Revisiting the causes of the Hatfield Rail Crash

By Prof Roger Kemp MBE FREng

Executive summary: In October 2000, an InterCity 225 train derailed south of Hatfield station, resulting in four fatalities and more than 70 people injured. The official inquiry blamed failures of the maintenance contractor and poor supervision by the infrastructure manager. Viewing the accident as the outcome of a failure of a complex system suggests that much of the blame rested with the governance arrangements created by the privatisation of the rail network.

Tags: transport, train derailment, train accident, business restructuring, privatisation, East Coast Main Line (ECML), qualitative analysis, complexity, budget commitments, United Kingdom

Section 1: Background and introduction

The accident

On 17 October 2000, an InterCity 225 train (IC225) bound for Leeds left London King's Cross at midday and was travelling north on the East Coast Main Line at 185 km/h when it derailed south of Hatfield station. The train travelled a further 1 km after derailment. The leading Class 91 locomotive and the first two coaches remained on the track. The rest of the coaches were derailed. The buffet car hit two overhead line structures after derailing, resulting in severe damage to the vehicle and the death of four people. In total, more than 70 people were injured, several seriously.

The case study

A model for complex systems failure produced by York University, as part of the Safer Complex Systems project[1], identified two main processes for reducing risk: design-time controls and operation-time controls. It is clear from reading its 2006 report that the official inquiry concentrated on the operation-time controls – in particular the performance and supervision of the maintenance contractor. In the 250-page document, there was almost no reference to how the railway had arrived at a situation where normal operation resulted in a hazardous situation.

This case study discusses how the inadequacy of design-time controls and a consistent and knowledgeable governance structure contributed to regular rail cracking in service. This is a complicated situation that involves both the dynamics and metallurgy of the wheel-rail interface and the politics and governance of the national infrastructure. An appendix provides more detail on technical issues.

The official inquiry

The Inquiry[2] concluded that "The immediate cause of the derailment of the Great North Eastern Railway express passenger train on 17 October 2000 was the fracture and subsequent fragmentation of the [outer] rail on the [northbound] fast line at the Welham Green curve. The rail failure was due to the presence of multiple and pre-existing fatigue cracks in the rail." The underlying causes identified by the HSE (Health and Safety Executive) investigation were that the maintenance contractor at the time, Balfour Beatty Rail Maintenance Ltd (BBRML), failed to manage effectively the inspection and maintenance of the rail at the site of the accident. The investigation also found that Railtrack PLC, the infrastructure controller at the time, failed to manage effectively the work of BBRML.

A preliminary investigation found that the rail had fragmented as trains passed and that the likely cause was rolling contact fatigue (RCF). Repeated high loading caused fatigue cracks to grow. When they reached a critical size, the rail failed. Portions of the failed track at Hatfield were reassembled and numerous fatigue cracks were identified.

The problem of RCF was known about before the accident. It had been studied in the British Rail's Railway Technical Centre during the 1970s and the Inquiry was shown a December 1999 letter warning that the existing Railtrack Line Specification was insufficient to guard against this type of fatigue[3].

Since privatisation, Railtrack had divested much of BR's engineering knowledge to contractors. "The Investigation revealed possible training deficiencies for some of the Railtrack staff involved in the auditing process. Railtrack's LNEZ Compliance and Engineering Manager, in interview, said he was

Royal Academy of Engineering
LR Foundation

unable to follow discussions of track work at Hitchin because of its technical nature. The Zone Quality Standards Manager stated in an interview: "I do not have knowledge of railway engineering nor railway safety". The job description for the Zone Quality Standards Manager requires 'excellent knowledge of railway engineering safety and contractual matters'.[4]

The effect on Railtrack

As a result of the accident, Railtrack suffered a major loss of reputation and shareholder confidence and was declared bankrupt. The infrastructure, along with its assets and liabilities, was taken over by Network Rail, a government-owned company.

In 2003, five managers and two companies – Network Rail (as successors of Railtrack) and the division of Balfour Beatty that maintained the track – were charged with manslaughter and breach of health and safety regulations in connection with the accident. The trial began in January 2005. In July, Balfour Beatty changed its plea to guilty on the health and safety charges and, on 6 September, Network Rail was found guilty of breaching health and safety law. All of the manslaughter charges against the executives were dismissed by the judge.[5]

Section 2: Analysis and insights

Why was the rail prone to RCF?

The wheel-rail interface is an area that has, over the years, been subject to many debates between train designers, operators and infrastructure managers. It is a complex technical area and the specification of the interface involves many compromises. (See appendix for details)

Rolling contact fatigue (RCF) is triggered by a combination of contact pressure between the wheel and the rail, the longitudinal forces between the wheel and the rail surface and the number of wheels passing the site.

Contact pressure is the weight on the wheel divided by the contact area. The latter is influenced by the wheel diameter and by how well the wheel profile is matched to the rail profile. Longitudinal force is determined by the levels of acceleration and braking, but also by suspension characteristics.

It can be seen from the appendix that the factors that influenced RCF were decided on the basis of disconnected criteria – some to reduce risk in other areas; some to keep down costs; and some to improve access for wheelchairs. Decisions were taken (or, at least, strongly influenced) by infrastructure managers, train operators and designers, safety authorities, pressure groups and the overriding government limit on costs. RCF was not specifically considered but was an outcome – a so-called emergent property.

How did this situation come about?

Privatisation

During the second world war, the British government took a management role in many key industries and the aftermath of the war saw the traditional balance between capital and labour shifted in favour of the latter.[6] The Conservative Government, elected in 1979, had an ideological commitment to reducing the power of the trade unions, shrinking the role of the state and 'correcting' the balance between capital and labour. Privatisation of nationalised industries contributed to these aims and, over the next 18 years, the national aerospace, electricity, oil, gas, coal, water, telecomms, council housing, buses and many other industries were sold.

The UK rail industry was privatised over a period, from 1984 to 1997. Initially ancillary businesses (hotels, ferries, etc) were sold, followed in 1989 by British Rail Engineering (the train building activity); then restructuring was implemented to establish strict *commercial* relationships between the different 'shadow franchises', infrastructure units and suppliers. In 1994, the railway infrastructure was transferred to Railtrack. This complied with the EU directive to separate infrastructure from operations, but went much further than in other member states. Finally, rolling stock and other assets were transferred to several dozen private sector businesses.

The assumption was that safety of the network would be assured by compliance with standards laid down by Railtrack's *Safety and Standards Directorate*. Mandatory standards on, for example, the width of gangways are easily managed by a standards regime. The international airline industry has demonstrated that high levels of safety can be achieved when aircraft, airports and air traffic control are managed by many separate organisations; so separation of ownership is not, per se, hazardous, but how the separation is managed is important. Achieving a good compromise between a dozen difficult-to-calculate parameters cannot be achieved by compliance with commercial standards written by bodies unfamiliar with the technical problems that need to be managed.

To some extent, Railtrack maintenance managers had been put in an impossible situation. The design optimisation work had not been done and the level of maintenance needed was well above that envisaged during the privatisation, or budgeted for with Balfour Beatty. It was obvious that a different strategy was needed, but Railtrack didn't have the financial resources, expert knowledge, access to machinery or the political weight within the industry to undertake a disruptive programme of re-engineering.

It should be noted that Network Rail, the successor of Railtrack, instigated a more intensive rail replacement, reballasting and rail grinding programme than either British Rail or Railtrack had achieved – but this required significant capital investment in plant and machinery and a 200% increase in subsidy. This is shown in **Figure 1**, taken from a 2018 government report.[7]

In retrospect, it is clear that privatisation of the rail infrastructure was based on an unrealistic business model that was unable to support the necessary maintenance costs.

Management of the wheel-rail interface

The appendix summarises the complexity of the wheel-rail interface on a railway and the effort that has to go into achieving a compromise between vertical forces, lateral forces, unsprung mass, performance, maintenance costs and all the other factors impacting the infrastucture and vehicles.

The management of bogie stability and the wheel-rail interface had never been particularly good under the British Rail regime and this deteriorated with preparations for privatisation. The strict commercial regime prevented the traditional engineering process of bringing the parties together round a table to decide on how best to resolve interface issues and achieve the 'least bad compromise' between competing objectives. As noted by the Inquiry, privatisation also resulted in responsibilities being allocated to people with no in-depth understanding of the underlying science and engineering.

However, the failure to consider RCF during the design phase cannot wholly be blamed on preparations for privatisation. It was never an issue that appeared in requirement specifications for British Rail locomotives or rolling stock. Probably, this was because it was a complex issue. It was not possible to lay down hard and fast rules in a specification that would 'solve' the problem. As discussed earlier, it was an emergent property that resulted from decisions taken by many different individuals or groups over a long period.

Section 3: Discussion and transferable learnings

The Health and Safety at Work Act and complex projects

The Health and Safety at Work Act 1974 is the primary legislation covering occupational health and safety in Great Britain. It replaced various Factories Acts (since 1833) and the *Offices, Shops and Railways Premises Act 1963*. The legislation was based on the 1972 Robens Report and was focused on factories, offices and other enterprises. Railways and other transport systems were specifically excluded from the report's recommendations.

The Act was designed for a world in which a duty holder could be identified as responsible for an enterprise. It required the duty holder to identify risks and reduce them to As Low As Reasonably Practicable (ALARP).[8] The concept of duty holder works satisfactorily for incidents like the Grayrigg derailment,[9] where investigators quickly came to the conclusion that it was caused by a badly maintained set of points. It works less well when there is not a single

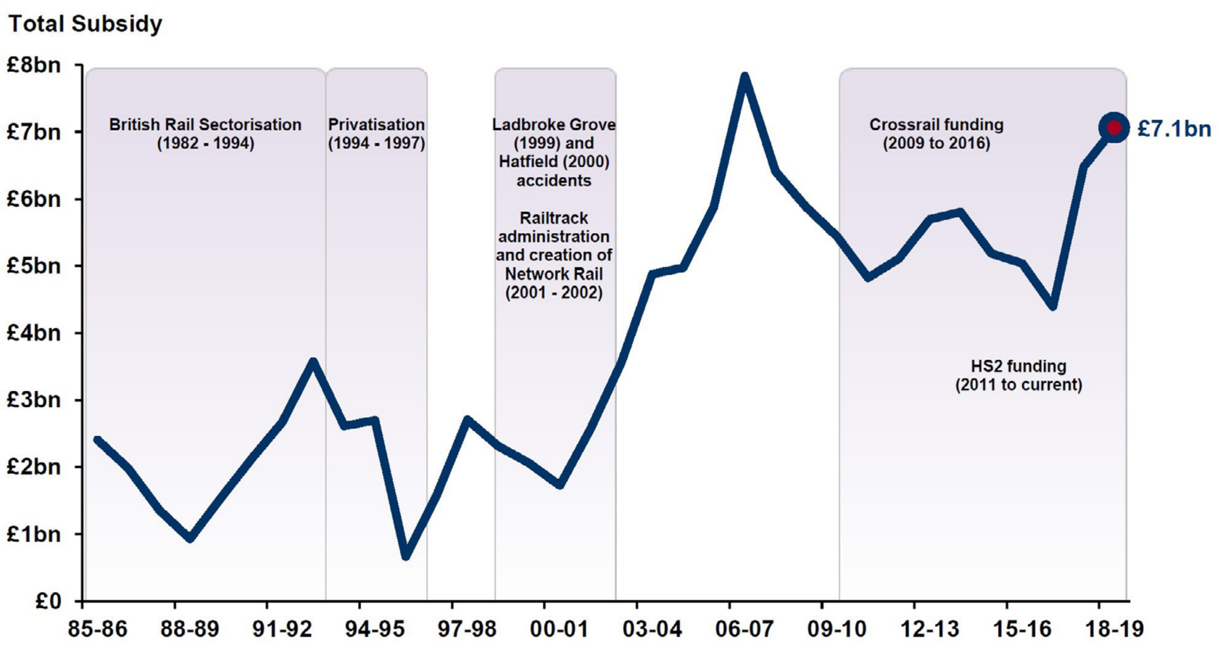

Figure 1: Subsidy to rail industry at 2018 prices.

organisation that can be held responsible. As a recent Lloyds Register Foundation[10] report states: "Many regulatory methods were designed for worlds and risks that can be very different from those faced today. Innovations using technology can now move seamlessly across sector or national boundaries at speeds and scales not previously experienced."

Dividend responsibilities and corporate memory

Under British Rail, responsibilities were split between the engineering and operating departments. In the last resort, the Chairman of the British Rail Board was the person accountable for overall railway safety and for ensuring that adequate precautions had been taken to avoid hazardous emergent properties. All departments of the railway could call on shared expertise on topics like RCF or bogie dynamics in the Railway Technical Centre.

In the privatised railway of the late 1990s,[11] trains were purchased by rolling-stock companies (ROSCOs) and were leased to train operating companies (TOCs) who, after competitive bidding, had been awarded a franchise by the Office of Passenger Rail Franchising (OPRAF), part of the Department for Transport (DfT). TOCs and/or ROSCOs were required to submit a safety case to the safety regulator and/or infrastructure owner (Railtrack) proving that vehicles complied with Railway Group Standards. This responsibility was normally discharged through contracts with suppliers who, in turn, were required to appoint an independent Vehicle Acceptance Body (VAB) to carry out the work. The infrastructure was owned by Railtrack, a private-sector company.

For many aspects, the strands of responsibility for the wheel-rail interface only came together in the DfT. In this structure, there was no single person or organisation accountable for overall railway safety. There was also no shared expertise and no forums where issues, such as managing emergent properties, could be discussed. The Hatfield incident demonstrated the rupture of corporate memory during the privatisation process.

For many years, the HSE has published guidance for company directors on the need to consider health and safety when planning company restructuring.[12,13] If an inquiry determines that a serious accident was, at least partially, the result of inappropriate business re-engineering, legal action might be considered. However, there does not appear to be an equivalent requirement for the restructuring of complete industries by government legislation.

Hatfield – failures of risk management

The introduction refers to a report by York University,[14] which describes a model for the evolution of systemic failures in complex systems, shown in **Figure 2**. The report identified two main processes for reducing the risk: design-time controls and operation-time controls.

Risks propagate through a complex system from causes to consequences to systemic failure. At different stages in the project there are design-time controls and operation-time controls that could reduce the risk. Effective design-time controls can reduce the potential consequences of intrinsic risks that are passed through to system operation. Across both phases, York identified three operational layers: governance, management and technical. In each, there could be exacerbating factors making them less able to manage risk.

When analysing the Hatfield crash, it appears that the York model is lacking a stage – the specification. Before there can be design-time controls, the design team needs to know there is a risk that has to be managed. In the procurement of the 1225 trains, RCF was not identified by British Rail as an issue that train designers needed to be involved with. In the frenetic activity to start work on a project that was won on the basis of a best and final competitive bid with a two-year delivery time and stringent penalties, there were no prizes for diverting design effort onto a list of difficult issues that were not in the specification.

The process of design → operation, assumed by the York report, is meaningful for a discrete project.

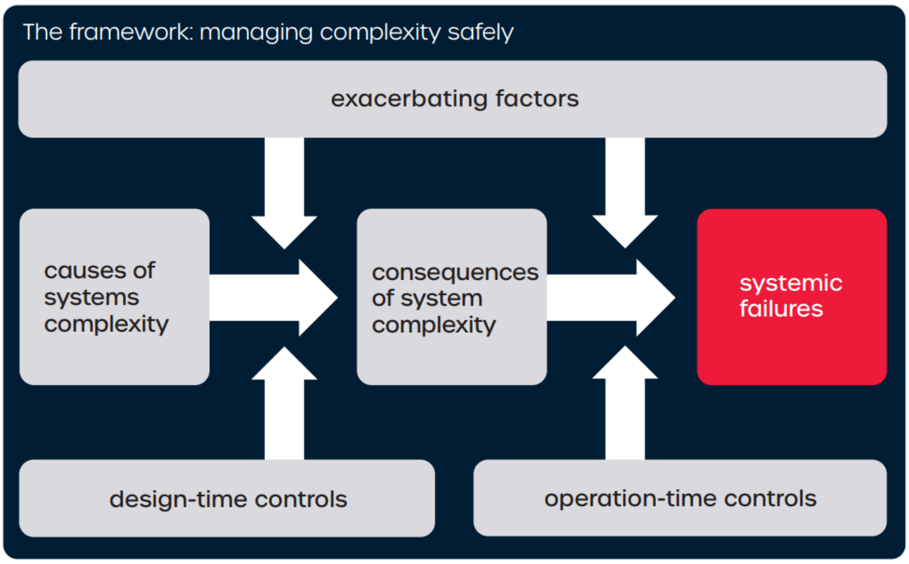

Figure 2: Sources of systemic failures.

It is less useful for managing established infrastructure that has been in continuous use since the mid-19th Century. What was needed, but was lacking, was ongoing technical oversight that kept emergent issues, like RCF, under review and advised on mitigating actions on both sides of the wheel-rail interface. There was no 'through life' governance that tracked, updates and recorded risk profiles through different phases of the evolution of the technology on the network.

The restructuring of the railways in the 1980s was based round a model of independent companies entering into legal contacts with each other where the management layers in the various parties were constrained to work within the Balkanised[15] commercial structure. People in the technical layer were recruited to ensure compliance with specifications, rather than to understand the science behind the systems they were working on. This was particularly true for the VABs which had a 'tick box' culture. As has been found in other investigations, such as that into building fire standards,[16] compliance with standards/ specifications does not necessarily mean something is safe (especially when those checking compliance do not adequately understand the principles behind the standards).

The failure of design-time controls was primarily an issue of governance. The industry was restructured in a way that did not allow interface problems to be adequately resolved during the specification and design phases and thus contributed to a complex system prone to a type of fatigue fracture that could have serious consequences and that placed high demands on the operation-time controls.

A new model of risk management

The 1974 Health and Safety at WorkAct worked well for the stable, self-contained, hierarchical manufacturing companies and similar organisations for which it was originally designed. However, triggered by the reforms of the 1979-1990 governments, the scope and structure of businesses are now radically different. Many public services have been privatised. Industries in both the public and private sectors have been disaggregated so a service or product is delivered by several organisations which may, or may not, have 'joint and several'[17] obligations to maintain a safe service. New funding models, such as special-purpose vehicles, private finance and debt financing, along with multiple layers of subcontracting and a wider use of consultants, have further diluted the sense that a named individual or board of directors is ultimately responsible for a project's safety performance.

Professor James Reason[18] proposed a Swiss cheese model of risk where different layers individually offered incomplete protection against catastrophe but, between them, they prevented hazards turning into disasters. In the current environment, one could consider that the layers include:

- An organisational layer, including a safety management organisation;
- A design and development layer;
- A process layer, including design reviews and safety audits;
- A skills and experience layer, and
- A culture layer.

Each of these layers could provide an impediment to a hazard from turning into a crisis. However, they all rely, to a greater or lesser extent, on the organisation having the appropriate structure and people. If, for example, a railway organisation does not have people with experience of how a railway operates – and how it can fail – it is unlikely that an appropriate safety management system will emerge. The situation prior to the Hatfield crash appeared to be that RCF mitigation in the design phase was largely ignored and safety relied on the single layer of inspection and maintenance.

Living with technology

Earlier sections of this case study, and particularly the appendix, illustrate some of the technical complexity of the wheel-rail interface, the factors that contributed to the growth of RCF and the failure to suppress it. This was partly because the politicians, civil servants and managers setting up the governance and management layers did not understand the RCF process or the risks that could be entailed by failure to manage it. This is hardly surprising – it is a difficult subject that, to understand adequately, requires a level of 'nerdy'[19] understanding not found in most railway managers, let alone in policy generalists.

This is not a problem unique to the rail industry. The National Transportation Safety Board (NTSB) report into the accident on 18 March 2018 – when an autonomous Uber test vehicle struck Elaine Herzberg as she was walking her bicycle across the street in Tempe Arizona – indicates the complexity and in-built assumptions of the automatic decision-making that went into the process of discriminating between a pedestrian, a cyclist and street furniture.

On a related topic, in a 2018 interview with The Guardian,[20] Alison Saunders, the retiring head of the Crown Prosecution Service (CPS), said that Britain's criminal justice system was "creaking" and unable to cope with the huge amounts of data being generated by technology. She said the CPS and police were failing to investigate thousands of cases efficiently – from rape to fraud to modern slavery – and were critically short of the skills and resources required to combat crime.

What general lessons can be drawn from this incident?

This case study has identified three fundamental issues that contributed to the crash at Hatfield:

1. When starting a completely new enterprise using new and potentially hazardous technologies, it is accepted practice to undertake a detailed risk assessment, HAZOP and/or similar processes. In established industries where developments progress slowly, over decades, there tends to be an assumption that the system is fundamentally safe and that each change merely requires a quick check that it does not exacerbate known risks. This is what Sidney Dekker refers to as 'Drift into Failure'[21] (discussed in the appendix).
2. Complex systems have emergent properties that create risk in the system. These can be the result of decisions taken by many different organisations, with no formal relationships. The emergent properties can override layers of safety management that are probably taken for granted, thus placing much greater responsibility on the maintenance processes.
3. Business re-engineering, as a result of takeovers, outsourcing, disaggregation or privatisation can result in a situation where no individual or organisation is responsible for taking a global view of safety. A lesson from this incident might be that, before implementing a major restructuring – such as privatisation or a merger of a safety-related industry or company – those responsible should be required to undertake 'safety due diligence' to investigate how the responsibility for safety would be transferred and to whom as well as the new organisation's vulnerabilities and how these might be affected by the proposed changes. For a large organisation, this could be of equivalent scale to a safety case for a new activity.

An important conclusion of this case study is that the governance, safety audit and regulatory arrangements for complex systems need to evolve at least as quickly as the systems being governed. Procedures originally conceived for regulating self-contained industrial activities with a clear hierarchical management structure may not be appropriate for regulating complex systems with responsibilities spread between many different entities.

Appendix – technical issues

The IC225 train consisted of a Class 91 power car (at the north end) and a set of nine Mark 4 coaches comprising six standard class coaches, a buffet car, two first class coaches and a driving van trailer (at the south end). The train had been specified to have a single power car to reduce costs and also comply with a safety ruling on electrical power transmission between vehicles.[22]

Train dynamics

The dynamic model of a railway vehicle, developed by the Railway Technical Centre (RTC) in Derby, was used by GEC Transportation Projects in the design of the Class 91 locomotive that was involved in the accident.[23] There was a wide variety of train types using the line through Hatfield and most of the design teams for newer models would have followed a similar process.

The Class 91 primary suspension system (between the wheelsets and the bogie frame), shown in **Figure 3**, used coil springs to provide vertical stiffness and rolling rubber ring units to give the necessary lateral and longitudinal restraint.

The means of primary longitudinal restraint is important in understanding the causes of RCF. When a train goes round a curve, the wheelsets attempt to align radially – that is to say the axles point towards the centre of the curve. If the longitudinal suspension is too stiff, the axles remain almost parallel and impose significant longitudinal forces on the rail at the contact with the wheel.

Conicity and bogie stability

On a road vehicle, driven axles are equipped with a differential so that, when going round a curve, the outer wheel can run faster than the inner wheel. On railway vehicles the wheels are linked by a solid axle, but can have different rolling diameters. This is shown, greatly

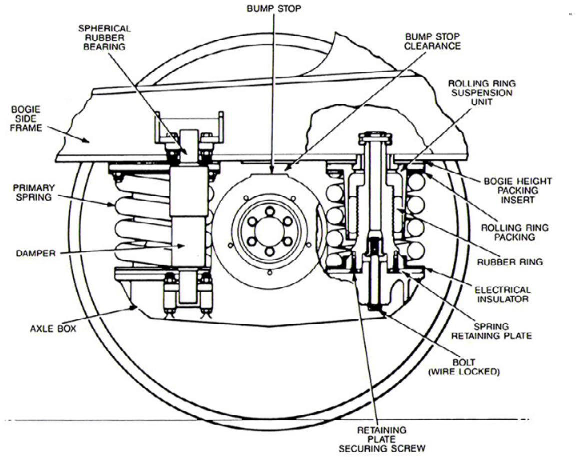

Figure 3: Class 91 primary suspension.

simplified and exaggerated, in **Figure 4**.

The wheel treads are to a first approximation, conical. On straight track, the wheels are central on the track, as shown. On a curve, the wheelset (the pair of wheels and the axle) moves outwards, away from the centre of the curve, so the outer wheel runs on a larger diameter and the inner wheel on a smaller diameter. Obviously, this only works on relatively gentle curves – on sharper curves the wheelset moves to the end of the conical section where there is a flange to prevent it moving further. It is usual to provide flange lubricators, either on the train or the trackside, that apply grease to the flange to prevent excessive wear.

The greater the conicity, the sharper the curve that can be traversed without flange contact and also the greater the centring force applied to the wheelset on straight track. If the centring force is too great and changes too rapidly for a small displacement, the bogie can 'hunt' (oscillate around its central pivot), noticeable by violent shuddering in the passenger vehicle. As a wheel wears, the effective conicity changes.

One of the factors driving up conicity on the Railtrack network was the insistence by infrastructure managers that they should be able to minimise rail replacement costs by transposing left and right rails. If the inside edge of each rail has worn down, by transposing them, the lightly-worn outside edge can be used. Unfortunately, contact between the sharp corner of the rail and the wheel profile created a very high effective conicity. Inevitably, this required high levels of damping in the suspension components. The Class 91 locomotive involved in the Hatfield crash was specified for wheel-rail conicities up to 0.4. In comparison, the French TGV-PSE, its near contemporary, was optimised for a 0.05 conical wheel profile, although it was stable at higher levels.

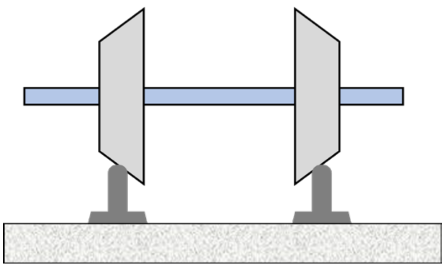

Figure 4: Illustration of conicity.

To avoid flange wear, railways apply lubricant to the flanges on the approach to curves. This can be by 'greasers' mounted on the sleepers that apply grease to passing wheel flanges or high-pressure lubricant sprays mounted on the bogie or stick lubricators (looking like oversize lipsticks) that bear on the wheel flanges. The British Rail privatisation raised several questions about responsibility for maintaining adequate flange lubrication – was it the train operator or the infrastructure owner? Too little lubrication results in flange wear and, in extremis, flange climbing and derailment; too much can contaminate the rail surface and extend braking distances, resulting in signals passed at danger (SPADs) and, potentially, accidents. Following the accident, it emerged that a large proportion of flange lubricators were not working, thus increasing the traction coefficient (see **Figure 6**).

Vertical forces and impact loading

On perfectly smooth track, vertical forces are determined by the axleload. However, real track is not perfectly smooth. Where lengths of track are welded together the weld can be harder than the base metal, so it wears less and, over time, the wheel sees it as a step up, followed by a drop back to the worn surface. There is a similar transient force seen when the wheelset traverses a dipped rail joint. This has long been seen as a problem – a pragmatic comparison of which locomotive types caused track damage (the 160 km/h electric Class 86, with 5 tonne unsprung mass) and which didn't the 160 km/h diesel-powered Deltic locomotives, with a 3.3 tonne unsprung mass). This resulted in the Deltic Criterion against which designs were assessed (**Figure 5**).

Rolling-contact fatigue – an emergent property

Both the conicity/stability criterion and the unsprung mass criterion were 'single input – single output' problems:

- Increase the conicity too much and the bogie goes unstable;
- Too high an unsprung mass causes track damage.

By comparison, rolling-contact fatigue (RCF) is an emergent property. It is caused by the coincidence of three key factors, each influenced by several parameters:

- Susceptible metallurgical properties in the rail;
- High contact stresses;
- High horizontal (particularly longitudinal) forces on the rail surface.

Rail steels are heat treated and quenched. This means that the outer layer of the rail cools and hardens, while the core is still hot. The core then slowly cools and attempts to shrink, thus leaving the outer layer of the rail in compression and the inner core in tension. For this reason, when a crack develops, it first progresses slowly through the outer layer and, when it reaches the core, changes direction and moves relatively quickly through the core, leading to a complete fracture.

A 1991 paper by Cambridge academics[24] provided a summary diagram of the factors that contribute to rolling contact fatigue in railway rails (**Figure 6** is a simplified version). While the

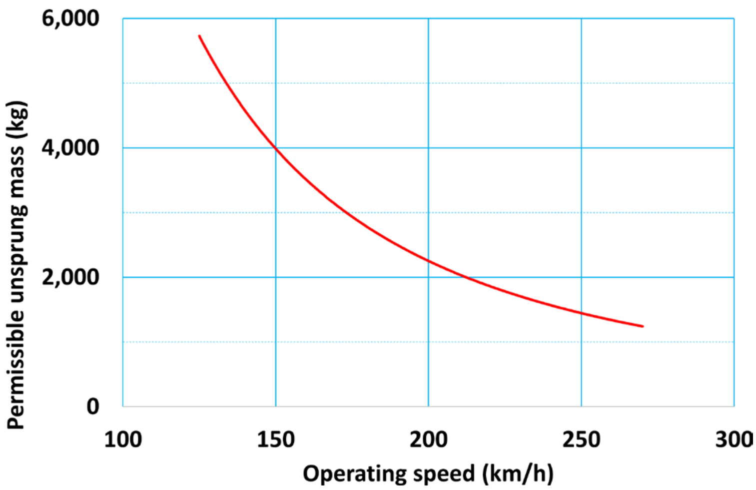

Figure 5: The Deltic criterion.

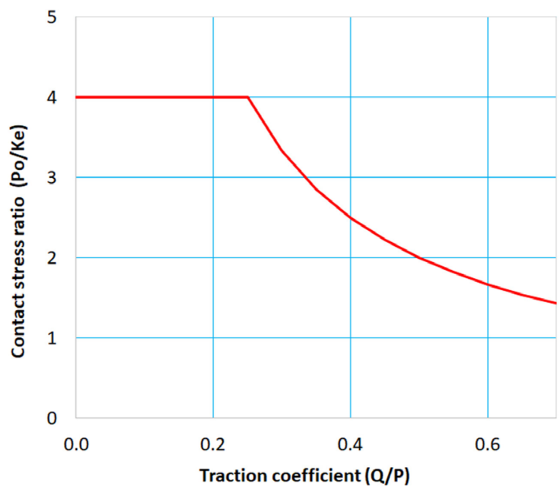

Figure 6: Susceptibility of rails to RCF.

operating point is in the elastic region, the rail surface flexes, but goes back to normal; if it is in one of the flow regions, it distorts permanently and, over time, can crack.

The two axes on the diagram are contact stress (P_o/K_e) and traction coefficient (Q/P). The four parameters are:

P_o – Contact pressure between wheel and rail

K_e – Yield stress of the rail material

Q – Horizontal traction force on the rail

P – Vertical wheel load

Contact pressure (P_o) is influenced by the wheel diameter, axleload, wheel/rail profile mismatch, track smoothness and cornering speeds. For passenger rolling stock, there was pressure to minimise wheel diameters to allow lower floors and ease wheelchair access. Reducing axleload (P) requires either more, but shorter, vehicles or advanced construction techniques using light alloys, rather than steel; both add cost.

Evolution of rail vehicle design

The way in which primary yaw stiffness and axle loads have evolved over the years is indicated in **Table 1**. (It must be stressed, these are particular examples of comparable passenger vehicles; not all vehicle types showed equivalent trends.)

The Mark 3 coach was the standard 125 mph British Rail coach from the mid-1970s, used, electrically-hauled by the Class 87 and Class 90 locomotives, on the West Coast Main Line and in the diesel-hauled HST (IC125). The Mark 4 coach was the 140 mph 1990s design used on the IC225. The Class 319 was designed in the mid-1980s as dual-voltage multiple units running under London from Bedford to Brighton. The Class 175 Coradia were diesel multiple units, originally running in North Wales and North West England. In both examples, it can be seen that the primary yaw stiffness has more than doubled and axleload has increased a little.

The other area where vehicles have evolved is in the tractive effort produced by a locomotive. Each of the Class 43 power cars, at either end of a 1970s IC125 train, produces 80 kN. The single Class 91 power car at the north end of an IC225 can produce 190 kN – more than twice the tractive effort.

Both passenger vehicles and locomotives had evolved to meet the commercial demands of the industry, but there appears to have been no recognition of the effect this evolution could have had on rolling contact fatigue. For an insight into this, it is interesting to consider how rolling stock on that route developed:

- Express steam locomotives, prior to 1961, had (by modern standards) very large wheels, so the contact stress was low. Coaches were wood bodied with low axleloads.
- The next generation consisted of Class 55 Deltic locomotives hauling Mk 1 or Mk 2 coaches. The Class 55 used two Deltic[26] engines, each rated at 1,230 kW. On a six-axle

Vehicle	Primary yaw stiffness (MNm/rad)	Axle load (kN)
Mk 3 coach	17	100
Mk 4 coach	41	115
Class 319	13	150
Class 175	49	155

Table 1: Evolution of bogie characteristics[25]

locomotive, this represented around 300 kW/axle, by the time train heating and auxiliaries had been taken into account.

- From 1978, Deltics were replaced by the 200 km/h High Speed Trains (HSTs), also called IC125. The 4-axle, 70-tonne Class 43 power cars produced 1,320 kW at the rail, or 330 kW/axle.
- Then, from the late 1980s, the IC125s were replaced by the IC225. The 225 km/h, 80-tonne Class 91 power cars produced 1,200 kW per axle.

It can be seen how the speed, weight, power and tractive effort of locomotives crept up over a period of 30 years. At the same time, passenger vehicles increased in weight, because of higher safety standards and improved passenger comfort (air conditioning etc) and their bogies, optimised for higher speeds, became stiffer and thus more prone to triggering RCF. This is what Sidney Dekker refers to as a 'Drift into Failure',[27] when a hazardous situation arises gradually as the result of a large number of small changes, none of which, in isolation, justified a safety analysis going back to first principles.

Endnotes

1. *Safer complex systems, an Initial Framework*, S. Burton, J. A. McDermid, P. Garnett and R. Weaver, University of York. Published by the Royal Academy of Engineering, 2020.
2. *Train Derailment at Hatfield: A Final Report by the Independent Investigation Board*, Office of Rail Regulation (ORR), July 2006 (page 3)
3. ORR op cit page 17
4. ORR op cit page 114
5. Wikipedia – description of the accident and investigation
6. Thomas Piketty, *Capital in the 21st Century*. Harvard University Press, 2014
7. Rail Finance: 2018-19 Annual Statistical Release. https://dataportal.orr.gov.uk/media/1548/rail-finance-statistical-release-2018-19.pdf
8. https://www.hse.gov.uk/managing/theory/alarp3.htm
9. Derailment of London to Glasgow Pendolino train at Grayrigg in Cumbria, 23 February 2007
10. *Foresight review of the future of regulatory systems: Regulating in a disruptive world*. Lloyd's Register Foundation, Report Series: No.2021.1, March 2021
11. Note: Organisations, roles and responsibilities have changed significantly, and several times, since the 1990s.
12. *Leading health and safety at work – Actions for directors, board members, business owners and organisations of all sizes*. INDG417(rev1), HSE June 2013, www.hse.gov.uk/pubns/indg417.htm.
13. *Business re-engineering and health and safety management*. HMSO 1996; ISBN 0 7176 1302 X
14. *Safer complex systems, an Initial Framework*, op cit, 2020.
15. **Balkanise** – (1) to divide a territory into small warring states (2) to divide a group or organisation into small factions. Collins English Dictionary.
16. The Independent Review of Building Regulations and Fire Safety https://www.gov.uk/government/collections/independent-review-of-building-regulations-and-fire-safety-hackitt-review
17. In contract, joint and several liability arises when two or more persons jointly promise in the same contract to do the same thing, but also separately promise to do the same thing. If any of the parties drops out, the others have a responsibility to ensure the contract is completed.
18. James Reason, *Human error: models and management*; BMJ 18/03/2000 pp 768-770 (and several other journals)
19. **nerd**, UK slang, a boring or unpopular person, especially one obsessed by something specified: a computer nerd. Collins English Dictionary, 2005.
20. https://www.theguardian.com/law/2018/oct/27/cps-alison-saunders-justice-system-cannot-cope-resources
21. Sidney Dekker, *Drift into Failure – from hunting broken components to understanding complex systems*, Ashgate, 2011, ISBN 978-1-4094-2222-8
22. At the time, electrical connections at 25 kV between vehicles were said to be prohibited (although no-one could identify a definitive document). Apparently, this was due to an incident on London Underground in the 1960s when a train with a 600 V busline came to rest across the boundary between different electrical sections, one of which was isolated, which caused a fire. The situation on the mainline ac network was completely different but the ruling resulted in the *Advanced Passenger Train* ATP-P having its power cars in the centre of the train – a bizarre train formation – and the single power car on the IC225. A more rational approach was subsequently allowed so the Channel Tunnel Eurostar, the West Coast Pendolino and many subsequent trains have high-voltage train lines.
23. R. J. Kemp & G. R. West, *British Rail Class 91 locomotives*, GEC Review Volume 4, No 3, 1988
24. A F Bower & K L Johnson; *Plastic flow and shakedown of the rail*

surface in repeated wheel-rail contact; Wear 144 (1991) pages 1 to 18, Elsevier.

25. Data from various sources, including Arup TCCI report, Jan 2001

26. So-called because the cylinders were arranged in a triangular formation, like the Greek letter Delta.

27. Sidney Dekker, *Drift into Failure – from hunting broken components to understanding complex systems*, Ashgate, 2011, ISBN 978-1-4094-2222-8.

Conflict of interest statement

Roger Kemp was Engineering Director of GEC Transportation Projects Ltd during the time that the Class 91 locomotive (the motive power of the IC225) was designed, built and commissioned. Following the acquisition of GEC Power Engineering and Metropolitan Cammell (the builder of the Mk4 coaches also involved in the crash) by the French company Alstom, he spent some time in Paris, first as systems Engineering Director and, subsequently, as Project Director for the Eurostar trains. At the time of the Hatfield crash, he was UK Technical and Safety Director for Alstom Transport and, subsequently, represented UK vehicle builders on the (short-lived) Wheel-Rail Interface System Authority (WRISA). From 2003 to 2020, he was a Professorial Fellow in the Engineering Department of Lancaster University.

Acknowledgements

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

Affiliations

Prof Roger Kemp MBE FREng, Emeritus Professor, School of Engineering, Lancaster University