events are enclosed in rectangles and connected to other events as a forward chain using horizontal arrows,
- Conditions are enclosed in ovals and are connected to events by vertical arrows,
- Events should range from beginning to end of the particular method of operation,

- Each event should be derived from the one preceding event save for initiating event,
- Colour coding is used to distinguish infrastructure manager (IM), railway undertaking or train operating (RU) domain, and user domain,
- Events are labelled with number or letters to identify the sequential flow of events in respective duty holder domain.

The Concept of Operations describes the operational scenario when the train is approaching the warning board and the train driver is in vigilant mode of information processing. However, the desription of the incident RAIB (paragraph 110) informs that the event of approaching the warning board was delayed due to train entering Staff Responsible, SR, mode [70]. The ABCL being located near the station inserted a delay in the normal specification of the ABCL task analysis, and no separate task analysis was performed by the Railway Understaking (RU) in question. The time to approach to the level crossing space is specified in the form of a time interval and no account was taken in the variation in the time for the tasks to be performed by the train driver due to differernt operating modes was undertaken by RSSB before granting deviation to the safety critical requirements specified in the Railway Group Standard – RGS GE/RT 8026 [51].

This is a latent error embedded into the system where engineering and organisational errors are committed. This is an instance of *Railway Senior Managers and Engineer Fallacies.* Further, this latent error refutes the European Railway Agency, and RSSB's idea that the management and regulation of the railway is designed to ensure that – if each transport operator meets its obligations with respect the safety of its own operation and the state also fulfils its duties – then the sum of the parts will lead to a whole that is safe. Further, the RSSB statement does not fit the idea of systems thinking that whole is more than sum of its parts. This idea is entertained by system engineers as well as human factors specialists. Moreover, this error does not align with the Best Practice of Decisions Under Risk of Prospect Theory, which is acknowledged by RSSB in its July 2014 document [6]. Given the nature of the latent error, it is clear that this decision not to conduct workload assessment is a violation from RSSB's own Best Practice for Human Factors Risk and Safe Decision Taking [58, 61].

Given the Concept of Operations diagram which the author has developed, introducing timing analysis into the scheme is not a difficult issue if the data from the human factors engineering is included as well. From the direct inspection of events sequence described in the diagrams shown in the Figure 4, the expected event labelled E-IM-13 in the Network Rail domain flashing white aspect, and contrary to the expected event labelled E-RU-6 in the Arriva Train Wales domain, the red light was perceived, suggesting that the barriers were raised and an obstruction may be expected in the path ahead of the train.

Realising this fact, train driver applied brakes but the train did not stop short of the crossing. Since this constitutes a safety critical deviation, it is necessary to inquire further as to why the driver's response was slow and what shaped that behaviour. The train driver's action was a skill-based error type where the spatio-temporal response was delayed [12, 36, 55, 52].

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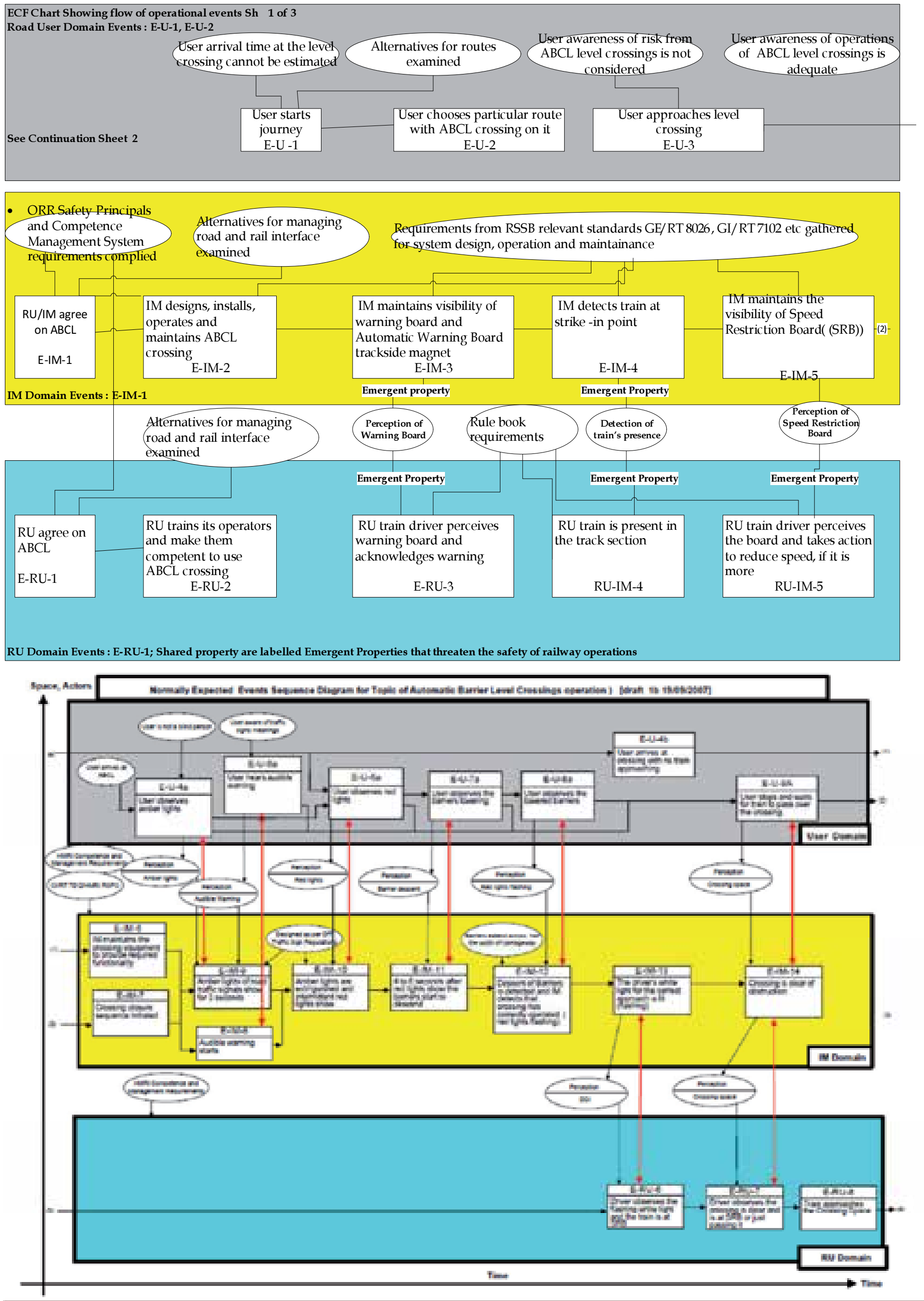

Figure 4. Representation of the concept of operations of ABCL Facility signalled by traditional lineside signalling

3.4. Energy barrier trace analysis

From the RAIB Report(s), the information available from the stakeholder organisations websites, the following worksheet is generated. This worksheet forms the starting point of the root cause analysis.

Harmful energy flow or harmful agent, adverse environmental condition SB1	Target vulnerable person or thing SB2	Barrier and controls to separate energy and target SB3
Kinetic hazard (train movement into the crossing space) when barriers are raised	None present at the time of incident	ERTMS Cab Signalling (not provided with movement and braking information when approaching level crossings) does not apply to national signalling infrastructure *(incomplete data for safety analysis).* Latent error: *status quo bias*
		Restriction on train speed (not provided with information at level crossings). Latent error: *status quo bias*
		Obstacle detection (not provided). Latent error: *habit bias*.
		Lifting barriers (provided) but not inerlocked with train movement. Latent error: *habit bias*.
		Approaching locking (not identified in the RAIB report). Latent error: *habit bias*.
		Interlocking system (did not provide function of locking barriers with train braking function). Latent error: *illusion of validity of driver's expertise.*
		Did not provide bridges, underpass, etc. Latent error: *illusion of control.*

Table 1. For Energy Barrier Trace Analysis (EBTA) worksheet

Logic of combinations may be applied to the following table. The author does not agree to the Pearson's idea that causation and correlation can be inferred in the same way [23].Credit to

God is given at the user level crossings where no indication of approaching train can be percieved or passenger manages to escape the accident [73, 74]. Otherwise, the table indicates that level crossings are accidents waiting to happen. This table can be interpreted again using the Prof James Reason's Swiss Cheese Model as well. The ECFA activity yields information on unsafe acts. But the precursor information on regulatory, organizational oversights is available from the EBTA and MORT charts.

It is clear from the foregoing particular description of the ABCL incident by RAIB, an ineffective system was deployed. The method of application of the MORT under the SIRI Methodology has been described in 2011 and 2012 [2, 6, 7, 9]. Call for replacement for bridges is not met easily due to failure on the part of social actors to percieve the risk correctly. Further erroneous interactions between distant components of Route Management System and level crossings user's intention leading to fatality at the level crossing site are noted in the accident literature [70].

To consider how and why the hazardous system was deployed and safeguards were not provided, it is necessary to apply the MORT questionnaire, as an organisation framework, to the RAIB report and related literature to arrive at all factors involved in contributing to the incident. MORT audit questionnaire is freely available online at www. nri.eu.com [35, 37].

3.5. Information on hazard causal factors: SIRI MORT representation

The application of MORT audit questions (2002 version) and the elicited following responses are characterised as human errors [35, 37]. Readers are requested to enlarge the images to make them readable. The Lessons learnt from the 2011 Incident and evidences drawn from the RAIB Report 11/2012 and 2010 RSSB Road and Rail Interface Report are described together with the evidence to support the reasoning in the form of a fault tree representation. The MORT Causal Trees for engineering and managerial are represented in Figure 5, Figure 6, and Figure 7. The hueristics and biases shown are not mapped to organisations involved in Figure 5. Such mapping may be carried out with the available information. The information contained in the MORT Top Tree derives from the managerial and engineering branches and evidences from the requirements for safety management system, generation, operation and maintenance of system safey case from UK and European Commissions Norms.

The inspection of the above diagram shows that how the hazards, and heuristics and biases involved in safety risk information processing at the knowldege -based level with a potential of loss of 32 lives with 99% probability as per standard Cauchy distribution with statistical median of 0.72 fatality per 1,000 ABCL level crossings and scale factor equal to 1 were not analysed. The neglect of base rates can be seen from the HS2 Risk Report [27]. Fault within fault tree analysis labelled as out of sight out of mind bias is self evident in this case study.

The mean weighted fatality rate of 0.72 fatalities for road vehicle passengers is taken from RSSB Report dated 2010 [60]. The basis of the calculations and more elaboration of the causal tree follows.

The information on the hazard causal factors will be appreciated when the information is placed in the frame of reference using the concept of operations diagram (see Figure 3).

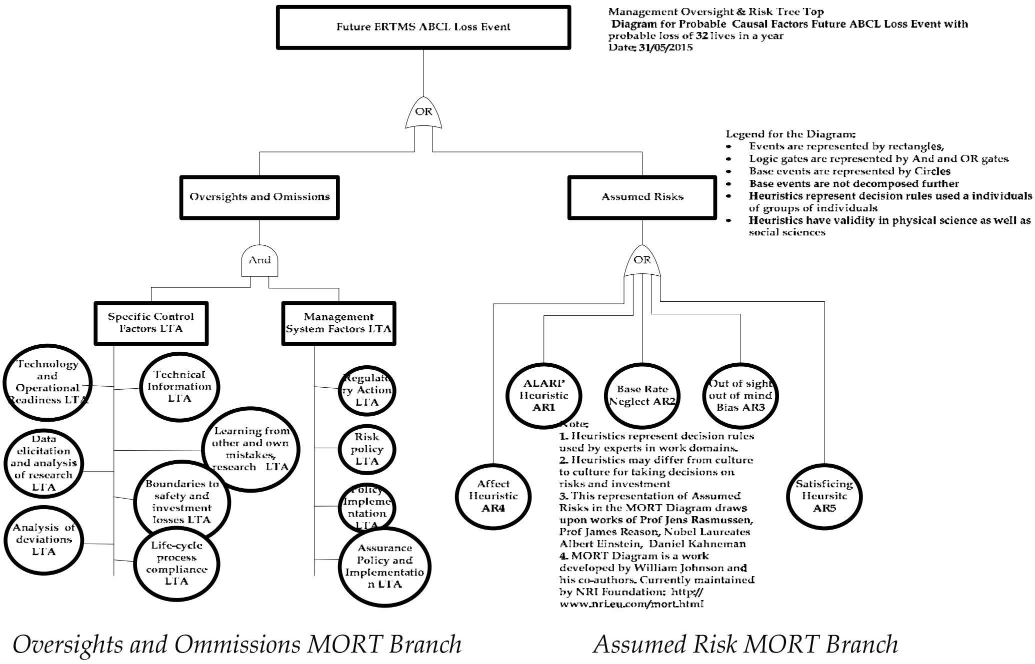

Figure 5. SIRI MORT Top Tree (Page 1)

It should be noted that ERTMS Safety Experts do acknowledge that Command Control & Signalling Technical Interoperability Specification (TSI) cannot itself gaurantee the safety of system since the National Part of Signalling System and an interface to it is outside the TSI Scope (pp. 206) [82]. The way to integrate man–machine interactions, operational rules, or non-inter-operability technical components into system safety analysis, as per the European Railway Agency, is to treat the safety performance of inter-operable constituents as a fixed factor and derive safety requirements for the non-TSI constituents. ERA arguments is that top down decomposition and allocation of probabilities ignores the human factors in risk assessments, fault tree analysis, and allocation of physical, human and social capital. The Consensus decision making process adopted at the RSSB Signalling Standards Committee level does not use any system analysis to detect conflicts between various types of requirements which give rise to human factor concerns. In other words, Group think bias due to assignable causes or optimism fallacy can manifest in such decision settings due to systematic human failings in lack of systems engineering process in specification of safety requirements, risk analysis & modelling and human factors investigation. ERA is aware of incompleteness of the generic risk analysis but RSSB does not include human factors concerns.

Less than adequate competence of professional heads of signalling, risk assessment, independent review, operations, human factors, safety, and systems engineering disciplines at regulatory, safety, duty-holder, supplier and validation organisations is a natural conclusion that can be drawn from the case study. The Greek philosopher, Plato once asked who will guard the guardians via Glaucon who thought it was absurd to consider their oversight (Plato's Republic). This was the original thesis stated by author in his 2006 publication [3]. The European Process for SafetyAuthorisation as defined in by Peter Winter in the UIC Compendium on ERTMS in 2009 for the safety certification did not assure the safety operability albiet technical inter-operability of components has been attained (pp.128) [81]. Identifying, interpretation of current state, evaluating of options, identification of target (safe) state, specifying the safety goal for the Cambrian ERTMS Implementation which forms five crucial stages of decision making of Skills-Rules-Knowledge Decision Model were less than adequate. The work groups invovled did not have the interest of public safety at the heart of their decision making activity (pp. 369) [49]. Management Oversight and Risk Tree's decision model provides the idea that noise generated by political rhetoric overshadows the signal of less than adequate design of level crossings. Author has observed the tendency on the part of safety organisations to club several safety and human factors engineering technqiues such as Hazop, Fault and Event Tree Analysis, Operator Task Analysis to conduct safety critical analysis and has raised this concerns with Chair of Human Factors Working Group of UK INCOSE set up recently [6]. The feedback on this document is awaited. However, the safety case for ERTMS/ETCS is difficult to generate using the existing safety management methods was argued by the author at RSSB in January 2010 [10].

Incomplete system definitions cannot be used for system safety analysis is learnt from the the literature of control systems engineering from the UK HSE Guidance Note HSG238 as well [73]. However, this vital fact has been omitted by RSSB research managers is learnt from reading this research paper published in 2011 [22]. In other words, if operator error and signalling technical error are contributory causes (ignoring latent errors) then to attain SIL4 target for the overall system, the state of being at risk due to technical and signalling equipment failure has to exceed one chance per hundred billion opportunities per hour. This is under the assumption train driver's behavior is logically equivalent to a low demand SIL2 system from past data and including effect of immutable human nature discovered by David Hume. [65, 66, 80].

In other words, human error rate has to exceed SIL4 level if we include latent errors as well. The question of conjunction fallacy naturally arises if the final cause of the hazard is to be investigated together with its material (national signalling failure rate), formal (failure rate of risk management system), and effective causes (failure of human factors), as per Prof Jens Rasmussen's idea of Aristoteleian causal representation as applied to hazardous events and theory of probability as well (36), (pp. 53) [53]. Thus, the idea of fat tail risk has escaped the attention of ERTMS specification writers, European Rail Agency safety experts, and safety risk experts at GB rail national safety bodies and duty-holders. This social phenomena is not new. Aircraft industry shows similar tendecies as well [13, 49].

The meaning of hazards management is restricted to storing information on databases rather than eliminate hazards can be seen from a metro railway project Report in 2009 [30]. Further, the idea of conjunction of random failure events of redundant information processors has been paid attention, but fat tail risk problem showing up as group-think bias is not entertained in the risk literature by ERTMS designers, regulators, duty-holders, and standard bodies as noted

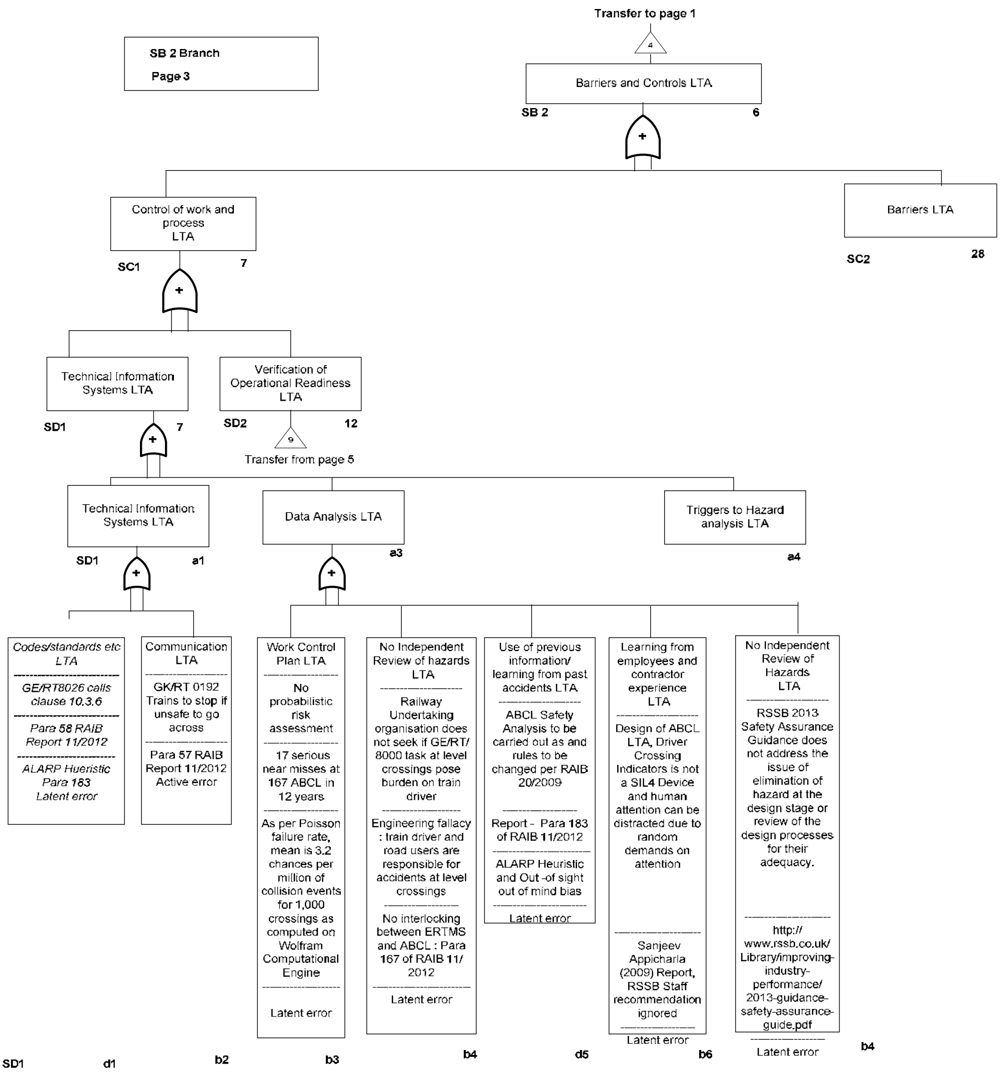

Figure 6. SIRI MORT SB2 Branch.

byNobel laureate Daniel Kahneman and Sanjeev Appicharla [4, 36]. Review of RSSB Safety Risk Model in 2012 did not refer to the errors that could occur in the usage of Bow-tie models as it has been shown in the accident investigation of loss of military aircraft, Nimrod in the Nimrod Report in 2009. Accident pre-cursor models do not include managerial, and engineering oversight and tendencyto assume risks can be seen from this review. Less than adequate technical review of fault tree analysis can be seen from this reference [24]. Further, the Review Report did not raise concerns over the subject matter experts using normalising constants in the risk equation as highlighted by Prof Paul Slovic [25, 36, 78]. Further, the familiar short-cuts have been taken to selecction of goals, task and execution of decision process as per Prof Jens

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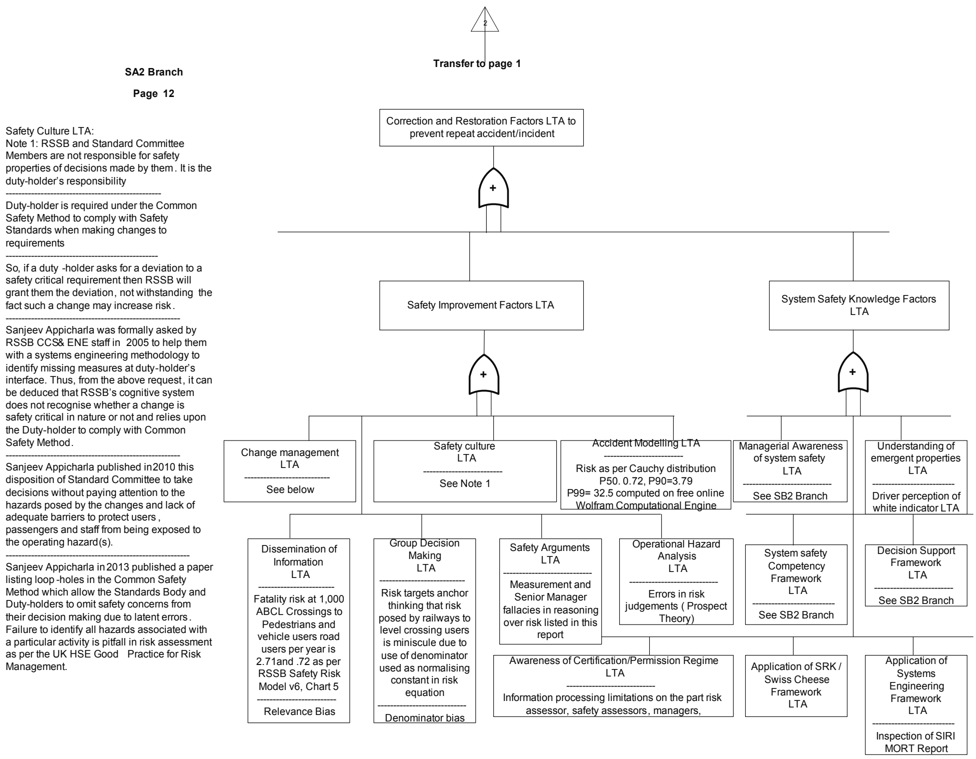

Figure 7. SIRI MORT SA2 Branch.

Rasmussen's SRK model of eight stage process of decision making and the potential hazard of train colliding with a road vechicle was not recognised by senior managers as per Prof James Reason's Swiss Cheese Model. The tendency not to eliminate risk within British Railway days is noted by risk and regulation expert, Prof Hutter [41].

The MORT results have shown the relevent hueristics and resulting biases incorporated into the MORT analysis shows a different risk picture than the expert railway safety and economic managers can imagine. An integrated analysis of quantified risk assessment, wider human factors via Swiss Cheese Model, and decision errors at the knowledge -based level called latent errors to show resident pathogens via cognitive systems engineering approach in an application of MORT is a novelty. This need is stated in RSSB Research Project calling for formal procedures to be applied to the task of assessment of rules and staff of RSSB as well [19, 2–11]. The decisions taken by various organisations show that these stakeholder organisations were not optimising safety for the road users, passengers, and staff.

The incident occurred as RSSB/Network Rail did not consider inclusion of level crossing functionality into the Cambrian ERTMS Automatic Train Protection System. The decision-making process used by RSSB Signalling Standards Committee for deciding upon the implementation of mandatory safety requirements specified within the Railway Group Standards was less than adequate as it failed to take into worst-case scenario of risk possible and the EU

Techncial Specification for Inter-Operability did exclude the functionality. The hazard analysis process used to close out the hazards failed to take into account wider and local human factors due to this exclusion [49, 55, 69]. Further, linear interaction between Design of the System with Operator (train driver and level crossing user) is not an hidden interaction in the work situationand therefore, from a complex systems persective, the ABCL Incident is simply a component failure accident [55].

4. Conclusion

The reasons for persisent use of wrong-but-popular approaches like cost-benefit analysis, and fault and event tree models for safety justification, identification of accident pre-cursors, and management of safety risk through independent safety assessment approach were presented in the chapter.

The Cambrian ERTMS case study has identified all engineering, managerial, organisational, and regulatory actions which have contributed to the ERTMS Safety Critical Incident using the SIRI methodology. The case study showed various heuristics and biases that were active in the railway industry. This is a novel use of hueristics and biases appraoch within the cognitive systems engineering tradition without omitting any stakeholder organisation in the SRK, MORT, and SCM analysis.

Acknowledgements

The author expressed thanks to the InTech publishers for invitation to contribute to the book. The author expresses thanks to anonymous reviewers for pointing out drafting and typographical errors in the text. Thanks are due to MORT team as well. Thanks are due to near and dear ones in the family as well. It is difficult to name every individual and organisation that has helped directly or indirectly in the production of case study.

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Chapter 4

Experimental and Simulation Study of the Superstructure and Its Components

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Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/61517

Abstract

The issues discussed in this chapter are of interest of both the manufacturers and the experts responsible for condition of the track superstructure. In general, stress in steel elements may affect the energy state, phase changes, and corrosion. It may reduce fatigue strength and cause damage and cracks of the rails. It is one of the causes of accelerated development of standard railhead defects. Proper selection of, e.g., bending process parameters provides uniform distribution and acceptable level of residual stresses in the bent components. Residual stresses that develop during manufacturing process in the railway turnout steel components can change their strength properties. The first part of this chapter presents ultrasonic measurement method and computer simulation that allowed to develop a method to diagnose state and distribution of residual stresses in steel components of the railway turnout (wing rails and switch blades) in the production process. The second part of this chapter includes experimental and simulation studies of superstructure in operational conditions. A track substructure with a crashed stone composite is a solution of reinforced standard track substructure. The results are used to draw conclusions concerning further development and possible modifications of a proposed solution. A significant number of simulation calculations also allow to determine the duration of guaranteed functionality of a reinforced track substructure.

Keywords: Railway turnout, residual stress, ultrasonic measurements, finite-element method, ABAQUS railway track, crashed stone composite

1. Introduction

The development of the railway infrastructure at the turn of the 20th and 21st centuries and the increase in passenger train speed to V_{max} = 300–350 km/h and freight train speed to V_{max} = 140–160 km/h on some routes are the results of railway vehicle design improvement and railway infrastructure optimization.

Track superstructure allowing to reach high speeds and transfer even higher stresses and loads up to 25–30 tonnes per vehicle axle is required to meet very strict strength and durability requirements.

The infrastructure is subject to complex dynamic effects, changing with the increase in load and speed. In the last several decades, standard railway track structure have not change significantly, even though it is subject to studies and improvements aimed at increasing railway traffic safety and limiting operating costs.

The durability of the track superstructure is also affected by the quality of materials used, e.g., steel components used in production of railway turnouts. Steel components of the track superstructure (rails, switch blades) show internal stresses even in the manufacturing process due to process treatment including surface hardening and bending. The treatment introduces additional energy to the material, i.e., stresses, which does not weaken the material, although may affect component operation and result in damage.

2. Review of the literature

Standard railway tracks include a permanent way with the rails and the sleepers on a ballast, operating under load in elasto-plastic state. The ballast is a source of permanent (plastic) deformation. The advanced technological and material solutions allow the operation of the rail bed under operating load in elastic state [1, 2]. Several developed mathematical models of the railway track, its components, and the effect of a vehicle on the track have been detailed in [4, 5].

Nowadays, a finite element method (FEM) is one of the most commonly used methods in addressing complex engineering issues. The method can be used in many fields, to easily create various areas and shapes of complex geometry. Numerical methods have been used in railway track component development for several decades. Extended studies have been performed by the Warsaw University of Technology, the Cracow University of Technology, and other research and development institutes. The studies have included residual stress analysis in steel turnout components, i.e., all rails, including flat-bottom rails.

The aim of the numerical calculations is to determine residual stresses in a rail after relieving and to determine the influence of different parameters on stress size and pattern. The results of numerical calculations have been compared to the results of ultrasonic stress measurements. The studies of international researchers have included modeling the effects observed as a result of rail rolling on roller straighteners. The studies [7] have included rail models and residual stress patterns after rolling simulation and the effect of the rolling process on stress size and pattern. A finite element method, as a basic tool in today's mechanics, has also found its use in railway track and bed development.

As mentioned in various studies, the authors of refs. [8, 12] have presented the results of numerical calculations for created models, as well as the results of measurements performed on testing track sections and in laboratory conditions. The author of this chapter uses FEM for simulation calculations of static and dynamic loads of the railway track components [13–15]. Standard railway tracks include a permanent way with the rails and the sleepers on a ballast, operating under load in elasto-plastic state. The ballast is a subject to permanent strain resulting in plastic deformation. The advanced technological and material solutions allow the operation of the rail bed under operating load in elastic state [16, 17]. The weakest point of the standard railway track is a compacted crushed stone layer. Several research studies on crashed stone quality, type, and grading as well as on the mechanical compaction methods [18] have been presented. The studies have not given satisfactory results in relation to the reduction of increase in non-uniform plastic strain intensity of the ballast. As a consequence, systematic and frequent repairs are required to eliminate unacceptable geometrical unevenness of a railway track. An energy generated at the wheel/rail interface is transmitted by the rail and rail fixings to the sleepers and via ballast to the rail bed causing an intense vibration field. Kinetic energy increases with the increase in train speed, and as a result, a vibration acceleration of rails, sleepers, ballast, and rail bed increases. It results in considerable tensile stresses within the ballast, affecting internal friction balance and causing ballast to breakup. The ballast subsidence (plastic strain) cannot be avoided, and at the same time it increases with the increase in ballast stresses and vibration acceleration.

Crashed stone ballast layer is subject to tensile stresses. Vibrations in the ballast layer cause acceleration exceeding the acceleration of gravity g, further reducing ballast resistance to tensile stresses. Crashed stone ballast layer at sleeper and ballast interface at operational loads is in a spatial compressive stress state. The principal stress tensor can be described as $\sigma_1 > \sigma_2 > \sigma_3 > 0$. It means that the crashed stone ballast is in a tri-axial compression state thus creating the best conditions for ballast operation. The most adverse conditions can be observed when the ballast is subject to pulsating and variable tensile stresses. Further analysis shows that the tensile stresses are most likely to occur near the rail fixing point, i.e., point of wheel-ballast-crashed stone ballast load transmission and in the areas from the side of the ballast face. Top ballast layer in those areas requires protection against factors that may cause deconsolidation. Stress analysis in the track subgrade shows that the tensile stresses decay in the track subgrade at the depth of 60 ÷ 80 cm.

3. Residual stress

Residual stresses are considered stresses counteracting each other inside the component, which is not affected by any external loads. Internal loads are a measure of elastic strain energy stored in a specific body area and are additional component loads. Assuming a plane internal strain state of the stresses on the component surface (rail), normal and shear stresses can be defined [20], see Figure 1.

Components of plane stress state:

- σ_x, σ_y, σ_z
- τ_{xy}, $\tau_{xz} = \tau_{yz} = 0$

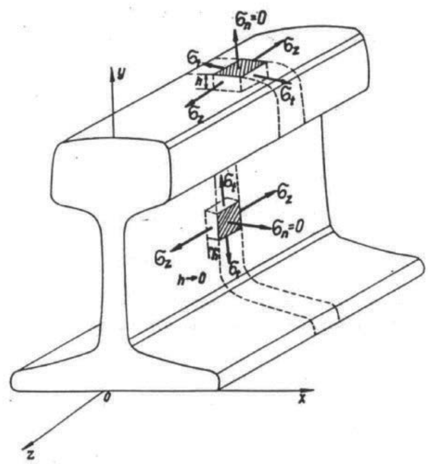

Figure 1. Components of plane stress state on rail surface [21].

The stresses on the rail surface are defined by normal stresses and tangential stresses σ_n, σ_t.

Each component at the rail surface without load meets the following condition:

$$\sigma_n = 0 \; i \sigma_t = 0$$

For those conditions, the relation between strain and stress is as follows:

$$\varepsilon_z = \frac{1}{E}\left(\sigma_z - \nu\sigma_t\right) \tag{1}$$

$$\varepsilon_t = \frac{1}{E}\left(\sigma_t - \nu\sigma_z\right) \tag{2}$$

$$\tau_{tn} = 0 \tag{3}$$

Residual stresses σ_z and σ_t can be determined based on Equations (4) and (5):

$$\sigma_z = \frac{E}{1-\nu^2}\left(\varepsilon_z + \nu\varepsilon_t\right) \tag{4}$$

$$\sigma_t = \frac{E}{1-\nu^2}\left(\varepsilon_t + \nu\varepsilon_z\right) \tag{5}$$

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where σ_t tangential stress, σ_z is the normal stress, ε_t is the tangential strain, ε_z is the horizontal residual strain, and ν is the Poisson ratio.

3.1. The phenomenon of residual stresses

The residual stress arises in the case of heterogeneous plastic deformation caused by

- bending and cold rolling
- thermal stresses
- heterogeneous phase transitions

For steel railway superstructure components, occurrence and change in residual stresses are due to thermal stresses and plastic strain resulting from bending and cold rolling.

Thermal stresses are a result of non-uniform phase transitions due to thermal treatment, including surface hardening, used for shaping the steel turnout components. The treatment aims to increase hardness of the surface layer of a wing rail or a switch blade.

The effect of generating residual stresses in this case is more complex compared to heterogeneous cold strain. It is affected by a temperature gradient and resulting thermal stresses, including phase change processes, recrystallization, relaxation, and dependence of material properties on temperature. For steel railway superstructure components, occurrence and change in residual stresses are due to thermal stresses and plastic strain resulting from bending and cold rolling. Thermal stresses are a result of non-uniform phase transitions due to thermal treatment, including surface hardening, used for shaping the steel junction components. The treatment aims to increase hardness of the surface layer of a wing rail or a switch blade.

Residual stresses in hardened steel components are due to a martensitic transformation at lower temperatures, where an overcooled austenite transforms into a martensite—a phase with lower density or other structures depending on requirements and thermal processes (hardening). The transformation of overcooled austenite can be conveniently analyzed based on an austenite decomposition graph, also called isothermal transformation diagrams (or time–temperature–transformation (TTT) diagrams). If the thermal and textural stresses overlap, as is the case with steel hardening, the direction and the size of residual stresses after the temperature is even in the component cross section are determined by the offset in the transformation initiation stage in the surface area and in the core in relation to the moment the thermal stress sign reverses. In other words, the textural stresses tend to increase or reduce the thermal stresses depending on the cross section, cooling rate, and steel hardening capacity [20].

The depth of hardened layer also affects the distribution of residual stresses after hardening. Non-uniform plastic strain or temperature gradient will thus result in residual stresses. The rails and switch blades after rolling and quenching do not often meet the requirements on straightness and require straightening using special roller straighteners. Maintaining the required rail straightness is particularly important at high travel speeds. The process introduces significant longitudinal residual stresses. For rails straightened on the roller straighteners, as a result of variable strain of surfaces in contact and not in contact with the rollers, 150–300

MPa residual stresses over the running surface of a head and at the bottom of a rail foot, and –100 to 200 MPa compressive stresses at a rail web are recorded.

3.2. Experimental studies of residual stresses

Residual stress values can be obtained by experiments and theoretical analysis. The methods of theoretical determination of residual stresses involve solving complex thermal, elastic, and plastic relations. It is a complex solution, due to lack of accurate data on actual loads exerted on an object. The theoretical analysis of residual stresses is bound up with the elastic theory and elastic properties, plastic flow and material hardening, heat transfer, phase transitions, thermal expansion, structure, and thickness of surface layer. The complexity of processes that occur in the material during process treatment means that the results of the theoretical analysis are based on simplified models and cannot be used to evaluate the residual stress state even in components with straight geometry and require use of the experimental method. The residual stresses have been the topic of interest for the researchers and scientist for several decades. Thus, various methods and techniques for measuring the residual stresses were developed. Generally, residual stress measurement methods in steel components can be divided into two categories: destructive and non-destructive methods. Destructive methods do not allow to determine the quality of tested objects without damage, whereas non-destructive methods allow multiple tests on the same object.

Ultrasonic method used by the author to determine the residual stresses is based on the relation between ultrasonic wave velocity and stress. Ultrasonic wave velocity is determined with an accuracy of a fraction of a meter per second to measure the residual stresses with required precision. To measure the absolute values, the effects of temperature and non-uniform distribution of elastic properties and material texture on the wave velocity must be allowed for. A relatively easy and simple method is the ultrasonic measurement with DEBRO-35 instrument. The method uses electro-acoustic effects, i.e., a relation between stress and velocity or time the ultrasonic wave requires to cover a specific distance (at the surface zone). The residual stresses are measured using a special measuring head system that records longitudinal and lateral surface waves (Figure 2).

The meter measurement circuits allow for the effect of rail temperature change to the velocity of wave propagation. The head system features temperature sensor, providing information required for automatic compensation of a velocity of wave propagation at different temperatures.

The advantage of the method is the ability to perform non-destructive testing in field conditions, compact and easy-to-use system, and the ability to display the measurement results. In addition, the preparation of tested section surface does not require time-consuming operations.

3.2.1. The experimental wing rail and switch blade tests

Experimental rail section tests were performed on components subject to rolling, surface hardening and bending into wing rails used in the railway turnouts.

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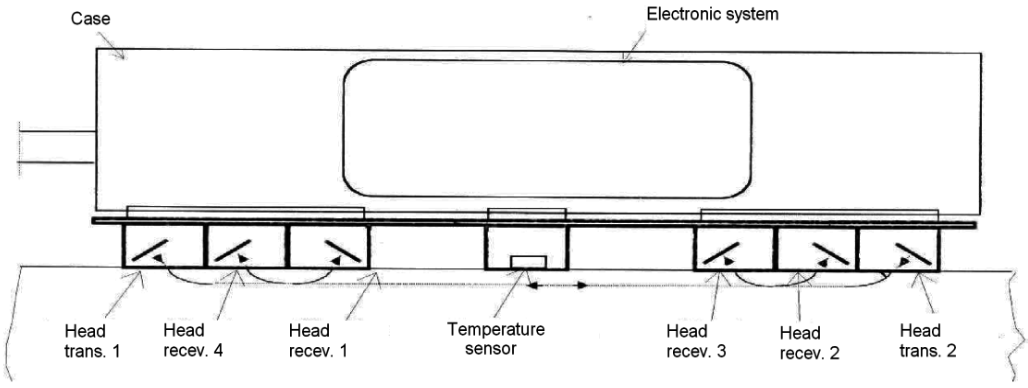

Figure 2. Special measuring head system in ultrasonic instrument DEBRO-35.

3.2.1.1. The transverse bending of the switch blades and wing rails

The specimens were bent in the steelworks manufacturing railway turnouts (former Koltram S.A., Zawadzkie), involved three- and four-point bending. Figures 3–6 show the method of section bending including the point of support and force causing the strain as well as cross sections used.

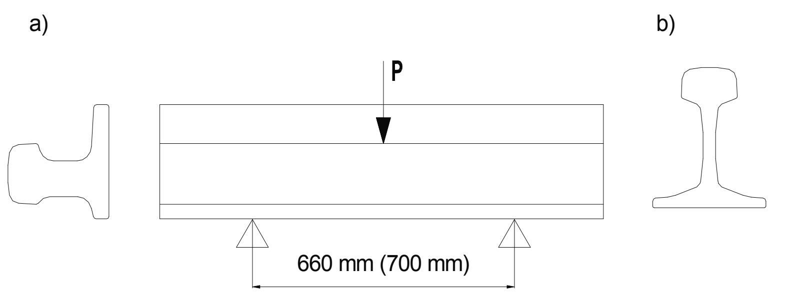

Figure 3. Three-point transverse bending of the switch blade I60 (a) and wing rail (b) sections.

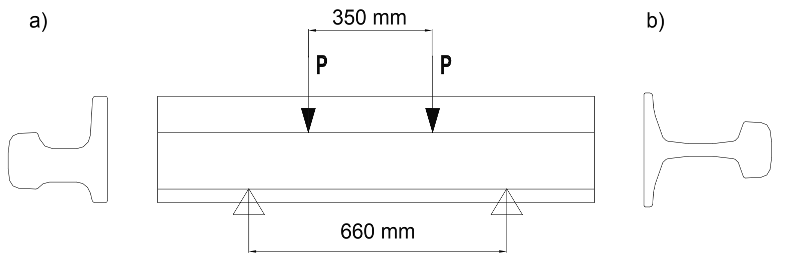

Figure 4. Four-point transverse bending of the switch blade I60 (a) and wing rail (b) sections.

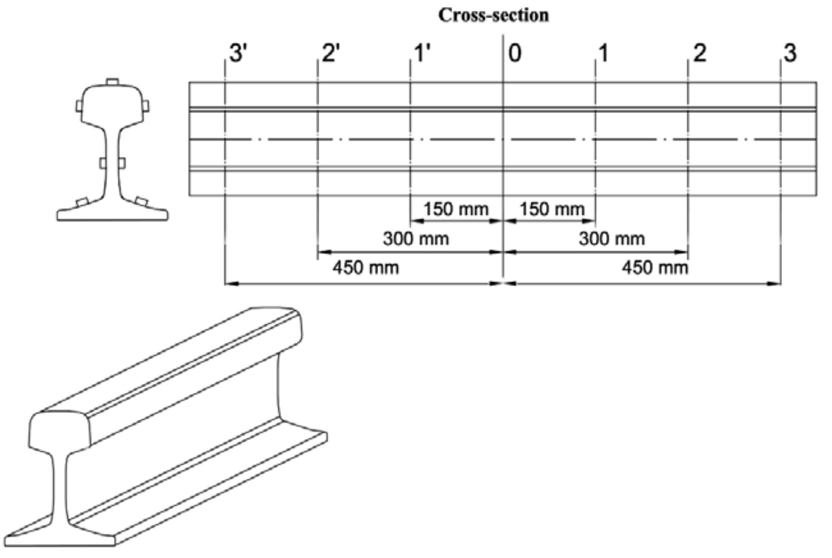

Figure 5. Measurement places at the circumference of rail UIC 60.

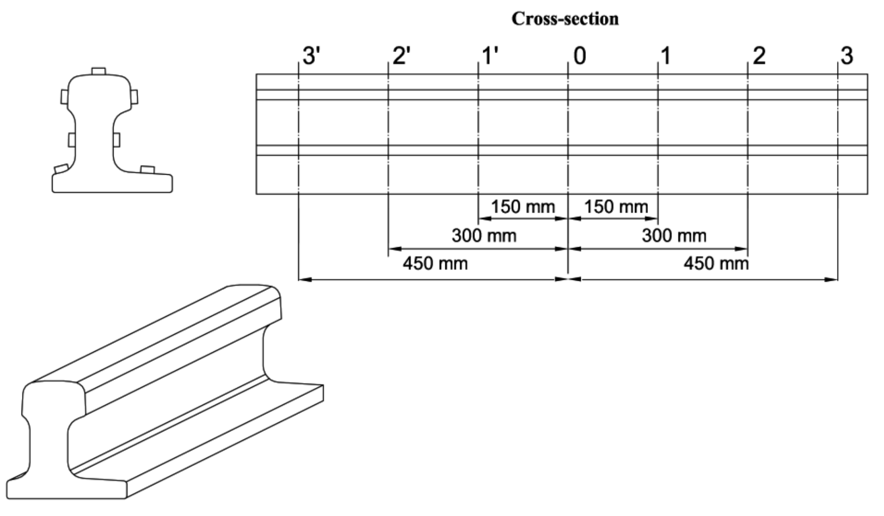

Figure 6. Measurement places at the circumference of rail I60.

3.2.1.2. Results of residual stress measurement—bending process

The diagrams (Figures 7–10) show example of longitudinal stress changes at the circumference of rail and switch blades after bending processes of selected sections. A horizontal axis represents a distance from the centre of a head rolling surface (measured at the rail and switch point surface), and vertical axis represents the longitudinal component of a residual stress.

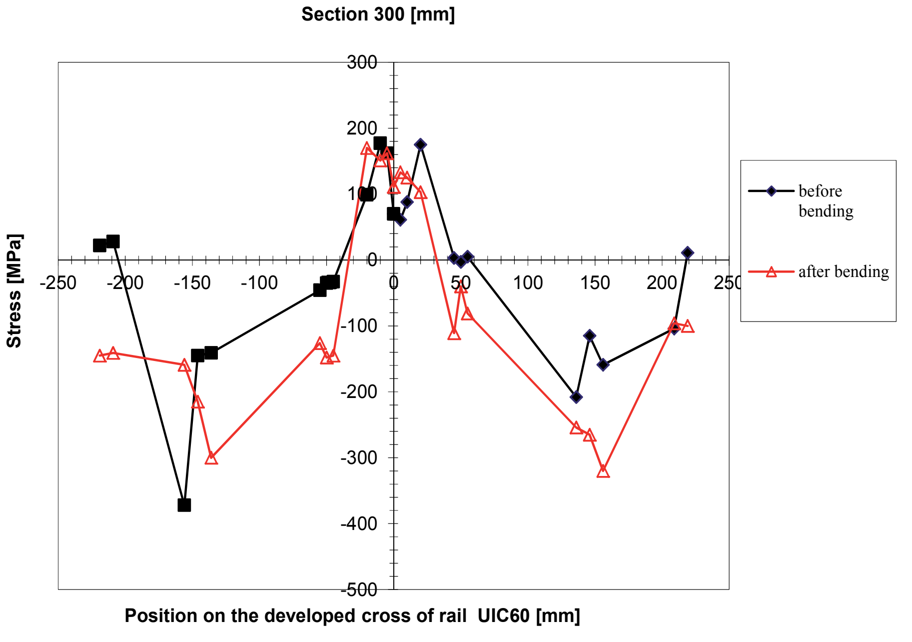

Figure 7. Longitudinal stress changes at the circumference of rail UIC 60 before and after three point bending processes (section 300 mm).

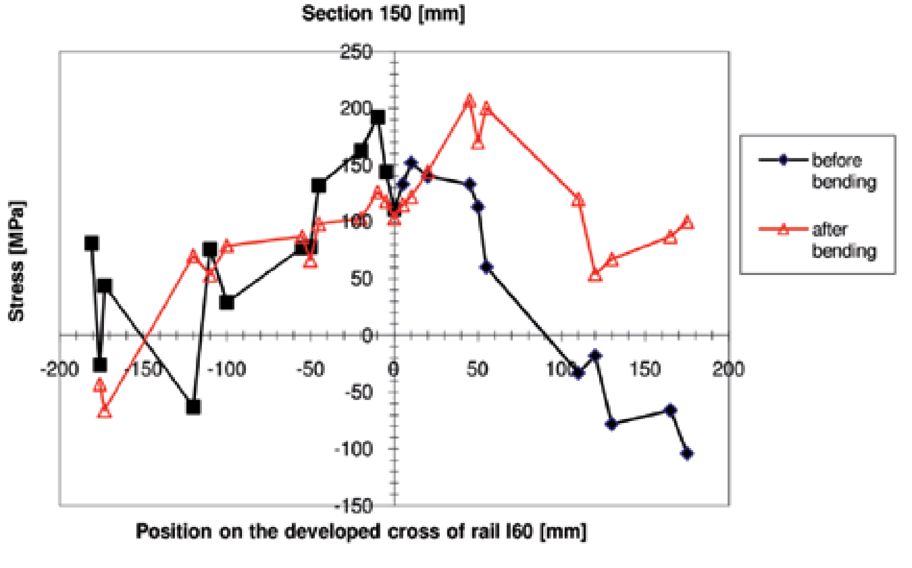

Figure 8. Longitudinal stress changes at the circumference of rail I60 before and after three point bending processes (section 150 mm).

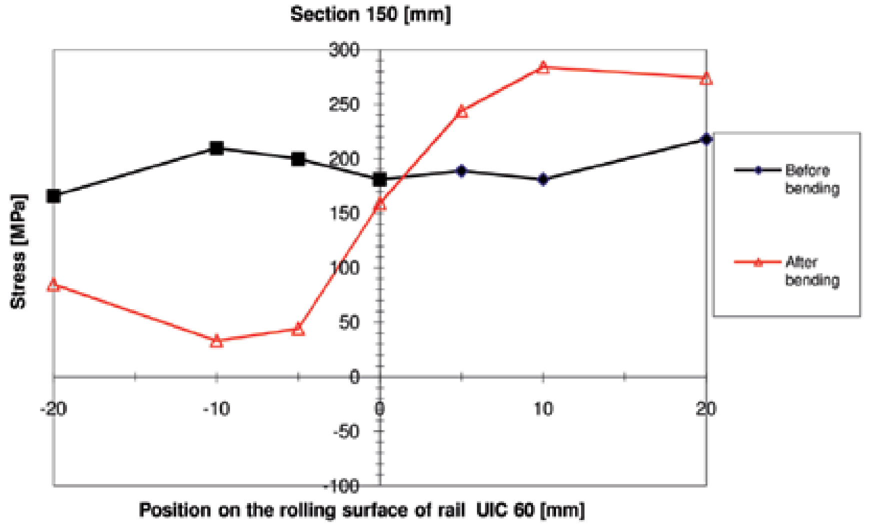

Figure 9. Longitudinal stress changes on the top surface of rail UIC 60 before and after four point bending process (section 150 mm).

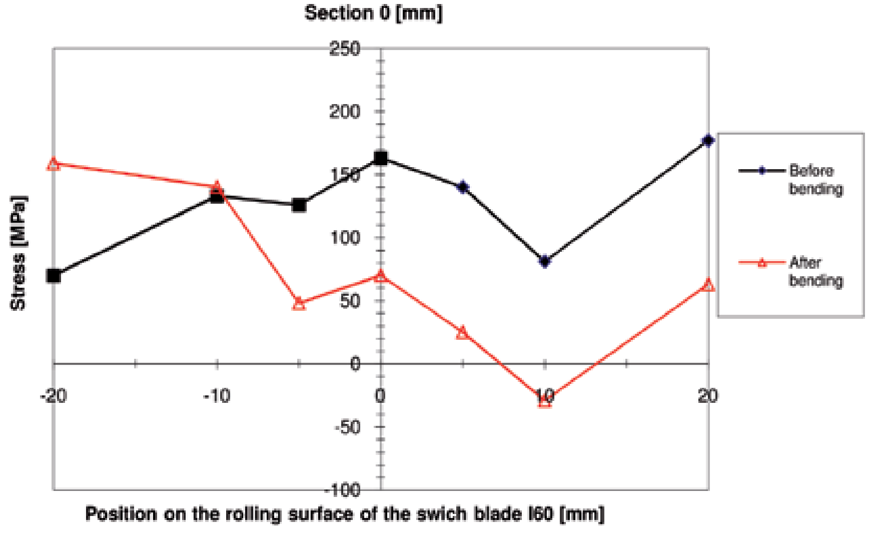

Figure 10. Longitudinal stress changes on the top surface of rail I60 before and after four point bending process (section 0 mm).

The results of measurements for residual stresses obtained with ultrasonic testing show after the bending tests that in case of four-point bending the distribution and size of residual stresses is more favorable and uniform compared to the three-point bending case. Numerous research works and service observations show that from practical point of view, the most dangerous proves to be the maximum tensile stress σ_{max}, which may accelerate the development of cracking process and cause permanent deformation of the steel components.

3.2.2. *Surface hardening switch blades and wing rails*

After the bending process, the switch blades and wing rails are subject to a pearlitizing process in the course of hardening the rolling surfaces. As a result of flame heating of a rolling surface to the depth of up to 20 mm, and subsequent cooling with water mist and compressed air, a fine pearlitic structure with specified hardness is obtained. The heat stream from flame heating is generated by the special nozzles (burners) installed on the surface hardening station. The temperature of heated running surface shall not exceed 673K (400°C). Figures 11 and 12 show hardening zones of steel components.

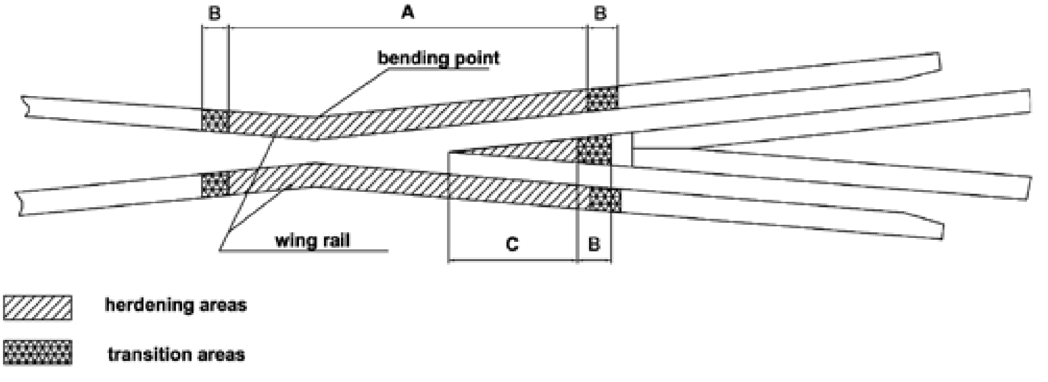

Figure 11. Heat treatment areas of the wing rail UIC 60 and actual frog point.

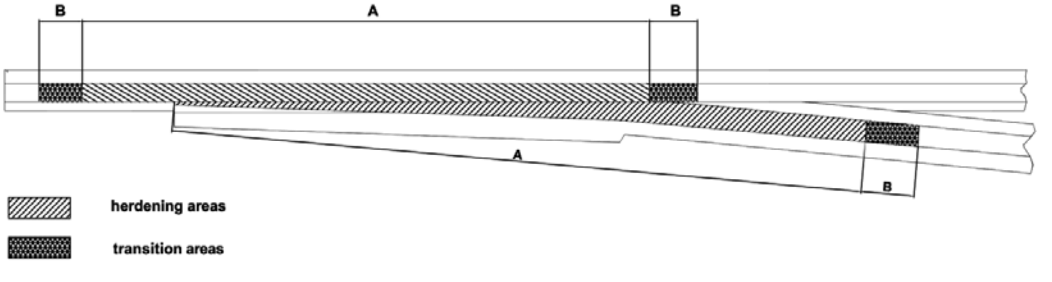

Figure 12. Heat treatment areas of the switch blade I60.

The diagrams presented further on (Figures 13 and 14) show examples of longitudinal stress changes at the circumference of rail and switch blade after hardening and bending processes for the selected sections.

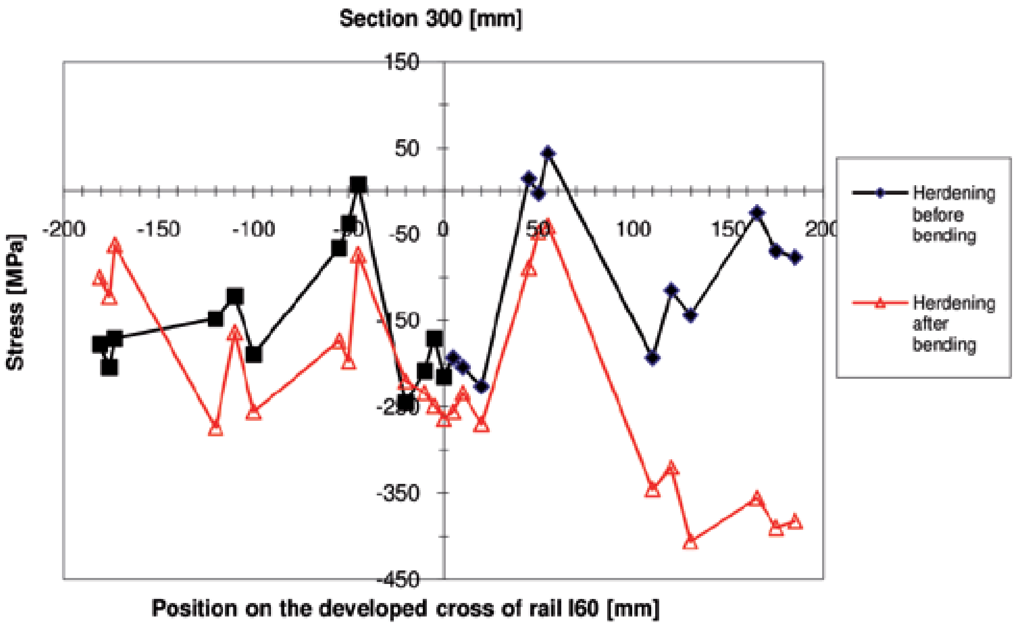

Figure 13. Longitudinal stress changes at the circumference of rail I60 after heat treatment and after bending processes (section 300 mm).

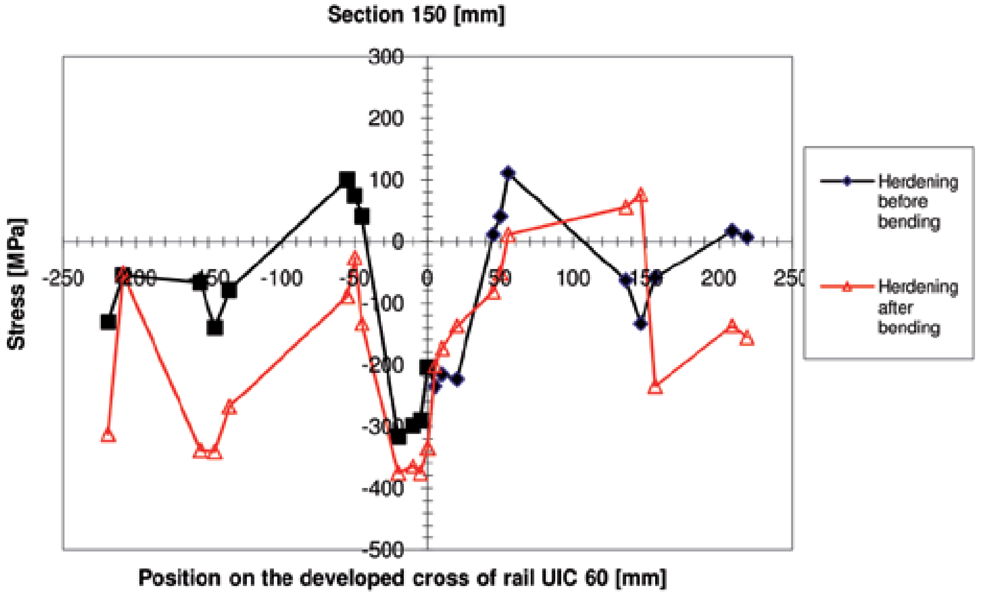

Figure 14. Longitudinal stress changes at the circumference of rail UIC 60 after heat treatment and after bending processes (section 150 mm).

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3.3. FEM simulation studies

The subject of the numerical analysis in this paper is simulation of three- and four-point bending, rolling, and surface hardening processes of the section samples of UIC 60 rail and I60 switch blade. The analysis concerns strains and stresses generated in the course of the above-mentioned technological operations. The main purpose of the numerical calculations is to determine residual stresses in the rail after the relief that happens after bending and/or hardening process. It is also to define the influence of different test parameters on the size and distribution of stresses. Structure models and numerical calculations were made using the ABAQUS—a software with an extensive capabilities of non-linear analysis of physical issues, including mechanics of the deformable solids.

3.3.1. The material of the model

Figure 15 shows experimental curve–stress σ vs. strain ε for a single axis steel tensile test (black line). Young's modulus E = 210.000 MPa and Poisson ratio ν = 0.3 were used for calculations. Point A is defined with a non-proportional elongation proof stress σ_A = 629.7 MPa. Point A in the approximation curve divides the elastic state from the plastic–elastic state with hardening. Point B is selected at the curvilinear hardening section for stress σ_B = 900.0 MPa. Point C is determined by maximum stress achieved during test, i.e., temporary strength R_m = 1069.0 MPa. Besides, stress and strain values for the approximation curves (red line) were determined for each temperatures represented in Figure 15.

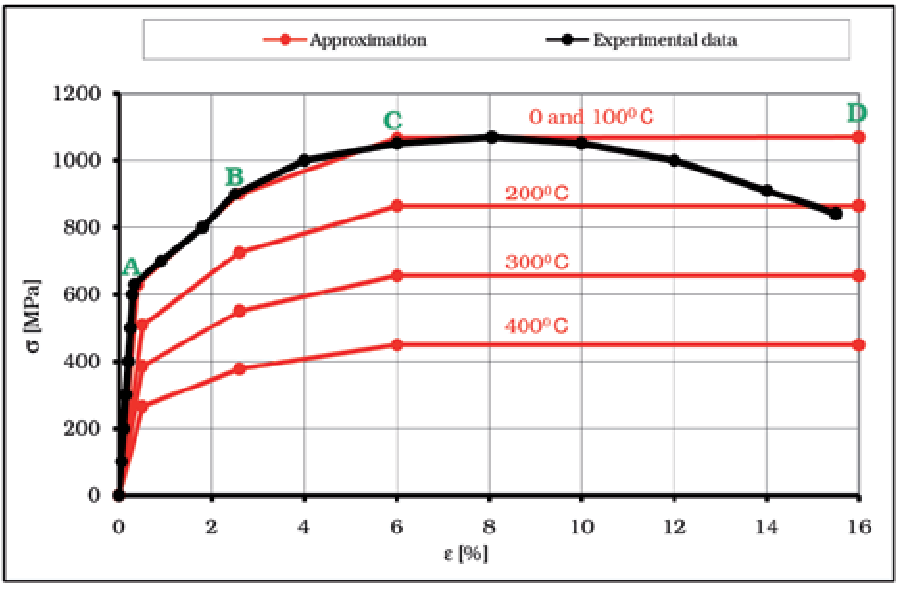
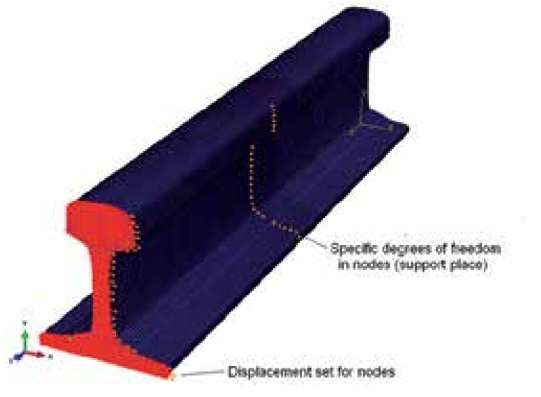


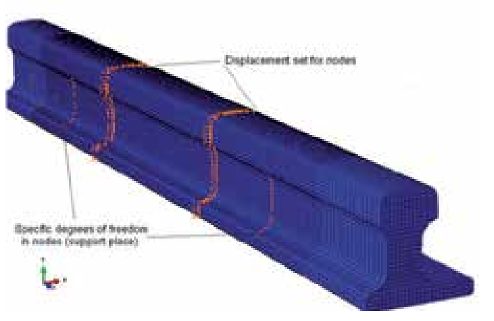
Figure 15. Experimental material curve and its approximation $\sigma - \varepsilon$ depending on the heating temperature.

3.3.2. *Load and boundary conditions*

The way of support and the load application used in the experiment were replaced by ideal boundary conditions in the numerical model. The calculation process was divided into two steps. The first corresponding to the loaded state condition, and the second corresponding to the condition realized state. The way of support was defined by reduction of the specific degrees of freedom in the nodes, which correspond to the experiment are present in the support sections (Figure 16). During simulation of the surface hardening, the rail may show longitudinal displacement as a result of material expansion due to rolling surface heating.



(a)



(b)

Figure 16. Finite element models of UIC 60 (a) and I60 (b) rail with boundary conditions and loading—three and four point transverse bending.

During simulation of the rail section rolling, the roller force on the rail and the roller speed are set. The load was increased gradually (incrementally), and the system of equation was solved to determine the increment in strain, stress, and displacement. The rail was supported by two adjacent rollers at specific centers (Figure 17).

3.3.3. *Results of numerical analysis*

Several simulation calculations covering different variants of section bending, surface hardening, and rolling process were performed. Figures 18–21 show the results of computer simulation for UIC 60 rail and I60 switch blade models. The figures show contours of the of reduced stress σ^{HM} and residual stress σ_{11} after relief.

Numerical calculation results shown in Figures 18–21 provided a number of interesting data in addition to the experimental tests. A location of extreme stresses around the periphery of analyzed objects may be determined based on the results obtained.

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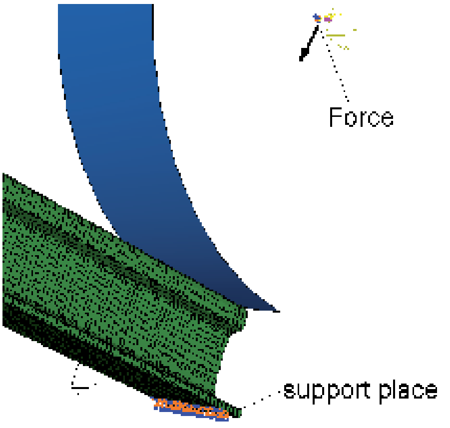


Figure 17. Finite element models of UIC 60 rail with boundary conditions and loading—the rolling process.

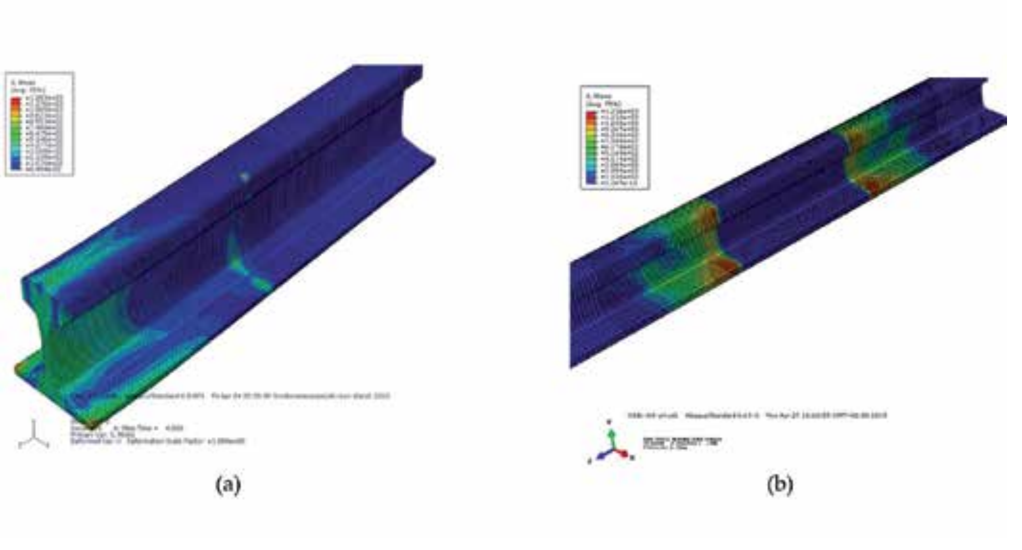


Figure 18. Contours of reduced stress σ^{HM} of the rail UIC 60 (a) and I60 (b) switch blade section after three (a) and four (b) point bending.

3.4. The evaluation of residual stresses

Use of ultrasonic measurement method (DEBRO-35 measuring instrument) and computer simulation allowed to develop a method to diagnose state and distribution of residual stresses in steel components of the railway turnout (wing rails and switch blades) in the production process [15]. The method involves summation of residual stresses measured prior to treatment (bending, hardening) and stresses during simulation. The method allows to assess the level and distribution of residual stresses achieved using different bending or hardening processes. The example results of diagnosing residual stresses are shown in Figures 22 and 23.

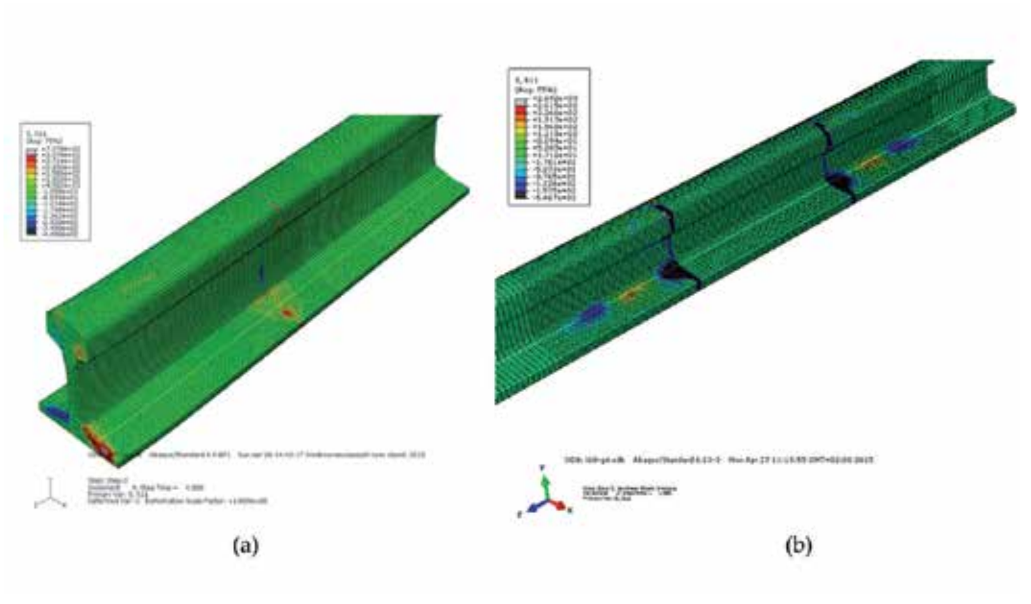


Figure 19. Contours of residual stress σ_{11} of the rail UIC 60 and I60 switch blade section after three (a) and four (b) point bending.

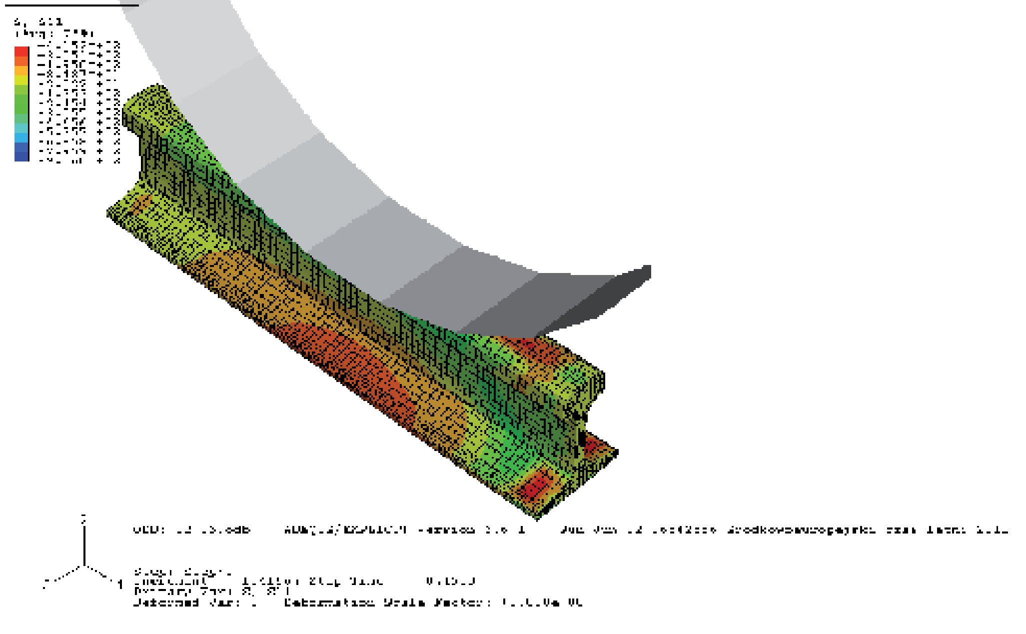


Figure 20. Contours of residual stress σ_{11} of rail UIC 60 after rolling process [14].

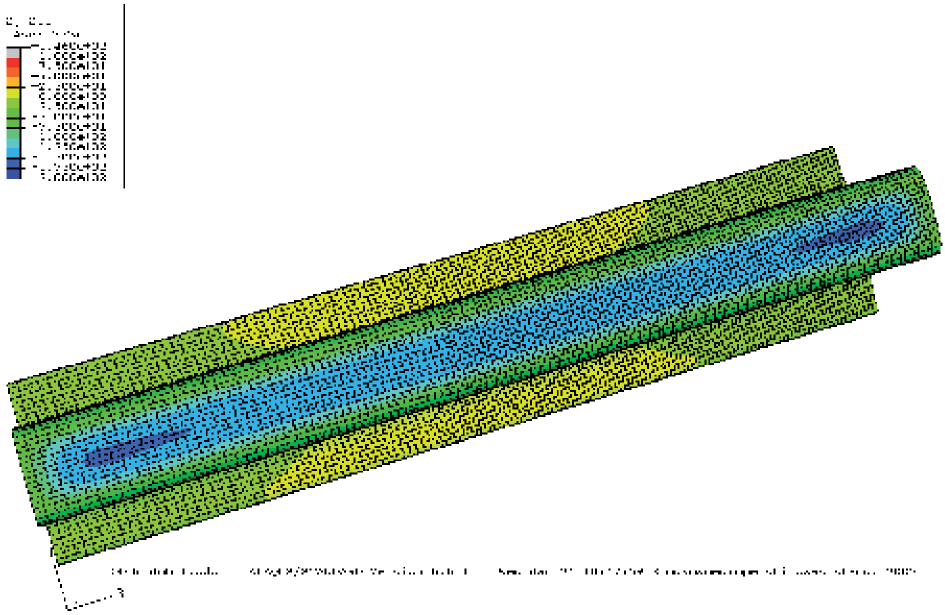


Figure 21. Contours of residual stress σ_{11} on the head of rail UIC 60 after heat treatment.

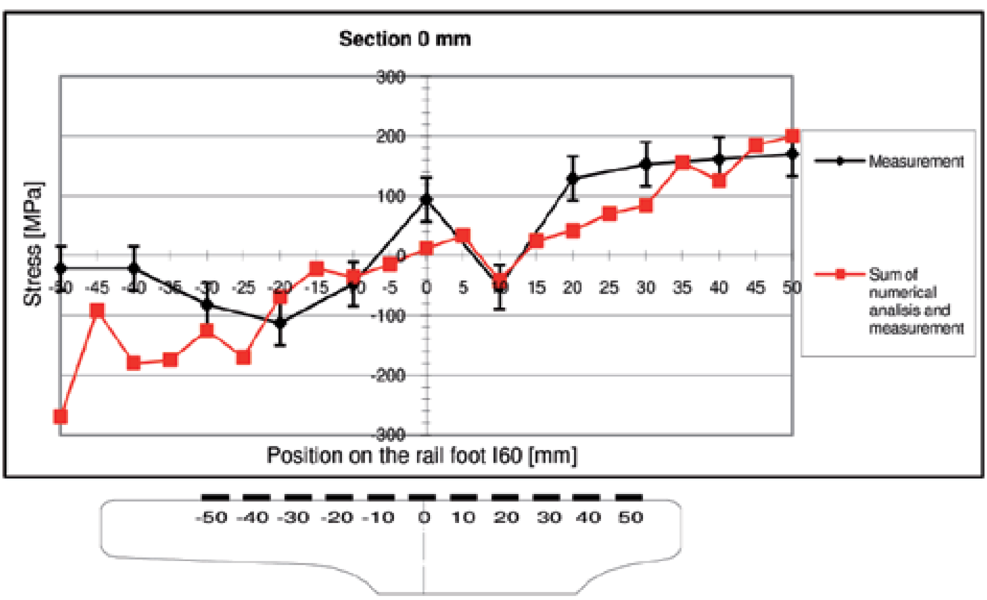


Figure 22. Comparison of measurement results of residual stress after cold bending (rail foot I60) with results summarizing stresses from the numerical analysis and measurements before bending (section 0 mm).

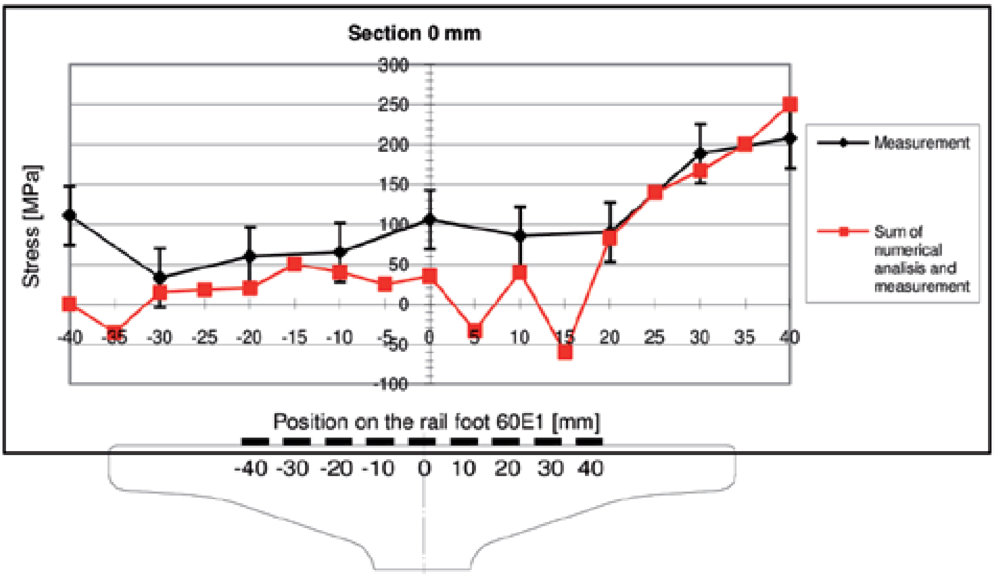


Figure 23. Comparison of measurement results of residual stress after cold bending (rail foot UIC60) with results summarizing stresses from the numerical analysis and measurements before bending (section 0 mm).

4. Operational research of superstructure

4.1. Experimental studies

Using crashed stone composite in the form of a ballast bed reinforced with geogrids and local chemical stabilization of crashed stone is one of the possible answers to the question how to improve the ballast resistance to deformation. The solution has been developed by the Division of Transport Infrastructure of the Warsaw University of Technology Faculty of the Transport (by T. Basiewicz, K. Towpik, A. Gołaszewski) [22]. The proposed crashed stone composite comprises a layer of crashed stone reinforced with a geogrid and stabilized with a polyurethane resin. The track superstructure with a crashed stone composite ensures a complex mechanical and chemical resistance of the ballast to deconsolidation. Mechanical resistance is ensured by reinforcement with at least two geogrids. The first geogrid covers the area of ballast contact with a subgrade. After the first crashed stone layer is laid and compacted, the second geogrid is placed. After the second layer of crashed stone is laid (to obtain a required thickness of ballast under the sleeper, as per standard requirements), it is compacted and supplemented to the standard shape of a stockpile. In the final stage with a dynamic surface stabilization, the structure is chemically stabilized with a special polyurethane resin by injection. Figure 24 shows the layer of ballast reinforced with the geogrid and the resin.

The key purpose of the track geometry measurements for the track structures section with crashed stone composite was to evaluate the deformability of the track vs. the adjacent

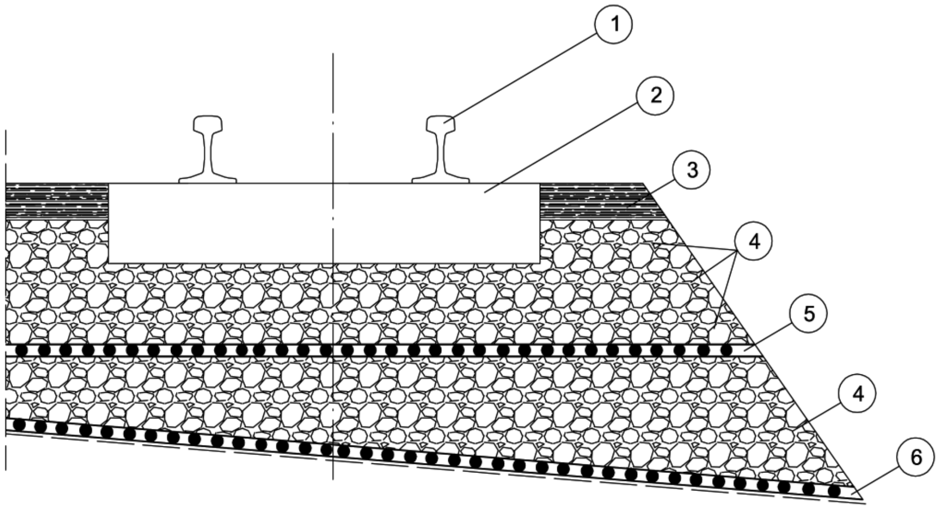


Figure 24. Track structures with crashed stone composite [13]. 1—rail UIC 60, 2—sleeper, 3—crashed stone layer with resin, 4—crashed stone layer, 5—top reinforcement (geogrid, geosynthetic), 6—bottom reinforcement (geogrid, geosynthetic)

comparative track sections. Results of measurements, of the EM 120 measuring motor car, made during 17 trips between 2008 and 2013 were used in the evaluation of track geometry deformability. The traffic load in that period was approximately 18 Tg. Changes in the quality index result and changes in the standard deviation for vertical and horizontal track irregularities provide an indirect description of ballast bed deformation.

The values of the quality index "J" were computed as follows

$$J = \frac{S_z + S_y + S_\mathrm{w} + 0.5S_\mathrm{e}}{3.5} \tag{6}$$

where S_z is the standard deviation for vertical irregularities, S_y is the standard deviation for horizontal irregularities, S_w is the standard deviation for track twist, and S_e is the standard deviation for track gauge.

The studies [22] present complete test results covering the entire test period. Figures 25 and 26 show selected test results for track superstructure with crashed stone.

4.2. Simulation studies

The simulations complement the experimental tests performed at the section of "CMK" (railway central trunk line—an element of the Polish railways network). Figure 27 shows a schematic railway track model used in simulation calculations, allowing for the rigidity and attenuation of each railway superstructure component.

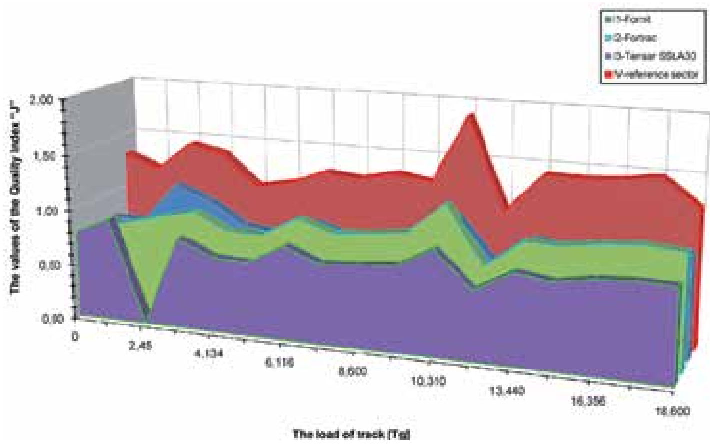


Figure 25. Values of the quality index "J" for different sections of existing subgrade (I1—section No.1 with geogrid; I2—section No.1 with geosynthetic; and I3—section No.2 with geogrid) vs. reference sector IV.

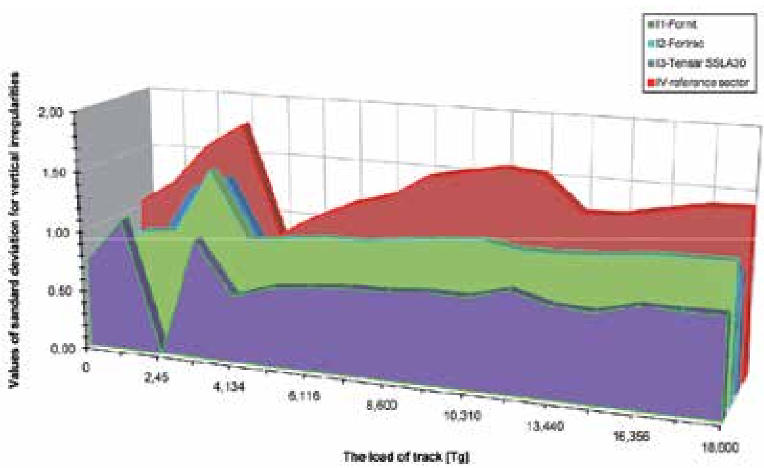


Figure 26. Values of standard deviation for vertical irregularities for different sections of existing subgrade (I1—section No.1 with geogrid; I2—section No.1 with geosynthetic; and I3—section No.2 with geogrid) vs. reference sector IV.

The motion of the system may be expressed by the following differential equations:

$$EI\frac{\partial^4 z_r}{\partial x^4} + m_s\frac{\partial^2 z_r}{\partial t^2} + c_{ps}\frac{\partial z_r}{\partial t} + k_{ps}z_r - k_{ps}z_s - c_{ps}\frac{\partial z_s}{\partial t} = P(t)\delta(x), \tag{7}$$

$$m_s\ddot{z}_s + c_s\frac{\partial z_s}{\partial t} + k_s z_s = k_{ps}(z_r - z_s) + c_{ps}\left(\frac{\partial z_s}{\partial t} - \dot{z}_s\right), \tag{8}$$

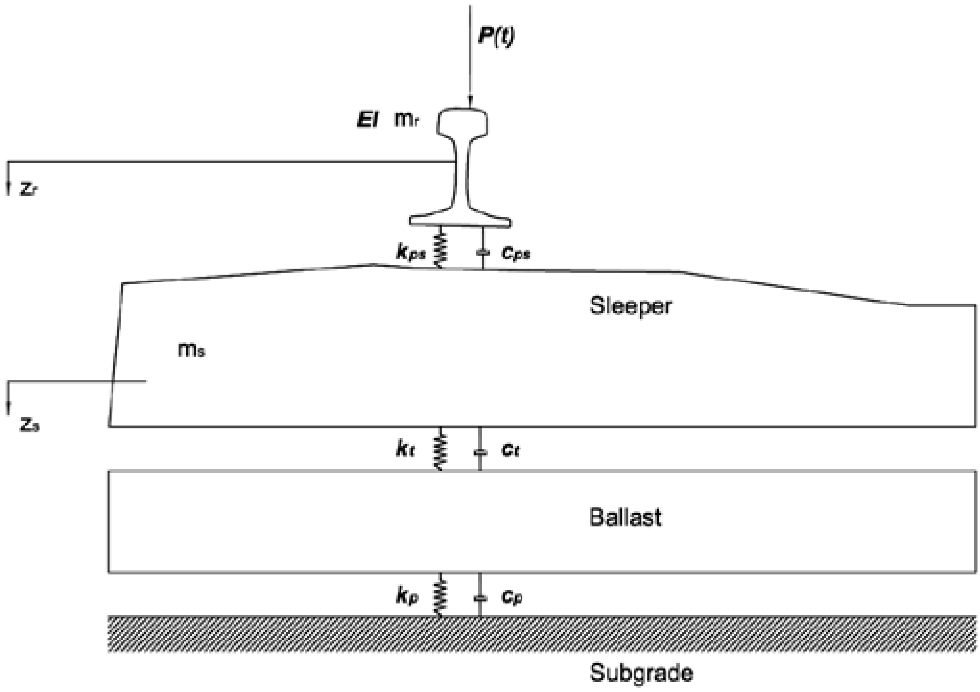


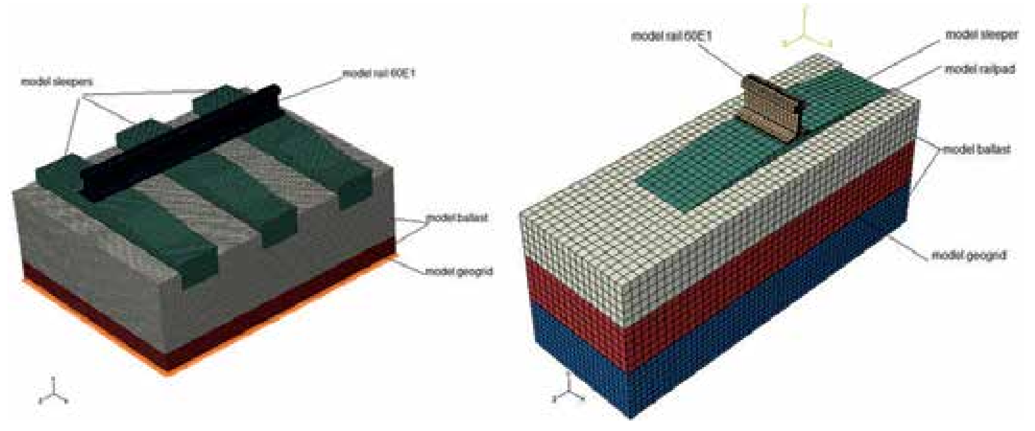
Figure 27. The schematic railway track model used in simulation calculations: $P(t)$—concentrated force; m—mass of elements; EI—bending stiffness of rail; c—damping; k—stiffness.

4.2.1. Model geometry— Finite element grid railway track

Structure models and numerical calculations were made using the ABAQUS—a software. A geometry of a numerical model is defined as a grid of nodes indicating position and size of finite elements. Simplified numerical models of the superstructure were developed, including a single sleeper or three sleepers buried in the ballast.

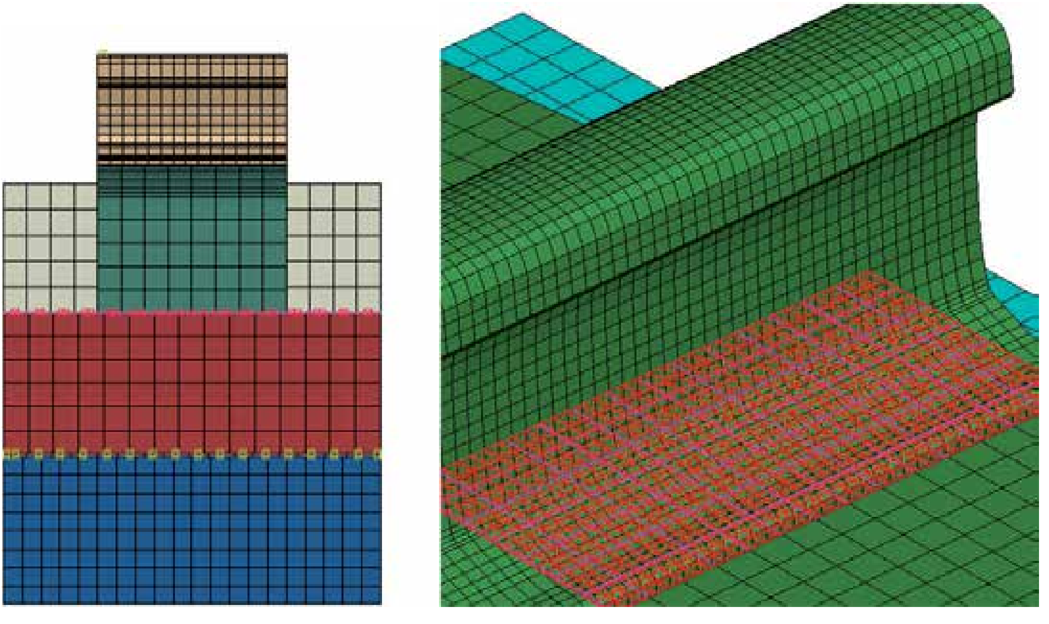
Due to the complex shape of modeled structures, apart from cuboids with six walls, additional three-dimensional components were also included, solids with a triangular base (with five walls). Square components are considered the most relevant for the description of the issues with bending as a prevailing treatment to better describe stress concentration and allow better approximation of curved shapes with lower number of elements. Figure 28 shows FE railway track models.

For simulation purposes, the interfaces between each of structure components were determined since the development of a complete model grid with the same degree of detail is not feasible. The grids for various components may vary in size. The interface is a surface connecting two adjacent grid segments with various grid densities to maintain the model continuity (Figure 29). It enables a proper distribution of load on adjacent grids to maintain the 3D model homogeneity.



(a) (b)

Figure 28. FE railway models of the reinforced surface for (a) three sleepers and (b) one sleeper.



(a) (b)

Figure 29. The interfaces for (a) sleeper/ballast and (b) rail foot/sleeper interface (unilateral constraints) [23].

4.2.2. Material model

In studies on the built simulation models, the parameters of stiffness and damping elements included in the track construction (Table 1) were also taken into consideration.

Notation	Parameter	Value	Unit
E_r	Elastic modulus of rail	210,000	MPa
k_{ps}	Rail pad stiffness	239	MN/m
c_{ps}	Rail pads damping	30	kNs/m
ρ_b	Ballast density	54	kg/m^3
ρ_r	Rail density	7,850	kg/m^3
E_b	Elastic modulus of ballast	150	MPa
νr νb νs	Poisson ratio of rail Poisson ratio of ballast Poisson ratio of sleeper	0.30 0.35 0.30	- - -
c_p	Ballast damping	250	kNs/m
k_p	Ballast stiffness	110	MN/m
ρ_s	Sleeper density	2,400	kg/m^3
E_s	Elastic modulus of sleeper	70,000	MPa
Eg νg	Elastic modulus of geogrid Poisson ratio of geogrid	2,200 0.5	MPa -
ρ_g	Geogrid density	0.00132	kg/m^3

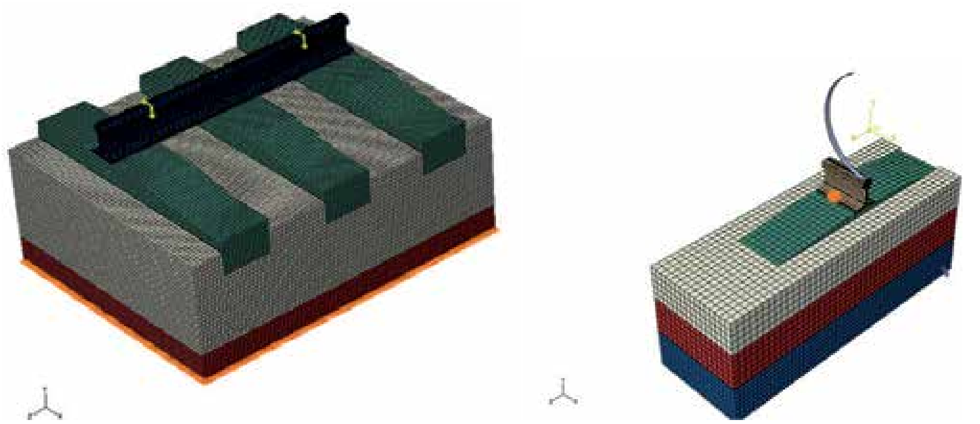
Table 1. 1The parameters of stiffness and damping elements in the track construction model

4.2.3. Model load and support conditions

Means of support used in the course of testing were substituted with ideal boundary conditions in the numerical model. A static and dynamic cylinder thrust of the cylinder on the rail and the speed of cylinder rotation simulating the vehicle speed were set. The load was increased gradually (incrementally), and the system of equation was solved to determine the increment in strain, stress, and displacement. Support conditions are defined by a specific loss of degree of freedom, preventing from displacement in specific directions (Figure 30).

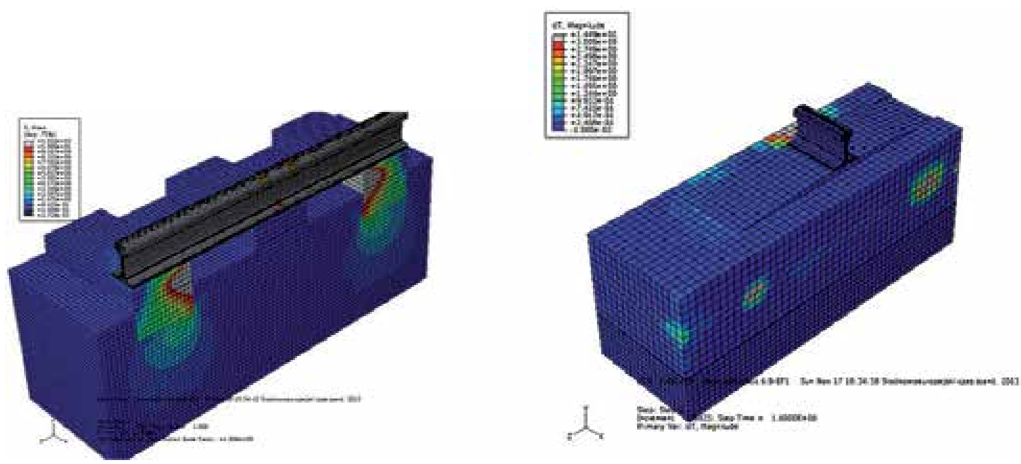
4.2.4. Results of simulation calculation

The selected results of numerical calculations, obtained using 3D models of a reinforced railway track in different arrangements, are shown in diagrams as Huber–Misess reduced stress contours and strain maps. The Huber–Misess hypothesis of the largest shear stress and the shear strain energy hypothesis are used in the calculation of structures and machine parts with elastic–plastic materials. Figures 31 and 32 show numerical calculation results.



(a) (b)

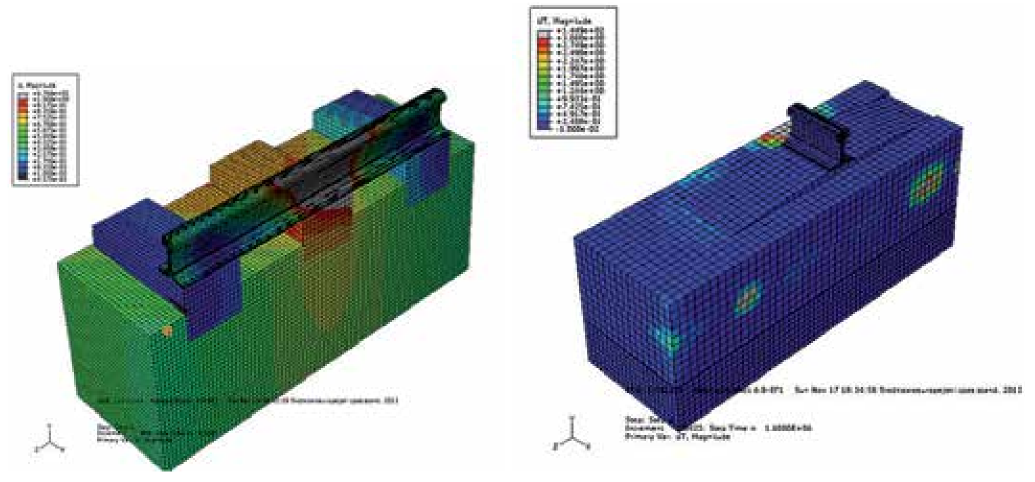
Figure 30. (a) Finite element model of rail track with boundary conditions and loading for three sleepers and (b) one sleeper.



(a) (b)

Figure 31. Contours of reduced stress σ^{HM} at the end of calculation for (a) three sleepers and (b) one sleeper.

Within the course of simulation, the extreme stresses appeared at the wheel/rail interface. An increase in stress and strain is observed with the increase in a number of load cycles. A location of extreme stress values around the periphery and inside the analyzed structure may be determined based on the simulation results. The simulation calculations will be used to determine the strength properties of suggested track substructure reinforcement at various static and dynamic loads. The advantages of the simulation include a reduced cost compared to service tests and mapping of the load in these tests, which would have taken years in operating conditions



(a) (b)

Figure 32. Contours of strain maps for (a) three sleepers and (b) one sleeper.

5. Duration of guaranteed functionality

The duration of guaranteed functionality is a graphic representation of a fatigue performance of any railway track component as a function of operating load. At the initial operational stage, a slope of a strain accumulation curve for railway track structure is close to 90° and results from the railway track stabilization (subsidence). The next stage includes operation under load until the slope of a strain accumulation curve aims to reach higher values. Based on the simulation results obtained by the author of this chapter, as well as test results [22], the author have attempted to plot the curves describing the service life of selected railway track components. Figure 33 shows test results and simulation results contributing to the plastic strain relation as a function of operating load.

The graph shows a comparison of plastic strain vs. load at the testing track section, with or without railway track reinforcement using a geogrid and a resin. A curve plotted using simulation calculations is also included, although due to a long calculation time, the simulation curve is limited to 18 Tg load. The determination of a strain accumulation curve slope requires further tests and analyses to increase the operating load and continue observations.

6. Development and testing of superstructure

The track superstructure as a basic element of the railway system is crucial to the operation and safe management of the railway traffic. Changes in operating conditions of the railway, i.e., increased operational speeds of passenger trains up to 350 km/h or increased operational speeds of freight trains as well as increased permissible load up to 250 kN, result in higher

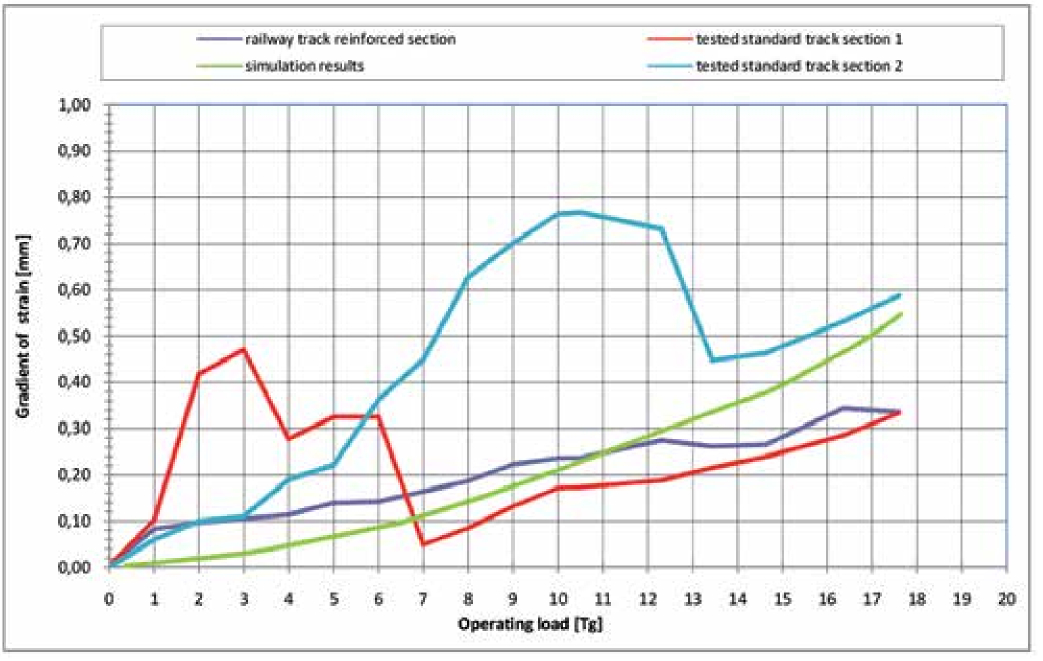


Figure 33. Theoretical model of duration of guaranteed functionality.

requirements for the track superstructures. The changes result in higher forces and vibration levels exerted on the superstructure. In addition, the economic aspects will force the designers and infrastructure operators to optimize the maintenance costs. A need to reduce the costs is one of the causes of using non-standard superstructures for high-speed rail networks. High operational speeds result in high ballast wear due to increased friction between the crashed stones. Increased wear requires more frequent ballast make up or replacement. Both standard requirements and technical specifications for interoperability (TSIs) guidelines for environmental protection, e.g., level of noise and vibrations are also key factors in improving track superstructure.

A question can be asked, if at the passenger train speeds over 350 km/h, is it reasonable to use standard ballast superstructure or use ballast-free solutions? More and more often, new solutions utilizing different materials used in the road engineering are also implemented in the railway solutions, including geomesh, geotextile, and various polyurethane resins, which may increase strength and durability of superstructures. It is also advisable to continue tests on fatigue effects at the rail/wheel interface and interactions between those surfaces. Incorrect mating between the railway vehicle and the rail may result in defects and damage to the running surface. Incorrect mating between the rail and the wheel may result from wheel polygonization and use of high-power trains, where incorrect wheel sidle protection (WSP) system is to prevent incorrect braking and starting. In high-speed trains, apart from basic braking system, also cleaning brake inserts are used to remove fouling from the running surfaces of wheels and railway track rails on which the trains travel.

http://dx.doi.org/10.5772/61517

7. Conclusions

The data presented in this section are a result of experimental and simulation tests performed by the author during 10 years of the research and scientific career. The discussed issues are a subject of interest for both manufacturers and experts responsible for the condition of a track superstructure. The stresses may affect the internal energy state of the material, phase changes, and corrosion of the material, reduce fatigue strength, and cause damage to the rails. The stresses are also one of the causes of accelerated development of standard railhead defects. The presented method of residual stresses evaluation using ultrasonic testing and numerical analysis in the course of the production process provides control over size and distribution of internal stresses due to bending and hardening processes. Another area of interest was related with the track superstructure tests, in particular involved seeking design solutions to reduce the maintenance costs by extending the time between repairs of the track superstructure components. The optimization of the maintenance costs by using advanced solutions in the track superstructure design may be an interesting method to extend its durability. The presented test results are the inspiration to continue the research in this area and seek new solutions, e.g., optimizing maintenance costs of the railway infrastructure, and determining structure durability using simulations.

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Chapter 5

Development of Track Condition Monitoring System Using On-board Sensing Device

Hitoshi Tsunashima, Hirotaka Mori, Masayuki Ogino and Akira Asano

Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/61077

Abstract

Monitoring the conditions of railway tracks is essential for ensuring the railway safety. In-service vehicles equipped with sensors and GPS systems can act as probes to detect and analyse real-time vehicle vibration. Recently, a compact on-board sensing device has been developed. This chapter describes the track condition monitoring system that uses a compact on-board sensing device and diagnosis software. The diagnosis software provides the function of detecting track faults using the root mean square (RMS) of the car-body acceleration. It also allows analysis in the time-frequency domain using wavelet transform. A monitoring experiment in a local railway line showed that the system is effective for practical application.

Keywords: Safety, Track, Condition monitoring, Fault detection, Vibration, Wavelet, Multiresolution analysis

1. Introduction

Preventive maintenance, in which responsible persons recognise unsafe or risky conditions and instigate repairs before accidents occur, has become an important issue for railways [1,2]. To facilitate preventive maintenance, it is desirable to monitor track conditions either continuously or at high frequency levels. Currently, the methods utilised for track monitoring include observations by trackmen, as well as the use of specialised track inspection and rail flaw detection cars. However, while these methods allow highly accurate track monitoring, the operational frequency at which they can be deployed to monitor tracks is extremely limited due to considerations such as cost and sustainability controls. Additionally, local railways suffer not only from significant age-related facility deterioration but also from difficulties in securing funding and maintaining technological advancements, which means that many railway operators are unable to perform adequate monitoring.

In-service vehicles equipped with simple sensors and GPS may serve as probes to detect and analyse real-time vehicle vibration and signalling systems while running. Probe vehicles [3,4] may dramatically change the current style of rail maintenance and thus contribute to establishing safe transport systems.

The probe vehicles can change the current maintenance style to focus on locations regarded as essential maintenance areas, utilising data acquired by real-time monitoring of actual vibration together with positional information obtained by GPS. Monitoring based on information obtained by in-service vehicles may enable the detection of maintenance problem at an early stage [4], thus contributing to the revitalisation of local railways by making maintenance tasks more efficient.

In response to these challenges, the use of probe vehicles, which consist of in-service vehicles to which simple sensors have been added, can be considered as a plausible technique for monitoring track conditions during the course of commercial operations. Previously, portable on-board devices have been developed to allow diagnostic track monitoring [5-8]. A number of long-term experimental studies conducted in cooperation with railway operators have demonstrated the feasibility of pinpointing the locations of track faults and the reproducibility of measured data.

In this chapter, we describe a compact on-board sensing device that represents an improvement on portable probe devices [8,9] along with a track condition monitoring system that utilises track condition monitoring software[10]. We then present an example of the diagnostic results obtained using this monitoring software. The root mean square (RMS) value of the vibrational acceleration was used as an assessment index in diagnosing rail condition. In addition to the RMS value of the vibrational acceleration, wavelet transforms are used in order to develop a system capable of more accurate diagnoses.

2. Track condition monitoring system

2.1. System overview

Several kinds of track faults can be detected by measuring the acceleration of bogies [11-13]. However, if track faults can be detected in-cabin, condition monitoring of track irregularities will be much easier. As the distinctive signal of track faults is hidden in natural frequency of car-body vibration, signal processing is necessary for the acceleration measured in-cabin to detect track faults.

Figure 1 shows a schematic overview of the track condition monitoring system. This system is divided into a vibration measurement unit and an analysis unit. The vibration measurement unit utilises a compact on-board sensing device to measure the vehicle vibration from within the car itself during ordinary commercial operation. The analysis unit uses track condition monitoring software to extract the requisite information from the measured data and then computes assessment values to diagnose the track condition. The compact on-board sensing device is described in Section 2.2, while the monitoring software is described in Section 2.3.

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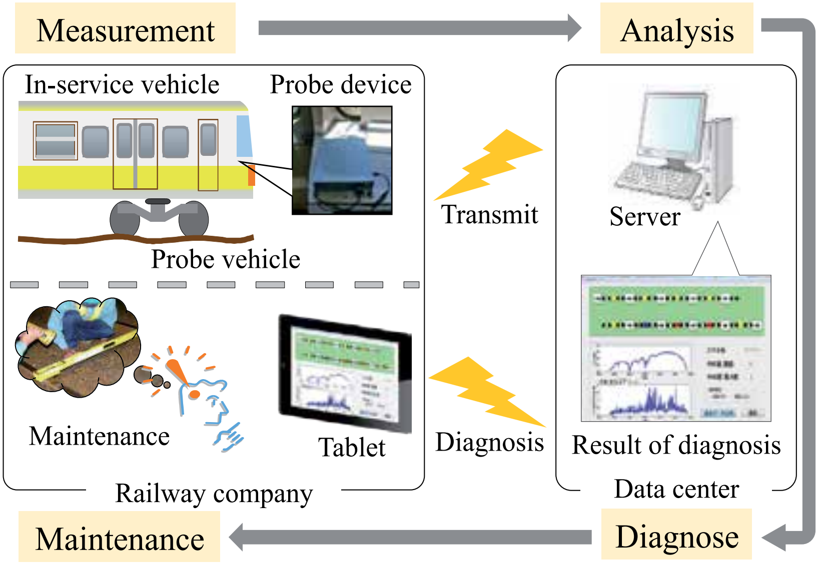

Figure 1. Track condition monitoring system [10]

The measured data obtained from the measurement unit are transmitted to the analysis unit either by a cellular telephone channel or by writing to external media. The diagnostic results produced by the track monitoring software are used to provide feedback to railway operators through online channels via smartphones or tablet computers. Railway operators can use this information to establish the track maintenance priorities, thus facilitating the maintenance planning and work.

In addition, the real-time measurement of railcar vibrations during commercial operation allows for rapid response, such as emergency track inspection and maintenance, in situations when railcar vibration observations detect irregularly large deviations from standard control values. Thus, the use of this monitoring system to perform continuous monitoring of railcar vibrations allows early detection of deterioration or other track irregularities, thus enabling railway operators to conduct effective maintenance work [9].

2.2. Compact on-board sensing device

Figure 2 shows the compact on-board sensing device used in the track condition monitoring system. This device comprises three-axis acceleration sensors, a rate gyroscope, a Global Positioning System (GPS) receiver that is used to determine the train position and travel speed and sensor interfaces that input sensor signals to a computer.

This device is battery-powered and capable of up to 6 h of sustained operation. Thus, the device need only be placed inside a cabin to enable vehicle vibration measurements and does not require human supervision. If the vehicle is equipped with an on-board power supply, the

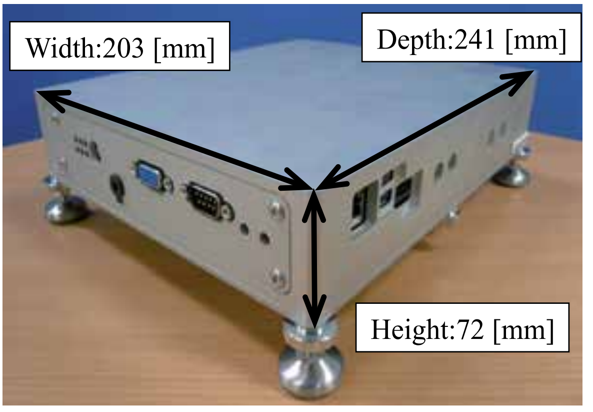

Figure 2. Compact on-board sensing device [10]

device is capable of continuous measurement. Furthermore, the device is equipped with function for automatically transmitting measured data to a server via cellular phone channels and writing data to a microSD card or other recording media. By further equipping the device with a noise meter, it is also possible to diagnose corrugation conditions from cabin noises.

2.3. Monitoring software

Using the compact on-board sensing device to diagnose track conditions required the development of an interface on the software side that is capable of establishing communication with the on-board devices and that offers features such as efficient handling of the large volumes of measured data that accumulate from the devices. It was also necessary to create visualisations to display the monitoring results and reduce the time interval required between measurement and diagnosis. Accordingly, we chose to implement a graphical user interface (GUI) for signal-processing operations on measured data and result visualisation in MATLAB (MathWorks). The following section discusses these operations in more detail.

3. Track monitoring software

3.1. Assessment indexes

Track irregularities not only cause vehicle vibrations that degrade rider comfort, they also increase the risk of derailments. For this reason, they are among the most important items to be monitored. Vehicle vibrations are strongly correlated with track irregularities, so the magnitude of vehicle vibrations is an effective means of assessing general track condition trends [2]. For this reason, sections of track over which high rates of vehicle vibrational acceleration are detected may be understood as indicative of degraded track conditions.

This monitoring software takes the amplitude of the vibrational acceleration as an index of track faults. The RMS value of this amplitude is then extracted and used to assess track conditions. However, because this assessment value alone does not convey frequency information, we augment it by performing time-frequency analysis using continuous and discrete wavelet transforms to obtain more detailed diagnostic information.

3.2. RMS values

We need to obtain localised RMS values over short time intervals to obtain the relationship between track condition and position. The RMS value may be obtained from measured values over a short time segment (the number of the data: N) at the time t according to

$$x_{rms}(t) = \sqrt{\frac{1}{N}\sum_{\tau=t}^{t+N-1} x(\tau)^2}. \quad (1)$$

Track irregularities include longitudinal level irregularities, alignment irregularities and cross level irregularities. To assess the longitudinal level irregularities, we determine the RMS values of the vertical acceleration measured by the compact-size on-board sensing device. Here we compute RMS values using $N = 26$ and a sampling time of 0.012 s.

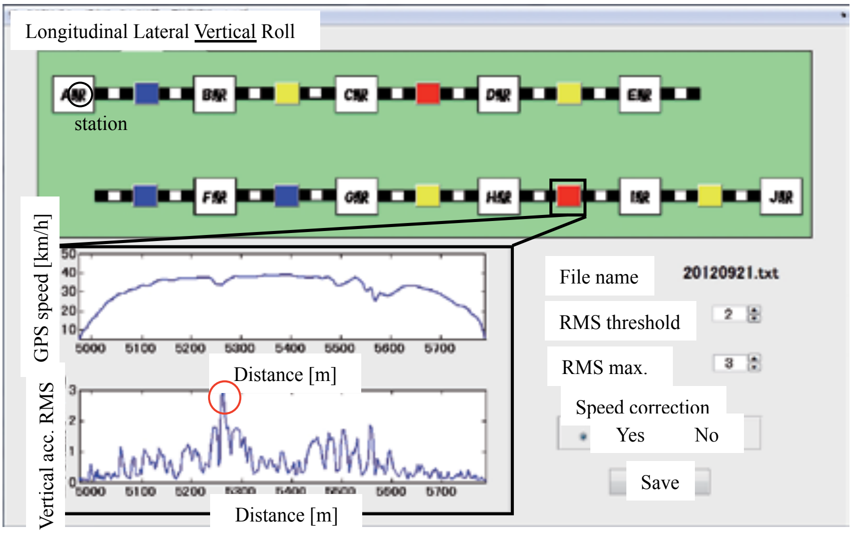

Figure 3. The main window of the track monitoring software [10]

Figure 3 shows the main window of the track monitoring software. The display here is an example of the analysis of actual measured data from a regional railway, as discussed in Section 5 below. The main window indicates an assessment of track condition based on the RMS value of the vibrational acceleration computed using Eq. (1). The track diagrams in the upper portion of Figure 3 indicate colour-coded assessments of track conditions for each station-to-station segment. The different colours (red, yellow and green) indicate the RMS value of the vibrational acceleration referenced to the threshold value determined for the system.

The lower part of Figure 3 shows the RMS value of the actual measured value and the travel speed for a selected station-to-station segment. By inspecting regions with large RMS values, it is possible to clarify the position at which track faults arise.

The upper portion of Figure 4 compares travel data for multiple journeys on specific station-to-station segments. Points at which the preset threshold value (2.0 m/s^2) was exceeded are plotted. The point at 5260 m was plotted a large number of times, suggesting the possibility of a track fault at that location. The lower portion of Figure 4 displays the RMS values (maximum values) of the points circled by the dashed-line curves in the upper portion for each of several dates. The decrease in the RMS value reflects the effect of repair work carried out between September 2012 and February 2013. This shows that the system enables specific points to be identified as segments requiring inspection, thereby facilitating long-term monitoring of track maintenance.

Consequently, whereas assessments of travel data from a single journey (Figure 3) fail to yield accurate assessments in some cases, assessments of travel data from multiple journeys (Figure 4) can allow accurate diagnoses based on the frequency with which track faults arise.

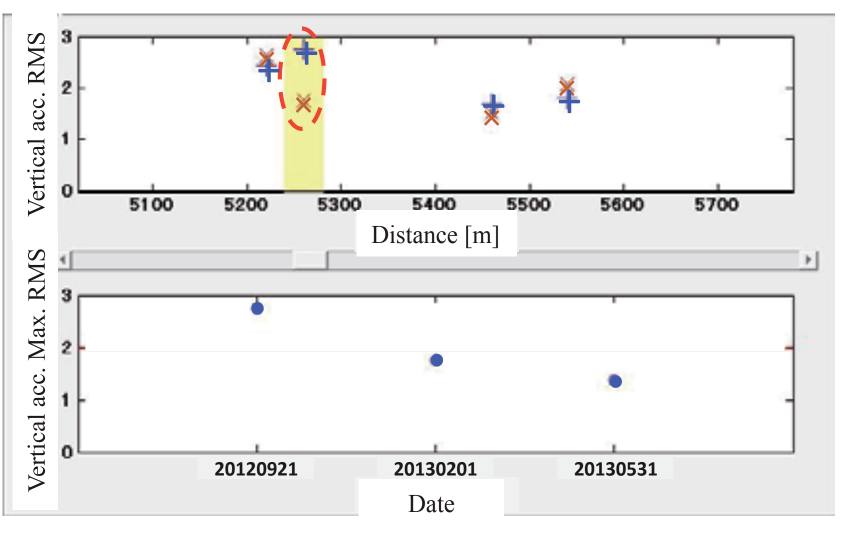

Figure 4. Assessments of travel data from multiple journeys [10]

3.3. Assessment using a continuous wavelet transform

In the previous subsection, we discussed the use of RMS values for simple monitoring of track conditions. However, assessments based on RMS values do not furnish frequency information and are thus poorly suited for characterising many varieties of track faults. To remedy this deficiency, in this subsection, we discuss an analysis based on the continuous wavelet transform, which is a method of time-frequency analysis, as a technique for yielding more detailed diagnostics.

The continuous wavelet transform proceeds by multiplying a target waveform $x(t)$ by a mother wavelet $\psi(t)$. This is a transformation technique that has the effect of emphasising certain portions of the waveform and suppressing others. The technique, which is well suited to the analysis of unsteady signals exhibiting sudden variation, is defined by

$$(W_\psi x)(a,b) = \int_{-\infty}^{\infty} \frac{1}{\sqrt{a}} \bar{\psi}\left(\frac{t-b}{a}\right) x(t)dt. \tag{2}$$

The parameters a and b are known, respectively, as the dilatation and location parameters; they have the effect of translating in time the mother wavelet $\psi(t)$ by a time shift b and $1/a$ on frequency. $\bar{\psi}(t)$ indicates the complex conjugate of $\psi(t)$.

Figure 5 shows a real-world example of the continuous wavelet transform feature implemented by the monitoring software. Users may select a station-to-station segment to display target vibrational acceleration waveforms, and their wavelet transforms, for that segment. The signal plane of the continuous wavelet transform is expressed by contour lines; colours closer to white correspond to larger amplitudes and contain large numbers of corresponding frequency components. The vertical axis of the signal plane displays the pseudo-frequency as obtained by conversion of the scale value.

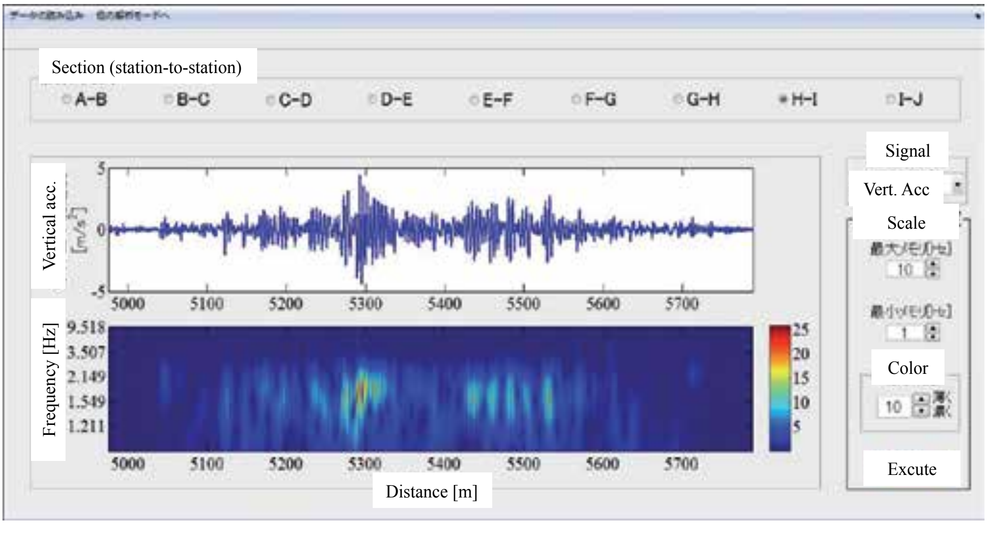

Figure 5. Real-world example of the continuous wavelet transform [10]

3.4. Discrete wavelet transform

Visualising analytical results based on continuous wavelet transform contour line maps is a convenient method of displaying for learning the properties of signals. However, for signal processing carried out by arithmetic operations, displaying information results by superposing multiple pieces of information is not always efficient. For this reason, we discretise the parameters a and b in Eq. (2) to give the following discrete wavelet transform:

$$D_{m,n} = \int_{-\infty}^{\infty} \psi_{m,n}(t)x(t)dt, \tag{3}$$

where

$$\psi_{m,n}(t) = 2^{-m/2}\psi(2^{-m}t - n). \tag{4}$$

Integer m and n are the scaling and the dilation parameters, respectively.

We now use this discrete wavelet transform to perform multiresolution analysis. In multiresolution analysis, a target signal $x(t)$ is decomposed into approximation coefficients (representing its low-frequency components) and multiple detail coefficients (representing its high-frequency components). Using the discrete wavelet transform with the decomposition level m_0, the signal $x(t)$ may be expressed as

$$x(t) = \sum_{n=-\infty}^{\infty} A_{m_0,n}\phi_{m_0,n}(t) + \sum_{m=-\infty}^{m_0}\sum_{n=-\infty}^{\infty} D_{m,n}\phi_{m,n}(t), \tag{5}$$

where $\phi_{m,n}(t)$ are scaling functions, defined by

$$\phi_{m,n} = 2^{-m/2}\phi(2^{-m}t - n). \tag{6}$$

The coefficients of the approximation component may be computed according to

$$A_{m,n} = \int_{-\infty}^{\infty} \phi_{m,n}(t)x(t)dt. \tag{7}$$

The detail coefficients of the signal at level m are given by

$$d_m = \sum_{n=-\infty}^{\infty} D_{m,n}\psi_{m,n}(t). \tag{8}$$

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Thus, the original signal $x(t)$ may be expressed in the form

$$x(t) = a_{m_0}(t) + \sum_{m=-\infty}^{m_0} d_m(t). \tag{9}$$

Figure 6 shows the results of a multiresolution analysis via discrete wavelet transform carried out by the monitoring software. Using this feature, the car-body vibrational acceleration of each station-to-station segment may be decomposed at any desired level, and the signal may be reconstructed from the required components. Thus, by inspecting particular components, it should be possible to detect track faults corresponding to those components. The decomposition level m_0 must be chosen appropriately based on the sampling frequency and the frequency band from which one wishes to extract features.

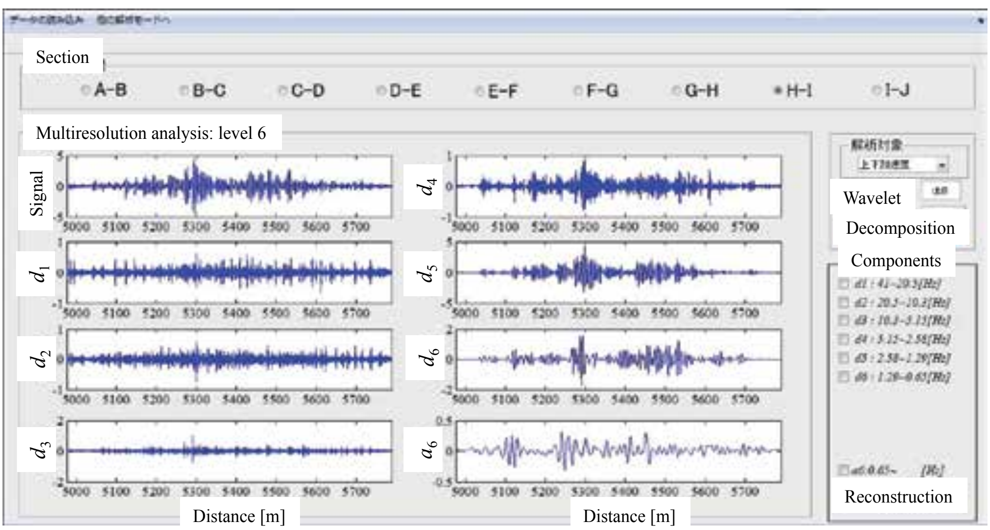

Figure 6. Multiresolution analysis via discrete wavelet transform (decomposition level m_0: 6) [10]

4. Simulation

The track condition monitoring system in this study is premised on the use of vibrational measurement devices to measure the vehicle vibrational acceleration. For this reason, we used simulations to investigate whether different types of track faults, including longitudinal level irregularities, corrugations and level differences in rail joints, may be detected from data on vehicle vibrational acceleration.

- Vehicle model

Figure 7 shows the vehicle model used in the simulation. The vehicle model is a linear model of a single car that considers two degrees of freedom (vertical motion and pitch) for the car body and two degrees of freedom (vertical motion and pitch) for each bogie, yielding a total of six degrees of freedom. The car runs at a speed of 50 km/h over a straight-line segment of track of length 300 m. Table 1 lists the parameters of the vehicle model.

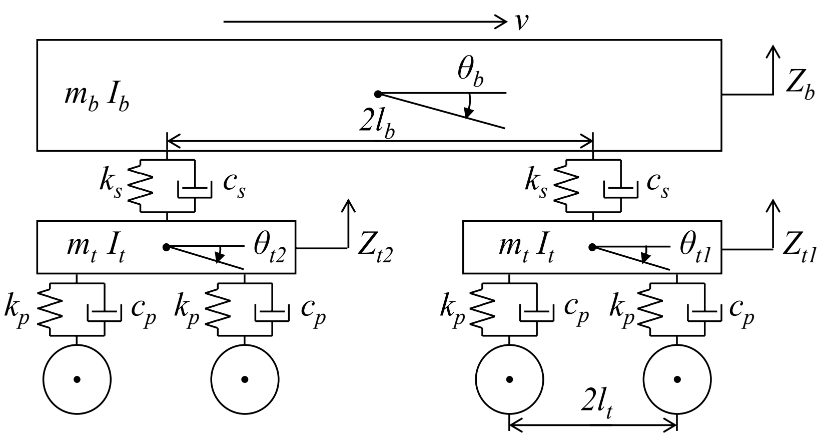

Figure 7. Vehicle model [10]

Symbol	Description	Unit	Value
m_b	Car-body mass	kg	14600
m_t	Truck mass	kg	2400
I_b	Car-body inertia	kgm^2	500452
I_t	Truck pitch inertia	kgm^2	2773.5
$2l_b$	Car-body base	m	14.1
$2l_t$	Wheel base	m	2.15
k_p	Primary suspension vertical stiffness	kN/m	1090
k_s	Secondary suspension vertical stiffness	kN/m	329
c_p	Primary suspension vertical damping	kNs/m	19.6
c_s	Secondary suspension vertical damping	kNs/m	27.2
v	Vehicle speed	km/h	50

Table 1. Vehicle parameters

- Track geometry

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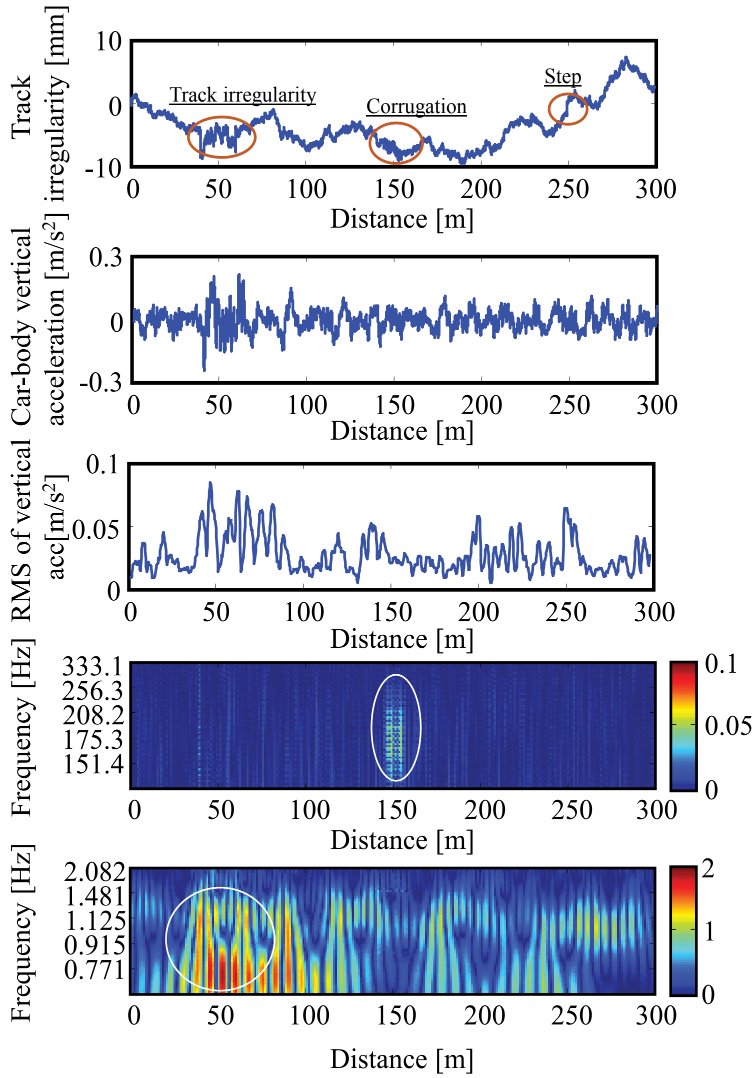


Figure 8. Assessments of the simulated data [10]

We created track geometry data whose frequency characteristic was inversely proportional to the spatial frequency; that is, the amplitude was larger at long wavelengths and smaller at short wavelengths.

Irregularities such as longitudinal level irregularities, corrugations and level differences in rail joints were artificially added to the basic track geometry waveforms constructed. The amplitude of the longitudinal level irregularities for positions between 40 and 60 m was set equal to two times the reference track irregularity. Corrugations were added over a 10 m stretch of track between positions 145 and 155 m; the corrugations were sinusoidal with total amplitude of 1 mm and a frequency of 175 Hz. The wavelength in this case is 0.08 m. At the 250 m position, we created a step-shaped level difference of 2 mm. These track irregularities are shown in the top part of Figure 8.

- Car-body vertical acceleration

We input the track geometry data, including the constructed irregularities, to the vehicle model of a single railcar shown in Figure 8 and then computed the car-body acceleration (in the vertical direction) above the centre of the front bogie. The sampling frequency was set to 820 Hz, the same as that of the vibrational measurement device. To the acceleration data computed in this way, we added white noise to represent observation noise and then output these data as the acceleration data (the second part from the top in Figure 9). The standard deviation of the measurement noise was 10^{-3} m/s^2.

- RMS values for the car-body vertical vibration acceleration

Using Eq. (1), we determined the RMS value of the computed car-body vertical acceleration (the third part from the top in Figure 8).

- Continuous wavelet transform of the car-body vertical acceleration

We applied a continuous wavelet transform to the computed car-body vertical acceleration (fourth and fifth part from the top in Figure 8). For the mother wavelet, we used *Morlet* wavelets.

- Discrete wavelet transform of the car-body vertical acceleration

We used the discrete wavelet transform to conduct a multiresolution analysis of vibrational acceleration. Using the *Daubechies* wavelets (generation index: eight), we set the decomposition level to be m_0=6 (Figure 9).

The effect of track irregularities may be partially discerned from the original waveform of the vibrational acceleration in Figure 8. However, discrepancies associated with other faults may not be discerned. The increased RMS value in the vicinity of 50 m reflects the effect of longitudinal level irregularities. On the other hand, the RMS value increases slightly in the vicinity of 250 m, but the level difference between this and the longitudinal level irregularity cannot be distinguished from the waveform. Thus, we conclude that the use of RMS values is poorly suited to distinguishing the different track faults.

Next, we consider results obtained with the continuous wavelet transform. Looking at the signal plane (151–333 Hz) of the continuous wavelet transform, we see a strong signal near 150 m around a frequency of 174 Hz. When corrugations of wavelength 0.08 m are run at a speed of 50 km/h, the frequency of the corrugations is 174 Hz. The appearance in the signal plane of features at this frequency and at the position in question may thus be understood as originating from corrugations. In addition, in the signal plane of the 0.7 to 2 Hz band, the signal strength grows extremely large in the vicinity of the natural frequency of the car body. This effect, which is particularly pronounced near 50 m, is thought to result from longitudinal level irregularities. Thus by using the continuous wavelet transform, we

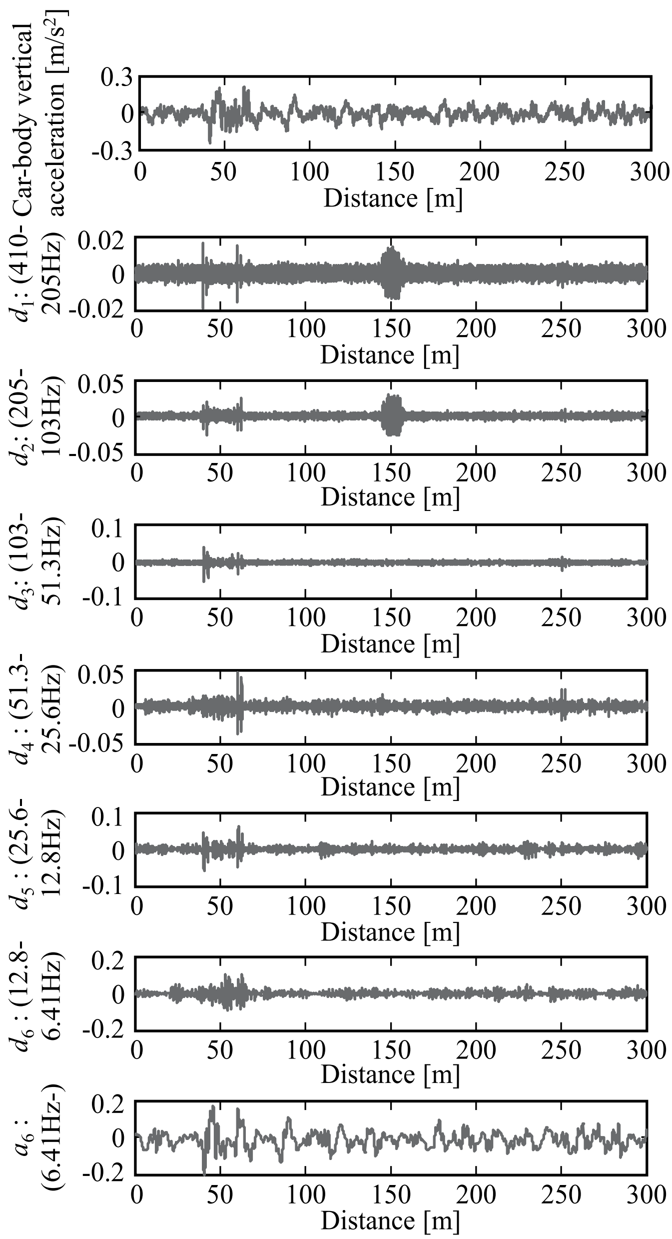


Figure 9. Multiresolution analysis of the simulated data [10]

have successfully detected information on longitudinal level irregularities and corrugations from vehicle vibrational acceleration data.

On the other hand, because the vibration response to the level difference, for example, is a step input, its properties are dispersed over a wide bandwidth. In the present case, since its strength is extremely weak, it is difficult to discern its effect from the signal plane. To remedy this difficulty, we perform multiresolution analysis using the discrete wavelet transform. Then, by inspecting the frequency components of the vehicle vibrational acceleration data (Figure 9) as decomposed into separate frequency bands, we can see that the effect of the level difference, though extremely weak, is visible in the d_4 component.

Figure 10 shows the frequency components that indicate the effect of corrugations (d_1+d_2), the components that indicate the effect of the level difference (d_4) and the low-frequency band components, in which the continuous wavelet transform indicated the effect of longitudinal level irregularities (a_6).

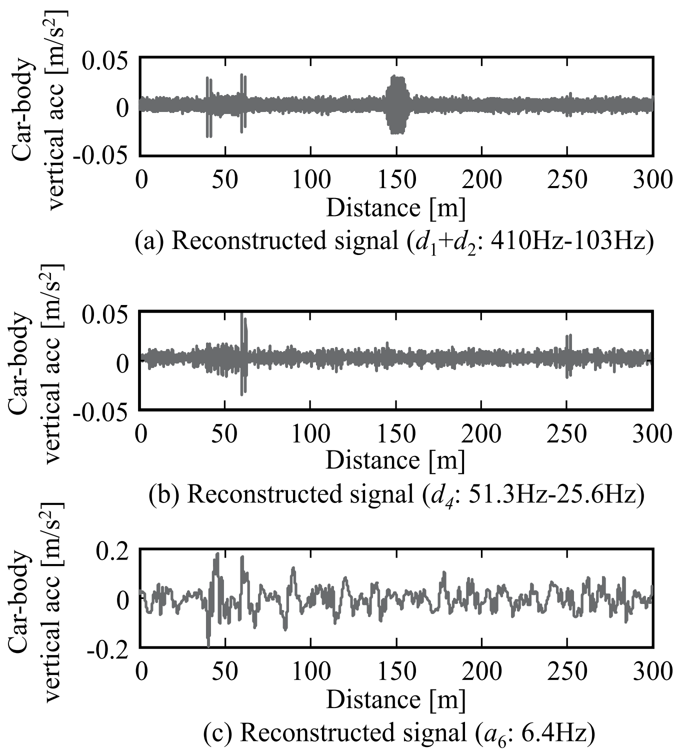


Figure 10. Reconstructed signals of Figure 10 [10]

We see that corrugations may be identified in the waveforms reconstructed from the high-frequency components (Figure 10(a)), that the level difference may be detected in the waveform of the d_4 component (Figure 10(b)) and that the longitudinal level irregularity may be identified in the waveform of the a_6 component (Figure 10(c)). Moreover, for the segment over which the magnitude of the longitudinal level irregularity was increased to twice the reference value for track irregularities, the rate of change of the connecting portion is discontinuous. Thus, we have detected discontinuities in the rate of change of the waveform (Figures 10 (a) and (b)).

This suggests the possibility that, by establishing reference values for waveforms extracted not from axle box acceleration but rather from car-body acceleration data, track faults that are difficult to detect from RMS values may be detected through the combined use of multiresolution analysis based on the discrete wavelet transform.

5. Monitoring example based on actual measured regional railway data

In the previous section, we demonstrated the efficacy of wavelet transforms for monitoring the track condition. In this section, we use actual measured value to assess the efficacy of the primary features of the monitoring software, namely, the computation of RMS values and signal analysis based on wavelet transforms. The actual measured value used for this assessment are taken from measurements made to date by the authors' research group in cooperation with a regional railway operator over an extended period time using the compact on-board sensing device [6,10].

For this railway line, we did not monitor corrugations. Therefore, in an effort to reduce the volume of handled data and increase processing speed, we reduced the volume of the measured data to 1/10 its original size. The sampling frequency of the reduced data is 82 Hz, whereupon from Nyquist's theorem, it follows that the maximum reproducible frequency is 41 Hz.

Figure 11 shows the results of analyses of the actual measured value performed by the monitoring software. The panels of the figure show, proceeding in order from the uppermost panel, the travel speed over the target station-to-station segment (as measured from GPS data), the measured waveform of the car-body vertical acceleration, the RMS value of the vibrational acceleration and the signal plane resulting from the continuous waveform transform. Based on the results of the previous section, the frequency bands of the signal plane have been divided into a low-frequency band, which captures the effect of longitudinal level irregularities, and the remainder of the frequency range. To observe the track condition, we performed visual inspections of the outer side of the track.

Looking at the RMS value waveform of Figure 11, we see a large RMS value in the vicinity of 3100 m, despite the fact that the travel speed is low at that point. In addition, the value appears large at continuous points in the vicinity of 3200 m. Another point of large RMS value appears near 3320 m. Looking at the signal plane (1.6–16 Hz) of the continuous wavelet transform, we see effects in the high-frequency band near 3100 m and 3320 m, while we see effects in the low-frequency band near 3200 m. Visual inspection of the track revealed a turnout near 3100 m; as the vehicle passes over this point, it exhibits large vibrations, whose effects are thought to be captured by the analysis.

Figure 12 presents the results of a multiresolution analysis (decomposition level m_0 = 6) of the car-body vertical acceleration. To assess the track condition from the decomposed signal, we reconstructed the signal into one portion containing components 1.28 Hz or below and another portion containing all other components (Figure 13). Based on analysis thus far, we

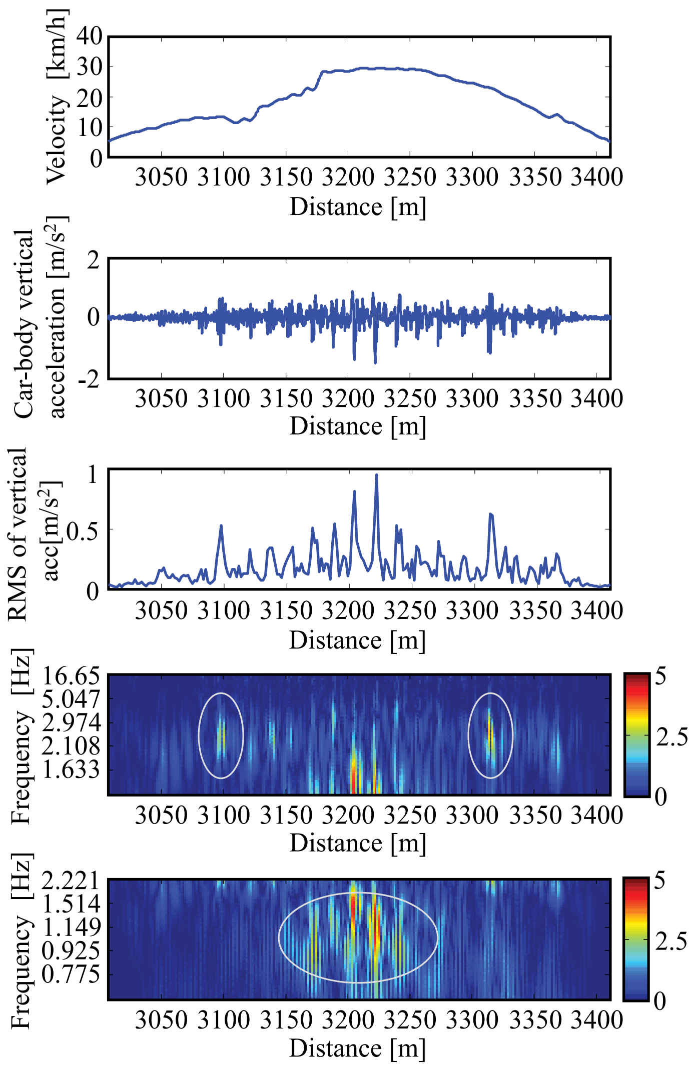


Figure 11. Assessments of the measurement data[10]

believe that the waveform (Figure 13(b)) of the low-frequency components indicates the effect of longitudinal level irregularities. Meanwhile, the waveform reconstructed from the remaining high-frequency components (Figure 13(a)) exhibits characteristic impulse-shaped peaks at fixed intervals. The lengths of the rails in this segment are 20 m, which roughly agrees with the interval of these impulse-shaped signals. This suggests the possibility that our data detected the presence of rail joints. In addition, the signal detected in the vicinity of 3320 m may indicate the effect of a loose sleeper. Accordingly, in our future work, we intend to collaborate further with the railway operator to investigate this possibility in more detail.

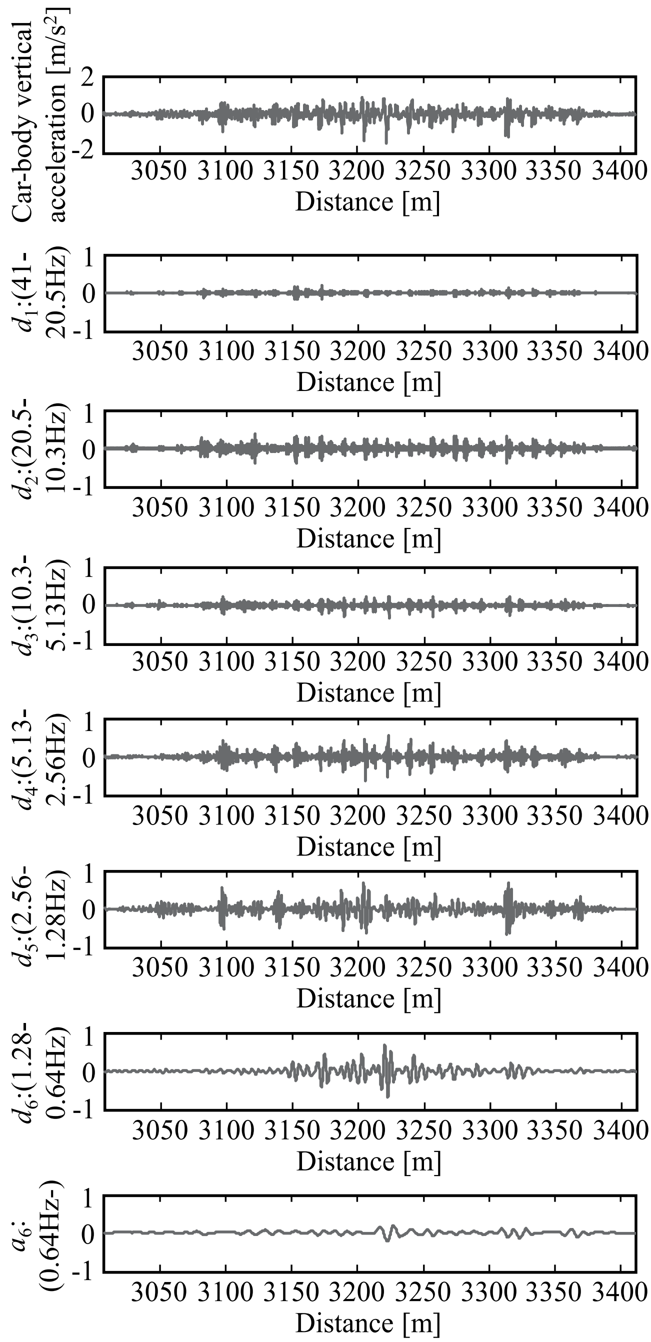
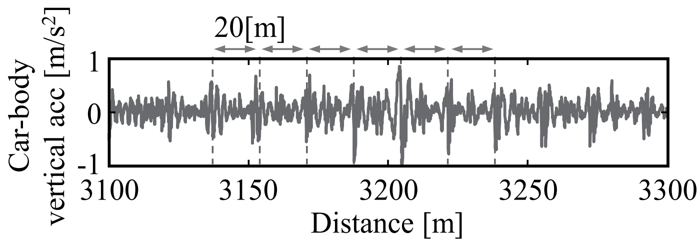
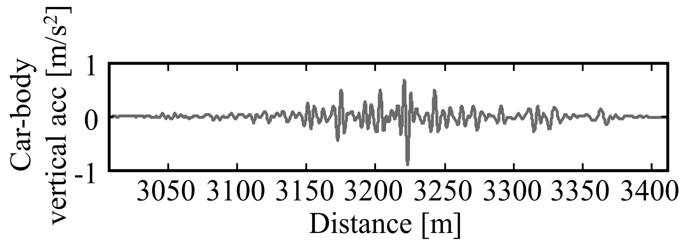


Figure 12. Multiresolution analysis of the car-body vertical acceleration [10]



(a) Reconstructed signal (d_1+d_2+ d_3+d_4 : 41Hz-2.56Hz)



(b) Reconstructed signal (d_6+a_6: 1.28Hz-)

Figure 13. Reconstructed signals of Figure 13 [10]

6. Summary

In this chapter, we described a track condition monitoring system that uses track monitoring software and a compact on-board sensing device. We described the development of the track monitoring software and presented an example of the diagnostic results the monitoring software produces. To confirm the efficacy of the track condition monitoring software, we tested it using simulations and actual measured data. The results demonstrated that our system is useful for continuous track condition monitoring.

We envision the following techniques for deploying our system in practice. First, a threshold level for the RMS value will be established, and segments over which the RMS value is large will be extracted as segments requiring inspection. Next, segments requiring inspection will be subject to detailed analysis using signal planes produced by a continuous wavelet transform and multiresolution analysis based on a discrete wavelet transform. Threshold values may also be established for the components reconstructed from the multiresolution analysis and used for maintenance purposes.

The proposed system enables the timely provision of feedback regarding track maintenance, and we expect it will reduce costs and facilitate maintenance efforts to reduce overall maintenance requirements. In the authors' future work, the plan is to collaborate with the maintenance departments of railway operators to demonstrate and improve the effectiveness of the developed system.

http://dx.doi.org/10.5772/61077

Acknowledgements

This study was supported by the Adaptable and Seamless Technology Transfer Program through Target-driven R&D, Japan Science and Technology Agency and JSPS KAKENHI grant number 26420182.

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Chapter 6

Modeling, Simulation, and Results of Their Use in Railway Vehicle Dynamics Studies

Krzysztof Zboinski

Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/62105

Abstract

This chapter focuses on problems related to building mathematical and numerical models of railway vehicle dynamics and then using these models in the process of vehicle dynamics simulation. Finally, the results of such simulations devoted to selected dynamical problems are presented, highlighting the importance of powerful tools such as both the modeling and the simulation. The dynamical problems selected for the presentation concern railway vehicle stability and importance of kinematics accuracy for the description of the dynamics. These selected problems focus on the vehicle dynamics in a curved track, both in the circular and transition sections. Type of the chapter should be defined as the review paper, however, based on the authors' own results in the main.

Keywords: Railway vehicle, vehicle dynamics, curved track, transition curve, numerical simulation

1. Introduction

The present review chapter is based on the authors' results gathered and published in subsequent parts for many years of his work in the field of railway vehicle dynamics with focus on a curved track motion. The idea of the chapter is to combine all the results on the one hand and to select them suitably on the other hand. Both these demands are fulfilled in order to give a picture of comprehensiveness of the combined issues and not overload the reader with excessive details that could spoil the presentation of the chapter's main aim. The aim is to present the outstanding role of modeling, simulation, and results of their use, in a shortened way, in the contemporary research questions of the railway vehicle dynamics. However, this is going to be done through exploitation of the author's own results. The reference could be done here to [1], the comprehensive monograph in Polish (371 pages). This chapter is profiled differently, however, and results are presented in the concise way and internationally accessible form, i.e. in English.

1.1. The fundamentals in rail vehicle dynamics

It is rather a well-known fact (e.g. Refs. [1–3]), however sometimes being forgotten, that in rail vehicle dynamics, perturbations of vehicle motion relative to vehicle general motion are of the primary interest. The general motion of vehicle is of lesser interest as it is predefined by the track alignment (shape). Hence, in the general view, the vehicle reproduces the motion imposed by the track centerline shape, as the vehicle is guided by the track (rails). Such a guided motion is already known. Instead, the perturbed motion relative to the track centerline appears to be of real importance in the rail vehicle dynamics problems.

Therefore, the description of such a perturbed motion makes the bases in the rail vehicle dynamics. As recently shown by the author in Ref. [1, 2], there are three options to perform such description.

Option 1. In this option, one adopts coordinates relative to inertial reference system of type A in Figure 1 and any formalism of equations building valid for motion relative to A:

$$fd\mathrm{B} = fd\mathrm{Z} \quad \Rightarrow \quad \{x = x(t), \dot{x} = \dot{x}(t)\} \quad \Rightarrow \quad \{x' = x - u(t), \dot{x}' = \dot{x} - v(t)\} \tag{1}$$

where fd is the operator representing any chosen formalism; B is the inertia forces in relation to A; Z is the external (active) forces; x, $\dot{x}$ are the coordinates and velocities, respectively; and $u(t)$, $v(t)$, $w(t)$ are the known functions of time representing displacements, velocities, and accelerations of transportation, that is, of system A' in relation to A.

Option 2. In this option, one adopts coordinates relative to noninertial reference system of type A' in Figure 1 and any formalism adapted to motion description relative to A' (the direct methods of relative motion dynamics):

$$fd\mathrm{B}' = fd\mathrm{Z} + fp\mathrm{P}(\dot{u}, \ddot{u}) \quad \Rightarrow \quad \{x' = x'(t), \dot{x}' = \dot{x}'(t)\} \tag{2}$$

where B' is the inertia forces in relation to A'; P is the imaginary forces (inertia forces arising from and dependent on the transportation); and fp is the operator of the imaginary forces, appropriate for the formalism adopted.

Option 3. In this option, one takes coordinates relative to A' and any formalism valid in A. In practice, this is any of the variational principles of mechanics or the formalism arising directly from it:

$$\left.\begin{aligned} fz\mathrm{B} &= fz\mathrm{Z} \\ x &= x' + u(t) \\ \dot{x} &= \dot{x}' + v(t) \\ \ddot{x} &= \ddot{x}' + w(t) \end{aligned}\right\} \quad \Rightarrow \quad \begin{matrix} \{x = x(t), \dot{x} = \dot{x}(t)\} \\ \{x' = x'(t), \dot{x}' = \dot{x}'(t)\} \end{matrix} \tag{3}$$

where *fz* is the operator representing the variational principle.

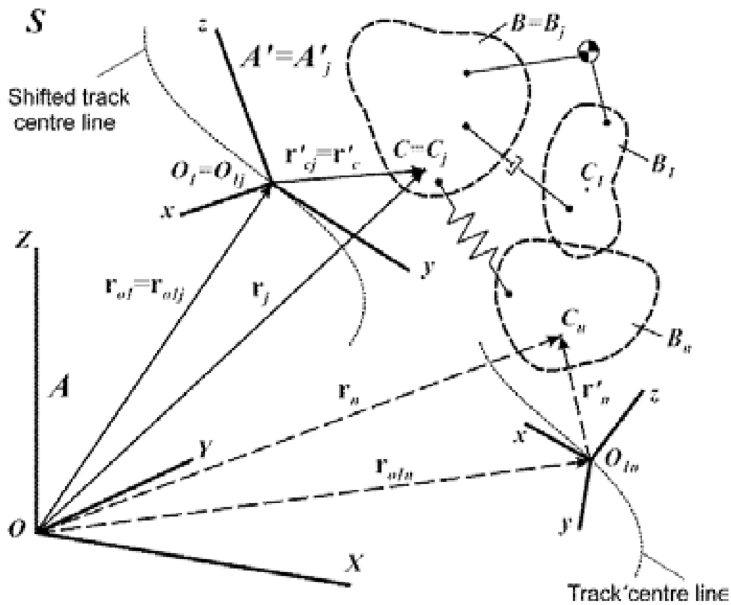

Figure 1. Multibody system *S* and useful coordinate systems

Commenting on Eqns. (1–3), one should note that the left-hand side equalities represent dynamical equations of motion. In case of Eq. (3), the equations of motion are supplemented with kinematical relations. They express absolute variables with the relative ones and need to be introduced into Eq. (31) when equations of motion are being solved. The general form of Eqns. (1–3) serves any form of the vectorial and scalar equations as well as the matrix form in certain cases. Meaning of the dynamical equations of motion is typical. It becomes obvious as B represents inertia forces relative to absolute (inertial) system, Z represents external forces, B′ represents inertia forces relative to moving (noninertial) system, and P represents imaginary forces (inertia forces depending on the transportation, i.e., motion of noninertial system relative to the inertial one). Moreover, the operators *fd*, *fp*, and *fz* do not change the meaning of the forces. The operators are introduced as a reminder that particular formalisms may need application of some specific coordinates, velocities, recording, and operations to make use of the formalism.

The curly brackets represent solutions of the equations of motion. As the equations are second-order ordinary differential equations, the solutions are displacements (coordinates) and velocities, both the linear and angular ones in general.

It is worth emphasizing that Eq. (2) is the only one that needs explicit form of the imaginary forces to be recorded. In contrast, in case of Eqns. (1) and (3), the inertia forces are also taken into account, however, in an inexplicit way. This is because $\mathrm{B}=\mathrm{B}'+\mathrm{P}$. In addition, if one uses the same formalism of building the equations to build Eq. (2) or to build either Eqns. (1) or (3), then form of the forces B and B′ is identical. The only difference is with their meanings that refer to absolute and relative motions. In order to highlight this, the superscript " ′ " is used. It is used, in fact, to distinguish all the relative variables in Eqns. (1–3) and also in the subsequent text.

Based on the denotation explained above, one can note in the curly brackets that Eq. (2) is the only one that leads directly to the solution representing the relative coordinates and velocities. Eq. (2) is advantageous as the relative variables are those of interest in most of rail-vehicle dynamics problems. In case of Eq. (1), the relative solution can be obtained indirectly, whereas in the case of Eq. (3) a part of the solution represents absolute variables and another the relative ones.

Discussing briefly the practical use of particular options, it has to be stated at first that numbers and types of application differ. The approach defined with Eq. (1) is definitely used most rarely. The approach defined with Eq. (3) is the one among all three that is used most often in the commercial software packages for automatic generation of equations of motion (AGEM). This includes the software suitable for the systems in a rail vehicle type. Currently, such software (e.g., MEDYNA, VAMPIRE, SIMPACK, or VI-RAIL codes) are used quite often mainly in solving many contemporary engineering problems. However, their use in scientific research is questionable. It is contested because of the so-called black box problem. Thus, following the formal scientific methodology, the researcher himself and the others should precisely know how the problem was resolved. Therefore, the assumptions and the way of modeling have to be elucidated, which allows others to repeat the study or to compare it with results for other similar but different approaches (for different assumptions and methods of modeling). Examples of use of this approach to build the models and the simulation software for the scientific purposes can also be found. However, for such purposes, the option defined with Eq. (2) seems to be used more frequently, where different levels of accuracy are used in practice. Thus, some authors neglect selected terms of the imaginary forces. The importance of these terms in the rail vehicle dynamics is comprehensively discussed by the author of the present chapter in Ref. [4].

2. Equations of motion based on dynamics of relative motion approach

In his studies, the author of the present chapter himself practices and is a supporter of option 2 described earlier. This option defined with Eq. (2) exploits direct results of the dynamics of relative motion. Both, the variables used and the equations of motion, are defined directly in relation to moving coordinate systems in type A' in Figure 1. In his studies, the author applied a few formalisms of equation building. He applied them in both the traditional and numerical approaches. In the first approach, equations of motion were derived on paper first and then implemented in the simulation software in order to solve them numerically. In the second approach, the AGEM was applied by the author to build and solve equations numerically. Lagrange type II equations (e.g., see Ref. [5]) were in use in the traditional approach. In the AGEM approach, the author exploited Kane's equations as presented in Refs. [1, 2, 6]. Here, five examples of the equations valid in noninertial systems will be presented. These are matrix equations for a single rigid body based on Newton and Euler equations; state–space form of Newton–Euler equations for a single rigid body; state–space form of Newton–Euler equations for the multibody system (MBS) with constraints; Kane's equations in its general form; and Huston's form of Kane's equation suitable in AGEM. Besides, the method valid for Kane's equations will be presented, which enables building the equations for the holonomic and nonholonomic systems based on the equations for the free (unconstrained) system. Derivations for all these equations can be found in Refs. [1, 2].

2.1. The Newton–Euler equations

Based on the fundamental kinematical relations for relative motion, relating absolute and relative velocities and accelerations,

$$\boldsymbol{p}_C = \boldsymbol{a}'_C + \boldsymbol{a}_{o1} + \boldsymbol{\varepsilon} \times \boldsymbol{r}'_C + \boldsymbol{\omega} \times (\boldsymbol{\omega} \times \boldsymbol{r}'_C) + 2\boldsymbol{\omega} \times \boldsymbol{v}'_C \tag{4}$$

$$\boldsymbol{\theta} = \boldsymbol{\omega} + \boldsymbol{\omega}' \tag{5}$$

$$\boldsymbol{\alpha} = \frac{d\boldsymbol{\theta}}{dt} = \frac{d\boldsymbol{\omega}}{dt} + \frac{d\boldsymbol{\omega}'}{dt} = \boldsymbol{\varepsilon} + \frac{d'\boldsymbol{\omega}'}{dt} + \boldsymbol{\omega} \times \boldsymbol{\omega}' = \boldsymbol{\varepsilon} + \boldsymbol{\varepsilon}' + \boldsymbol{\omega} \times \boldsymbol{\omega}' \tag{6}$$

and vectorial forms of Newton and Euler equations, the vectorial equations of relative motion for translation and rotation of a single free rigid body can be obtained as those presented in Refs. [7, 1, 2]. Based on these vectorial equations, their matrix forms can be recorded in several ways as shown, e.g., in Refs. [1, 2, 8–10]. The forms as in Refs. [1, 2] are as follows:

$$m\mathbf{a}'_C = -m(\mathbf{a}_{o1} + \widehat{\mathbf{r}}'_C\boldsymbol{\varepsilon} + \widehat{\boldsymbol{\omega}}\widehat{\boldsymbol{\omega}}\mathbf{r}'_C + 2\widehat{\boldsymbol{\omega}}\mathbf{v}'_C) + \mathbf{R}_C = \mathbf{Q}_1 + \mathbf{R}_C \tag{7}$$

$$\mathbf{J}\boldsymbol{\varepsilon}' = -\widehat{\boldsymbol{\theta}}\mathbf{J}\boldsymbol{\theta} - \mathbf{J}\boldsymbol{\varepsilon} - \mathbf{J}(\widehat{\boldsymbol{\omega}}\boldsymbol{\omega}') + \mathbf{T}_C = \mathbf{Q}_2 + \mathbf{T}_C \tag{8}$$

The meanings of the denotations present in the above Eqns. (4–6) are as follows: $\boldsymbol{p}_C$, $\boldsymbol{\theta}$, $\boldsymbol{\alpha}$ are the absolute acceleration of body mass centre C, absolute angular velocity of body B, and absolute angular acceleration of body B; $\boldsymbol{r}'_C$ is the radius vector of C in O_1xyz system; $\boldsymbol{v}'_C$, $\boldsymbol{a}'_C$ are the relative velocity and relative acceleration of C in relation to O_1xyz; $\boldsymbol{\omega}'$, $\boldsymbol{\varepsilon}'$ are the relative angular velocity and relative angular acceleration of B; $\boldsymbol{a}_{o1}$, $\boldsymbol{\omega}$, $\boldsymbol{\varepsilon}$ are the absolute acceleration of O_1 origin (i.e., in relation to $OXYZ$), transportation angular velocity, and transportation angular acceleration (i.e., of O_1xyz in $OXYZ$). In Eqs. (7, 8), m, $\mathbf{J}$ are the mass and inertia tensor (its matrix representation) of body B in relation to C; $\mathbf{R}_C$, $\mathbf{T}_C$ are the matrix of resultant external forces acting on B and matrix of resultant external torques acting on B in relation to C; and $\mathbf{Q}_1$,

$\mathbf{Q}_2$ are the matrices representing sums of the inertia terms. The remaining denotations are matrices that have their counterparts in the vectors defined in Eqns. (4–6).

One should realize here that in order to express all matrices in Eqns. (7, 8) through their elements selection of the vector bases $\boldsymbol{i}_m$ (m=1, 2, 3) for Eqns. (7) and (8) is necessary.

Equations (7, 8) can easily be recorded in one matrix equation:

$$\mathbf{I}\dot{\mathbf{x}}'_{\mathrm{II}} = \mathbf{Q} + \Lambda \tag{9}$$

where

$$\dot{\mathbf{x}}'_{\mathrm{II}} = [\dot{\mathbf{x}}'_{\mathrm{IIi}}]^{\mathrm{T}} = [\mathbf{a}'_{Cj}, \boldsymbol{\varepsilon}'_j]^{\mathrm{T}} = [\dot{\mathbf{v}}'_{Cj}, \dot{\boldsymbol{\omega}}'_j]^{\mathrm{T}} \ \left(i = 1,...,6; j = 1,\ 2,\ 3\right); \tag{10}$$

$$\mathbf{I} = \begin{bmatrix} m\mathbf{E} & \mathbf{0} \\ \mathbf{0} & \mathbf{J} \end{bmatrix}; \qquad \mathbf{Q} = \begin{bmatrix} \mathbf{Q}_1 \\ \mathbf{Q}_2 \end{bmatrix}; \qquad \Lambda = \begin{bmatrix} \mathbf{R}_C \\ \mathbf{T}_C \end{bmatrix} \tag{11}$$

and $\mathbf{E}$ is the unit matrix. Besides, for any vector $\boldsymbol{c}$ the denotation $\frown{\mathbf{c}}$ represents the vector's skew-symmetric matrix, while generally the matrix $\mathbf{I}$ is not the symmetrical one.

On analyzing Eq. (10), the variables $\mathbf{x}'_{\mathrm{II}}$ and $\mathbf{x}'_{\mathrm{I}}$ (velocities and coordinates) are the same as those in Newton and Euler equations. They define translation of the centre C and rotation of B around C. In their case, the linear kinematical relation holds $\dot{\mathbf{x}}_{\mathrm{I}} = \mathbf{K}(\mathbf{x}_{\mathrm{I}})\mathbf{x}_{\mathrm{II}}$.

It can be shown that the equation similar to Eq. (9) can be obtained when arbitrarily chosen set of variables $\mathbf{w}'_{\mathrm{II}}$ and $\mathbf{w}'_{\mathbf{I}}$ are adopted. If matrix $\mathbf{K}$ is not singular then for variables

$$\mathbf{x}'_{\mathrm{I}} = \mathbf{X}_{\mathrm{WI}}(\mathbf{w}'_{\mathrm{I}}, \mathbf{t}); \dot{\mathbf{x}}'_{\mathrm{I}} = \mathbf{H}(\mathbf{w}'_{\mathrm{I}}, \mathbf{t})\dot{\mathbf{w}}'_{\mathrm{I}} + \mathbf{h}(\mathbf{w}'_{\mathrm{I}}, \mathbf{t})$$

and linear kinematical relations

$$\dot{\mathbf{w}}'_{\mathrm{I}} = \mathbf{G}(\mathbf{w}'_{\mathrm{I}})\mathbf{w}'_{\mathrm{II}}$$

the equation can be written as follows:

$$\mathbf{x}'_{\mathrm{II}} = \mathbf{K}^{-1}\dot{\mathbf{x}}'_{\mathrm{I}} = \mathbf{K}^{-1}(\mathbf{H}\dot{\mathbf{w}}'_{\mathrm{I}} + \mathbf{h}) = (\mathbf{K}^{-1}\mathbf{H}\mathbf{G})\mathbf{w}'_{\mathrm{II}} + \mathbf{K}^{-1}\mathbf{h} = \boldsymbol{\Omega}\mathbf{w}'_{\mathrm{II}} + \varsigma \tag{12}$$

while the derivative equals

$$\dot{\mathbf{x}}'_{\mathrm{II}} = \mathbf{\Omega}\dot{\mathbf{w}}'_{\mathrm{II}} + \dot{\mathbf{\Omega}}\mathbf{w}'_{\mathrm{II}} + \dot{\varsigma} \tag{13}$$

After the introduction of Eq. (13) in (9), one gets

$$\hat{\mathbf{I}}\dot{\mathbf{w}}'_{\mathrm{II}} = \hat{\mathbf{Q}} + \hat{\Lambda} \tag{14}$$

where

$$\hat{\mathbf{I}} = \mathbf{I}\mathbf{\Omega}; \quad \hat{\mathbf{Q}} = [\mathbf{Q} - \mathbf{I}(\dot{\mathbf{\Omega}}\mathbf{w}'_{\mathrm{II}} + \dot{\varsigma})]; \quad \hat{\Lambda} = \Lambda \tag{15}$$

As shown explicitly in Refs. [1, 2], the result represented by Eq. (14) can be generalized to the case of constraint system with holonomic and nonholonomic constraints (e.g., see Ref. [7]). Then it can be extended so that the inertia matrix becomes symmetrical one what enables to get the corresponding inverse matrix and finally to solve the equations. This can be done through the left-hand side multiplication of the equation by the transpose matrix $\mathbf{\Omega}^{\mathrm{T}}$. As a result of the described operations, one arrives at

$$\breve{\mathbf{I}}\dot{\mathbf{w}}'_{\mathrm{II}} = \breve{\mathbf{Q}} + \breve{\Lambda} + \breve{\Lambda}_{\mathbf{z}} \tag{16}$$

where

$$\breve{\mathbf{I}} = \mathbf{\Omega}^{\mathrm{T}}\hat{\mathbf{I}} = \mathbf{\Omega}^{\mathrm{T}}\hat{\mathbf{I}}\mathbf{\Omega} \quad ; \quad \breve{\mathbf{Q}} = \mathbf{\Omega}^{\mathrm{T}}\hat{\mathbf{Q}}; \tag{17}$$

$$\breve{\Lambda} = \mathbf{\Omega}^{\mathrm{T}}\hat{\Lambda}; \qquad \breve{\Lambda}_{\mathbf{z}} = \mathbf{\Omega}^{\mathrm{T}}\hat{\Lambda}_{\mathbf{z}} = \mathbf{\Omega}^{\mathrm{T}}\mathbf{\Phi}^{\mathrm{T}}(\mathbf{w}'_{\mathrm{I}},\mathbf{t}) \tag{18}$$

In the equations above, $\mathbf{t}$ is the indicator of the dependence on time t; $\mathbf{\Phi}, \boldsymbol{\lambda}$ are the so-called constraint matrix and column matrix of Lagrange's multipliers (e.g., see Refs. [8, 1, 2]). If one is going to solve Eq. (16) then all equations of constraints have to be added to the system of equations to make it possible.

When one is not interested in values of the constraint (internal) forces $\breve{\mathbf{\Lambda}}_{\mathbf{z}}$ then it is reasonable to express equations of motion for the reduced set of independent variables $\mathbf{y}'_{\mathbf{I}}$ and y'_{II}. This reduces the number of equations by the number of constraints. The relation at the velocity level between maximum and reduced (minimum) set of the variables is represented through matrix representation of explicit constraint equations at the velocity level:

$$\mathbf{w}'_{\mathrm{II}} = \varphi\mathbf{y}'_{\mathrm{II}} + \xi \tag{19}$$

After Eq. (19) is exploited in Eq. (14), the state–space equation in the independent generalized velocities takes the following form:

$$\tilde{\mathbf{I}}\dot{\mathbf{y}}'_{\mathrm{II}} = \tilde{\mathbf{Q}} + \tilde{\Lambda} \tag{20}$$

where

$$\tilde{\mathbf{I}} = \varphi^{\mathrm{T}}\hat{\mathbf{I}}\varphi \quad ; \qquad \tilde{\mathbf{Q}} = \varphi^{\mathrm{T}}[\hat{\mathbf{Q}} - \hat{\mathbf{I}}(\dot{\varphi}\mathbf{y}'_{\mathrm{II}} + \dot{\xi})] \quad ; \qquad \tilde{\Lambda} = \varphi^{\mathrm{T}}\hat{\Lambda} \tag{21}$$

Note that inertia matrix $\tilde{\mathbf{I}}$ is symmetrical due to the left-hand side multiplication by $\boldsymbol{\varphi}^{\mathrm{T}}$. The kinematical relations corresponding to Eq. (20) in the linear matrix form can be expressed as $\dot{\mathbf{y}}'_{\mathrm{I}}=\hat{\mathbf{Y}}_{\mathrm{I}}(\mathbf{y}'_{\mathrm{I}})\mathbf{y}'_{\mathrm{II}}$. In case nonholonomic constraints exist in the system, they have to be provided to make the solution of Eq. (20) possible.

The final Eqns. (16, 20) are valid for a single rigid body. It was shown in Ref. [8] for inertial systems that forms valid for a single body can directly be generalized to any number of rigid bodies. As in principle the structure of equations for noninertial systems differs in additional inertia terms of correction character only (see, e.g., Eqns. (2, 3)), this result can be extended to noninertial systems. In terms of the notation, it is trivial and means that Eqns. (16) and (20) valid in noninertial systems remain unchanged for any number of rigid bodies.

2.2. Kane's equations

Any of the formalisms of analytical mechanics valid in inertial systems can be adapted to describe the relative motion in the noninertial system. The author of the chapter performed such an adaptation for Kane's equation. It was done in a formal manner, that is, corresponding equations of relative motion were derived as shown in Refs. [6, 2, 1].

The partial velocities are fundamental to original Kane's approach [11]. The corresponding relative linear and angular partial velocities were introduced by the author as shown in Refs. [6, 1, 2]. Let us introduce them for the simple nonholonomic system [11] of l degrees of freedom composed of j (j=1,...,n) rigid bodies by defining linear $\boldsymbol{v}'_j$ and angular $\boldsymbol{\omega}'_j$ relative velocities of the mechanical system:

$$\boldsymbol{v}'_j = \sum_{\rho=1}^{l} \frac{\partial \boldsymbol{v}'_j}{\partial u_{j\rho}} u_\rho + \frac{\partial \boldsymbol{r}'_j}{\partial t} = \sum_{\rho=1}^{l} \boldsymbol{v}'_{j\rho} u_\rho + \boldsymbol{v}'_{jt} = \sum_{m=1}^{3}\left(\sum_{\rho=1}^{l} v'_{j\rho m} u_\rho + v'_{jtm}\right)\boldsymbol{i}_m^{(j)} \tag{22}$$

$$\boldsymbol{\omega}'_j = \sum_{\rho=1}^{l} \frac{\partial \boldsymbol{\omega}'_j}{\partial u_{j\rho}} u_\rho + \frac{\partial \boldsymbol{\varphi}'_j}{\partial t} = \sum_{\rho=1}^{l} \boldsymbol{\omega}'_{j\rho} u_\rho + \boldsymbol{\omega}'_{jt} = \sum_{m=1}^{3}\left(\sum_{\rho=1}^{l} \omega'_{j\rho m} u_\rho + \omega'_{jtm}\right)\boldsymbol{i}_m^{(j)} \tag{23}$$

where $\boldsymbol{v}'_{j\rho}$, $\boldsymbol{\omega}'_{j\rho}$, $\boldsymbol{v}'_{jt}$, $\boldsymbol{\omega}'_{jt}$ are the functions of generalized coordinates $q_1,\ldots,q_k$ and time t. At the same time, $\boldsymbol{v}'_{j\rho}$, $\boldsymbol{\omega}'_{j\rho}$ are the ρth relative partial velocity of body B_j mass centre C_j (or any point P_j) and ρth relative angular partial velocity of B_j in relation to A', respectively; $v'_{j\rho m}$, $\omega'_{j\rho m}$ are the scalar components of $\boldsymbol{v}'_{j\rho}$, $\boldsymbol{\omega}'_{j\rho}$, called coefficients of partial velocities; u_ρ is the quasi-velocity ($\rho = 1,\ldots,l$) ; m is the indicator of unit vectors (base vectors) $\boldsymbol{i}_m^{(j)}$ (m=1, 2, 3) defining axes directions of reference systems, where $\boldsymbol{v}'_j$ and $\boldsymbol{\omega}'_j$ are expressed (there is no need for $\boldsymbol{i}_m^{(j)}$ to have the same directions for translations and rotations and for all bodies B_j).

Form of the adapted Kane's equations is as follows:

$$
\begin{aligned}
&\sum_{j=1}^{n}\boldsymbol{v}'_{j\rho}\cdot\left(-m_j\boldsymbol{a}'_j\right)+\sum_{j=1}^{n}\boldsymbol{v}'_{j\rho}\cdot\boldsymbol{R}_{Cj}\\
&\quad+\sum_{j=1}^{n}\boldsymbol{v}'_{j\rho}\cdot\left[-m_j\boldsymbol{a}_{o1j}-m_j\boldsymbol{\varepsilon}_j\times\boldsymbol{r}'_j-m_j\boldsymbol{\omega}_j\times\left(\boldsymbol{\omega}_j\times\boldsymbol{r}'_j\right)-2m_j\boldsymbol{\omega}_j\times\boldsymbol{v}'_j\right]\\
&\quad\;+\sum_{j=1}^{n}\boldsymbol{\omega}'_{j\rho}\cdot\left(-\mathbf{J}_j\cdot\boldsymbol{\varepsilon}'_j-\boldsymbol{\omega}'_j\times\mathbf{J}_j\cdot\boldsymbol{\omega}'_j\right)+\sum_{j=1}^{n}\cdot\boldsymbol{\omega}'_{j\rho}\cdot\boldsymbol{T}_{Cj}\\
&\quad\;\;+\sum_{j=1}^{n}\boldsymbol{\omega}'_{j\rho}\cdot\left[-\mathbf{J}_j\cdot\boldsymbol{\varepsilon}_j-\boldsymbol{\omega}_j\times\mathbf{J}_j\cdot\boldsymbol{\omega}_j-2\boldsymbol{\omega}'_j\times\left(\mathbf{J}_j-0{,}5\vartheta_j\mathbf{E}\right)\cdot\boldsymbol{\omega}_j\right]\\
&\quad\;\;\;=\sum_{j=1}^{n}\boldsymbol{v}'_{j\rho}\cdot\boldsymbol{R}_j^{*}+\sum_{j=1}^{n}\boldsymbol{v}'_{j\rho}\cdot\boldsymbol{R}_j+\sum_{j=1}^{n}\boldsymbol{v}'_{j\rho}\cdot\boldsymbol{R}_j^{**}\\
&\quad\;\;\;\;+\sum_{j=1}^{n}\boldsymbol{\omega}'_{j\rho}\cdot\boldsymbol{T}_j^{*}+\sum_{j=1}^{n}\boldsymbol{\omega}'_{j\rho}\cdot\boldsymbol{T}_j+\sum_{j=1}^{n}\boldsymbol{\omega}'_{j\rho}\cdot\boldsymbol{T}_j^{**}=0\qquad(\rho=1,\ldots,l)
\end{aligned}
\tag{24}
$$

Most of the denotations in Eq. (24) are as already defined. Here, the meanings in Eqns. (4–8) are helpful. Note, however, that in Eq. (24) the j rigid bodies are described, while in Eqns. (4–8) just one. Besides, subscript C was omitted in $\boldsymbol{r}'_C$ resulting in $\mathbf{r}'_{Cj} \equiv \mathbf{r}'_j$. The undefined is ϑ – trace of $\mathbf{J}$, that is, $\vartheta = J_{11} + J_{22} + J_{33}$. In addition, $\boldsymbol{R}_j^{*}$, $\boldsymbol{T}_j^{*}$ are the inertia forces and torques, respectively, of motion in relation to noninertial systems of A' type; $\boldsymbol{R}_j^{**}$, $\boldsymbol{T}_j^{**}$ are the resultant imaginary forces and torques, respectively; while $\boldsymbol{R}_{Cj} \equiv \boldsymbol{R}_j$ and $\boldsymbol{T}_{Cj} \equiv \boldsymbol{T}_j$.

Equation (24) can be expressed in the shortened matrix form as follows [6, 2, 1]:

$$F_\rho^{*} + F_\rho + F_\rho^{**} = 0 \qquad (\rho = 1,\ldots,l) \tag{25}$$

where scalar components are defined with

$$F_\rho^{*} = \sum_{j=1}^{n}(\boldsymbol{R}_j^{*}\cdot\boldsymbol{v}'_{j\rho} + \boldsymbol{T}_j^{*}\cdot\boldsymbol{\omega}'_{j\rho}) \;= R_{jm}^{*}v'_{j\rho m} + T_{jm}^{*}\omega'_{j\rho m} \tag{26}$$

$$F_{\rho} = \sum_{j=1}^{n} (\boldsymbol{R}_j \cdot \boldsymbol{v}'_{j\rho} + \boldsymbol{T}_j \cdot \boldsymbol{\omega}'_{j\rho}\ ) \quad = R_{jm} v'_{j\rho m} + T_{jm} \omega'_{j\rho m} \tag{27}$$

$$F^{**}_{\rho} = \sum_{j=1}^{n} (\boldsymbol{R}^{**}_j \cdot \boldsymbol{v}'_{j\rho} + \boldsymbol{T}^{**}_j \cdot \boldsymbol{\omega}'_{j\rho}) = R^{**}_{jm} v'_{j\rho m} + T^{**}_{jm} \omega'_{j\rho m} \tag{28}$$

In the above Eqns. (26–28), F^{*}_{ρ}, F_{ρ} i F^{**}_{ρ} are the generalized inertia forces (relative to non-inertial system(s)), generalized external forces (identical with those in inertial system(s)), and generalized imaginary forces; R^{*}_{jm}, R_{jm}, R^{**}_{jm}, T^{*}_{jm}, T_{jm} and T^{**}_{jm} are the scalar components of resultant forces and torques $\boldsymbol{R}^{*}_{j}$, $\boldsymbol{R}_{j}$, $\boldsymbol{R}^{**}_{j}$, $\boldsymbol{T}^{*}_{j}$, $\boldsymbol{T}_{j}$ and $\boldsymbol{T}^{**}_{j}$. The final forms of Eqns. (26–28) exploit results for inertial systems by Huston (e.g., see Refs. [12–14]). Also note that signs of sums over *j* and *m* are omitted in these final forms. The original Huston's convention is used here, in which summations over repeated indices have to be performed instead.

Equations (24–28) are not useful in AGEM approach as they are too close to the vectorial origin of Kane's equations. Nevertheless, final forms of Eqns. (26–28) can be treated as the initial ones for the process of deriving the useful form. The process is based on the Huston results [12–14] for the inertial scleronomic systems and present author's extensions [6, 2, 1] to non-inertial and rheonomic systems. Consequently, invoking results from Refs. [6, 2, 1] one can write

$$\Theta_{\rho\pi} \dot{u}_{\pi} = f_{\rho} \qquad (\rho = 1,\ldots,l) \tag{29}$$

where

$$\Theta_{\rho\pi} = m_j v'_{j\rho m} v'_{j\pi m} + J_{jsm} \omega'_{j\rho s} \omega'_{j\pi m} \tag{30}$$

$$\begin{aligned} f_{\rho} = F_{\rho} + F^{**}_{\rho} &- (m_j v'_{j\rho m} \dot{v}'_{j\pi m} u_{\pi} + J_{jsm} \omega'_{j\rho s} \dot{\omega}'_{j\pi m} u_{\pi} + e_{rsm} J_{jsw} \omega'_{j\pi w} \omega'_{jqr} \omega'_{j\rho m} u_{\pi} u_{q}) \\ &- [m_j v'_{j\rho m} \dot{v}'_{jtm} + J_{jsm} \omega'_{j\rho s} \dot{\omega}'_{jtm} \\ &\quad + e_{rsm} J_{jsw} \omega'_{j\rho m} (\omega'_{j\pi w} \omega'_{jtr} u_{\pi} + \omega'_{jqr} \omega'_{jtw} u_{q} + \omega'_{jtr} \omega'_{jtw})] \end{aligned} \tag{31}$$

Besides, in Refs. [6, 2, 1], the form of imaginary forces corresponding to Eqns. (30) and (31) was presented as follows:

$$\begin{aligned} F^{**}_{\rho} = &-m_j a_{o1jm} v'_{j\rho m} - e_{swm} m_j \omega_{js} (e_{wrq} \omega_{jr} r'_{jq}) v'_{j\rho m} \\ &- e_{rsm} J_{jsw} \omega_{jw} \omega_{jr} \omega'_{j\rho m} - e_{swm} m_j \alpha_{js} r'_{jw} v'_{j\rho m} - J_{jms} \alpha_{js} \omega'_{j\rho m} \\ &- 2e_{swm} m_j \omega_{js} v'_{j\rho m} v'_{j\pi w} u_{\pi} - 2e_{rsm} (J_{jsw} - 0{,}5 \vartheta_j E_{sw}) \omega_{jw} \omega'_{j\rho m} \omega'_{j\pi r} u_{\pi} \\ &- 2e_{swm} m_j \omega_{js} v'_{j\rho m} v'_{jtw} - 2e_{rsm} (J_{jsw} - 0{,}5 \vartheta_j E_{sw}) \omega_{jw} \omega'_{j\rho m} \omega'_{jtr} \quad (\rho = 1,\ldots,l) \end{aligned} \tag{32}$$

The supplements to Eq. (29) are kinematical relations:

$$\dot{q}_\sigma = P_{\sigma\rho}(q,t)u_\rho + p_\sigma(q,t) \;\; ; \qquad (\sigma = 1,...,k), \;(\rho = 1,...,l) \tag{33}$$

where in the above equations e_{rsm}, e_{swm} are the permutation symbols; k is the number of generalized coordinates of the nonholonomic system; $P_{\sigma\rho}$, p_σ are the functional matrix and vector (column matrix). Besides, the square bracket in Eq. (31) (being the extension to rheonomic systems) and p_σ vanish for scleronomic systems.

Equations (24, 25, 29, 32, 33) serve nonholonomic, holonomic, and free systems. In Eqns. (25, 29, 32, 33), the difference between particular systems is taken into account by suitable values of partial velocities' coefficients $v'_{j\rho m}$, $\omega'_{j\rho m}$. For holonomic systems l=k, while for free ones l=k=6n. In addition, equations for free and holonomic systems and kinematical relations are sufficient to be solved. For nonholonomic systems, equations of nonholonomic constraints have to be provided additionally to get the solution.

It was shown by the author in Refs. [6, 2, 1] for the rail vehicle systems, taking account of their moderate dimension, nonoccurrence of nonholonomic constraints, limited number of holonomic constraints, identical coordinates and transportation for each rigid body within vehicle model, that it can be reasonable to make use of equations (or particular type of forces) for free systems. Assuming holonomic and nonholonomic constraint equations as

$$u_\sigma = \sum_{\rho=1}^{l} B_{\sigma\rho} u_\rho + D_\sigma \qquad (\sigma = l+1,...,k) \tag{34}$$

$$u_s = \sum_{\rho=1}^{k} A_{s\rho} u_\rho + C_s \qquad (s = k+1,...,6n) \tag{35}$$

the following formula enables to build equations (or selected forces type) for constraint nonholonomic system based on the equations (or selected forces type) for free system [6, 2, 1]:

$$F_\rho = \tilde{F}_\rho + \sum_{s=k+1}^{6n} \tilde{F}_s A_{s\rho} + \sum_{\sigma=l+1}^{k} \tilde{F}_\rho B_{\sigma\rho} + \sum_{\sigma=l+1}^{k} \sum_{s=k+1}^{6n} \tilde{F}_s A_{s\rho} B_{\sigma\rho} \qquad (\rho = 1,...,l) \tag{36}$$

If the system is holonomic then Eq. (34) vanishes, while Eq. (36) is reduced to just two first addends. In Eqns. (34–36), the following so far undefined notations appear: u_ρ, u_σ, u_s are the independent, dependent through nonholonomic constraints, and dependent through holonomic constraints quasi-velocities, respectively; $A_{s\rho}$, $B_{\sigma\rho}$, C_s, and D_σ are the functional coefficients depending on generalized coordinates q_1,...,q_k and time t; and F, $\tilde{F}$ are the representations of any type of generalized forces F^*, F, F^{**} as defined in Eqns. (25–28) or of their sum for constraint and free systems, respectively.

2.3. Discussion of the equations

Taking account of Refs. [15, 16], both the Newton–Euler and Kane's equations are those most often used in AGEM. This is an interesting fact because major differences between both approaches exist. Therefore, the equations are worthy of discussion in this context.

It can be seen in Section 2.1 that building Eq. (16) and (20) that represent receipt useful in AGEM are operations on matrices. To perform these operations, the matrices have to be defined with their components. To do this, one needs to adopt base vectors $\boldsymbol{i}_m^{(j)}$ for the chosen reference systems. Unfortunately, operation must be performed at the beginning of the equations building, that is, jet in Eqns. (7, 8). Despite simple forms of Eqns. (16, 20), the method of obtaining equations for a given mechanical system is not short. Every time one builds equations, he has to choose vector bases, define matrices, and perform matrix calculations as described in Eqns. (12, 13, 15, 17, 18, 19, 21). These calculations are multiple, often in each of the mentioned equations. In the case of nonholonomic systems and interest in constraint forces, Eq. (16) is used, which together with constraint equations form differential-algebraic equation (DAEs) set. Such a set is difficult to solve in general case. On the other hand, when constraint forces are of no interest then a reduced number of ordinary differential equation (ODE) set is used (Eq. (20)).

Equations (29–33) form the receipt useful in AGEM of Kane's equations. Their forms might seem discouraging as they are complex, especially while comparing with Eqns. (16, 20). This impression is misleading as equations possess serious advantages as well. The advantage is the same form of either scalar (Eq. (24)) or matrix equations (Eqns. (29–33)) for free, holonomic, and nonholonomic systems. The most distinguishing advantage of Kane's equations, appearing just for this formalism, is the moment the components of vectors and tensors are defined through the vector bases selection. This is done at the very end of the equations building. This is possible since Eqns. (24, 29–33) originate directly from Eq. (24) based on vectors. Therefore, Eqns. (24, 29–33) are valid for any vector basis. An additional advantage is the type of Kane's equations that are always ODEs.

3. Example objects, nominal models, and numerical models

3.1. The objects and their nominal models

Equations of motion of mechanical system are referred to as its mathematical model. In order to make use of the general methods of building equations of motion as shown in Section 2, the nominal model of particular vehicle (object) has to be first determined. In case of railway vehicle, its nominal model projects its structure and selected physical features of the structure elements. The nominal models of two example objects will be presented below. Both are of British origin and possess relatively simple structure that is suitable for the basic character of the author's research. The first model [1, 5, 17] corresponds to 2-axle hsfv1 freight car and is shown in Figure 2. The second one [1, 18] corresponds to 4-axle MKIII passenger car and is shown in Figure 3.

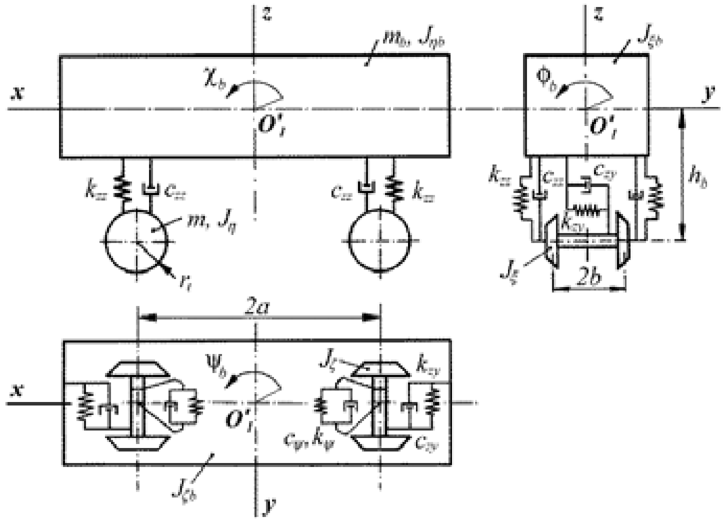

Figure 2. Nominal model of 2-axle freight car hsfv1 [1, 5, 17]

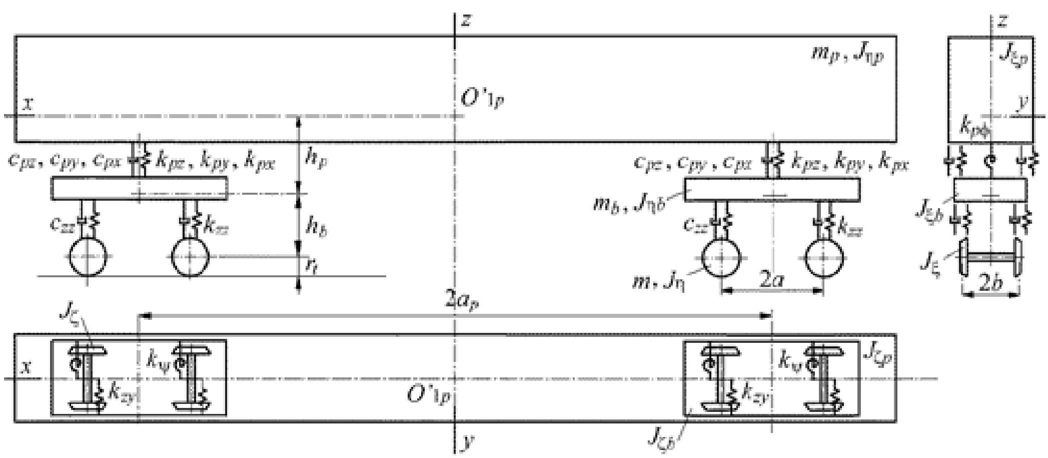

Figure 3. Nominal model of 4-axle passenger car MKIII [1, 18]

If the flexibility of track is going to be taken into consideration in the study, then some track nominal models should be adopted. In case one considers low-frequency dynamics of the vehicle motion (not more than 50 Hz) but not the higher-frequency phenomena in the track itself, then it is reasonable to build the track model that is composed of rigid bodies. Then the whole vehicle-track system model is a multibody model. Separate models for lateral (Figure 4) and vertical (Figure 5) directions as used by the author in his studies are presented below [1, 5, 17, 18].

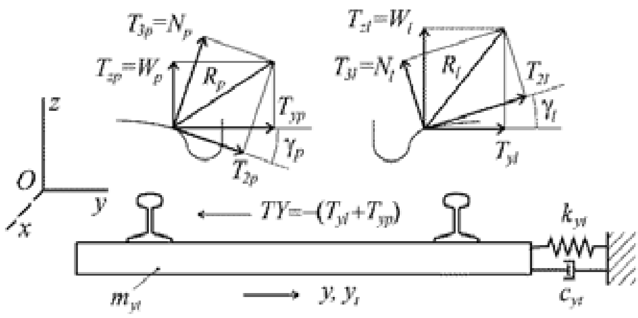

Figure 4. Nominal model of track flexible laterally [1, 17, 18]

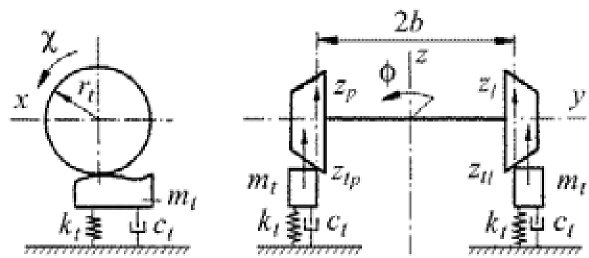

Figure 5. Nominal model of track flexible vertically [1, 17, 18]

The denotations used in Figures 2–5 are as follows: m is the mass; J_ξ, J_η, J_ζ are the inertia moments in longitudinal, lateral, and vertical directions, respectively; k, c are the stiffness and damping in the flexible elements in general; k_z , c_z , k_p , c_p are the stiffness and damping in the flexible elements of primary and secondary suspension, respectively; x, y, z are the linear displacements (coordinates) in longitudinal, lateral, and vertical directions, respectively (if used as indices, they indicate the corresponding directions); ϕ, χ, ψ are the rotations (angular coordinates) around axes of longitudinal, lateral, and vertical directions, respectively (if used as indices, they indicate the corresponding rotations); 2a, 2b are the vehicle or bogie base; h, r_t are the vertical dimensions and wheel rolling radius; N, T, W are the normal, tangential, and load forces in wheel/rail contact, respectively; γ is the contact angle. The indices used indicate p as the passenger car body or right-hand side, l the left-hand side; b the bogie or freight car body; and t the track. Values of the abovementioned parameters of models can be found in Refs. [1, 5, 17].

The whole hsfv1 car-track system model has 18 degrees of freedom (DOFs). The whole MKIII car-track model has as many as 38 degrees of freedom.

3.2. Numerical models

When mathematical models derived traditionally are available, based on general methods of the equations building as described in Section 2 and adopted nominal models as, for example, those shown in Section 3.1, then they have to be converted to numerical models. When AGEM approach is used to build the equations, based again on the results of Section 2 and Section 3.1, then equations automatically form the numerical model. The numerical models are indispensable, since rail vehicle systems are multidimensional ones. In addition, their nonlinear versions are mainly used at present. The only way to solve dynamical differential equations of motion of such systems is numerical integration. In order to do this, the numerical model representing the mathematical model in a form understandable to computers must be built, which means that the equations have to be coded in some of the programming languages. In the case of this author, it is Fortran. Then, the equations are solved with use of one of the numerical methods of equation integration. The author uses Gear's method [19]. The software containing traditionally derived equations of motion or generating the equations automatically combined with the integration procedure is called the simulation software in railway vehicle dynamics.

In order to make use of the procedure, shortly described above, three additional major elements have to be provided. The first one is to adopt the model and then to build its numerical module to take account of relative kinematics arising from description in moving coordinate systems. Strictly speaking, the linear and angular velocities and accelerations of transportation, represented with functions $u(t), v(t), w(t)$ in Section 1.1 and with vectors $\boldsymbol{a}_{o1}, \boldsymbol{\omega}, \boldsymbol{\varepsilon}$ in Section 2, have to be determined. The author of this paper worked out a general method of their determination, which is a numerical calculation-oriented method [2, 1, 20]. Its generality arises from any three-dimensional track shape acceptable in the method. The most important requirement in the method is the description of the three-dimensional curve by parametric equations, with its length as the parameter. In fact, the three-dimensional case corresponds to transition curves (TCs) with the superelevation ramps, while circular (regular) curves (CC) and straight track (ST) are two- and one-dimensional special cases, respectively. The components, expressed analytically, of the velocities and accelerations of transportation for several types of TCs, CC, and ST can be found in Refs. [1, 20]. The sources for the algorithm to numerically determine the components for polynomial TCs are Refs. [21, 1].

The next element is tangential contact forces calculation. These forces arise from wheel/rail relative slip (creepage). Consequently, the longitudinal, lateral, and spin creepages are the inputs in the existing methods of the tangential forces calculation. Generally, one can talk about the exact and simplified numerical methods of nonlinear tangential contact forces calculation. The problem with the exact methods, as, for example, Kalker's CONTACT program [22], lies in the very slow calculations for the simulation purposes of rail vehicle dynamics. Thus, simplified methods are in use in the simulation programs (numerical models). One of them is Kalker's FASTSIM program [23]. This is just the software used by the present author in his models and so in the studies. Usually, the adopted value of the friction coefficient, necessary for the program to run, in the author's studies is μ=0.3. Other possibilities of tangential contact forces calculation are discussed in Refs. [24–27].

The last among three elements to be discussed is the problem of nonlinear contact geometry. This author uses ArgeCare RSGEO program [28] to address this. The program resolves normal contact problems and purely geometrical ones. As a result, contact areas become known and geometrical variables in the contact. The most important geometrical variables are instantaneous contact angles, rolling radii, and contact point positions on the wheel and rail for any lateral relative shift between wheel and rail. In addition, the program is capable of taking account of the influence of wheelset yaw angle on the parameters. Both the left- and right-hand side wheel and rail parameters are calculated in the same step. The results of ArgeCare RSGEO program (the author uses) are tabulated before simulations for a given wheel and rail pair of profiles as a function of the discrete lateral wheel/rail displacements and yaw angles. To get the contact parameters for any relative displacement and yaw rotation between wheel and rail, the tabulated data are linearly interpolated.

At the end, let us return to the issue already discussed at the beginning of Section 2. It is the way in which the equations of motion in the simulation software (numerical model) are introduced. Here, this refers to the traditionally derived and automatically generated equations of motion (AGEM approach). Now, we will provide some references corresponding to both approaches. If one is interested in samples of the equations traditionally derived by this author, then he could find them in Ref. [29]. If one is interested in details of the package ULYSSES and its core program TITAN co-built by this author, then he can find them in Refs. [1, 2, 6]. The software packages based on AGEM built by other authors are discussed in Refs. [15, 16].

4. Example results of the selected simulation studies

The author of the present chapter has exploited simulation in his studies for more than 20 years. There is no possibility to refer to all of them. Readers interested in earlier applications of simulation by the author can find reviews of the corresponding references in Ref. [20]. Similar review, however, also including current applications, is done in Ref. [1]. Total number of all author's applications runs to tens. Due to the limit of space, just two applications of simulation used in currently studied problems will briefly be discussed in the following sections. Their content will be focused more on the achievements, contributions, and final results than on the details of the methods or procedures used in those studies. Interested readers will be informed about the essential publications where the details can be found. These publications can also be treated as a main base source for the results discussed further. The secondary source is Ref. [1]. The applications in view concern the stability and kinematics issues.

Two other applications extensively studied at present are connected with TC shape optimization with the use of simulation and optimization methods as well as with dynamics of railway vehicles in TCs at velocities around the critical v_n. The example publications on these problems are Refs. [21, 30] and [31, 32], respectively.

4.1. Results of simulation use in rail vehicle nonlinear lateral stability studies

The serious interest of the author on the stability problems started with reference [17]. The most important results were presented many years later in Refs. [33, 34]. The fundamental reference to the methods used by this author, based on bifurcation approach and on usage of the simulation, is [35]. Recently, the remarkable contributions have been by H. True and his coauthors (e.g., see Refs. [36, 37]). Works by O. Polach (e.g., see Ref. [38]) are also interesting. Much more comprehensive and detailed literature review can be found in Refs. [1, 33, 34].

The meaning of stability is fundamental in the discussed problem. This author could describe its meaning in most of his works as follows. The used method of nonlinear lateral stability analysis regards formal theory of stability. By contrast, it is not so formal as compared with the methods based strictly on the theory. Instead, one finds the tool to be more practical. The simplification is based on adoption of certain assumptions as well as on behavioral expectations for the studied system. They arise from commonly existing knowledge about the systems in the type of rail vehicle. Therefore, one can skip formal adoption of some solution as the reference in the simplified approach. Moreover, he can skip introducing some perturbations into the system to examine whether the new solution stays close enough (in narrow vicinity) to the reference solution. Such a stay is required by the formal definition of the stability theory. Taking account of that, bifurcation plot building for the system is the main task in the method. However, formal verification whether the solutions enabling to build this plot are stable in completely formal sense is not such a task. The assumption exists in the method that any typical solution of rail vehicle system (either stationary or periodic) is stable. It might be accepted with care basing on understanding that periodic solutions in rail vehicle dynamics are self-exciting vibrations being governed through the wheel–rail tangential contact forces. Following that, the theory of self-exciting vibrations can be useful in order to predict/expect typical periodic behavior of the system. The adopted assumption enables to limit the number of simulations for different initial conditions but the same given velocity. Such simplified approach is described in Ref. [29]. In case of any doubts if obtained solution is stable or about the possibility of multiple solutions existence, more formal check for the stability is a must. Then, reasonably a denser sweeping over the initial conditions, to introduce the perturbation, is performed. Such a more accurate approach is called the extended analysis and is described in Ref. [30].

The author has been especially interested in the stability of rail vehicles in a curved track from the very beginning of his interest in stability problems. The studies were initiated as a result of the observed periodic solutions in a circular curve of track. They appear for velocities v greater than the nonlinear critical velocity v_n, exactly as in a straight track. The only difference relative to ST case is asymmetry of the results in relation to track centerline. Results of such kind are shown in Figure 6. Based on that fundamental observation, the studies were carried out focused on the influence of chosen factors on the stability in CC.

They involved curve radii R from the small to large ones and ST as well, where $R=\infty$. The principles of these nonlinear stability analyses were adopted from the analysis in a ST. However, the important supplements to ST analysis were necessary. These supplements are shown in Figure 7. They finally resulted in the formally presented method of the nonlinear stability analysis in a curved track (CC).

It was successively improved for years and recently published in Refs. [33, 34]. The essence of this method is included in Figure 8.

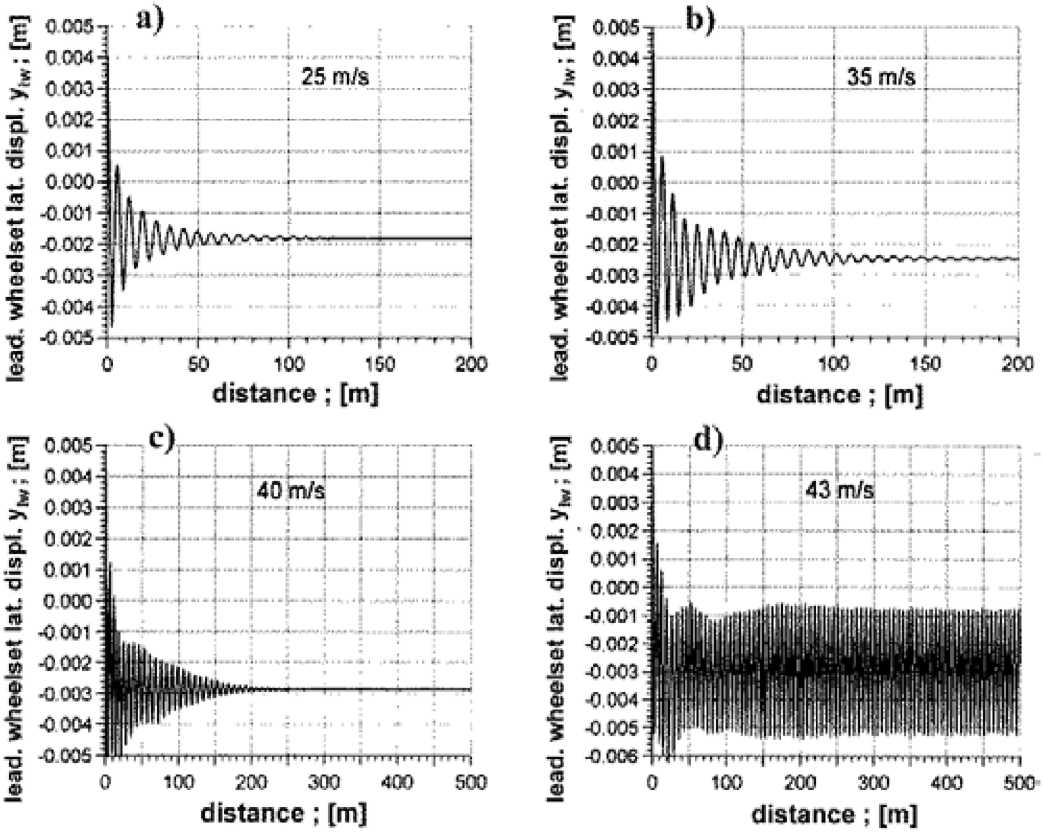

Figure 6. Stable stationary and periodic solutions for R=600 m and velocities v below and above v_n [1]

The meaning of the symbols and acronyms present in Figure 8 is as follows: v_c, v_n, v_s is the linear critical velocity, nonlinear critical velocity, velocity of calculation stop due to unbounded growth of the solution, respectively; sss, sps are the stable stationary and periodic solutions, respectively; uss, ups are the unstable stationary and periodic solutions, respectively; SNB, HSB are the saddle-node and Hopf's bifurcation point, respectively. All these notions are well known in the nonlinear stability studies in ST. The method consists in building a pair of bifurcation plots as in Figures 8a and 8b based on the results of simulation as shown in Figures 8c and 8d and obtained subsequently for whole range of velocity of motion v and given curve radius R. If one decides to include in both bifurcation plots results for whole range of R, then one obtains complex bifurcation plots. Such a pair of the complex bifurcation plots was named stability map in Ref. [39]. The example stability maps, as in Refs. [33, 1], are shown in Figures 9 and 10. Note that the unstable solutions are omitted in these figures as those are less important because they are not observable in the real systems.

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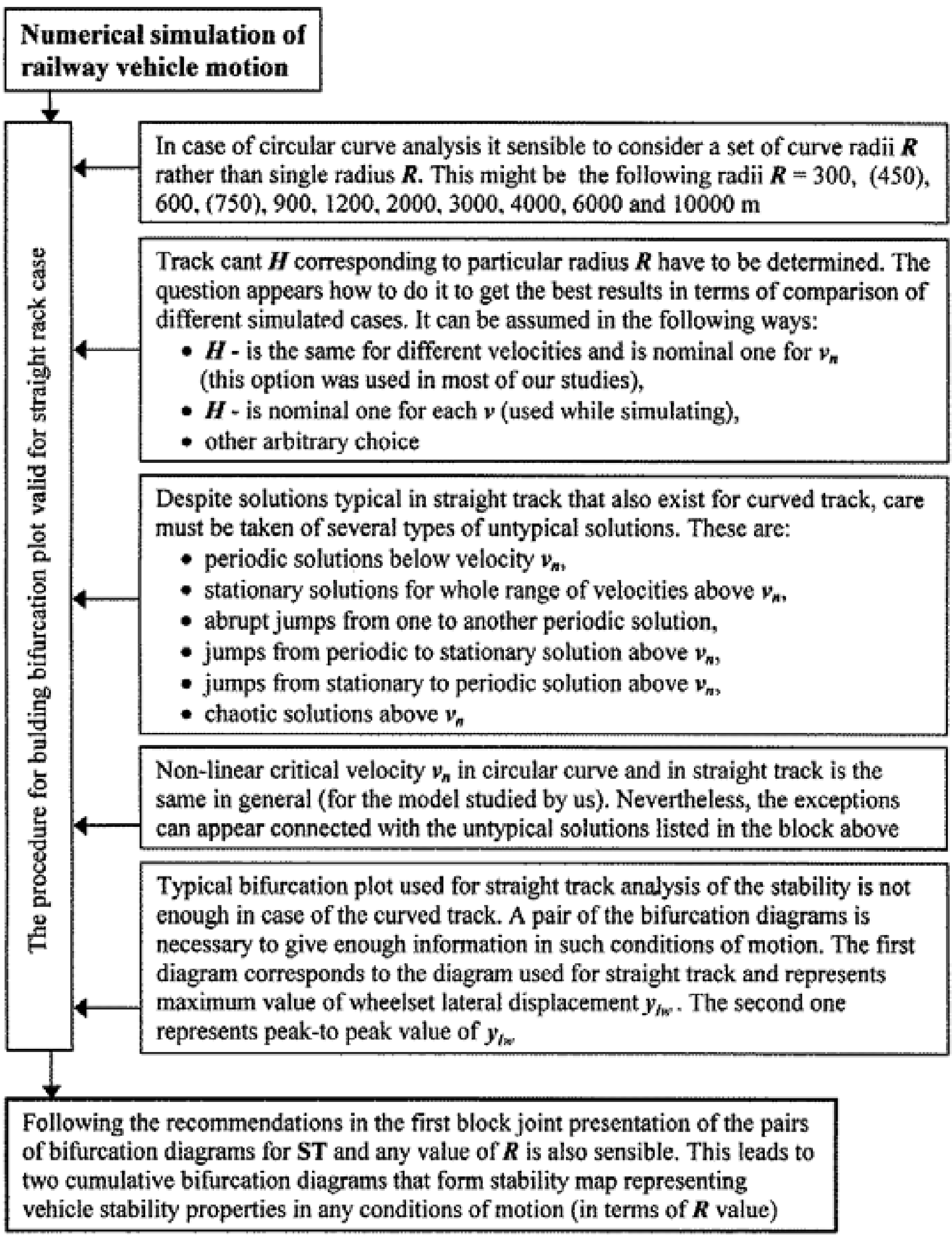

Figure 7. Supplements to the nonlinear lateral stability analysis in ST, necessary in CC analysis [33, 1]

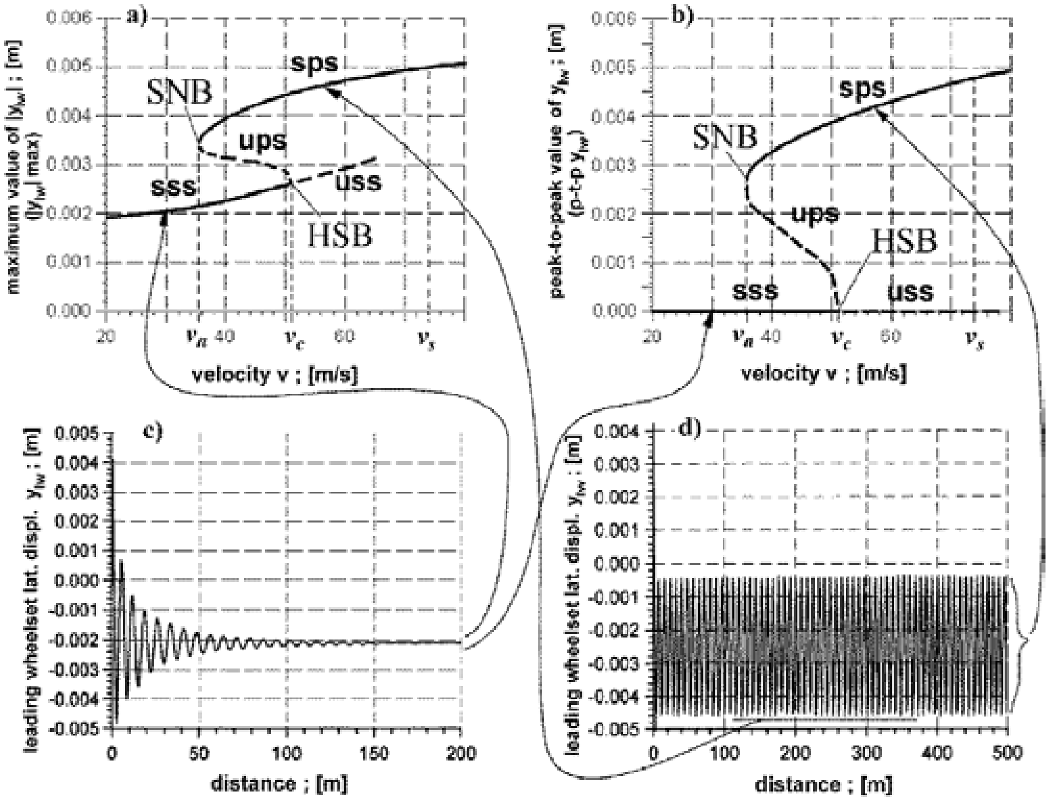

Figure 8. The essence of method of stability analysis in a CC, i.e., building the bifurcation plot [34, 1]

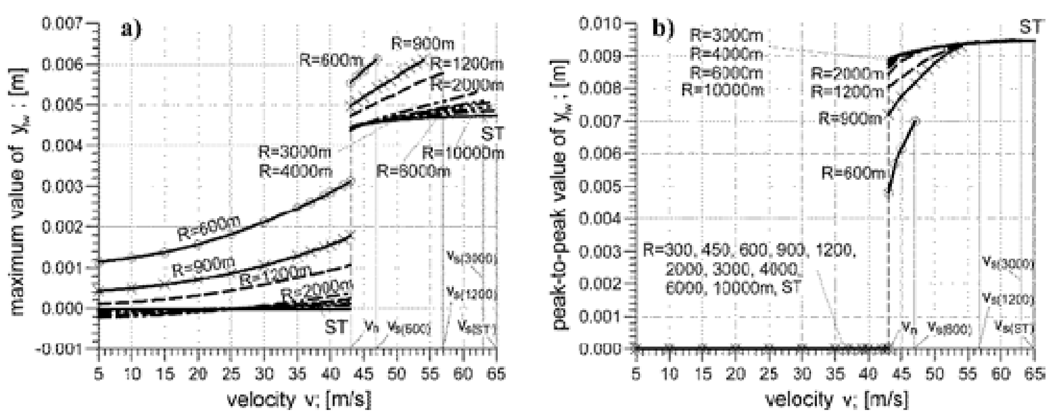

Figure 9. Stability map for hsfv1 car for S1002/UIC60 wheel and rail profiles: (a) leading wheelset lateral displacements y_{lw} and (b) peak to peak values of displacements y_{lw}

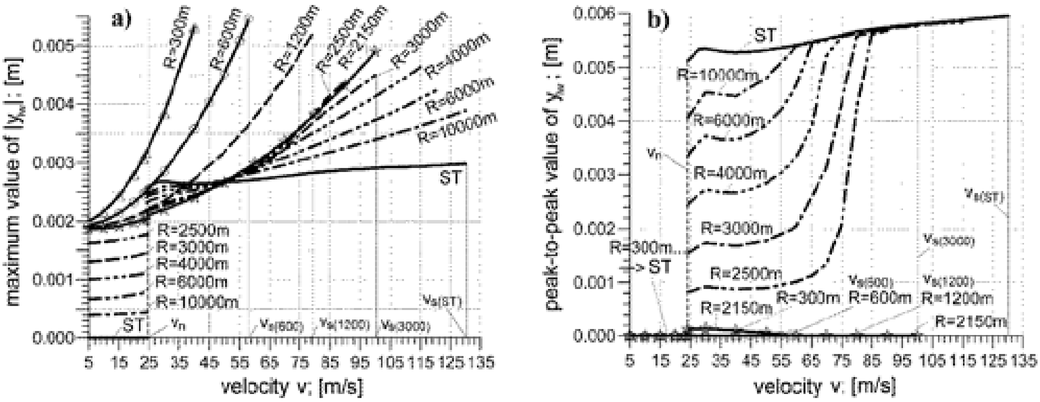

Figure 10. Stability map for hsfv1 car for SZDwheel/R65 wheel and rail profiles: (a) leading wheelset lateral displacement absolute values y_{lw} and (b) peak to peak values of displacements y_{lw}

The influence of several factors on the stability was studied based on the stability map technique. Among the factors studied are accuracy of wheelset's angle of attack determination, track superelevation, types of nominal wheel and rail profiles, type and value of the wheel and rail wear, stiffness and damping values in suspension, type of vehicle (car and bogie), rail inclination, way of mean rolling radius modeling, track gauge, and value of coefficient of friction. Figures 9 and 10 can represent part of the results for one of the factors, namely the wheel profile shape. Both maps were obtained for the same object, however, with different nominal wheel profiles. One can observe significant differences between both maps. One among the most important differences are nonlinear critical velocities v_n of 43 and 24.1 m/s, respectively. Another is the existence of quasi-static solutions for R<2150 m in Figure 10. This can be easily recognized as no vibrations appear, resulting in p-t-p y_{lw}=0, for such values of R in Figure 10b. In Figure 9, vibrations appear for all R values represented there. More differences are discussed in Refs. [33, 1].

The results in Figures 9 and 10 refer to 2-axle freight car hsfv1 of the model shown in Figure 2. Example results of stability studies for the model of MKIII passenger car shown in Figure 3 can be found in Ref. [18].

4.2. Use of the simulation in studying the influence of kinematics accuracy on vehicle dynamics in a curved track at variable velocity

Use of Option 2 from Section 1.1 to build mathematical and numerical models of vehicle-track systems by the present author, made it natural that he was always interested in the importance of accurate modeling relative kinematics connected with description in moving reference systems. This interest was amplified since an additional work is necessary as compared with description in absolute reference systems. Besides, some of the authors neglect additional terms (imaginary forces) in their equations of motion, without proper justification. Good examples of such works might be provided in Refs. [3, 40–42]. Author of this book chapter undertook two stage attempt to finally resolve the problem of particular inertia terms importance. The first one concerned vehicle motion with constant velocity. It finished with publication [5]. The second attempt concerned the motion with variable velocity and finished with publication [4]. Publication [4] is also verification of the results from [5], as motion with constant velocity was just a special case in Ref. [4]. Therefore, Ref. [4] is the main source for results forthcoming in the current section. These results were also published in Ref. [1]. Both Refs. [4] and [1] present the issue in a comprehensive form. Here, only samples of the results and most general conclusions will be represented.

The idea of the study was to compare the results for the vehicle model with all imaginary forces included with those for the model in which the imaginary forces were omitted. In order to precisely determine importance of particular terms types, the forces (and torques) were selectively, rather than totally, omitted. Let us now recognize the generalized imaginary forces according to Ref. [7]. Here, equation (24) will be useful. The forces' terms are present in the second line of this equation and the torques' terms are present in the fourth line of it. Note that all the terms are multiplied by the corresponding linear and angular partial velocities. Therefore, we can refer directly to content of the square brackets in lines 2 and 4. Making use of that idea, the 1st term in the square bracket in line 2 represents inertia forces of translation. The 2nd term in line 2 and 1st one in line 4 form inertia forces of rotation. The 3rd term in line 2 and 2nd one in line 4 correspond to centrifugal forces of inertia. The 4th term in line 2 and the 3rd in line 4 make gyroscopic forces. The abovementioned four categories of imaginary forces' terms appear in the equations as the terms' components corresponding to the direction a particular equation of motion describes. Finally, the omissions of all components for given directions were performed. In fact, these were longitudinal, lateral, and vertical directions. At the end, for the given direction, the analyses were performed to find the components of the terms of particular (practical) importance among all.

The variable velocity was realized in the studies with use of the uniform variable motion. The change in velocity is indirectly represented by the corresponding acceleration value a. Consequently, negative values of acceleration a mean deceleration, corresponding to vehicle braking, the positive values of a mean vehicle acceleration, corresponding to its speeding up, while zero value of a means motion with constant velocity, that is, v=const. Different intensity of braking or speeding up were realized with different acceleration values.

4.2.1. Scope of the studies and example results of simulation

Generally, the tests described in Ref. [4] represent seven different routes and two different vehicles. The routes included radii R=300, 600, 1200, and 2000 m and were composed in continuation either as ST, TC, and CC or as ST, TC, CC, TC, and ST. Thus, the entrance TCen and exit TCex transition curves were considered. The TCs were of the 3rd degree parabola type. Characterizing all the routes briefly, it has to be stated that their two general types existed. The first type corresponded to real railway conditions. The second one represented the case with unnaturally shortened TC in order to get stronger effects for research purposes. As concerns the two vehicles used in Ref. [4], the first one was hsfv1 car described in Section 3.1. Second was vehicle referred to as the 2-axle freight car in Ref. [5]. Both models have the same structure as shown in Figure 2, and they are supplemented with the same track models from Figures 3 and 4. This also results in the same number of DOFs for both of them. The major difference is that first model represents empty car, while the second one the laden car. The other minor differences in the parameters (see [5]) are negligible, here.

Two types of simulation results are presented below. The first type is imaginary forces being omitted in the study. They are a cause for the solution differences being of interest. The imaginary forces are shown in Figures 11, 14, and 16. The second type of simulation results is those representing the differences between solutions for the whole model and the model with particular imaginary force omitted. They are represented with Figures 12, 13, 15, and 17. Results for complete model are drawn with the solid line, while for the model with imaginary torques omitted with the dashed line.

Just two routes appear in the mentioned figures. The route I is as follows: ST (l=10 m, H=0 m); TCen (l=7 m, R_{min}=300 m, H_{max}=0.15 m); CC (l=30 m, R=300 m, H=0.15 m). Initial velocities for route I were between v_0=10.25 and 15.0 m/s, where the smallest value corresponded to a=0 m/s^2 and the biggest one to a=6 m/s^2. Route I includes TC with length unnaturally shortened for research purposes. Route II is as follows: ST (l=10 m, H=0 m); TCen (l=102, 4 m, R_{min}=600 m, H_{max}=0.128 m); CC (l=60 m, R=600 m, H=0.128 m); TCex (l=102.4 m, R_{min}=600 m, H_{max}=0.128 m); ST (l=40 m, H=0 m). Initial velocities for the simulations were v_0=19.91, 22.0, and 22.09 m/s. They corresponded to a=2, 0, and −2 m/s^2, respectively. Route II entirely corresponds to real railway conditions. In the above given brackets, the denotations are l is denoted as the length of the track section, R as the circular curve radius, and H as the circular curve superelevation. Values of the corresponding accelerations are given directly in the figures in round brackets.

It is worth noting in Figure 11 that it includes the biggest values of the imaginary torque obtained in the author's studies. As is seen, it is the roll imaginary torque $P_{\phi b}$ of hsfv1 car body related to longitudinal direction. Character of the torque changes is rectangular, that is, nonzero values of the torque exist for TC only. Values of this torque depend strongly on value of the acceleration a. The value is biggest for the biggest acceleration a=6 m/s^2 and smallest as well as equal to zero for a=0 m/s^2. The last fact means no influence of this torque on motion with constant velocity v=const. In the case of Figures 12 and 13, strong influence of omission of torque $P_{\phi b}$ from Figure 11 can be observed. The two mostly influenced coordinates are shown. They are roll ϕ_b and yaw ψ_b angles of hsfv1 car body, respectively. Note that the influence on angle ψ_b (Figure 13) is approximately one order of magnitude smaller than on angle ϕ_b (Figure 12).

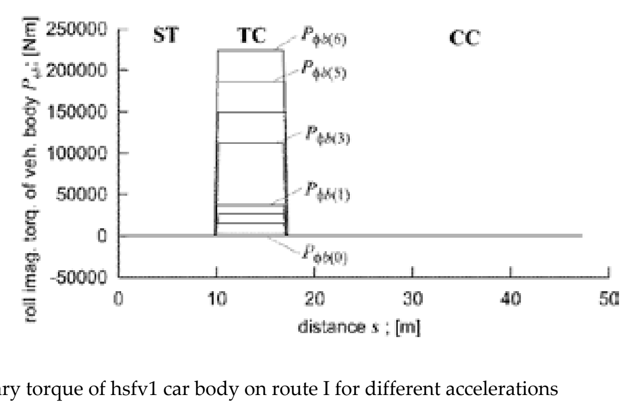

Figure 11. Roll imaginary torque of hsfv1 car body on route I for different accelerations

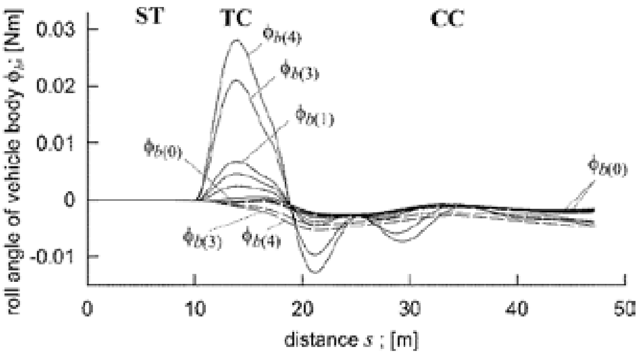

Figure 12. Roll angle of hsfv1car body on route I for different accelerations and roll imaginary torque of hsfv1car body omitted

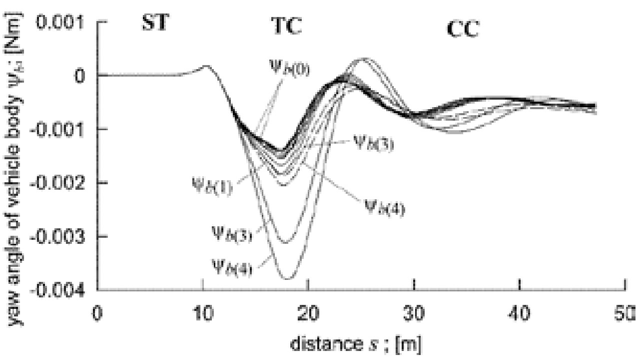

Figure 13. Yaw angle of hsfv1car body on route I for different accelerations and roll imaginary torque of hsfv1car body omitted

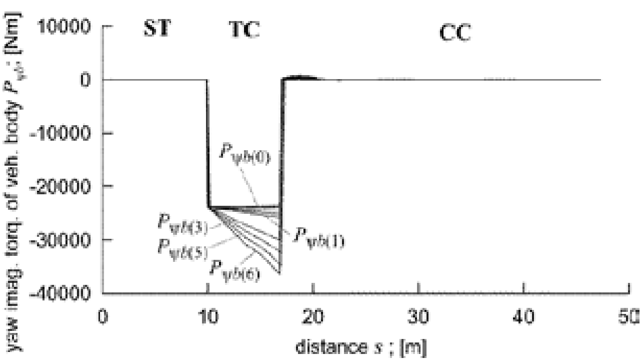

Figure 14. Yaw imaginary torque of hsfv1 car body on route I for different accelerations

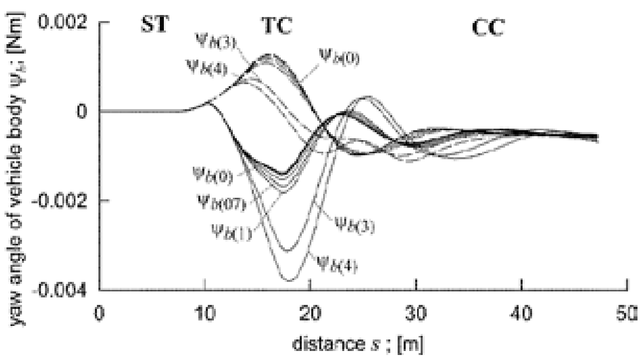

Figure 15. Yaw angle of hsfv1car body on route I for different accelerations and yaw imaginary torque of hsfv1car body omitted

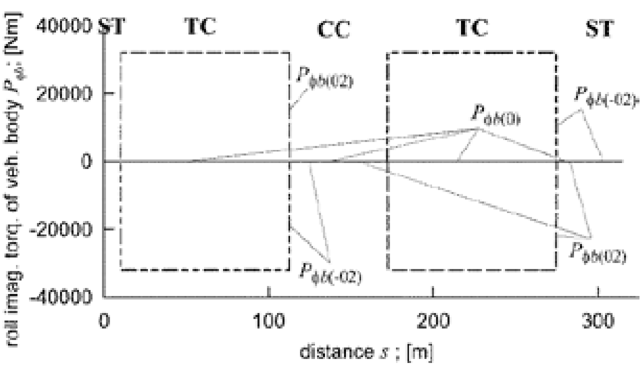

Figure 16. Roll imaginary torque of 2-axle freight car body on route II for different accelerations

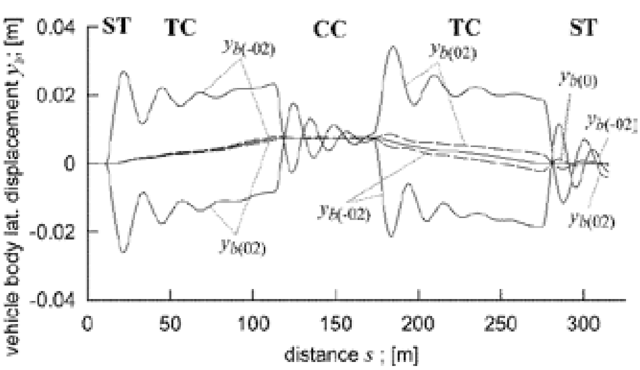

Figure 17. Lateral displacement of 2-axle freight car body on route II for different accelerations and roll imaginary torque of 2-axle freight car body omitted

In Figure 14, the value of the imaginary torque $P_{\psi b}$ of hsfv1 car body, related to vertical direction, is represented. Character of the torque changes corresponds to rectangle supplemented with triangle. The rectangle part is independent of the acceleration a. Therefore, it exists also for a=0 m/s^2. Increase of the supplementary triangle part grows with increase of a. Therefore, the torque value is biggest for the biggest acceleration a=6 m/s^2 and smallest for a=0 m/s^2. Overall, this means that in case of v=const. and a=0 m/s^2 influence of $P_{\psi b}$ omission exists; however, for a>0, it is bigger. This is also the case in Figure 15 for ψ_b, where very strong influence of the omission can be seen. The biggest influence for a=6 m/s^2 is of the same order of magnitude as in Figure 13 related to $P_{\phi b}$ omission. Therefore, it can be concluded that influences of $P_{\phi b}$ and $P_{\psi b}$ omissions on ψ_b values accumulate.

In Figure 16, the character of torque $P_{\phi b}$ for 2-axle freight car is in accordance with that in Figure 11. The difference exists, however, that results from route II configuration. One can observe opposite signs of $P_{\phi b}$ for the entrance TC (TCen) and exit TC (TCex). The sign becomes also opposite when opposite acceleration a sign is adopted. In Figure 16, this case corresponds to a=2 m/s^2 and a=−2 m/s^2. In Figure 17, for 2-axle freight car very strong influence of $P_{\phi b}$ omission on vehicle body lateral displacements y_b can be observed. The changes in signs for y_b correspond to those for the $P_{\phi b}$ described above provided one remembers that if $P_{\phi b}$>0 then y_b<0 and vice versa.

4.2.2. General conclusions from the study

Except the important influences described in Section 4.2.1, some other important influences were found and indicated in Ref. [4]. Therefore, except influences of $P_{\phi b}$ on ϕ_b, y_b, and ψ_b, the important influence on the wheelsets' lateral displacements y_{lw} and y_{tw} exists. Except the influence of $P_{\psi b}$ on ψ_b, very serious influence on the wheelsets yaw angles ψ_{lw} and ψ_{tw} exists. Assuming that lateral component (parallel to track plane in curved track) is known for its importance, the vertical component (perpendicular to the track plane) was studied. It appeared that the influence of this component omission on the results, especially vehicle body vertical displacements z_b, is also significant.

Conclusions from the studies, including track section, character of velocity, vehicle elements, direction defining equation, and purpose of calculations, were summarized in table form in Ref. [4]. Here, we present them in Table 1. This table is analogous to that in Ref. [4] in terms of merits. Nevertheless, Table 1 is differently arranged.

Generally, the most important are longitudinal and vertical direction terms related to car body. The influence of eventual term omission is particularly important in TCs. The centrifugal force is important in both the TCs and the CC sections. The influence in TCs increases as compared with CC when the vehicle moves with variable velocity. The stronger the change in velocity (both accelerating and braking), the greater the influence. The last column represents a direct recommendation of terms that should not be neglected.

Group of the imaginary forces	Term/line no. in Equation (24)	Force/Torque	Importance generally	Important sections of track	Important directions	Velocity constant/variable	Important elements of vehicle	Particularly important conditions	Practice/Research	General recommendations for omission
Inertia forces of translation	1/2	Force	Yes	ST, CC, TC	Long. (O_1x)	Var.	All	Always, big $\|a\|$	p/r	**No**
Inertia forces of rotation	2/2	Force	No	---	---	---	---	---	---	Yes
	1/4	Torque	Yes	TC	Long. (O_1x) vert. (O_1z)	Var. const. (vert.)	Body	Short TC (long.& vert.), big $\|a\|$ (long.)	p/r	**No**
Centrifugal forces	3/2	Force	Yes	CC, TC	Lat. (O_1y) vert. (O_1z)	Const. var.	All (lat.), body (vert.)	Always, big v, small R	p/r	**No**
	2/4	Torque	No	---	---	---	---	---	---	Yes
Gyroscopic forces	4/2	Force	No	---	---	---	---	---	---	Yes
	3/4	Torque	Yes	CC	Long. O_1x	Const.	Wheelset	Small R (R<600m), big v (v "/>v_c)	r	No

Table 1. Importance and recommendations for imaginary forces omission in rail vehicle dynamics

5. Concluding remarks

The author of this chapter has been involved in technological problems of railways for about 30 years. More precisely, his involvement concerns part of the railway system that are railway vehicles. Within the railway vehicles, many areas of studies can be mentioned as, for example, material issues, production technical issues, braking systems issues, traction systems issues, construction issues, exploitation issues, control issues, safety systems issues, etc. The author is interested in dynamics of vehicle motion with a special regard to the motion in curved sections of the track. It is obvious that the chapter was devoted to these last aspects. The author focused his efforts on giving the idea to the readers how important and powerful tools are methods of modeling and simulation when used for the purposes of the rail vehicle dynamics.

In Sections 1 and 2, the general methods of modeling dynamics in moving coordinate systems, useful for multibody systems of rail vehicle type, were represented. The Newton–Euler and Kane's equations in the form suitable in AGEM approach were discussed. At the end of Section 2.2, the method profiled for rail vehicle systems was also presented. These methods help build mathematical models of rail vehicle dynamics. In Section 3, example nominal models of rail vehicles were introduced, as used by the author. In that section, the issue of building numerical models corresponding to the mathematical ones was also discussed.

In Section 4, two examples of the author's simulation studies, with use of the numerical models, were discussed. The first example represented in Section 4.1 concerned the problem of rail vehicle stability in a curved track. Due to the author's systematic and consequent simulation studies, the method was formulated suitable for rail vehicle nonlinear lateral stability studies in a curved section of the track. The examples of the so-called stability map, being the most important result in the studies, were shown and briefly commented on. The stability maps approach was used by this author to study the influence of different factors on the results of stability analysis in a curved track.

The second example is represented in Section 4.2. It was devoted to the use of the simulation in studying the influence of kinematics accuracy on vehicle dynamics in a curved track at variable velocities. In fact, both the constant and variable velocity cases were of interest. Due to the consequent author's interest in this issue, it appeared possible, based on the direct results of simulation and equation terms analysis, to resolve the problem in full. The author presents tabular conclusion of the results in Section 4.2.2. The table states precisely which imaginary forces terms, in what conditions, and for which vehicle major elements (bodies) may have an important influence on the simulation results. The last column states that imaginary force of translation, imaginary torque of rotation, and centrifugal force should not be neglected in both theoretical and practical analyses (calculation). The gyroscopic forces should not be neglected in the theoretical issues as well.

Both described results of the simulation studies are original and important contributions to the knowledge on rail vehicle dynamics. These contributions would not be possible without the mathematical, nominal, and numerical models of vehicles build based on the modeling methods discussed in the chapter. Therefore, it is hoped that the readers have obtained an idea of the efficiency and importance of both the modeling and the simulation for the development of contemporary rail vehicle dynamics, and thus the railways in general.

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http://dx.doi.org/10.5772/62105

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Edited by Krzysztof Zboinski

This book focuses on selected research problems of contemporary railways. The first chapter is devoted to the prediction of railways development in the nearest future. The second chapter discusses safety and security problems in general, precisely from the system point of view. In the third chapter, both the general approach and a particular case study of a critical incident with regard to railway safety are presented. In the fourth chapter, the question of railway infrastructure studies is presented, which is devoted to track superstructure. In the fifth chapter, the modern system for the technical condition monitoring of railway tracks is discussed. The compact on-board sensing device is presented. The last chapter focuses on modeling railway vehicle dynamics using numerical simulation, where the dynamical models are exploited.

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